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Section 1 – Executive Summary

Many locations around the world do not have reliable energy sources. A lack of reliable energy in these remote locations, resist 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. Some of the energy sources available are generators, hydroelectric, wind, and photovoltaic power. Generators are very reliable sources of energy, but are hazardous to the environment. In the process of producing energy CO_2 is emitted from the generator. Carbon dioxide in the atmosphere causes a greenhouse effect and destroys the ozone. Hydroelectric power is efficient and clean, but there are geographical constraints. In order to implement a hydroelectric power station a source of flowing water is essential. Wind power is a clean energy source, but one of the drawbacks is that it requires sustained winds. Photovoltaic power generation is an abundant source of clean energy and low maintenance.

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 generated is greater than the power drawn, power is distributed directly to the load and the excess is stored into a battery bank. If the battery bank is full then the excess energy is used for float mode. When the power generated is less than the power drawn, the battery bank is used to supplement the lack of power being generated. An inverter is needed to convert the energy into usable power for consumption.

Providing power will set a strong foundation for the village to prosper. The power provides energy for lighting and computers. The computers will be a source of knowledge and entertainment for the community. This energy will also be used for essential communication devices, such as cell phones and radios.

Solar power generation sets the boundaries between progress and retrogression. The energy will give them access to educational information on the internet. Applying this knowledge to a real world problem will help in the development of this community. Communication is another benefit of electricity. Now the community will be able to get emergency information from a radio and the internet. This project has set a foundation of energy independence. The flexibility of the design will allow for future expansion of the system. Our expectation from the community is to take advantage of the benefits that this system will provide to them and grow as a community.

Section 2 – Project Description

In order to implement a self-sustaining and renewable energy system, which does not have an impact on the environment, photovoltaic panels are 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 consists of four photovoltaic panels each capable of outputting 235 watts of power during peak conditions. The power supply feeds DC current to the charge controller to charge the battery bank.

A microcontroller was installed to monitor the system in the charge controller. The charge controller must monitor the voltage input and output to change the duty cycle of the buck-boost dc-dc converters to regulate the input voltage to charge the batteries. There are four buck-boost dc-dc converters in parallel to split the current of the panels to regulate the voltage. If the batteries are less than 90% charge then it goes to float mode and slowly charges the last 10% of the battery bank. The output voltage is based on the state of charge of the battery bank.

The battery bank has three 6 volt deep-cycle batteries in series to create a 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 220V and 50 Hz. This module consists of multiple parts. First, the inverter module has an inverter component, the H-bridge, to convert the power from DC to AC. Then, a perfect sine wave generator is 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 using a transformer.

Section 2.1 – Project Motivation and Goals

The motivation for the clean energy power generation project comes from having the desire to help others, set new standards, and the excitement to solve a real world problem for our senior design project. We believe that our group is the perfect candidate to carry out this project. Our team is composed of individuals that are leaders and understand the concept of working as a team. As good leaders we have stepped forward to deliver this project to the best of our ability. The reason we have selected this project is because we know that we can put our skills and work ethic together and get the job done to help others in need. There are South African villages that have no food, education, or electricity. The purpose of this project is to be able to provide clean energy at low cost and ensure high efficiency, low maintenance, safe to operate, user friendly, and inexpensive to repair.

We are excited about the opportunity this project has given because our group likes to help people and we also have an interest in power systems. We saw the opportunity to incorporate both. Knowing that the users of our system have little to no education we know our project needs to be low maintenance and user friendly. For the safety of the users we created a system that people with little experience in electronics can safely operate. We created a system that would be inexpensive to repair in order to keep the cost low when replacing parts. Lastly, given a limited budget we were focused on creating a high efficiency system as this will play a very important role due to the village's energy consumption. Our project will open new frontiers for the South African people to have a better lifestyle and be able to start an education through the recreation center.

The goal of this project was to generate, store and distribute energy to the recreation center. The first goal of the project was to create a self-sustaining power system that will help a village in South Africa who is unable to afford electricity and few simple pleasures of life. It was our focus to supply enough power where they are able to charge their cell phones, use their projector, their computer, and a few lights. This project will allow the people of the village to have a better quality of life being able to have some entertainment, education, and communication with others. The computer and projector can be set up for entertainment purposes like movie nights, while on the other hand, for educational purposes as in teaching a session. The computer will also be a great learning tool especially for the younger individuals. Communication will be more accessible do to having charged cell phones and also a computer where internet is viable to send electronic mail or instant messages.

The second goal of the project was to work together as an engineering team and getting real world experience designing a system. The project gave the team a chance to design two subsystems in the project that need extensive research, and purchasing the remaining subsystem to create a successful project. The two subsystems were needed to be compatible with the other subsystems and be able to handle a set of specifications in order to benefit the South African village. A focus of working together as a team, was communication, we realize this was one of the most important skills we gained from this project. Another focus of ours was to better understand the effort that goes into designing, prototyping, and testing a project that will be used.

Section 2.2 – Objectives

The objective was to design a 1000 watt power system. The system is self-sustainable, reliable, clean, and easy to maintain and repair. These features allowed for a challenging design process that tested the knowledge of each group member. Each system works and communicate with each other to determine the best response on how to handle the current state of the entire system.

Section 2.2.1 – Environment

There have been many environmental issues that have presented themselves throughout the recent years, as a result of obtaining or in attempt to obtain a reliable energy source. Many towns, here in the United States, have had their water supplies contaminated with poisonous chemicals. To prevent environmental complications a charge controller was implemented. The charge controller distributes power directly to the batteries. A fully featured charge controller is important to the environment because the batteries cannot be overcharged. The controller must recognize when the batteries are fully charged and respond appropriately to the state of the whole system. When the batteries are fully charged the battery bank will go into float mode to keep the batteries charged at full power. The result of overcharging batteries can be catastrophic. Overcharged batteries could crack and leak acid. The acid is harmful to clean up because it can burn skin. The acid can be absorbed into the ground and cause environmental issues in the future. The charge controller must work properly to prevent damage to the system and the environment.

Section 2.2.2 – Efficiency/Safety

The system must run as efficiently as possible. All the subsystems need power to operate. Since the energy that is being generated is highly valuable to the community, the system must run efficiently to give the community the most amount of power possible. Using parts that require less energy is vital to the project. The design must be energy efficient because the power being generated from the system is renewable, but not always abundant.

When generating power there are safety issues that arise. The system must be designed in an organized manner that promotes safety by reducing cluttered wires and clean electrical connections. Designing with safety in mind is a tedious task, but the most important design aspect. By knowing what part of the system is broken, repairs can be done efficiently. Taking apart subsystems that do not need repairs, just to test them, can cause more problems if they are not reassembled incorrectly.

Section 2.2.3 – Performance

The system must be self-sustaining. In order to achieve that objective the charge controller must be reliable and robust. There are many parts of the systems that need to be monitored. In order for the charge controller to monitor all the subsystems it must be able to process all the data. In order to process the data, the charge controller has enough pins for numerous circuits and it is able to process the data that it receives in a timely and efficient manner.

The devices that will be plugged into the power system have strict power consumption requirements. The devices need to have an input of 220Volts and 50Hz frequency. If the power supplied to these devices does not meet these specification it can cause damage or malfunctions of the devices. The design of the inverter maintains a low level of error. With a low level of error the devices will function properly, increasing the life span of the devices. The objective of the inverter was to create a pure sine wave. The inverter does ensure safe operations of the devices that will rely on the systems for power.

Section 2.3 – Project Requirements and Specifications

The system is a standalone and not connected to a power grid. It supplies solar power to the power storage only. The power storage system are in a series combination to get enough voltage to allow the transformer to step up the voltage to 220. This system cannot be able to connect to a power grid.

The system is easy to maintain and control for a novice person with technology. The users will be able to monitor the system using an array of LEDs to tell the user the status of the battery bank.

Section 2.3.1 – Power

The solar panels is able to withstand the heat of the sun daily for a period of 13 hours, during the summer and less for the winter, for the next fifteen years. The town's people will be able to use the solar panels for additional power generation if they decide to replace or upgrade the system in future years. The charge controller is able to handle the max current coming in from the power supply.

The wire to connect the solar panels to the charge controller is a fourteen-gauge wire, it is sufficient to handle the maximum current coming into the system, 32 amps. The power from the solar panels splits to the four buck-boost converters to regulate the voltage. All of the major connections will use a zero-gauge wire. The battery bank, which stores the power, will be connected using zero gauge wire, as there can be much more current leaving the system than entering.

The charge controller is responsible for charging the battery bank. The charge controller has some feedback features to monitor the system. The microcontroller has a circuit to find out the input power and output power to handle the conditions. The microcontroller also gets feedback from the batteries to know if they are charged. The inverter uses a perfect sine wave generator to maximize the power. The inverter is responsible for the DC to AC conversion and a step up transformer to power and use the different electronic devices or machines. The inverter outputs 220 volts alternating current at 50 hertz and up to 1,000 watts. The power that will be inverted will come either from the batteries directly. The charge controller displays how charged the battery bank is using a LED stack light.

The solar panels peak at 235 Watts and there are four of them in our system connected in parallel. The currents merge and the output voltage is the minimum of the four panels. The charge controller takes up to 40 amps of input because the maximum input of the solar panels is 31.68 amps. The charge controller will output 20 volts to the battery bank to charge it. There must be three batteries that are six volts at 215AH to be able to store enough power for the system. The batteries will not discharge more than 50% of their power; otherwise, the system will shut down. The system at peak performance will be able to output a 1,000 watts of power. The system should last 7.5 hours at 10 amps per hour.

Section 2.3.2 – Temperature/Climate

Another factor for specifications is the climate conditions of South Africa. The climate can play a major factor on the operation and efficiency of the electrical components. For example, semiconductor devices have an operating range of temperatures; if the temperatures go outside of the range then the device is not guaranteed to work. According to table 1 the temperatures in South Africa range from -2°C to 27°C throughout the year. In order to achieve high reliability of the system military grade components was used for most components. Military grade components operate in the temperature range of -55°C to 125°C. Using military grade components will insure that the system will be able to operate in the hot summers and freezing winters of South Africa. Without knowing the exact storage location of the system, using military grade will ensure that even if the system is enclosed with systems that are producing heat, the device will be still operate in a hot enclosure. The largest concern for the operating range for military components for the project is what components will be producing heat and how will the heat affect the rest of the components.

Month	Temperature °C			
	Average		Absolute	
	Max	Min	Max	Min
January	27.22	12.89	34.78	0.00
February	26.72	20.70	33.39	1.78
March	25.22	10.61	34.11	0.00
April	22.72	6.39	31.22	-4.00
May	5.50	1.61	27.00	-10.00
June	17.39	-1.78	24.11	-9.00
July	17.28	-2.22	24.61	-12.50
August	20.22	0.61	27.39	-10.22
September	23.72	4.28	30.72	-6.78
October	25.11	8.11	31.89	-2.89
November	11.67	10.00	32.78	0.22
December	27.00	11.89	36.39	3.22

Table 1 Meoweather converted from °F to °C

Another concern that is unknown due to the unknown storage situation is the humidity. Since water and electricity do not mix, the components chosen are able to operate in high humidity. Humidity can cause short circuiting on integrated circuits. Similarly, precipitation is also a concern, so the components were to be placed in weather proof enclosed case. The integrated circuits will have to be enclosed in plastic cases.

Section 2.3.3 – Tolerance

The tolerance of the system is very important. High level of accuracy is essential to the longevity of the system. Many individual components must be very accurate in order to achieve the goal of the project. The accuracy will ensure that components that rely on other components will function properly and not be damaged.

In order to achieve this level of accuracy in the system, components that have a high level of accuracy were used. Metal thin film resistors were used. Metal thin film resistors have a tolerance of less than 1%. Since several components will be using the resistors it is very important that the resistors are accurate to prevent an inaccurate issue from cascading. For the feedback circuit a variable resistor was used to get a more accurate reading to be sent to the microcontroller. The microcontroller has a 10 bit resolution so that the pin is sensitive to almost 5 millivolts. The microcontroller relies on the accuracy of the variable resistor and the metal thin film resistor to get an accurate reading of the voltage input and output on the charge controller to change the mode between buck and boost mode and to change the duty cycle in order to regulate the voltage to the proper value. The microcontroller will rely on the voltage divider to let it know when the batteries are charged or need charging. In order for the charge controller to function properly and protect the battery bank, it needs to know very accurately what the voltage in the batteries is. Since the accuracy of the voltage is dependent on a voltage divider, the tolerance of the resistance is important to the shunt regulator.

Section 3 – Research

The technology surrounding the components of a fully functional photovoltaic system have been studied, developed and used for more than sixty decades. The study of this technology has been intensively researched, but the truth is that it is still far away from delivering is full potential and even farther away from becoming the present solution for our colossal energy needs around the world.

Due to this reason we cannot rely on this type of technology, as consequence it cannot be used as the replacement for the other type of non-renewable energy sources used in the present. Many other renewable energy power systems have been created; its use varies from main or secondary energy sources depending on the size and required functionalities. In the following sections, a few similar projects will be introduced with the purpose of comparing the project presented in this report with other projects created with similar objectives and requirements. Relevant technologies and strategic components for this report will be introduced with the purpose of acquiring a general knowledge of the expectations and minimum requirements the project may need. Finally, a brief introduction to key diagrams and architectures will be shown for a better understanding of the general design of the project.

Section 3.1 – Existing Similar Projects

There are many projects over the last 20 years of people researching and buying solar panels. As research has progressed, like any technology, it has become more cost effective and more viable for people to purchase and utilize. The decrease in cost now has solar renewable energy at competitive pricing to destructive fossil fuels. Businesses and governments are putting up solar panel systems because they see the savings and to help stimulate the economy. The decrease in price has also helped many people put up small systems in their backyard to reduce their carbon footprint and pay less every month to the electric company or sometimes store credit with their electric company, if they are using less than they are producing. This ideal is spreading quickly as governments also have incentive packages to install solar panels and are looking to become more energy independent.

Besides the typical homeowners putting up home solar systems, so have small towns and communities. Rural areas in other countries, in most cases if they are able to front the cost, it is practical, more affordable, and safer to put up and use renewable or alternative energy sources compared to the typical energy counterpart, as what is later mentioned.

Section 3.1.1 – A Solar Japanese Village

The Japanese project convinced some villagers to build a large renewable energy source. The decision for the project came shortly after the Fukushima nuclear disaster. The small village of Sanno has less than a dozen homes. Just over a year after deciding to use solar power as the village's main energy source the solar panels are now fully functional. The power system being designed will be donated to the town, unlike how the Sanno people received some help from their government. The government bought some of the Sanno people's land from them. The After 17 million Yen or about $215,000 the village now has a system that generates 40,000 kilowatt-hours per year. This is just enough power to supply the homes with electricity. The electricity is sent to the local power company and they deal with the conversion and storage of the power. The company will spend about $23,000 per year. A major difference between the two projects is that this design will not be connected to the grid, whereas Sanno was able to and they came to an agreement with the power company. The great benefit is the towns people will not have to worry about another Fukushima and the panels cover all of their energy expenses. The Japanese project is similar to this project because it is on a small scale and will be able to handle the needs of the community center sufficiently, much as Sanno covers their town's energy needs (Coldewey).

Section 3.1.2 – Small Town Renewable Energy

The small town of Fowler has just over 1,000 residents and about half a million head of cattle. It is in between a 150-mile stretch between the city of Pueblo and the Kansas border. Being in a rural area in a down economy they price of electricity was on the rise. Much like this project, the township of Pomolong has access to the grid, but it is unaffordable to the township to connect to it. Fowler tried looking to alternatives to help with energy needs. Some of the ideas that were discussed were utilizing the cow manure for methane, to a wind farm, and solar panels. Pomolong does not have any major resources to bargain with, but they are reaching out to solve their energy needs. The $1.2 million solar projected generates about 4.2 megawatts of electricity. Fowler now pays about half of the rate the utility company charges. Their efforts attracted help from Colorado State University, the National Renewable Energy Laboratory. They celebrated the completed project with the visit of the governor. In the future, Fowler also wanted to add another 2-megawatt system to the southern part of the town. The town's administrator at the time also mentions that if this additional system were to be completed the town would purchase electricity for $0.06 per kilowatt and the utility rate is about $0.15 per kilowatt (Levitan, 2012).

Section 3.1.3 – Bicycle power Generator Design for DC House

This project created by California Polytechnic State University implemented the creation and installation of a power system that will provide energy without grid dependence. DC power will be produced by a properly designed stationary bicycle. This energy will be stored in batteries and it will be delivered for the daily use of electronic devices and lights. This project is relying in the power production that comes from the conversion of mechanical power to electrical power. Another focus on the project was to create energy not only in specific places or situations, but also with the intention of being portable to be delivered globally. It is more efficient than most of the other bicycle power generators created in the past. The decision that inclined this project to produce power coming from a bicycle, was in theory to the fact that all of the natural power sources are not truly independent in its purest definition. Natural power sources are sustainable but are not independent due to the fact that water, wind or solar energy depends on the will of nature. The advantage is that it will not only work as regular source of energy, but it will also be of use in an emergency in the case of a failure from the other main sources. This source of alternative energy is also of great use to improve consciousness towards energy conservation. The energy will be produced by the people; as a consequence, people will understand how important it is to use it adequately. (Hayes & Goguely, 2011)

As independent and clean this power is, it depends on humans. It is clearly known that humans cannot exercise to create clean power for extended periods of time. This type of energy production can only be used on small scale and in emergency situations.

Section 3.1.4 – Design and Implementation of a Solar Power System in Rural Haiti

The Massachusetts Institute of Technology created this project back in 2004 to provide energy for a school and a health center in Haiti. This project had a requirement to be able to produce enough energy for lighting and refrigeration. As noticed, the project in general seems to be very alike to the project presented in this report. The Haiti project contains solar panels, battery banks and a controller, but it avoids the use of a DC/AC inverter. Their decision to avoid the use of the inverter component was taken to stay away from any power loss and inefficiency. As consequence they knew that their system would be much more limited in end user applications due to the lack of an AC system. The similarities in this project compared to the one in this report are focused on minimizing the cost and maintenance of the system. They also wanted a simple system that can be easily maintained by the community. A disadvantage for this kind of system is that it depends on the sunlight, which makes it inefficient in cases were the weather conditions does not allow the system to capture enough sunlight. (Hussam, 2004)

Section 3.1.5 – Tohoku Relief Project – Wind/Solar Energy Power Generator

This project created at UCF is similar to the project presented on this report. In this case, their project focus was to generate energy not only with solar panels, but also with a wind turbine in their system. Similarly, their motivation was to help a community in Japan, after the tsunami disaster. Their objective was to provide energy in a university to essential devices to hold classes without interruption in case of a power outage. While the senior design group was not directly involved in the beginning of the project, their focus was to improve its functionalities. As a result the system became more efficient, portable, and more cost effective. Another focus of the project was to create a system with minimum interaction and maintenance so it could remain practically autonomous. In contrast to the project in this report, the main difference is the purpose of its creation. The purpose of the *Tohoku Relief Project* was created to serve as a secondary source of energy in case of an outage from the grid. Some of the green energy sources that have been highlighted are the bicycle generator, solar power, and wind power systems, but more than 90% of the electricity generated in the United States is nonrenewable energy. (Ali, Comer, & Walls, 2012)

Section 3.1.6 – Nonrenewable Energy Sources

One of these nonrenewable sources of energy production is coal. Starting with the positive points, this combustible is very abundant around the globe. It is the only source of energy abundant enough to keep up with the demand that the United States requires. Coal energy production accounts for 40% of the electric generation in the United States and 70% of China’s electric generation. The reason why it is popular is not only because of its abundance, but also its low price. Coal is the cheapest energy source available, even cheaper than wind, it offers a continuous power and it is a mature industry. Its entire infrastructure has been developed and improved over many decades and it gives a false impression of a lower capital investment compared to other sources such as nuclear energy or gas. The truth is that while we are coal dependent, it does not mean it is a good source of energy. There is a finite supply and coal is the largest contributor to global warming. Coal energy causes severe environmental and social and health impacts created by disposal issues. While many people may not know it, coal creates higher levels of radiation than nuclear plants. The truth is that while many people consider coal as a cheaper energy source compared to any other used today, the environmental costs it creates makes it much more expensive. (Siegel, Clean Coal: Pros and Cons, 2012)

Natural Gas is the second largest source of electrical power generation in the Unites States. This kind of energy source has become more popular with the population; the news has been promoting natural gas as a solution to our energy problems due to the fact that it has been perceived as a less environmentally destructive source of energy. Natural gas has many positive reasons to be used. It is the cleanest source of energy of all the fossil fuels, it burns efficiently and compared to coal and oil, it emits 45% and 30% less CO2 respectively. There is an abundant supply and its delivery infrastructure has already been implemented. It can also be used as automotive fuel and has many more uses. It certainly is a nonrenewable fuel; it emits CO2 and contains huge amounts of methane, its transportation requires expensive and extensive pipelines, it is potentially a dangerous explosive, and increases the environmental effects of hydraulic fracking. This source of energy is definitely not a solution to our energy production problem. The reality is that gas should be uses as transitional source of energy while sustainable energy alternatives become more reliable. (Siegel, Natural Gas: Pros and Cons, 2012)

Another popular source of energy used not only in the United States, but also around the world is nuclear energy. While it lost a lot of prominence in the 70’s it is now a viable option because it emits fewer greenhouse gases than coal or other power sources due to the development and improvement accomplished with the newer nuclear plants compared to the traditional power plants. The technology for nuclear energy has been unreliable and unsafe in the past. Now that the technologies have improved it has become a viable solution. This kind of technology has been well developed and researched, creating a great advantage for delivery and efficiency. It contains the capability of creating large amounts of power needed for a whole city and a lot of recycling processing technologies has been improved to control the nuclear waste created by these plants. On the other side of the coin, nuclear energy created a lot of problem for the environment. The construction of these power plants is expensive and in case of an accident the risks are too high and its consequences are dangerous for the surroundings around the nuclear plants. (Buzz , 2009)

Hydroelectricity is another source of energy production. This electrical power is generated by the flow of water. This kind of energy is widely used around the globe contributing to 16% of the electricity around the world. The reason why this kind of energy is used widely is due to its relative low cost in comparison to other kinds of renewable energy sources. However, this kind of technology requires large amounts of land occupancy and that directly affects the ecosystem surrounding it. Wildlife and population around the area must be displaced. The construction of a large hydroelectric facility takes years to finish; but once the project is done the production of CO2 or any kind of waste is considerably lower than for example coal, nuclear or natural gas power energy plants. (Atkins, 2012)

Section 3.2 – Relevant Technologies

Solar power systems have been researched and developed for over 60 years. A solar power systems as previously described includes multiple parts. Each part has had many scientific advances since the early days of their respective creations.

Solar cells have used different types of cell materials in order to convert energy from the sun, using the photoelectric effect. Not only including the different materials, but also making the materials either more pure or using them differently.

The storage systems have had some advances as well. The oldest of batteries, used in solar applications, is the lead acid. Some of the newer ones on the market are the Absorbed Glass Mat batteries and the Gel batteries, which have been increasingly more popular in solar storage because of their internal architecture.

Third, the way the different batteries are charged. As electrical circuitry have made advances in creating new components as well as make the existing components more efficient. Microcontrollers are able to monitor the storage system and extend the life of the power storage because different methodologies have been able to be implemented. On the same token, the inverters are now able to be more efficient as different topologies and circuit components are able to invert the power more effectively. This section will explain the different technologies for the different parts of the system and how the technology is applied.

Section 3.2.1 – Monocrystalline

Monocrystalline has been the leader among the industry of solar cells. It is the oldest, most efficient, and most dependable way to produce electricity from light. Monocrystalline has a continuous crystal lattice structure which makes it highly purified and very efficient. That is why this technology is capable of converting the highest amount of solar energy into electricity. The tradeoff for this high efficiency is cost. The process of manufacturing silicon with a single crystal structure makes it more expensive. Monocrystalline panels were the first generation of solar technology and its longevity has proven to be promising. Panels that were installed in the 1970’s are still producing electricity today. These panels have also been tested in rigors space travel. It has been suggested that monocrystalline silicone panels can last up to 50 years. Although they can last a long time, their efficiency is lost on average of 0.5% per year. These modules have a 17% conversion efficiency, which means that it can convert 17% of the sunlight into electrical energy. The disadvantage of this technology is that it comes at a higher cost than any other solar technology.

Something else to consider is that these panels are fragile and they can be broken relatively easy by falling trees, branches or objects carried by strong winds. Monocrystalline panels are affected by temperature and their output is reduced once temperatures go above 25°C (Advantages and Disadvantages of Monocrystalline Solar Panels, 2011).

Section 3.2.2 – Polycrystalline

Polycrystalline panels are very competitive as far as cost. They are among the cheapest panels available in the market. They are made up of multiple crystals which make up a module. These modules are less effective than monocrystalline panels, but they are much cheaper. Polycrystalline panels are capable of converting 12-12.5% of the sunlight's energy into electrical energy. The longevity and durability of this panel is equivalent to a monocrystalline panel. These panels are also affected by temperature just as much as monocrystalline panels (Advantages and Disadvantages of Polycrystalline Solar Panels, 2011).

Section 3.2.3 – Thin-Film

Thin-Film Solar panels are starting to become a big competitor in the solar market. This technology can achieve conversion efficiencies between 7-13% and future modules are expected to reach 10-16%. This relative new technology grew at a 60% rate from 2002 to 2007. Another great characteristic of this module is that it is cost effective. A more important and unique characteristic that stands out from other modules is that it is flexible. This means that it is not as fragile as the other modules and it has potential for new applications. High temperatures and shading have less impact on the performance of this solar panel.

It is important to review the different types of technology that are available to select the correct panel for a solar project. The main factors that were seen between the different types of technology were price, conversion efficiency, temperature effects, and fragility of the modules (Whitburn).

Section 3.2.4 – Absorbed Glass Mat (AGM) Batteries

The AGM batteries are a newer battery that is sealed and deep cycle. These batteries use the mats within the battery to hold the acid and as such, they will not leak acid even if they work to break. The Oxygen and Hydrogen recombine within the battery so there is minor water loss through the electrolysis process; it is about 99% efficient (Northern Wind & Arizona Sun). They batteries do not heat up during charge or discharge because there is such a low internal resistance. Most of these batteries do not have charge or discharge current limits. These batteries are practically immune to freeze damage because there is no liquid in the battery (Northern Wind & Arizona Sun). They have a very low self-discharge rate. These batteries tend to cost one in a half to two times more than a typical flooded battery (Northern Wind & Arizona Sun).

Section 3.2.5 – Gel Batteries

The cells in these batteries have Silica Gel that has been added to the acid to create a gel substance that is similar consistency to Jell-o (Northern Wind & Arizona Sun). The great thing about these batteries is they are unable to spill acid because of the jelly substance, which makes them non-hazardous. They must slowly be charged or as a result, the gas created from charging will damage the gel (Northern Wind & Arizona Sun). If they batteries are ever over charged they will lose battery capacity due to damaged cells.

Section 3.2.6 – Flooded Deep Cycle Batteries

The deep cycle batteries are meant to have a heavy discharge to the battery and recharge. Most deep cycles are able to handle 50% - 80% discharge, but too many discharges at 80% will greatly shorten the batteries life, so a 50% discharge is recommended. These batteries are created using thick Lead plates to handle these deep discharges and recharges. The thick Lead plates do not allow room for much surface area therefore they are not good to use for short bursts of energy, but rather longer more constant current draw. These batteries produce a gas when charging and need to have ventilation. Clean water should be added to the batteries periodically to keep the batteries in good condition.

Section 3.2.7 – Flooded Starter Batteries

These batteries are quite the opposite of the deep cycle.   They use thinner Lead plates and more of them to increase the surface area of the plates. This allows the battery to be able to output a large current for a short period. These batteries can usually take a 2% - 5% discharge thousands of times, but would only be able to handle about 100 deep cycles at 50% because of the chemical break down to the lead plates (Northern Wind & Arizona Sun). These batteries like the deep-cycle also need to be maintained by adding water to the cells periodically and keep the batteries in a well maintained area due to the gas produced during charging.

Section 3.2.8 – Constant Voltage/ Current Charging

Constant current charging is great to slowly charge a battery. This charging method sends a small amount of current to the battery over an extended period, 12-24 hours, of time to charge the battery. Using constant voltage or constant current is ideal for some batteries like the lithium-ion, nickel-metal-hydride, and nickel-cadmium batteries that need a constant voltage or constant current while charging. Charging at a constant voltage will initially allow a big flow of current to the battery for a quick charge, as the potentials between the battery and the charger are great (U.S. Department of Energy). The last 30% or so of the battery will take the majority of the time to charge because current will not be able to flow as easily now that the voltage of the charger and the battery are approaching each other. Since the constant voltage gives a quick initial charge, this method works great for cheap car chargers.

Section 3.2.9 – Maximum Power Point Tracking (MPPT)

In a MPPT system, the maximum power point tracker senses the voltage and current that is coming in from the solar panels. The tracker then finds the maximum power point either via P-V curve or the I-V curve as shown in figure 1.

Once the maximum power point (MPP) is selected the DC/DC converter will know how to convert the incoming power. The DC/DC converter consists of a DC/AC converter and an AC/DC converter followed by a voltage regulator. The reason for the conversion is to not lose power when regulating the voltage, but rather maximize it. The excess voltage gets converted to current. This method of using the MPP allows the system to have about 98% efficiency (Lohmeier).

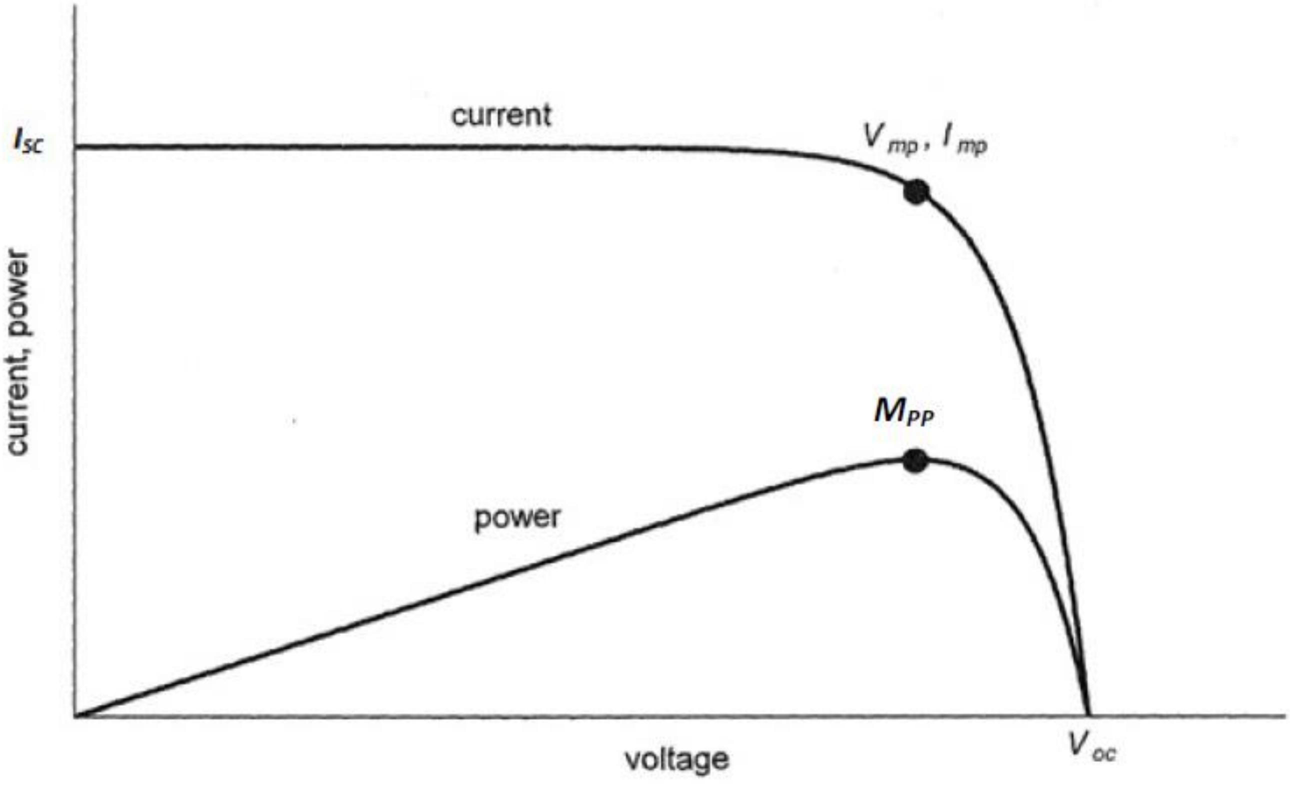


Figure 1 A representative I-V and P-V curve for a solar cell showing the MPP, permission from Lohmeier.

Two methods can be implemented to find the MPP, perturb and observe (PAO) method and the incremental conductance. First PAO, it constantly checks to see if the operating voltage needs to increase or decrease. The PAO method checks the old power output compared to the new power output if the new power output is greater, the change is kept and so is the voltage direction, increase or decrease until this computation is false, then the opposite voltage direction is taken. This method is a continuous check and the output power will oscillate around the MPP, and never stabilize. A problem with this is if the incoming irradiance levels rapidly change, it can cause the algorithm to take the wrong direction (Buckley).

The second method is incremental conductance, which considers the slope of the P-V curve is zero at the MPP, negative at the right of the MPP, and positive at the left of the MPP. They system will compare the incremental conductance (change of current/change of voltage) with instantaneous incremental conductance (current/voltage). This system will only lose the MPP if the current or the voltage changes, then a new MPP will need to be found. This method is slower to find the MPP than its PAO counterpart, but is saves power because it does not oscillate around the MPP. An added benefit is that the under rapidly changing conditions it will be able to find the MPP more accurately than the PAO method (Buckley).

Section 3.2.10 – Pulse Width Modulation (PWM)

Pulse Width Modulation is the standard in most charge controllers. PWM is not necessary, but it serves as a method to allow the batteries to have a longer life expectancy (Morningstar Corportation). This type of charging technology also shortens the amount of time needed to fully charge the battery and give the battery a good charge rather than a quick one (Morningstar Corportation). When a battery is charged rather quickly it will tend to have a quicker discharge and shorten the battery life because more cycles are used.

It is called a “pulse width” because a square wave is used and the length of the width determines the duty cycle of the PWM, the longer the width the higher the duty cycle. Duty cycle is a ratio that refers to the amount of “on time” to the amount of “off time” (TFT Central). A PWM that has a 100% duty cycle will send all of the power to the output. If the duty cycle is 75% then 75% of the power will be sent to the output, and so on. The controller will send a frequency of about 300Hz, which means each cycle will last 1/300th of a second (TFT Central).

Section 3.2.11 – 3-Stage Charging

The first of the three stages is the bulk charge. This type of charge is used initially when the battery is below 70% - 80% charged to ramp up the power stored in the battery. For a battery that is deeply discharged, the bulk stage is most useful because this stage will charge the bulk of the battery. In general, this stage about half of the required charge time. This stage is also known as the constant-current stage. The stage will have constant-current and an increasing voltage (Cadex).

The second stage, also known as the absorption stage, begins when the battery reaches 70% – 80% depending on the charger. This charging stage tops the charge. In this stage, the voltage peaks and stays constant while the current reduces as the battery charges. The input current tapers off because the internal resistance of the battery increases as less current is able to fit in the battery. This stage provides saturation to give the battery a good charge (Cadex).

The third stage begins when the battery reaches full charge, about 98%. This stage is also known as maintenance, trickle, or more formally as float charge stage. The idea of this stage is to keep the battery at full power as it charges the battery at a rate that is equal to its discharge rate under no load. The charger will send spurts of power to the battery. Reducing the charge voltage below the battery's voltage prevents gassing and prolongs a battery's life (Cadex). As current decreases between the absorption stage and the float stage, the battery is able to cool allowing the battery to absorb more power over time of the charge. The three stages are illustrated below in Figure 2.

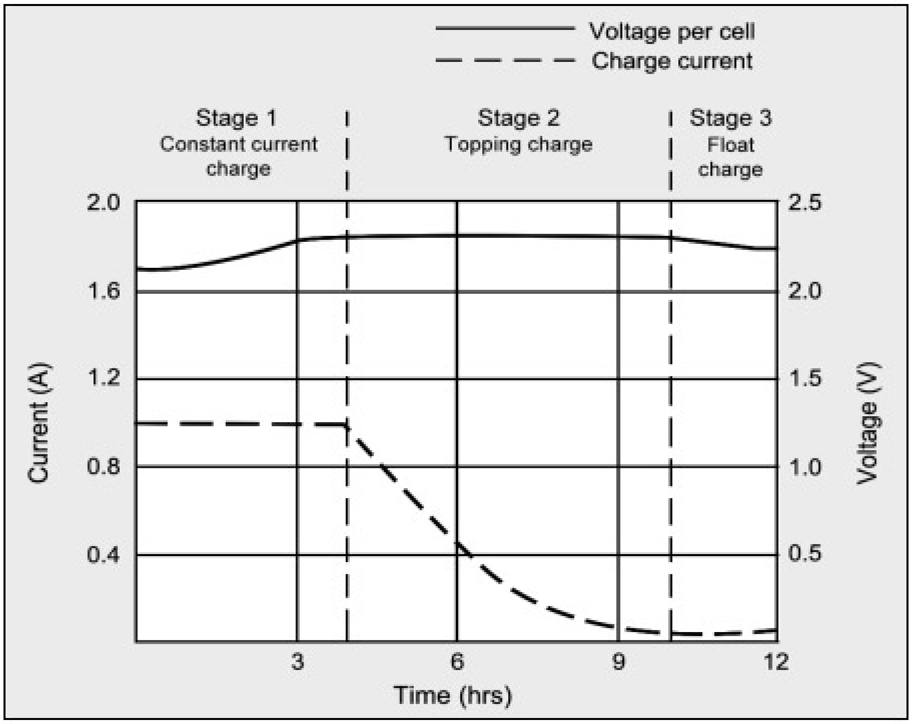


Figure 2 Charging stages of a lead acid battery, permission pending from batteryuniversity.com

Section 3.2.12 – Equalization

When a flooded lead acid battery is purposely overcharged is called equalization. This reverses buildup that is harmful to the battery. Equalizing will undo the stratification effect, which is where the acid concentration is larger at the bottom of the battery than the top. Likewise it will remove the sulfate crystals that might of built up on the plates. Not equalizing the battery every month or so will reduce the overall capacity of the battery, as the chemical properties of the battery cannot be fully utilized. The battery is equalized when the battery is not connected to the load. Equalization is known to be completed when the specific gravity no longer rises. One way to achieve equalization is to input a voltage that is 3 – 4 volts that is higher than the battery for a set amount of time, as for not to have the battery reach an unsafe voltage level (Battery Tender).

Section 3.2.13 - Inverters

Inverters are categorized into three basic types of technologies which are Square wave, Modified Square wave, and sine wave. The three deferent types of inverters have its advantages and disadvantages. The square wave inverter is the cheapest and most simple type of inverters to implement as far as cost and complexity. The square wave inverter can be a great alternative to use with non-sensitive electronic devices due to its low cost and simplicity of the design. The second type of inverter is the modified square wave inverter. The modified square wave inverter is an improved square wave inverter. This technology uses step function to approximate a sine wave. This approach is capable of powering up a larger variety of electronic devices and it is still reasonably low cost for its performance. The design of the modified square is a little more complex than a square wave, but the benefits are of having more flexibility to powering other electronic devices are very well worth it. Finally, the sine wave inverter is the best type of inverter. This method approximates the wave form that is delivered by electrical company. This type of inverter is capable of powering any type of devices including medical equipment which is known to have very sensitive electronic components. This is the most expensive type of inverter due to the many components that go in it and the complexity of the design of the circuit. For this project a sine wave inverter will be used to power up the community center.

Section 3.3 – Strategic Components

In this section a review of the critical components that make up a solar system will be discussed. Solar systems are composed of the following subsystems: solar panels that supply energy to the system, a charge controller to regulate charge to the batteries, a battery bank for storage, and an inverter to covert power from DC to AC.

Section 3.3.1 – Solar Panels

Solar panels are the most important component since it is the energy source of the system. In order for a system to be reliable and effective, it must be designed properly. Photovoltaic modules are commonly found as flat rectangular shapes that can produce anywhere between 5 to over 200 watts of power. Some of the factors that need to be considered when selecting a module are: load resistance, intensity, cell temperature, and sunlight exposure.

Loads or battery banks determine at which voltage the module will operate. The goal is to operate the PV system close to the maximum power point, resulting in the highest possible efficiency. If the load resistance increases, the system starts running at a higher voltage. That causes the current output to decrease. The relationship between the load and photovoltaic array is important for system efficiency. To meet that requirement a maximum power point tracker will be built in the charge controller.

The output current of a module is directly proportional to the intensity of solar radiation that the panel is exposed to. The voltage is also affected by sunlight, but has a very small effect. That is why it is important to compare the conversion efficiency when selecting a solar module.

As discussed previously, solar cells are affected by temperature. When temperature starts going above 25°C or 77° F, it becomes less efficient and voltage starts dropping. As the voltage gets affected at higher temperatures, the overall power is decreased. That is why it is critical to have good airflow under and over the modules to keep temperatures down. For this project, some voltage lost is not a big concern because it is a stand-alone solar system.

Partial shading can also result in dramatic output reduction on photovoltaic modules. For example, one completely shaded cell can reduce as much as 75% of the module’s output. It is critical to have no shade during sunlight hours; otherwise, the required output will not be met.

Section 3.3.2 – Charge Controller

The charge controller is another critical component in the solar system. The function of a charge controller is to serve as a voltage regulator. Its primary duty is to prevent the battery bank from being overcharged by the solar panels. The controller keeps track of the battery voltage and it stops charging once the battery is fully charged. Another feature of the charge controller is to protect the battery bank from being overly discharged. Once the controller detects that the battery bank is near 20% full, it will alert the user and it will disconnect from the load. This will also prevent any unmanaged discharge from damaging the batteries. To help the user keep track of the charging status a voltmeter digital display will be available. A Maximum Power Point Tracker will be built into the controller to optimize solar panel output. Charge controllers are classified in four different types which are: shunt, single-stage, multi-stage, and pulse controller.

Shunt controllers prevent the system from over charging by shunting or bypassing the battery bank when the charge is completed. The controller monitors the voltage at the battery bank and once it is full, it redirects excess current by a power transistor to be consumed by a dump resistor. A blocking diode is necessary to prevent current to back flow from the battery bank to the solar modules. The advantage to this controller is that it is inexpensive. The disadvantage is that it can only be used on low power circuits and it requires good ventilation since it produces heat.

In single-stage controllers the way this controller prevents the battery bank from overcharging is by switching the current flow off at pre-set value. This pre-set value is called the charge termination set point (CRSP). Once the controller detects that the batteries have reached their CRSP, it will automatically reconnect to recharge. To prevent reverse current flow, this controller has a sensor to break the circuit instead using of a blocking diode. Single-Stage controllers have a greater load capacity, are inexpensive, small in size, and do not require a lot of ventilation.

Multi-Stage controllers automatically establish different charging currents at different stages. Once the battery bank is nearly full, it uses a trickle charge to fully charge it. It is said that this type of charging prolongs the battery life. To prevent reverse current flow, a relay is used.

Pulse controllers top off the charge by switching the full charging current on and off when the batteries are fully charged. A blocking diode may be used to prevent reverse current flow.

When designing a controller there are several factors that need to be considered for safety and reliability. A simple but important factor is that it must match the voltage coming from the array. The controller must be design to handle the maximum load current that will go through the controller. Additionally, the maximum amperage at short circuit current of the solar panels should be used for safety. It is recommended to use an additional 25 percent safety margin. The NEC requires that the PV solar panel current does not exceed more than 80 percent of the controller rating. Temperature compensation needs to be taken into account for high and low temperatures. A compensation sensor can be used to change the charging voltage for different temperatures.

Section 3.3.3 – Battery Bank

A battery bank is essential on stand-alone systems. Stand-alone systems depend on storage since solar panels can only produce energy during sunny days. In order to use the energy at night a battery bank will be necessary. A battery bank is a buildup of multiple batteries wired in series, parallel, or a combination of both. Batteries store electrical energy in chemical form for later use. Since power coming from the solar panels can be inconsistent due to variations in sunlight, batteries can provide a relative constant source of power. An advantage of having a battery bank is that repairs or maintenance can be made to the solar panels without interrupting power. Since batteries are not 100 percent efficient, energy gets lost during heat transfer and chemical reactions. Therefore, the energy lost needs to be taken into account and needs to be compensated for to achieve desired outputs. Rechargeable nickel cadmium batteries are commonly used for large loads and may be re-charged with solar systems. Manufacturers of nickel cadmium batteries assure that their batteries will deliver more charge/discharge cycles than lead-acid batteries. A battery charge/discharge cycle is often used to measure the life expectancy of the battery. A cycle occurs once a day in residential photovoltaic systems. There are different types of batteries that are offered in the market but only batteries that relate to photovoltaic system will be discussed in this section. Some of the commonly used batteries in photovoltaic systems are: Lead-acid batteries and alkaline batteries (Solar Energy International, 2004).

Lead acid batteries are the most commonly battery in the photovoltaic industry. These types of batteries are similar to car batteries, however, car batteries are not recommended for photovoltaic systems. The reason is that car batteries are designed to discharge large amounts of current in a short period of time and then immediately be recharged. In photovoltaic systems, deep cycle batteries are used and they perform opposite to car batteries. Deep cycle batteries discharge small amounts of currents over a long period of time and they get recharged under irregular conditions. The amount of discharge that a deep cycle batteries can take is about 80%. This is the reason why they are preferred in the photovoltaic industry. To protect the battery life expectancy, it is not recommended to discharge the battery more than 50% of its charge. Another great quality of this battery is that if properly sized and maintained, it can last up to ten years of service. Lead-acid batteries can be categorized into liquid vented and sealed lead-acid batteries (VRLA) (Solar Energy International, 2004).

Liquid vented batteries have the same structure as automobiles batteries. They have a positive and negative plate that is made of lead and lead alloy materials. These plates are place in a solution of sulfuric acid and water. When the battery reaches near full charge, hydrogen gas is produced and it gets vent out of the battery. A special precaution is needed with this type of battery. No types of open flames or sparks are allowed near this battery since hydrogen is a very explosive gas. Components such as generators, gas space heaters, and gas water heaters must be placed away from the batteries. Vented batteries require to be periodically refilled because water is lost when waste gases are vented.

Sealed lead-acid batteries are referred to as a valve regulated lead acid batteries. These batteries are considered maintenance free because there is no access to the electrolyte. The two types of sealed batteries that are used in photovoltaic systems are gel cell and absorbed glass mat (AGM). In gel cell batteries, silica gel is used to turn the electrolyte into gel mass. Silica glass mat is used in AGM batteries to suspend the electrolyte and it provides pockets to recombine the gases generated during recharge. A great quality of sealed batteries is that they are spill-proof and even when broken gelled electrolyte cannot be spilled.

Alkaline batteries are structure the same way as lead-acid batteries. They have positive and negative plates with the exception that they are made out of nickel-cadmium or nickel-iron. Their name derives from the alkaline electrolyte of potassium hydroxide. The downside to this type of battery is that it is expensive and it can have compatibility issues with certain inverters and controllers. The advantage on the other hand is that this battery is not affected by temperature as much as other batteries. This type of battery is recommended when temperatures are expected to be below -50°F or less.

The battery bank is a significant part of the total cost of the entire system. For residential photovoltaic systems lead-acid batteries are recommended. After looking at cost, safety, environmental, and maintenance challenges, battery banks are critical to provide the flexibility needed on stand-alone systems.

Section 3.3.4 – Inverters

Alternating current has been a worldwide standard for delivering power over long distances. Therefore, most electrical devices and loads are designed to operate on alternating current. Photovoltaic systems and battery sources are only capable of delivering direct current. In order to be able to work with direct current and alternating current, an inverter will be required. Inverters have the capability of converting direct current into alternating current. In the past, inverters have been known to be inefficient and unreliable causing large trade-offs on overall system performance. Improvements have been made on inverters and appliances where some of the performance issues have been improved.

Inverters are split up into two categories. The first category is synchronous or line-tied inverters, where the photovoltaic system is integrated to the grid. The second category is stand-alone or static inverter, where the photovoltaic system is off-grid. Since a grid system is not available for the South African village, the focus will be on stand-alone inverters.

Inverters are also classified by the type of waveform that they produce. The waveforms that are most commonly used are: square wave, modified square wave, and sine wave as shown in figure 3.

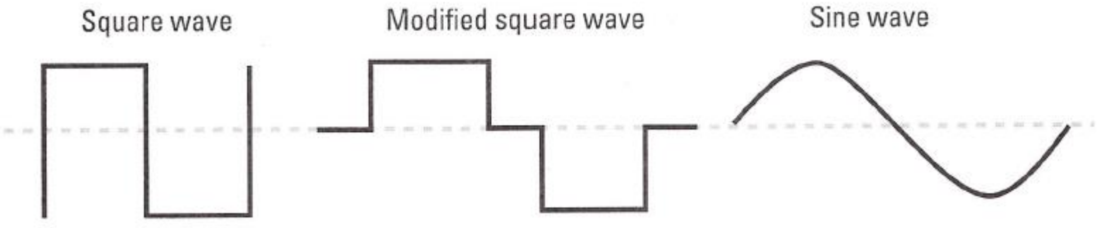


Figure 3 Common Waveforms Produced by Inverters. Adapted from by "Photovoltaic Design and Installation Manual," by Solar Energy International, p.81. Copyright 2004 by Solar Energy International. Adapted with permission pending.

The first type of inverter is a square wave inverter that switches direct current input into a step-function alternating current. This kind of inverter has little output voltage control, limited surge capabilities, and produce considerable harmonic distortion. Square wave inverters are only used on small resistive heating load, incandescent lights, and small appliances. Although, square wave inverters are inexpensive, they are not recommended for the use of motors and sensitive electronic devices.

The second type of inverter is the modified square wave. This kind of inverter uses field effect transistors or silicon controlled rectifiers to perform the switching of direct current input to alternating current output. This kind of inverter is capable of handling large surges with a reduced harmonic distortion output. Modified square wave inverters have a wider range to operate a variety of loads such as motors, lights and standard electronics. Even though this inverter has a much better performance than a square wave inverter, certain electronic devices can pick up noise from the inverter and not function properly. Some devices like clocks or digital time keepers can run either fast or slow due to phenomena. Also it is not recommended to charge batteries for cordless tools using a modified square wave inverters.

Sine wave inverters are used to operate sensitive electronic devices that require a high quality waveform. The distinguishing feature of sine wave inverters is that their output has little harmonic distortion. This type of inverter is capable of powering even the most sensitive electronic equipment. The disadvantage of this type of inverter is that is it can be very costly.

Selecting the appropriate kind of inverter is essential since not all inverter will perform in same way. Having a clear idea of the intended use for the system can be beneficial and cost effective. If the system will be used just to power some incandescent lights and small appliances, a square wave will be a suitable and inexpensive choice. If sensitive electronics are required such a medical equipment, a sine wave may be required.

Section 3.4 – Possible Architectures and Related Diagrams

As with every projects design phase, this project has had many different implantations proposed. The component with the must amount of design possibilities for the project was the charge controller. There are several good architectural designs for power distribution. The biggest problem that this project is facing is time and budget. The charge controller itself could be an entire design project.

If there is not a load being draw and the batteries are charged the power must be use somehow. This condition requires a dump resistor. The dump resistor is an important part of the architectures. It will prevent extreme overloading of the system. An excess of power cannot be stored in the system with nowhere to go.

Section 3.4.1 – Charge controller

One possible design of the charge controller is using the batteries as a capacitor, when power is being generated by the solar panels. The charge controller will charge the batteries when they need to be charged. Also, when there is draw from the user, the charge controller will allow the power to be directed toward the batteries, even if the batteries are full. The draw will cause the batteries to be bypassed and the power will go straight to the user. This architecture is simplistic and economical. Even though these are two big factors that are taken into account for the project, the disadvantages are great.

Using the batteries as capacitors will reduce the life span of the batteries. When charging batteries it is important to charge them when they need to be charged, not just a little bit at a time. Abuse of battery charging can be damaging to the batteries. Abuse of the batteries can cause “passivation of the electrodes, crystal formation and gas buildup”. If you allow current to flow through the batteries every time a draw occurs the batteries are not begin used properly.

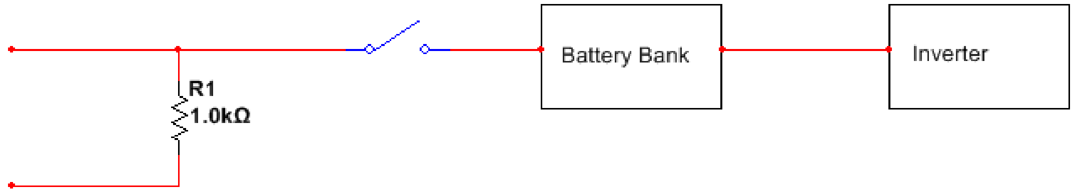


Figure 4 The batteries are being used as capacitors. All the power that is generated has to flow through the battery bank.

As shown in figure 4 the only path for the load is to go across the batteries. This can be damaging to batteries. The damage can occur if the batteries are partially drained and the load enters the battery to charge then is immediately pulled from the batteries to supply the needs of the load. The results of the damage limit the life and efficiency of the batteries. This causes a great problem when the PV panels are not producing power. This can occur during cloudy days and in the winter when sunlight is limited. In this situation the batteries are the source of power. If the batteries are not functioning to their fullest, the system is useless when power is not being generated. Power needs to be outputted is a consistent manner in order to prevent further damage to the inverter and ultimately the device(s) that are relying on the system for power.

There are also subsystems that will not be designed, such as the battery bank and solar panels. The use and implementations of these components will be critical in the design of the project. Batteries can be arranged in two configurations; series and parallel. The configuration is important, so the charge controller will know how to respond to the voltage changes. Similarly, with the solar panels the charge controller must know how much power each solar panel is producing to determine how to distribute the power.

In order to prevent damage to the batteries, they can be bypassed. By bypassing the batteries when a draw is required, the current of the load is not being directed through the batteries as shown in figure 5. This will allow the charge controller to charge the batteries when it is appropriate. In order to achieve this design requirement a shunt it required. The shunt will signal when a voltage exceeds a limit. When the upper limit is reached the shunt will short circuit and allow a signal to be present. The signal can be used in multiple ways. One way of using the signal is sending a visual signal and having the power cut off manually. An example of this could be using an LED to signal when the batteries are full. A person can watch for the LED to light up and manually switching the charger off. This method was used by Renewable Energy UK. Another method on monitoring the charge is to use a microcontroller. The microcontroller would be able to receive the signal instead of an LED and respond accordingly by sending a signal to a switch to open it. Once the switch is opened the batteries will stop charging.

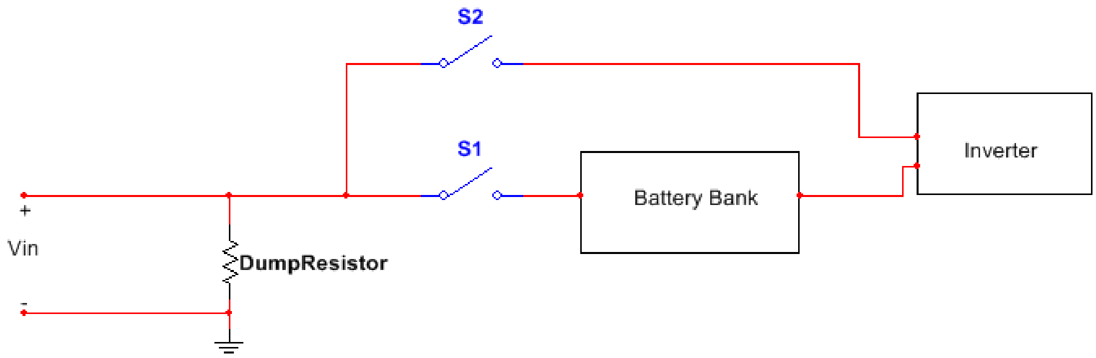


Figure 5 The microcontroller will be able to bypass the battery bank.

A third design is a combination of the previous two architectures, which will be the most efficient. In this case, the power generated will be able to go to the batteries and the inverter at the same time. The microcontroller will monitor the power being generated and the power being consumed. When the power being generated is greater than the power being consumed, then the power that is needed will go directly to the load and if the battery bank is able to charge then it will take the power and begin charging. If the batteries are full then the excess power will go to the power dump. This architecture will be the most efficient, as it utilizes most of the power that is being generated, whereas the previous architectures discussed throw the excess power away. A circuit will have to be made in order for this architecture to work properly. The circuit will need to be able to know how much power is required and send variable power to the inverter and make a decision to send the power to the battery bank or to send it to the power dump.

In addition to diverting the power this circuit will also need to regulate the voltage that is sent to the inverter because the inverter needs an input of 24 volts.

Section 3.4.2 – Inverter

The purpose of using this kind of component on the design is to be able to produce an oscillating electronic signal. The electronic oscillator is the perfect choice because it allows us to convert a DC signal from a power supply (in this case the solar panels or the battery) to an AC current. For the purpose of our project it is needed to create a sine wave, a square wave and a triangular with its respective electronic oscillator design.

A sine wave oscillator is needed for our design, so that it can be used as a reference and a testing device in the inverter. As it is known sine waves only have a single frequency, and have no harmonics present in ideal conditions. This sine wave oscillator will function as a device that measures the amount of distortion of the generated sine wave on the inverter. An Op-amp sine wave oscillator is the optimal choice that fits within the required parameters for the project. This kind of oscillators function by applying a synchronized combination of positive and negative feedback with the purpose of driving the op amp into an unstable state, the reason for this is to cause a back and forth cycle in the output so that it functions at a continuous rate. The project presented in this report requires a low frequency spectrum and this is the reason this kind of sine wave oscillator is a great choice. Op-amp oscillators because of its design do not have the required bandwidth to achieve low phase shift at high frequencies, this characteristic restricts this oscillators to the lower frequency end of the frequency spectrum (Mancini & Palmer, 2001)**.** As mentioned this kind of oscillators work at low frequencies, and these can be as low as 10 Hz. Crystal oscillators are the complete opposite, and they work at frequencies as high as MHz ranges, this is why there are not optimal for the design implementation. (Mancini & Palmer, 2001)

As it was already stated there are many different types of electronics oscillators, similarly there also are many types of sine wave oscillators. These designs differ on its applications, frequency rage and desired output. A very popular oscillator design is the Wien Bridge Oscillator; this is one of the simplest oscillators and is main use is focus on the audio circuits, it contains few components and its frequency is very stable. Other popular oscillator is the phase shift oscillator; its advantages are less distortion compared to the Wein Bridge Oscillator and good frequency stability. This type of oscillator can vary from very few components to a more complex system depending on the requirements for the system. The last sine wave oscillator mention on this section will be the Bubba oscillator, and it is the one that will potentially fulfill the necessary requirements that the design needs.

The Wein Bridge Oscillator is a very common and easy to implement circuit. Its advantages are the simplicity of its design, few components and a good stability. On the other hand, the output it produces is right at the rails of the op amp, creating saturation within the transistors inside the op amp and causing a lot of distortion on the output signal. Before introducing a couple of techniques to diminish this distortion, the following circuit will illustrate the schematic of the Wein Bridge circuit.

The Wein Bridge Oscillator is a very common and easy to implement circuit. This circuit is a two-stage RC coupled amplifier circuit that has a very good stability around its resonant frequency, low distortion and considerably easier to tune and setup than most oscillators, giving it a big popularity in audio frequency oscillators as an example. This type of oscillator uses both negative and positive feedback to achieve a desirable constant state of oscillation. This feedback circuit consists of a series RC circuit connected with a parallel RC circuit. These two RC circuits with the same component values produce a phase delay or a phase advance circuit depending on the frequency adjustment. In figure 6 at the bottom shows these two circuits connected together.

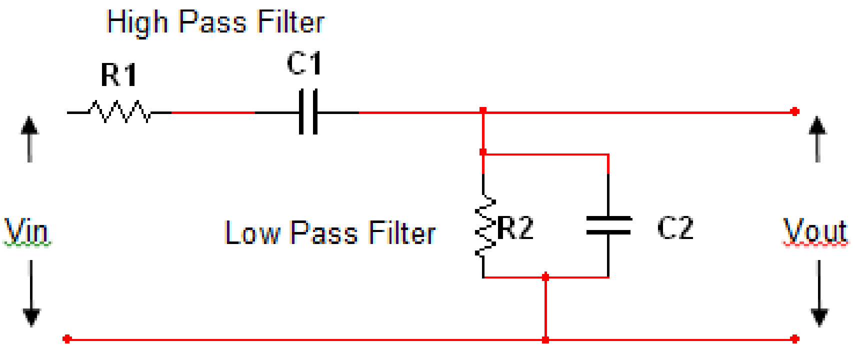


Figure 6 RC Circuit

As it was mentioned at the top a phase delay or a phase advance can be produced depending on the frequency levels. At high frequencies the capacitor reactance of C_2 gets very low and creates a short circuit on the output. While this occurs, the output voltage reaches its maximum value; this high frequency is then called *resonant frequency* (f_r). At low frequencies the reactance of the capacitor C_1 is very high causing the capacitor to act like an open circuit. This reaction blocks any input signal at Vin, in consequence there is no output signal Vout. At resonant frequency the reactance of the circuit is equal to its resistance making the phase shift between the input and output equal to zero degrees. Therefore the magnitude of the output voltage is as its maximum and is equal to 1/3 of the input voltage. It is good to highlight the importance of this resonance frequency, because with the RC network forms the basis of the Wein Bridge Oscillator. (Mancini & Palmer, 2001)

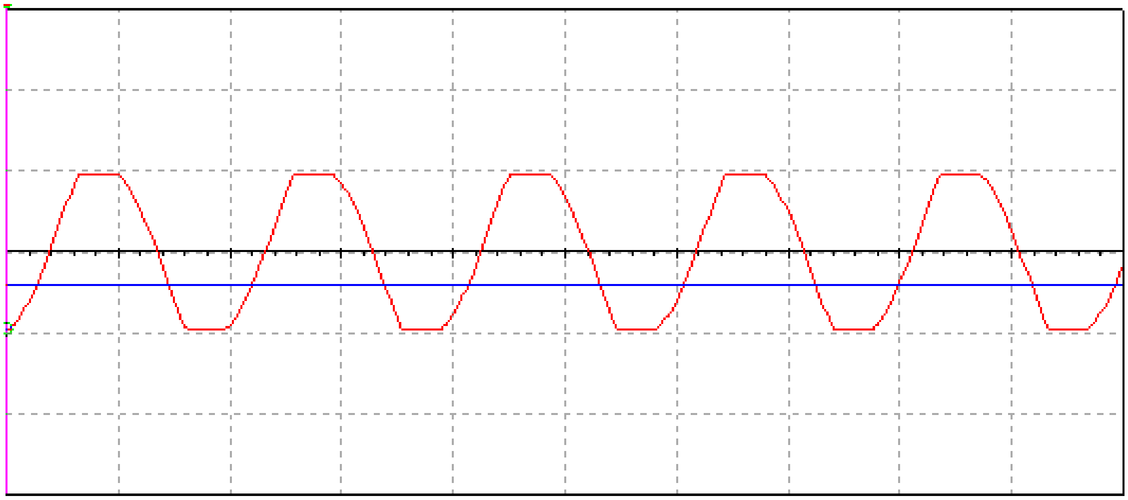


Figure 7 Wein Bridge Oscillator

Figure 7 illustrates a general setup of the Wein Bridge Oscillator allowing a better understanding of the system. It can be noticed that the output of the operation amplifier is being feedback into both of the inputs of the amplifier. One part of this feedback signal is directly connected to the inverting input terminal (on the negative feedback) through the resistor divider network of R_1 and R_2 allowing the amplifier voltage gain to be precisely adjusted. On the other part, the feedback goes to the non-inverting input terminal (on the positive feedback) through the RC Wein Bridge Network. This RC network has zero phase shift and only one frequency. When the Wein Bridge Oscillator is configured at the proper resonant frequency, both of the voltages (on the inverting and non-inverting inputs) will have the same phase. This causes the positive feedback signal to be canceled with the negative feedback signal creating oscillation in the circuit. Another requirement for this kind of oscillator is its minimum voltage gain that must be equal to 3 to be able to create oscillations in the system. This value is dependent on the feedback resistor network, specifically by the ratio of $\frac{-R_1}{R_2}$. This oscillations system cannot operate at frequencies higher than 1 MHz without the use of high frequency operational amplifiers due to the open-loop gain limitations of the components regularly use on this kind of oscillator. (Mancini & Palmer, 2001)

An advantage of the Wein Bridge oscillator circuit is that it does not requires an input signal in order to produce output oscillations. It is also a very good choice for audio equipment due to the fact that its frequency range is very wide, perfect for radio equipment. As is it already know this oscillator can be used with inverting amplifiers, but it is also works properly with non-inverting amplifiers. Another detail that must be put into account is the resistance of the amplifier; this one must be higher than R so that the RC network does not overload and alters the whole system. On the other hand, it is well known and documented that this type of oscillator requires a method to stabilize the amplitude of the oscillations. If this is not stabilized and the voltage gain of the amplifier is not big enough, the expected oscillation will decay and just stop; on the contrary, if the voltage gain of the amplifier is too large, the output amplitude will rise uncontrollable reaching the rails of the op amps, which saturates the op amp and finally causes distortion on the sine wave output sinusoidal. After getting to know the design and functionality of the Wein Bridge Oscillator it does not seem to be the right fit for our project, due to the problems it has when a bigger voltage input is required. This happens because of the simplicity of the circuit itself; the lack of extra components within the system does not allow control of stability of the sinusoidal signal. While component upgrades can be made, this design shown in figure 8, falls short compared to other circuit that require a little more complexity but give much more stabilization to the sinusoidal output signal

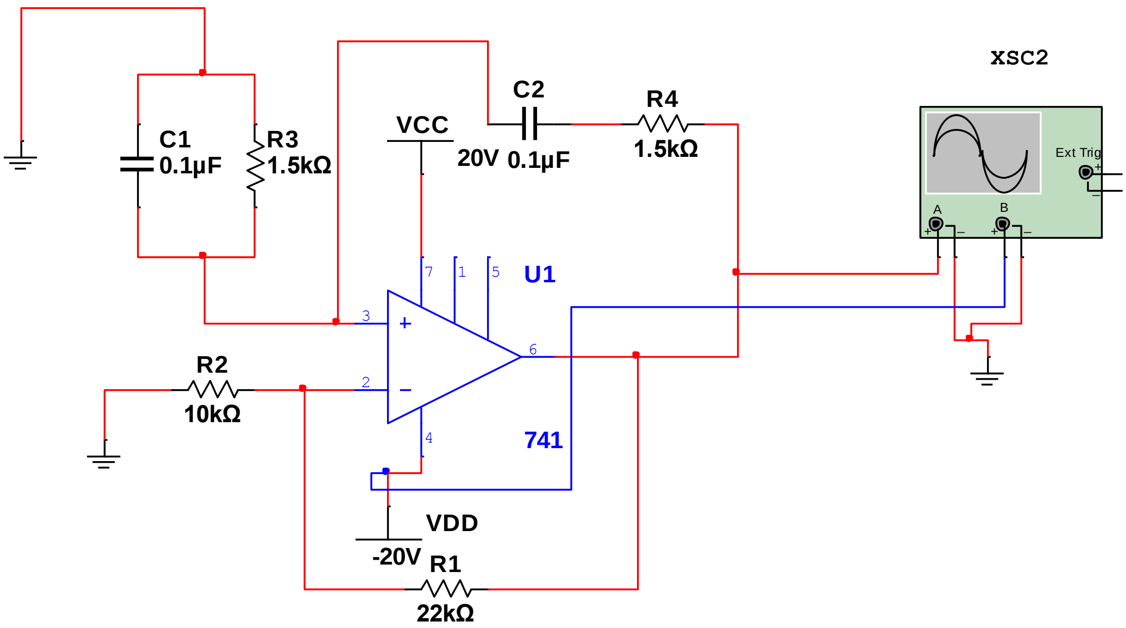


Figure 8 Wein Bridge Circuit

The Phase Shift Oscillator is a linear electronic oscillator created with the purpose of producing a sinusoidal wave form. This type of oscillator contains an inverting amplifier such a transistor or an operational amplifier. The output of either of these components will be feedback to its input through a phase shift network connection containing resistors and capacitors. In this type of oscillators the input is shifted 180 degrees through the amplifier stage and shifted 180 degrees again through the second inverting stage to get a total of 360 degrees shift, which is the equivalent to 0 degrees. This equivalency gives us the necessary feedback for a whole loop. In the diagrams below it will be show how the shifting occurs through the RC network (Mancini & Palmer, 2001).

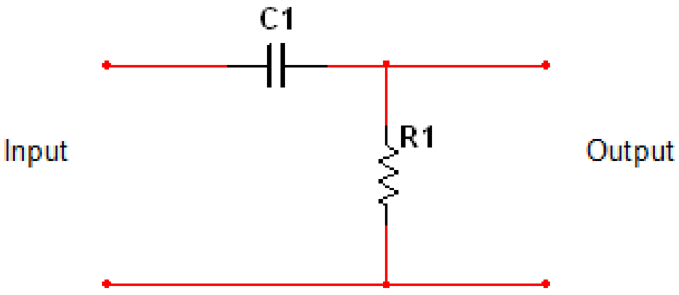


Figure 9 Single Stage Circuit

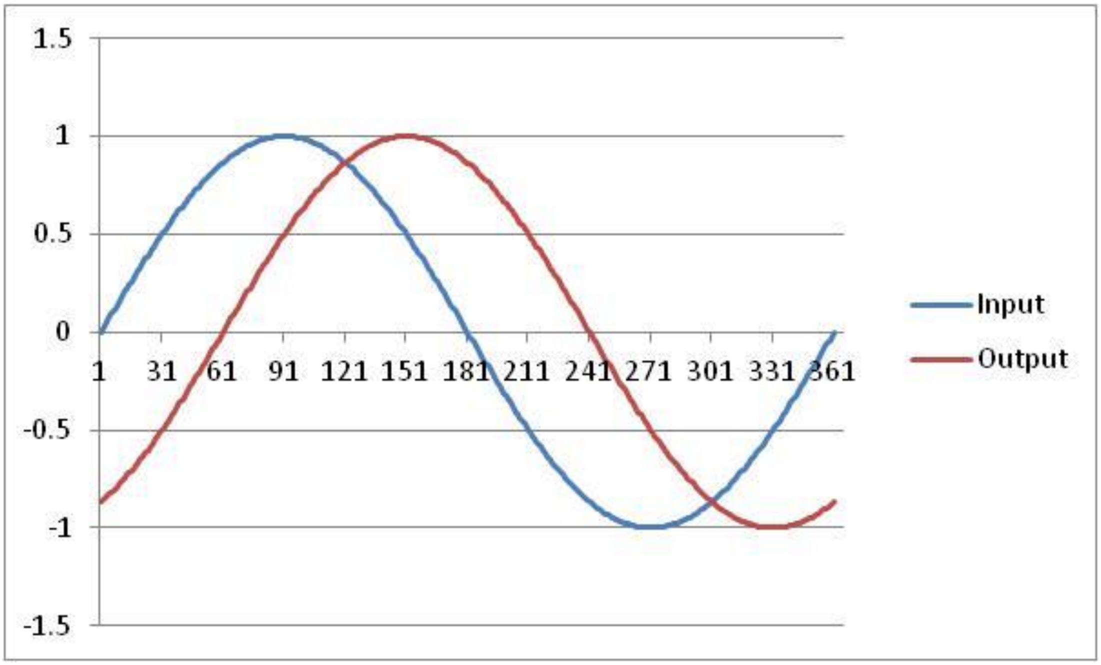


Figure 10 Single Stage Phase Shift

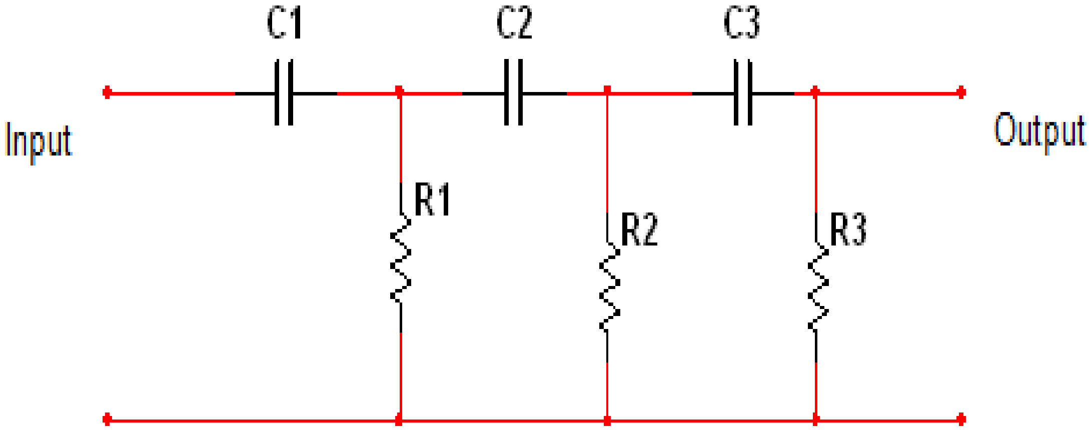


Figure 11 Three Stage Circuit

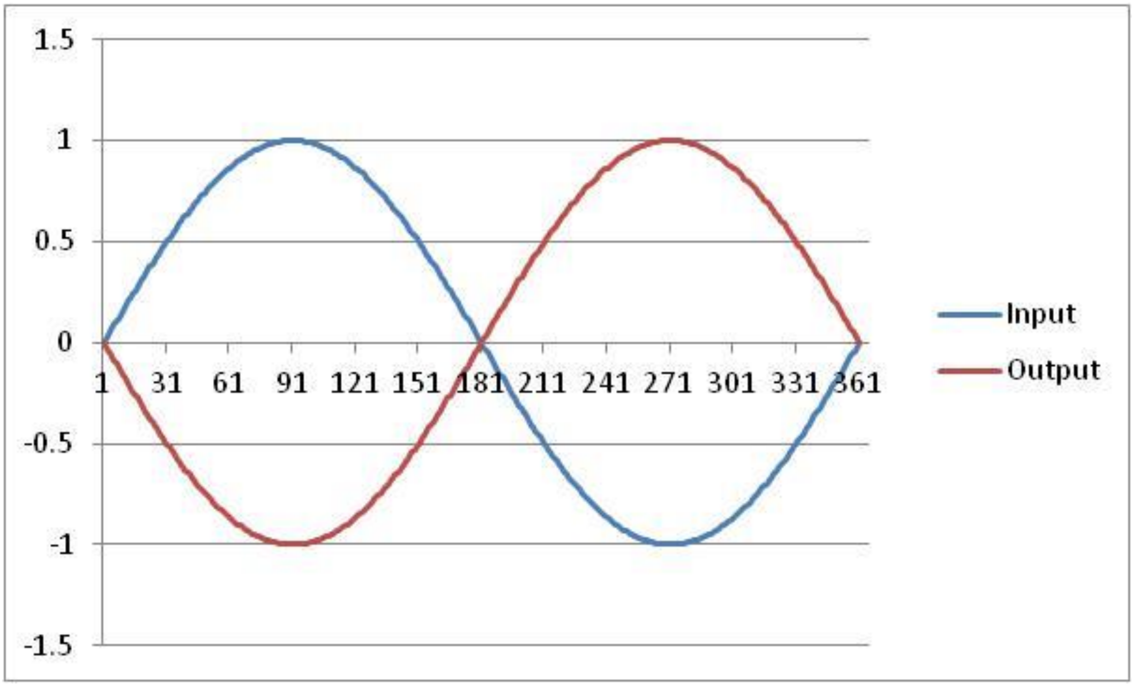


Figure 12 Three Stage Phase Shift

On the first circuit, a single RC network is shown. This network outputs a voltage that compared to the input voltage is leading by angle less than 90 degrees. Ideally a single RC circuit network is expected to produce a phase shift of 90 degrees, but the requirement for oscillation is a shift of 180 degrees, so at least another single RC circuit network must be introduced to reach this required phase shift (in the ideal cases). The truth is that the amount of phase shift created by the network depends on the values of its components (the capacitor and the resistor) and the frequency of these oscillations. In the second diagram it is noticed that three RC networks are connected so that the total phase shift between these is 180 degrees, as a result it is expected to output a phase shift of 60 degrees from each RC network so that it can be able to output the required phase shift. As stated before, it is needed to use an amplifier circuit; this is done with the purpose of producing a phase-shift of 180 degrees between the input and the output, adding up to 360 degrees which are required to produce enough phase shift. This phase shift is necessary to regenerate the feedback of the system. This regenerative feedback is happening because the capacitor is able to store the electric charge. (Mancini & Palmer, 2001)

As shown in the figure 13 below, we can connect the circuit in such way that a leading phase shift can be produced or if interchanged, a lagging phase shift can also be produced. It does not matter if any of this is produced the outcome will still be the same, because the sine wave oscillations will happen at a phase shift of 360 degrees. To vary from a leading phase shift to a lagging phase shift the frequency can be varied by modifying one of the capacitors, which can be easily done with a variable capacitor. It is also good to remember that a combination of a resistor and a capacitor causes the network to behave as an attenuator, causing losses within the system. To solve this problem in the case of the circuit below, an amplifier of a gain of 29 is required to counteract the attenuation caused by the components of the network. However, this amplification created by the amplifier also has an effect on the frequency of the generated sine wave oscillations, causing oscillating frequencies higher than expected. This problem requires another component within the system that takes the high impedance output sources and feeds it into a low impedance load such as an Operational amplifier. (Mancini & Palmer, 2001)

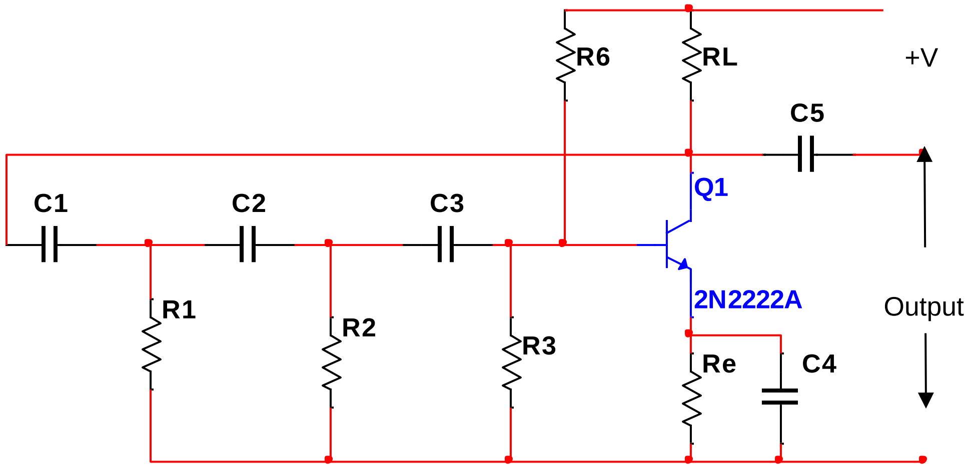


Figure 13 Basic RC Oscillator Circuit

The best way to utilize a Phase Shift Oscillator is with the incorporation of an operation amplifier, which is more common in this type of oscillators. This oscillator will then consist of a negative-gain operation amplifier and as illustrated before a three section RC network in charge of producing 180 degrees of phase shift. This phase shift network will be connected from the op-amp output back to its no-inverting input like in figure 14 (Below).

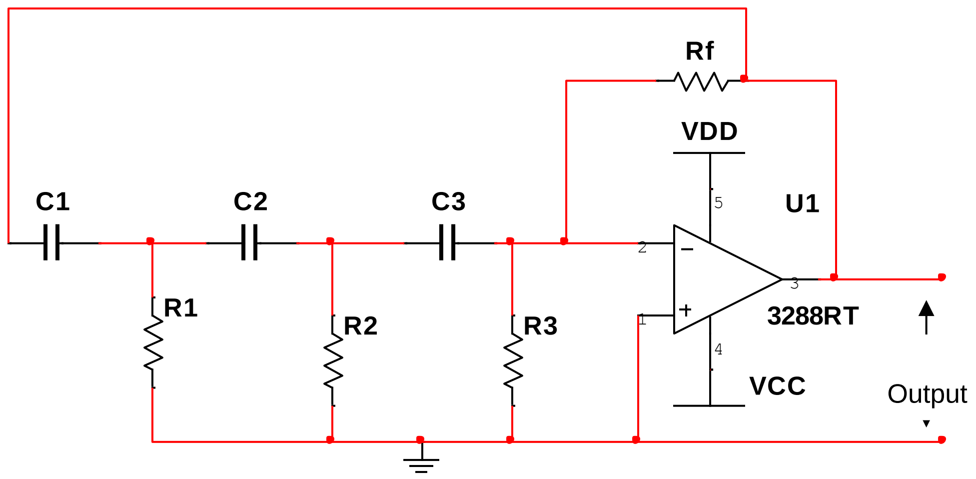


Figure 14 Op-Amp RC Oscillator Circuit

By analyzing the circuit in more detail, it can be seen that as the feedback is connected back into the non-inverting input, the op-amp is consequently connected as an “inverting amplifier” which produces 180 degrees phase shift while the RC network is also producing 180 degrees phase shift adding up to the required 360 degrees phase shift. The RC network can function with only two RC sections rather than three to produce the required 180 degrees of phase shift, each section contributing 90 degrees phase shift, but the truth is that while the circuit may become simpler the stability will be very poor at low frequency which is undesirable. Now that the RC Oscillator contributes greatly to better frequency stability or poorer frequency stability. It can be possible to put even a greater amount of RC stages to provide better frequency stability. For example, the use of Phase Shift Oscillators with four stages is generally used because a lot of available hardware in the market comes in quad IC packages which make easier the implementation of a 4-stage oscillator with a 45-degree phase shift. (Mancini & Palmer, 2001)

The implementation of Phase Shift Oscillator circuits is very popular in the market, because they are stable and provide a very good sinusoidal output waveform. With the help of a variable capacitor its frequency range can be amplified, improving its functionality. However, the Phase Shift Oscillators are restricted by the frequency of the application, even when improving its range; this is due to the fact that its bandwidth limitations do not allow it to produce desired phase shifts at high frequencies. This limitation leaves no option but to implement another kind of system that can be able to create sinusoidal wave forms at high frequency levels, which are going to be very common in this project.

The Bubba oscillator, shown in figure 15, is another phase-shift oscillator that provides the advantages of creating any frequency desired depending on the configuration of the resistors and capacitors of the circuit. To complete this task, the circuit contains four operational amplifiers. Unlike many other phase shift oscillators that require phase shifts of 90 degrees this oscillator contains four RC sections that requires 45 degrees of phase per section, this improves the minimal frequency drift and yields low impedance quadrature outputs, additionally the stability of the frequency is sustained which results in a low distortion for the output. The addition of this four op amps create as a result a total shift output of 180 degrees. The problem with this oscillator is that it is not possible to create an exact amplification of the signal. In the case of the bubba oscillator, this negative effect occurs in a smaller scale because whenever the signal passes through the op-amps it is clipped at the peaks of the sine wave. This happens when the rails of the op-amp are reached creating stabilization so that non-linear feedback is needed. The following equations allow the design to be properly created. (Eggleston, Doucet, & Shaw, 2007)

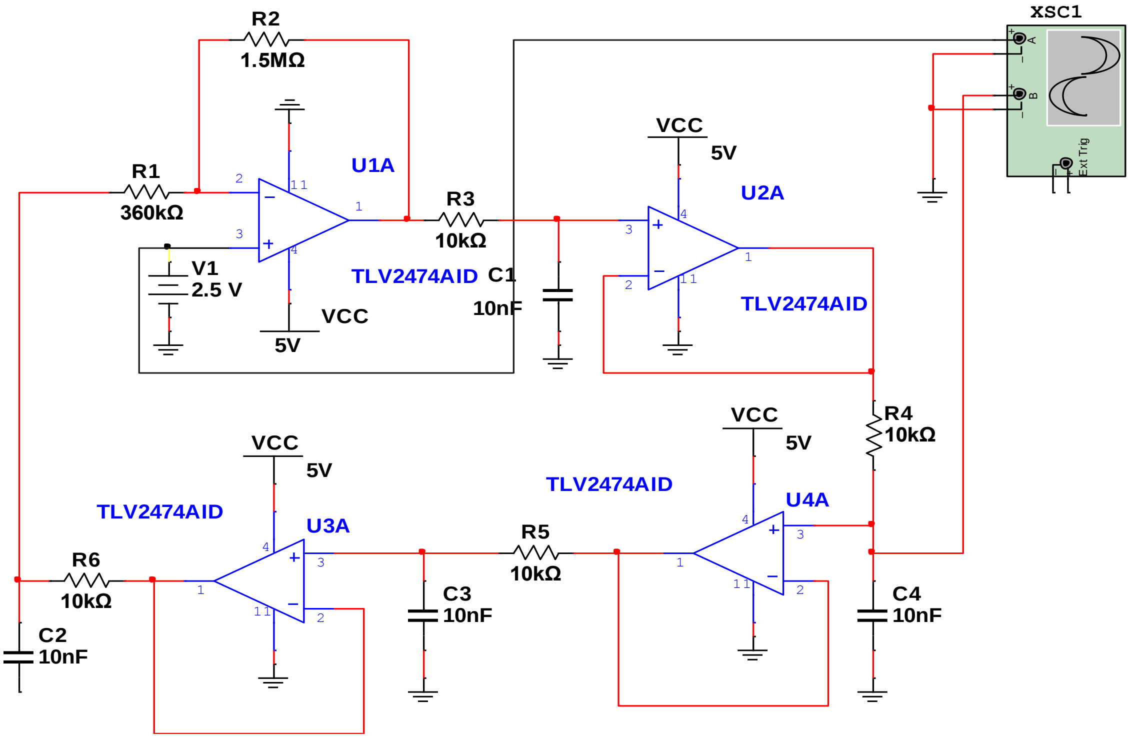


Figure 15 Bubba Circuit

$$A\beta = A\left(\frac{1}{RCs+1}\right)^{4}$$

$$|\beta| = \left|\left(\frac{1}{j+4}\right)^{4} = \frac{1}{\sqrt{2}^{4}} = \frac{1}{4}\right|$$

$\theta = \tan^{-1}(1) = 45°$

(Mancini & Palmer, 2001)

It is also very important to notice the importance of another component within the Bubba Oscillator. This component is the RC filter that can be found on every output of every op amp. These filters are in charge of phase shifting the signal by 45 degrees each. The addition creates a total of 180 degrees, as consequence the phase shift is now returned to 0 degrees; this cycle is repeated and restarted every time it is placed across the inverting amplifier. The following equations give a better understanding of the math around an RC filter.

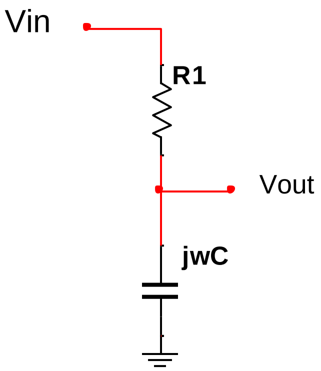


Figure 16 RC Filter Circuit

$$Vout = Vin\left(\frac{\frac{1}{jwC}}{R + \frac{1}{jwC}}\right) = \frac{Vin}{jRwC + 1}$$

$$w = \frac{1}{RC}$$

$$A = \frac{Vout}{Vin} = \frac{1}{j + 1}$$

$$\measuredangle A = \frac{\measuredangle 0°}{\measuredangle 45°} = \measuredangle 45°$$

(Eggleston, Doucet, & Shaw, 2007)

It must be noted that the filtering process creates attenuation around the signal, as consequence the signal must be amplified in order to have the oscillator working. This oscillation effect can only work if we pass the same starting signal into the system every time the cycle is repeated. In the equations found below it can be noted that the total attenuation created through the system is ¼ of the original signal, this attenuation must be amplified by the inverting amplifier by a factor of 4 so that the original equation can be finally brought back into the system.

$$|A| = \left|\frac{1}{j+1}\right| = \frac{1}{\sqrt{2}}$$

$$A_{Total} = \left(\frac{1}{\sqrt{2}}\right)^4 = \frac{1}{4}$$

As previously stated, the main purpose of the inverter amplifier is to recover the original as much as possible to keep the oscillator working properly. On the contrary, the reality shows that it is impossible to generate the same original signal. In some cases, the amplification is too large and it will keep amplifying until it reaches the rail of the op-amp, however in other cases the amplification can be too weak and the oscillator signal will decay until it vanishes. It is necessary to implement a non-linear feedback system to be able to produce a stable sinusoidal wave because of this imperfection. The theory explained in the last paragraphs it is easily understandable why the use of the Bubba Oscillator is recommended, its very nature automatically provides the non-linear feedback needed to create a stable sine wave. Figure 17 shows the result of the produced sine wave from the Bubba Oscillator. (Mancini & Palmer, 2001)

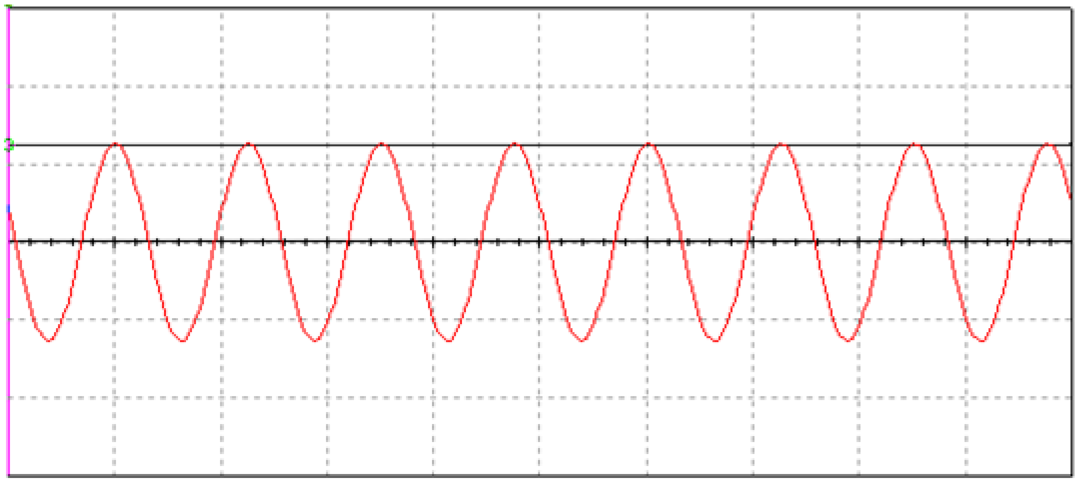


Figure 17 Bubba Oscillator graph

Another important section of this inverter that might be used is a proportional-integral controller (PI Controller). When the inverter is producing the corresponding output, this is directly connected to a load. This output voltage at the load is not generated perfectly, as consequence it must pass through a sensing mechanism and its feedback must be send to a comparator so that it can compare the output to the desired signal and produce the voltage error between this two. This error signal will be fed into the PI controller. This controller improves the signal by reducing significantly the error between the reference signal and the actual voltage signal every time it is feedback into the PI controller. This error is improved by forcing it to remain within the range of the amplitude of a triangular wave form. Figure 18 illustrates the position on which the PI controller will be placed in order to work as it was described before. (Majhi, 2012)

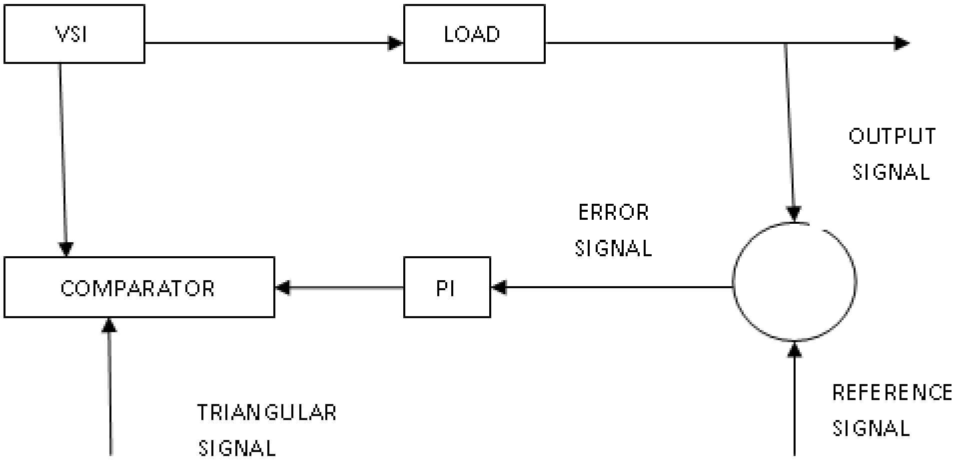


Figure 18 VSI Pi Control

As stated before, the PI controller detects the error value between the output signal and the reference signal. This controller minimizes this error by controlling the system inputs. The elements of the PI controller as its name states are the proportional (P) and the integral (I). The Proportional part is assigned to reduce the error while the Integral part reduces the offset of the system. The Proportional section is dependent on present errors of the system, while the Integral section depends on the past errors of the system. Figure 19 at the bottom illustrates the path of the PI controller and the formulas that need to be implemented to improve the response of the system. (Majhi, 2012)

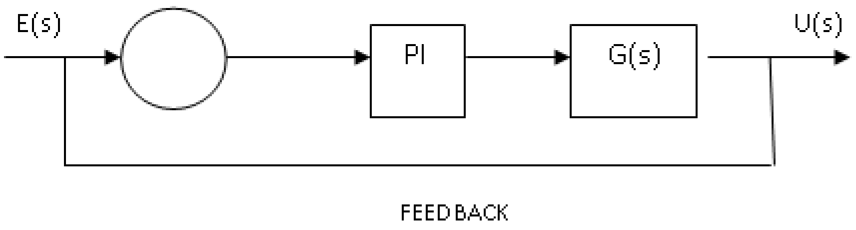


Figure 19 Pi Control

$$\frac{U(s)}{E(s)} = PI * G(s)$$

$$PI = Kp + \frac{Ki}{s}$$

$$\frac{U(s)}{E(s)} = \left(Kp + \frac{Ki}{s}\right) * G(s)$$

Where,

Kp = Proportional Gain.

Ki = Integral Gain.

Table 2 explains the effects each proportional gain causes if its value is modified.

Response	Rise Time	Overshoot	Settling Time	Steady State Error
Kp	Decrease	Increase	Minor Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate

Table 2 PI Controller table

Section 3.4.3 – Battery Bank in Parallel/Series

The battery bank is a critical part of the system. When there is no power or not enough power being generated, the batteries are relied upon to supplement the need. This critical roll must be fulfilled by the batteries at any time. The batteries must be optimized and cared for, and every precaution should be taken. This includes the design of the batteries. Batteries can be connected in both series and parallel. Selecting a battery configuration is important for the needs of the project. Another important aspect to consider is using batteries of the same chemistry. Using different chemistry “the charge rates will be different and the capacities may be different" (ZBatteries, 2012). When one battery is charged the other battery will not be. This will cause damage to occur in the batteries.

Putting batteries in series will increase the voltage of the battery bank while maintaining the same current. This causes a slower rate of power consumption. The batteries will be able to provide power for longer, but at a lower power. Many components and devices have minimum voltages. For example, the inverter requires a minimum voltage to run, when the voltage drops to low then the device will cutoff. If the voltage of the battery input drops below the threshold then the inverter will not function. Without a functioning inverter the battery bank will not be able to supply the power that they have stored. With a faulty battery, the voltage across the batteries is reduced and may not meet the requirements of the system. This decreased voltage can cause the battery to malfunction. If the voltage in the battery deteriorates low enough the cells of the battery will short circuit and cause cracks and leaks in the battery's case (Battery Tender).

The design of the systems requires a well-rounded approach. Implementing the battery bank in a parallel and series combination is a suitable approach for achieving a good balance for power. Having two parallel combinations of two batteries in series will achieve a high current and high voltage as shown in figure 20.

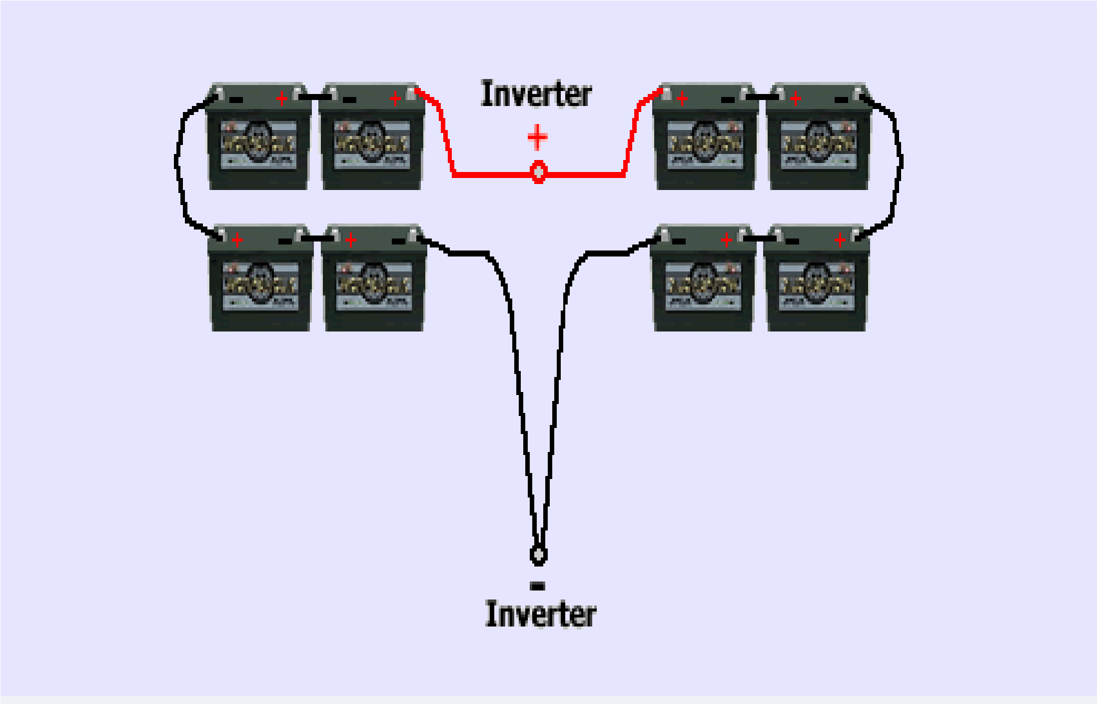


Figure 20 Batteries in a parallel-series combination

Section 3.4.4 – Battery Bank in Series

Putting the batteries in series has its benefits and its disadvantages. The benefits of putting the batteries in series are that they will be able to have a large voltage going into the inverter and using a minimal amount of current. This will allow the current to leave the battery slowly which, mimics the same amount of power leaving the batteries using a lower voltage and a higher current because they are inversely proportional to each other. The disadvantage of this is that not enough current will be able to pass through the inverter to power the load that is required. Even though power is the same, the load may require more current in order to operate. Another point is that the amount of current that can be drawn is limited because when batteries are stacked in series their potentials add, while the current stays constant. As shown in figure 21, taking two 12-volt batteries at 110ah the resulting output will be 24 volts and 110ah. The next benefit is that when power is drawn from the batteries there is an even flow of power coming from each of the batteries.

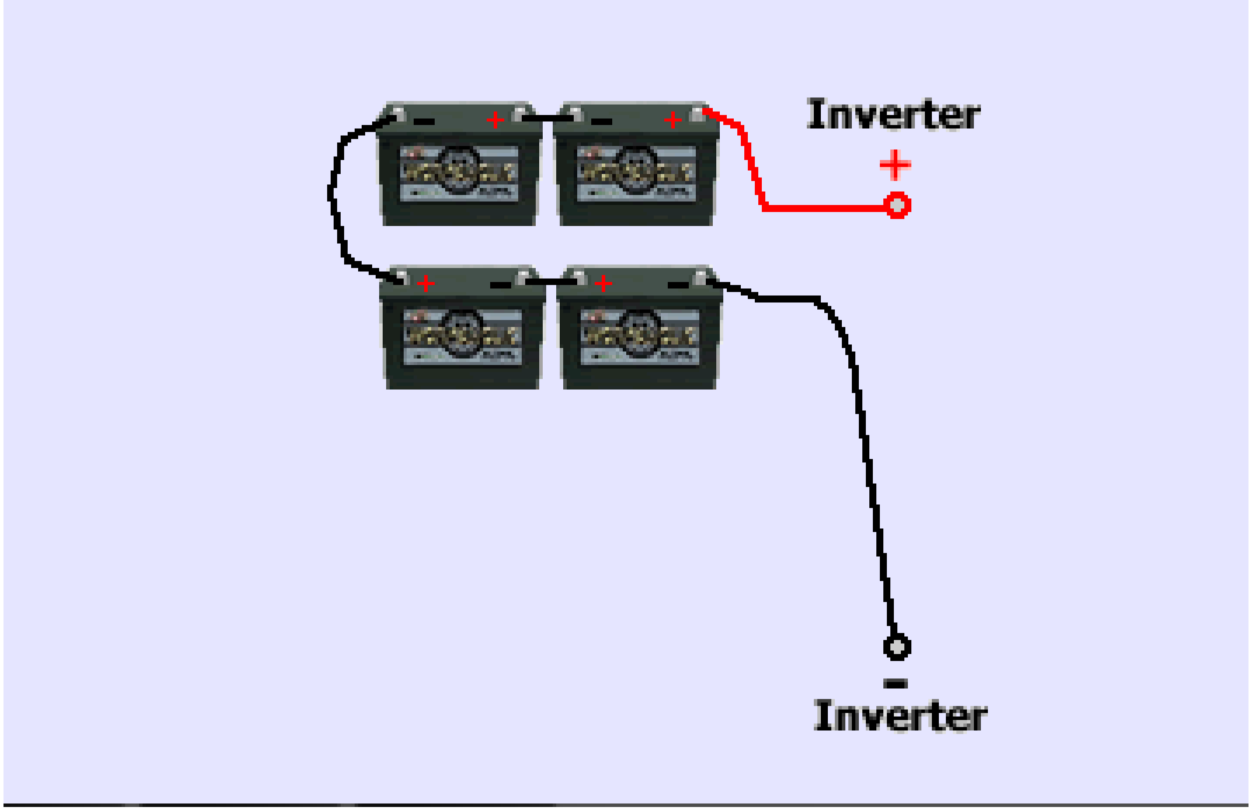


Figure 21 Batteries in series

Section 3.4.5 – Battery Bank Parallel

The last configuration is to put the batteries in parallel where every positive terminal is connected to every other positive and vice versa for the negative terminal. In this configuration, the batteries share potential, but the batteries' currents are added together. If there are three 6-volt batteries and each has 200ah then the resulting output would be 6 volts and 600ah. The batteries are then able to output a lot of current at a low voltage. This causes more work for the inverter as they will be need to have a bigger step up transformer to get to 110 volts or 220 volts. Another disadvantage to this set up is that in parallel the battery that is closest to the inverter will experience the most draw and the least amount of charge because it is farther away from the charger. Batteries in parallel will allow more current to be drawn from the system at a faster rate compared to other configurations.

Batteries in parallel, as shown in figure 22, will maintain the voltage of the batteries. Batteries in parallel will have an increase in current compared to the higher voltage and lower current of batteries in series. This allows the system to draw power at a higher rate, but the batteries energy will be consumed at a much faster rate.

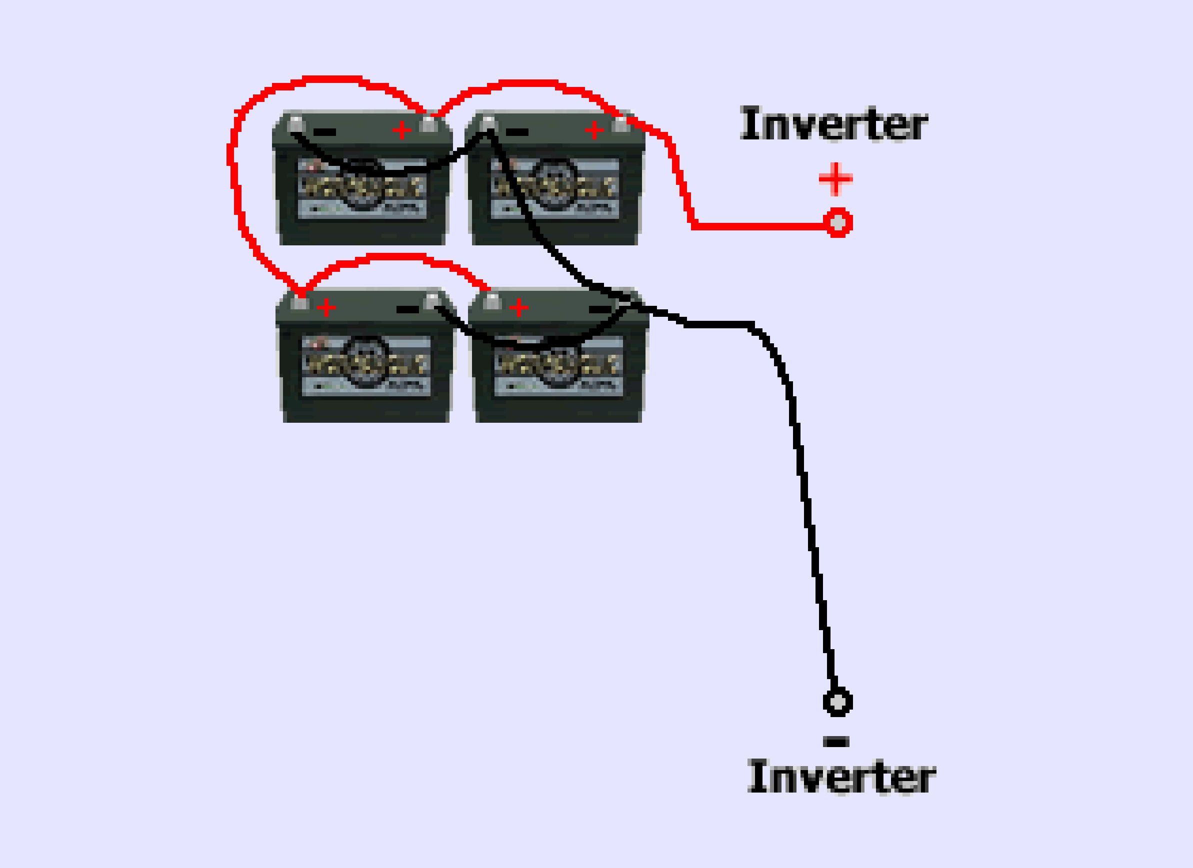


Figure 22 Batteries in parallel

Section 3.4.6 – Solar Panels

There are many different types of solar panels available and some are more efficient while others may be more aesthetically pleasing. First, are the thin film technologies, which are sometimes used with roofing shingles so the solar panels do not protrude from the roof as most other panels do (GetSolar). The compounds used to make the different semiconductors in the solar cells are different and have different properties. For instance, the Copper Indium Diselenide semiconductors cannot be produced in a large scale production setting because of its associated cost, but it does have a high efficiency (GetSolar). Amorphous silicon cells are cheaper to produce, but are not as efficient as crystalline silicon. The Amorphous silicon uses a random network of bonds whereas the crystalline lattice of the crystalline silicon keep the network of bonds in order and well connectedInvalid source specified.. Following the thin film technologies are the solar thermal systems.

The solar thermal systems are unlike most solar energy systems because they use the solar radiation to heat water or space within a building and do not generate electricity. Solar thermal energy systems are great because they offer a fast payback and help with heating costs. Water heaters for a pool or a house can use up a lot of power and be a big portion of the electric bill. With this in mind, there are two types of solar systems to help reduce the financial burden, active and passive systems. There are two sub categories of an active system the closed loop and the open loop. A closed loop system is generally for cooler climates, in this system, an antifreeze mixture passes through the solar collector and a heat exchanger heats the potable water, instead of running the potable water through the solar collector directly (GetSolar). In contrast, the open loop system is simpler to implement and the potable water runs directly through the solar collector and into a holding tank (GetSolar). The open loop system is cheaper to maintain and does not have the extra pipes that the closed loop system has, since the potable water goes directly through the solar collector. The thermosyphon technology is a sub category of two that are a part of the passive system, but the thermosyphon technology is the one that is more widely used Invalid source specified.. The passive systems are great because of their low maintenance and they are able to operate without electricity (GetSolar). The hot water rises to a tank above and the cooler water flows to the solar collector to be heated. Then there is also the concentrated solar energy that uses panels to concentrate the solar rays into a collector.

The concentrated solar energy has different configurations, but one of the ways the mirrors heat up the collector is using a parabolic shape. The collector runs though the center of the parabolic mirror and as the water heats up the steam uses mechanical energy to turn turbines and create electricity (U.S. Department of Energy, 2001). This is a large scale system and takes about as much space a fossil fuel plant, when accounting the mining area and space that is used for road building (U.S. Department of Energy, 2001). This is a better system than the traditional fossil fuel plant because is almost produces no emissions and more people would be able to work in these types of plants versus the fossil fuel plants. Lastly, the most popular and growing of energy sources are the use of photovoltaic panel.

Section 4 – Project Hardware and Software Design Details

The system design itself for a solar power system are all more or less the same and includes four major components that will make the system run. The charge controller, the inverter, the battery bank, and the power supply. 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.

Section 4.1 – Initial Design Architectures and Related Diagrams

The initial architecture for the project is the battery bank as a capacitor. This allowed the system to have to have a simpler architecture. If there is not enough power coming from the solar panels then the inverter is able to pull power from the battery bank to supplement power output.

Section 4.1.1 – Solar Panels

The solar panels that were chosen are the STP235/20Wd panels. These panels produce 235 watts of power with a maximum voltage of 30.20 volts and a maximum current of 7.95 amps. With four panels combined together they will supply approximately 1,000 watts of power on a sunny day for about 5 hours. The panels are connected in parallel so the currents will merge and the voltage of the solar panel array is the minimum of the four solar panels. If there are four solar panels that have different levels of exposure to the sun, they will not produce the same amount of power; this means that the voltage and current outputs will not be the same. Hooking up the solar panels in parallel will take care of this problem so the charge controller will be able to see the solar panel array as one input with a given voltage and current.

In order to monitor the status of the solar panels and batteries a stack light was going to be implemented. The stack lights would display the voltage that each solar panel is producing. The stack lights would be attached to the Texas Instrument TL431QPKG3 shunt regulator. There would be several of the shunt regulators for each light in the stack. Each shunt regulator would have a different clamping voltage.

The clamping voltages for the stack lights would have a step of 5 volts. Five volts was chosen because that step of voltage will give an estimate of where the solar panels are operating without over populating the stack lights. Since the solar panels are not always going to have a voltage the steps have to go down to 5 volts. This is less accurate than the batteries because there is a larger range of voltages. The solar panels need a larger step of clamping voltages because the voltages would range from 0 to 30 volts. The shunt regulators were not used because it was an additional feature and there was not enough time to install this feature.

Section 4.1.2 – Battery Bank

The battery bank supplies power to the inverter when power is not being generated. The battery bank will have to supply 18 volts, so the inverter can operate efficiently. There are three batteries in series; the batteries are 6 volts each. The batteries that were chosen are the SLIGC110. The batteries have a rating of 215 amp-hours. The batteries are powerful enough to supplement the power needs of the community while the solar panels are not producing power.

The battery bank would also have a stack light for charge monitoring. The battery would have two shunt regulators that would clamp at the charging limits of the batteries. The batteries would also have a set of stack lights that would visually indicate the charge of the batteries. The steps for the batteries would be more accurate than the stack lights for the solar panels since the range of voltages for the charge of the battery is much smaller. In order to be effective, the steps of the voltage clamping will have to be smaller. The battery is fully charged when the open circuit voltage is 6.7 volts and is dead when the open circuit voltage is 5.2 volts. The step size to have 12 LED lights will be 0.15 volts.

Instead of using the shunt regulators for each of the batteries separately a LED stack light was used for the entire battery bank. The using a microcontroller a feedback signal was sent so the microcontroller knew how charged that batteries are and lit the appropriate amount of LEDs. All 10 of the LEDs are lit if the battery bank is at 100% and the last LED are lit if the battery bank is less than 50%.

Section 4.1.3 – Shunt Regulator

The Shunt controller that was chosen for the stack lights was the TL431QPKG3. The shunt regulator has clamping voltage between 2 to 36 volts. This meets the requirements for the stack lights of both the solar panels and the batteries. This shunt regulator also meets the requirements for military specifications. It will be able to withstand the temperatures of South Africa and any possibly closed storage condition.

The shunt regulator cannot operate independently. The shunt regulator uses a voltage divider for a reference voltage. The reference voltage will determine when the shunt regulator will clamp. Since the reference voltage is part of the voltage divider it will always be proportional to the input voltage from the battery.

Once the input voltage reaches the limit that is needed to clamp the shunt regulator, voltage reference will reach the voltage that will cause the shunt regulator to clamp.

The circuit for the shunt regulator must also have high resistance. The high resistance of the circuit will prevent the high current of the batteries or solar panels to pass through the shunt regulator directly. This is important because the shunt regulator is specified as a lower current device. Another component in the circuit that requires the current to be low is the LED indicators. LEDs operate on voltage.

Section 4.1.4 – Charge Controller

The charge controller needs a microcontroller as the brains of the system. The microcontroller that was chosen was the PIC16F887. The PIC16F887 has the 40 pin ports that are required. One port would have been used for the shunt regulators. Each battery would have two shunt regulators that will denote the state of the battery; needs charging, is charged, and fully charged. If each battery has two shunt regulators that are being used as signals than the port from the microcontroller will have to be 8 pins.

The microcontroller will have to have two analog to digital converters. The microcontroller will have to compare the values of the voltage to make decisions.

Once the decision of how to divert the power, the microcontroller will turn the switches that divert the power accordingly. The microcontroller has the two output pins that are required to control the two switches.

A PIC microcontroller was used to determine the voltage input and output. The PIC microcontroller plays a major role in the decision making of how the power will be distributed. The PIC microcontroller must function properly because if it does not and the charge controller makes the wrong decision due to wrong data the batteries could over charge. Over charging the batteries can cause catastrophic failure. It is important that a durable analog to digital converter was chosen.

The PIC microcontroller has a pin designated for converting voltage to a digital signal. The voltage pin will have a reference from a voltage divider, so a large voltage will not damage the PIC microcontroller.

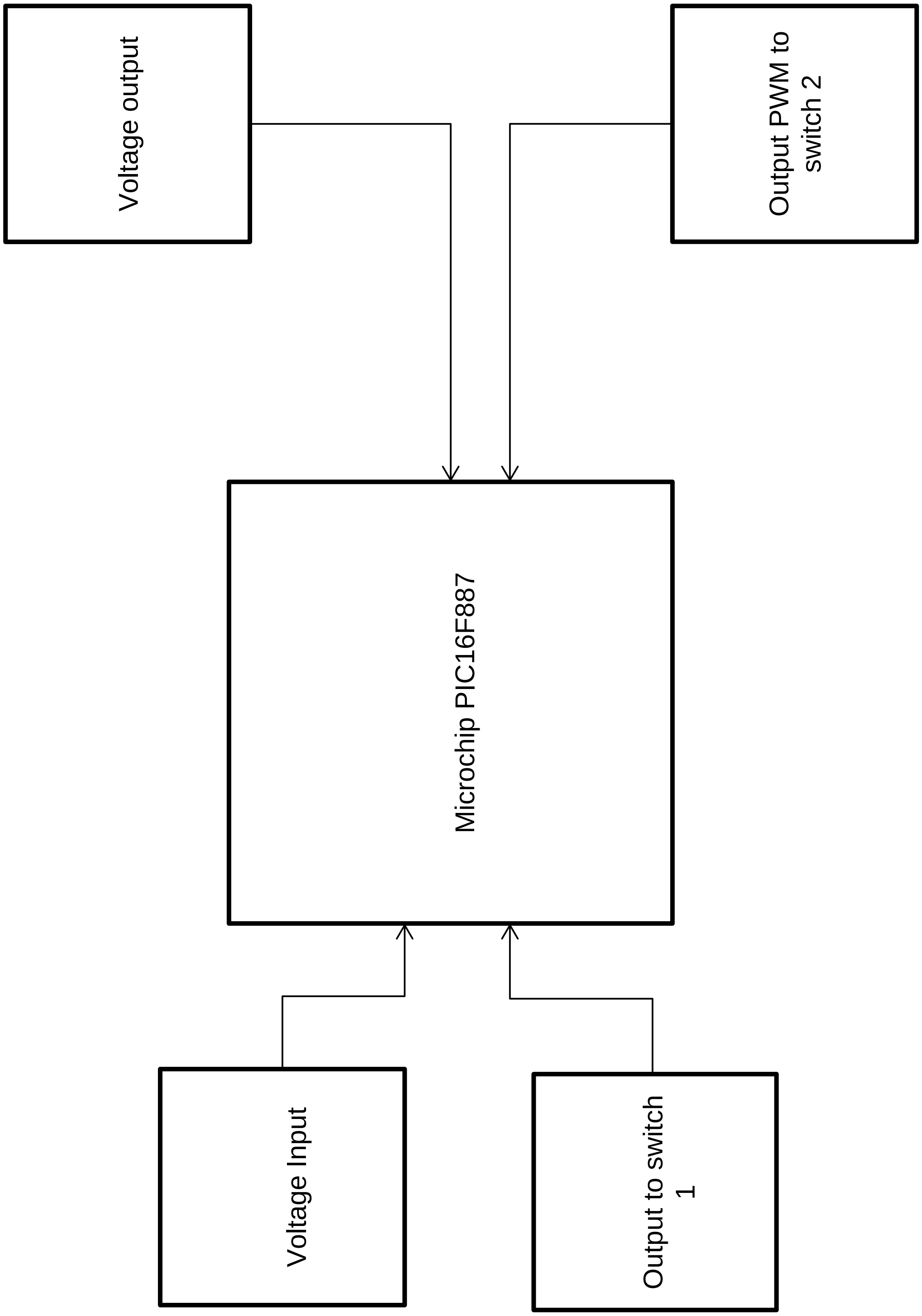


Figure 23 Block diagram of the charge controller

Section 4.1.6 – Inverter

The inverter is an important component for solar power systems. The type of inverter selected for this project is pure sine wave inverter. This inverter can be divided into two major sections which are low voltage and high voltage. The low voltage side of the inverter is the control side which controls the H-bridge to modify the DC input. The high side of the inverter ensures to bring the 24 VAC signal up to the 220VAC. In figure 23 a flow chart of the internal circuitry of the inverter is shown and it can be followed along with the explanation given in this section.

On the low voltage side of the inverter there is a microcontroller that will be used to control the H-bridge. The way the microcontroller will control the H-bridge is by creating a triangular wave and a sinusoidal wave. The sinusoidal signal is used are a reference signal and the triangular wave form is use as carrier signal. The intersection of these two signals is used as data points to activate the gate drive. Once the gate drive receives the signal from the microcontroller it drives the IGBTs at high and low frequencies. These switches will be driven at 20 KHz and 50 Hz. The 50 Hz reference signal is the frequency that determines the output signal for the inverter. The low side of the circuit has blocking diodes to protect the circuit. The low side of the circuit is protected from the high voltage side. It is usually referred as an isolation circuit. The isolation circuit it is important to prevent short circuits in the system. From here it will be explained the high voltage side of the inverter from the flow chart.

On the high stage of the inverter a 24VAC input coming from the battery bank will be supplied. In order to step up the voltage from 24VAC to 220VAC the 24VDC input will be stepped up through a boost converter to the appropriate voltage. The voltage needs to be stepped higher than the required voltage since there will be some loses on the circuit. After the voltage has been stepped it will go to the H-bridge that is composed of four IGBTs. The IGBTs are controlled through a microcontroller that was explained on the low side of the circuit. Once the high voltage goes through H-bridge the output will be modified by the IGBTs. The output of the H-bridge is going to be in the form of pulses which it will be an unfiltered sine wave. At this point the output will be put through low pass filter to get rid of the high frequencies. The output at the low pass filter will be a pure sine wave. This will be the output going to the load and this point it should be 220VAC signal at 50 Hz sinusoidal wave form. (Haider, Alam, Binte, & Salim)

After the project was prototyped and completed, some primordial modifications of the system were modified due to time constraints, and device malfunctioning in the prototyping phase. One of the biggest differences between the initial project design and the final project design were the voltage step up procedure. While in the initial design a boost converter seem to be a possible technique for DC-DC conversion, it created unexpected problems that required another type of approach. Now, in the final design the low voltage will run inside the inverter and it will finally be step up after it comes out of the inverter. The new and final design is briefly explained in the following lines.

The inverter received two isolated voltage signals. One of the signals was running with low current in order to safely operate components such as the microcontroller, drivers, capacitor, diodes, resistors, and many other devices that do not require high current and cannot handle it. On the other side a high current was used to create the desired sinusoidal signal. This high signal ran through the H-Bridge, this circuit is mainly composed of very fast switching devices, in this case the MOSFETs were used and can handle the specifications of the circuitry for proper operation.

In order to be able to step up the voltage from 24V to 220VAC, it was taken into account that the input voltage for the inverter must me a root mean square value (rms). This means that the real value of the DC equivalent input signal must be greater than 24V in order to properly step up the 24VAC. The value that should actually be input into the inverter is of 33.94VDC. If this concept is misinterpreted, the final output of the sinusoidal AC signal will be much lower than the required output voltage value for the inverter. Now that the input is properly set up, it needs to be step up to 220VAC. While many transformers in the market can step up the voltage to lower or even higher values than the ones used, this kind of step up ratio is rare; as consequence the type of transformer needed is expensive and much bigger in size than other common transformers with other kind of step up ratios. After a proper transformer is selected, the signal will be step up and ready for the following stage. The next stage now that the signal was step up is filtering. This process requires two components that are capable of blocking any undesirable signals or noise, so that at the end a pure sine wave signal is outputted and ready to be use. The components conform what is commonly known as an LC filter (and inductor and a capacitor), and while they seem to be an easy section of the inverter circuitry, the proper selection of this components is critical so they can handle high voltage and high current. Another aspect that is critical for the configuration of the LC filter is its operation with the transformer. If more detail is taken into consideration, it can be notice that the operation of the LC filter is altered by the transformer when working together. This happens because the transformers works as an inductive load, which then creates an LCL circuit, this configuration is not desired, but at the same time it cannot be avoided. This is why the best way to find the proper values for the circuitry is not only by mathematical procedures, but also with trial an error with different component configurations. In the following figure a general block diagram is displayed in order to facilitate a better understanding of the circuit connection.

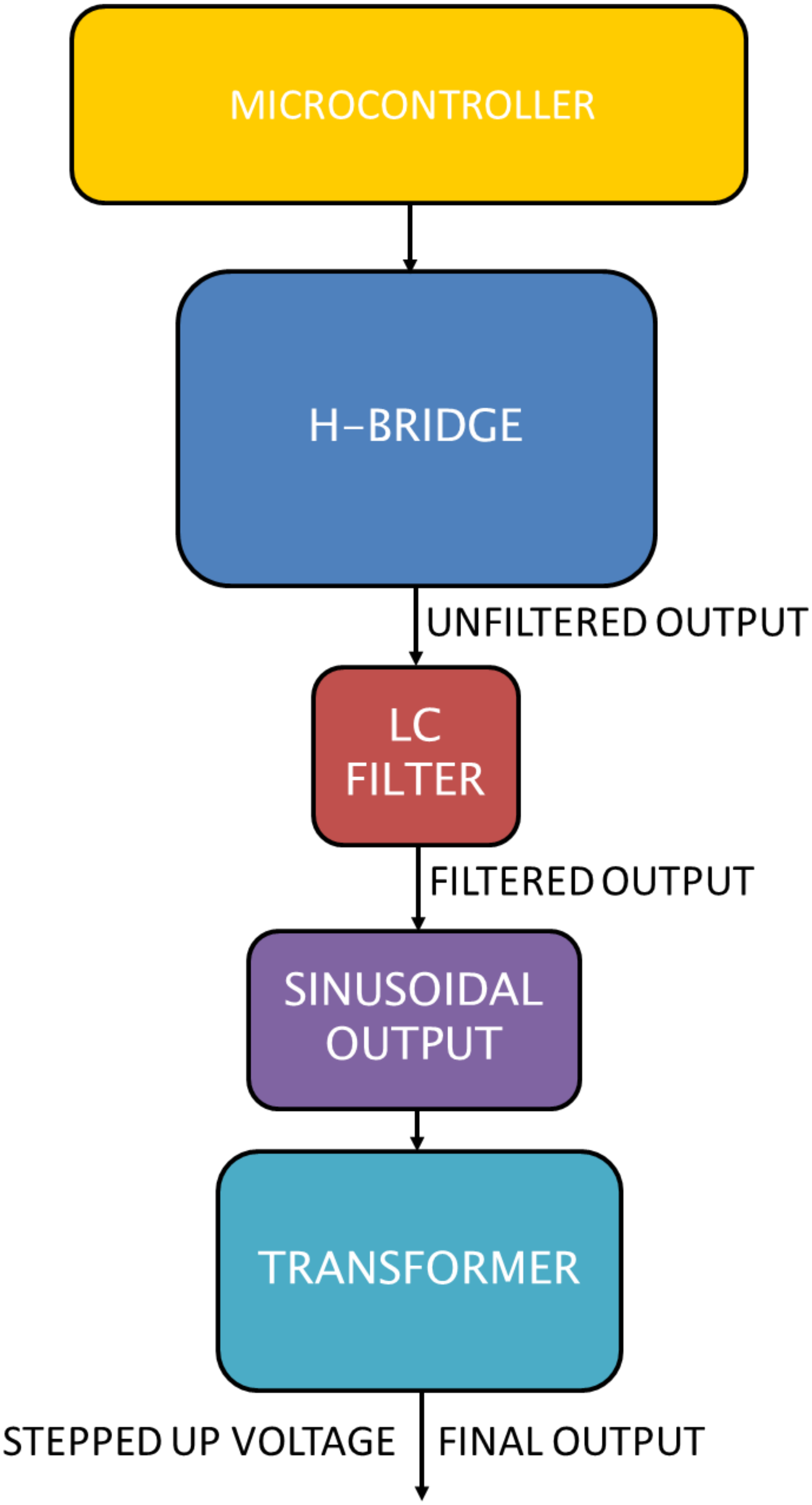


Figure 24 Block diagram of the inverter

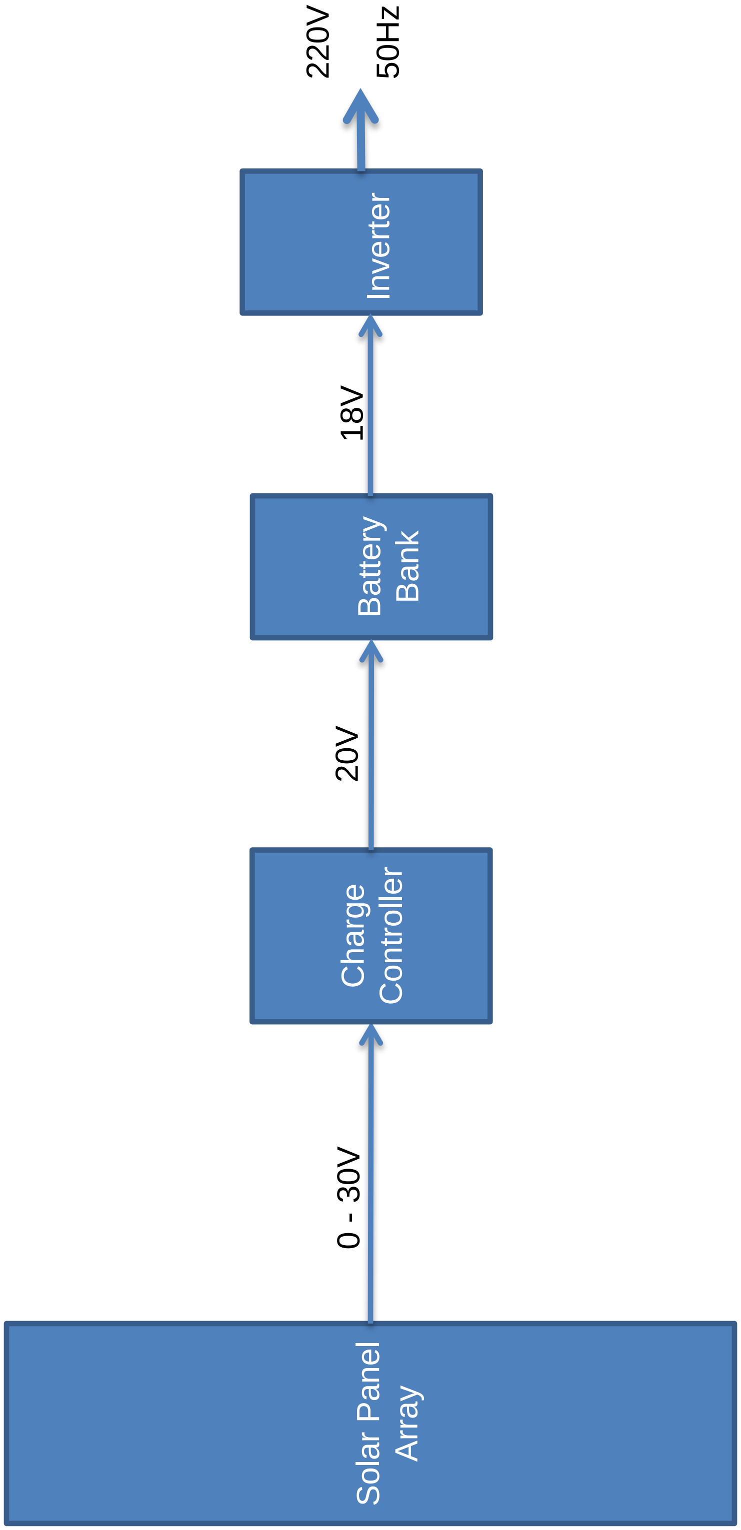
Section 4.1.7 – Overview

All aspects of the system were designed independently, but had requirements for input and output. It is critical that the requirements are met in order to integrate all the components together. Starting with the power generation the solar panels had a requirement of a 30 volt output. The voltage output of 20 volts is monitored by the charge controller is sent directly to the battery bank. The inverter has a requirement to have an input of 18 volts. The battery bank supplies the required 18 volts. The inverter's final output requirement is 220 volts at 50 Hz.

The solar panels will absorb the sunlight and convert it to electricity. The intensity if the sun on the solar panels will affect the output voltage and current of the panels. Since there is a fluctuation in voltage output and the output requirement is 20 volts, the output voltage must be regulated through a voltage regulator. Once the voltages of all the solar panels are regulated, they must be merged into a single channel. Merging the power from the solar panels would have been done by a bus bar. The bus bar creates a common node for all the outputs of the solar panels to be merged into one, but merging the power from the solar panels will be done by using a parallel combination of the solar panels. This will merge all the currents generated from each of the solar panels and the voltage output will be equal to the voltage of the panel that is producing the least. The requirement of a node is that the potential must be the same for all connections. Then a dc-dc converter will be used to step the voltage up or down.

The power can be distributed in two different directions. The Charge controller will need to determine if the batteries are full or need to be charged. If the batteries need to be charged the charge controller will divert the power the battery bank. If the batteries are fully charged, then the power will be sent to the batteries, and set to a lower voltage so as not to overcharge the battery bank.

The inverter can take the input from either the battery bank or the charge controller. The inverter will take the 18V input and step it up to 220V which is the standard input in South Africa for devices to operate. Another requirement for the inverter is to have an output frequency of 50 Hz. The power will go to a distribution panel for final consumption.


Solar Panel Array
0 - 30V
Charge Controller
20V
Battery Bank
18V
Inverter
220V
50Hz

Section 4.2 – Charge Controller

The charge controller is an intricate part of the overall system. It is truly the backbone of the overall system. The design of the charge controller helped determine the design of all the other components.

The charge controller must be able to monitor the system and respond to the changing conditions. The microcontroller must have the ability to cycle through a checklist of components. The checklist must be able to determine the state of every component and how to respond to that state.

There are two factors in making a decision. The microcontroller needs to look at the input and make a choice of weather to use buck or boost mode. Then by using a feedback system the microcontroller will need to make a choice weather to increase or decrease the duty cycle.

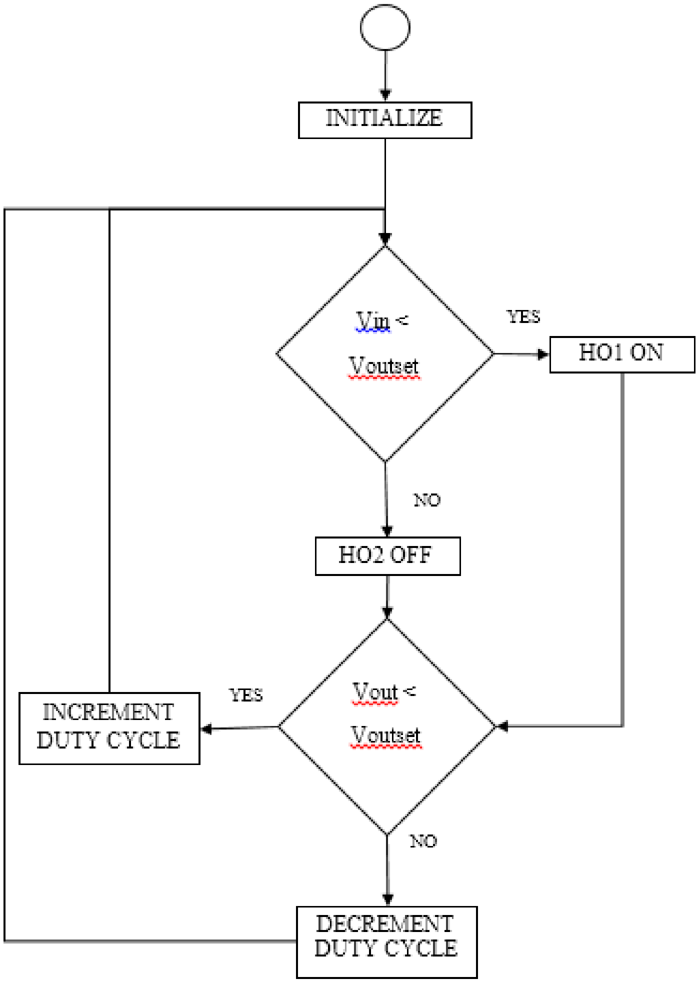


Figure 26 Duty Cyle Flowchart

Section 4.2.1 – Coding

The back bone of the charge controller is the decision making. The charge controller was programmed to handle different situations based on the power being produced and the charge level of the batteries.

The first situation is where the batteries need to be charged and there is power being generated. The output will be set to 20 volts and based on the input the microcontroller will be set to buck or boost mode. If the voltage is above the 20 volts then the microcontroller will be set to buck mode to bring down the voltage to 20 volts to charge the battery bank. If the solar panels are not producing the 20 volts necessary then the microcontroller will be set to boost mode to step up the voltage to 20 volts.

The second condition is when the batteries are charged and there is enough power being generated. Enough power includes excess power being generated and the exact amount of power being generated that is needed to supply the consumption load. The excess power, if there is any, will be directed to the dump resistor.

The third condition is when the batteries are charged and there is an insufficient amount of energy being produced. The batteries will need to be utilized. The power will be directed across the batteries. The batteries will be losing charge even though the batteries are being charged because the draw will exceed the charge.

The fourth condition is when the batteries have a low charge and there is an insufficient amount of power being generated. This situation is the extreme condition of the previous condition. When the situation becomes extreme enough the system will need to be shut down.

The shutdown process will need to start with alerting the users that the power is low. This will give them an appropriate amount of time to shut down the devices that are being used. After the alerts have been given, the system must set its self into a “default” state. That will allow for a re-initialization of the system, when power is introduced back into the system. The initialization will also need to done when the system is first assembled.

The shunt regulators would help identify any batteries that are not charging properly. This would have been achieved by comparing all the batteries to each other. If there is a battery that is not charged and all the other batteries are charged then it will be identified as a defective battery. The microcontroller will be able to notify the users that there is a defective in the battery bank, allowing for timely repairs.

The charge controller will need to know if power is being generated. If the solar panels are not producing power then the charge controller will have to open all the switches to prevent power from the batteries to be directed back into the power generation subsystem. This will put the charge controller in a standby state until enough power is being produced by the solar panels.

In a worst case scenario of the battery bank being depleted of all its charge and the solar panels not producing any power, the charge controller will be restarted when power is restored. The charge controller will need to run through a startup sequence. The startup sequence will be the first set of code to run. Once the setup sequence is run, it will not be run again until the microcontroller is reset or loses power. In order for the microcontroller to keep track of whether the microcontroller was reset by pressing the reset button or by a total loss of power a flag will be established. When the charge of the batteries and the amount of power from the solar panels has reached a critical level, the flag will have to be set. If the system recovers from the critical situation, the flag will be set back to normal operation.

Section 4.2.2 – Shunt Regulator

The shunt regulator that was chosen for the charge controller is the Texas Instrument TL431QPKG3, which is in the TLXXX family, and is military grade. South Africa has hot summers and cold winters. It was chosen because it can operate with a range of temperatures at -40°C to125°C. This will allow for the systems to be running at full power in the middle of summer in South Africa and during cold winters.

The shunt regulator has a voltage reference between 2.5 – 36V. This allows for an adaptive design of the battery bank. With 6 volt batteries the shunt regulator will be able to monitor the charge level of the batteries. The shunt regulator will be an integrated circuit. The shunt regulator will have an LED stack light circuits on the board, a regulator for full charge and a regulator for low charge will be directed to the microcontroller, so the microcontroller will be able to distribute the power appropriately. The microcontroller will stop charging the batteries when the regulator for the full charge is clamped. The microcontroller would not allow the batteries to charge again until the low charge shunt stops sending a signal. This indicates when the batteries have reached their minimum charge, subsequently indicating they need to be charged again. There are multiple conditions that can arise when the system is running that the shunt regulators will help in the decision making.

The microcontroller will be able to determine the state of the batteries by using a shunt regulator for a high and low voltage. The high voltage shunt regulator will send a signal when the batteries are full charged at 6.7 volts. The low voltage shunt regulator would send a signal when the batteries do not need to be charged. Once the signal is not being sent, the microcontroller will know that the batteries need to be recharged.

Low voltage	**High Voltage**	**Notes**
0	0	The batteries are dead
1	0	The battery bank is not full charged, but the batteries are not dead.
1	1	The batteries are fully charged.

Table 3 Logic table for the shunt regulator

The low shunt regular not sending a signal and the high shunt regulator sending a signal is an impossible condition because if there is enough voltage to clamp the high shunt regulator then there must be enough voltage to clamp the low shunt regulator, since it requires less voltage to clamp the shunt regulator.

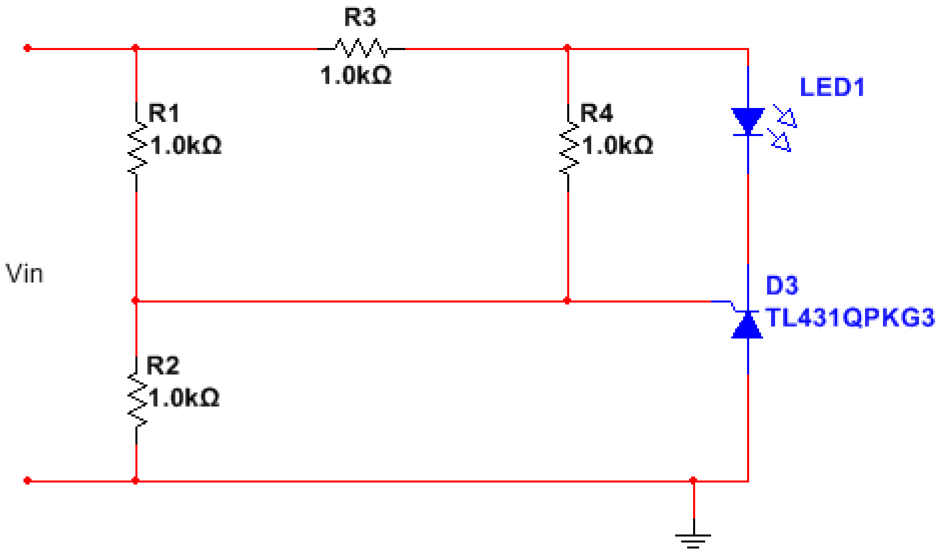


Figure 27 Circuit for the shunt regulator not knowing the clamping voltage. This circuit was designed by Renewable Energy UK.

The shunt regulator is a small signal circuit that would measure the input voltage by using a voltage divider, referencing R2. The voltage across R2 will be the reference voltage that will cause the shunt regulator to be clamped. The LED can be used to symbolically represent a signal being sent to the charge controller for the high and low charged shunt regulator on the LED stack. When the shunt is clamped allowing current to flow, the LED will turn on or a signal to be sent to the microcontroller. Setting the reference voltage to 5 volts and the full capacity to 6.7 volts and setting R1 to 1k make R2 to equal to 1.54k. Using the formula from Renewable Energy UK.

$$V_{limit} = V_{ref} * \left(1 + \frac{R_1}{R_2}\right)$$

The LED must also have enough voltage to turn on. Using R1, R3 and R4 another voltage divider must be used. The resistance of the resistors will vary because the voltage reference will change for every clamping effect.

The voltage across the LED is very important because a high enough voltage will cause damage to the LED. Since the voltage across R1 is 7.7 volts a voltage divider will be needed to drop the voltage across R4. This can be designed using the voltage divider equation. (Renewable Energy UK, 2012).

Using these equations for both V_{ref} of the shunt regulator and the voltage across the LED are ratios. The actual values must be very high in order to minimize the current flow. The low current is vital to the design of the shunt regulator because the high current that the batteries and solar panels are able to produce can damage the low current components; the shunt regulator and the LED.

Another shunt regulator that is available in the TLXXX family of shunt regulators from Texas Instruments is the TL431IPKG3. The TL431IPKG3 does not meet the requirements of the project. The TL431IPKG3 shunt regulator has an operating temperature range of -40°C to 85°C. This falls within the requirements of the climate, but the requirements of the project are military grade components that have a range of -40°C to125°C. Although the low range of -40°C is well within the range of the project, the high range of 85°C does not because it is unknown where the system is going to be stored. If the shunt is stored in a closed room with other components of the system that produce heat, the shunt could eventually break down due the high heat of the environment and the excess heat being generated.

Neither of these shunt regulators were used in the design because the same thing could be accomplished using a voltage divider and send the reference signal to the analog to digital converter of any microcontroller.

Section 4.2.3 – PIC Microcontroller

In order to measure the power that the system is generating, a PIC microcontroller was going to be implemented. The PIC microcontroller can measure voltage using an analog to digital converter. The voltage is measured using a voltage divider. The resistance of the reference outputs needs to be chosen, so the reference voltage is small enough that the microcontroller will not sustain damage.

The voltage divider is a simple circuit that will reduce the voltage across one resistor and divide it across multiple resistors. The ratio of the resistor in series will correspond to the ratio of the voltages across each resistor.

The PIC microcontroller has two pins, pins 2 and 3 that will take the analog signal, so the signal can be converted to digital.

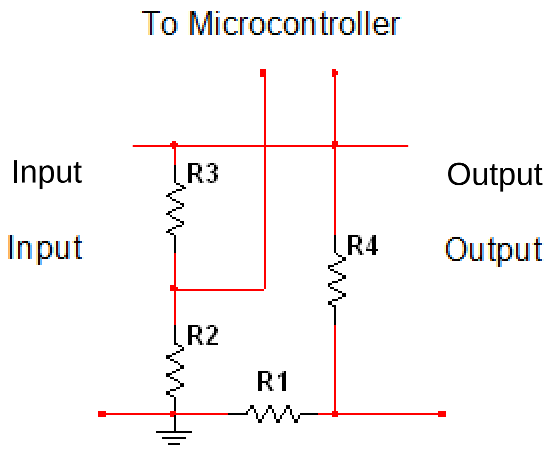


Figure 28 Voltage and Current Divider

The PIC microcontroller can be programmed using C programming. This will allow for simpler coding that will require less time to program. The PIC microcontroller is a single chip that will need to be programmed via a programming board. The programming board will interface with a computer through a USB port and have the PIC microcontroller attached. The PIC microcontroller then can be removed from the programming board and attached to the microcontroller.

Section 4.2.4 – Microcontroller

The Toshiba TMP89FS60 is an 8-bit microcontroller, from the TLCS-870C1 category, that will be in control of charging the power storage. This microcontroller runs up to 8 MHz and is able to operate in -20°C to 85°C environment. It is highly efficient and only uses 93.5mW to operate. Using an energy efficient microcontroller will have a minimal impact on the power storage, making the system better overall.

There are 60k bytes of space available to program the microcontroller for all of our needs. The bulk of the programming will be getting some digital input and turning the switches on or off factored by the conditions of the system. The random access memory will be able to access 3k bytes of the flash memory. The microcontroller will be programmed using the C programming language.

One of the primary functions of this microcontroller will be to control the charging of the battery bank. It has 64 pins and 58 pins for the input/output ports. Having this many pins for the input/output will allow multiple components to communicate to the microcontroller. Another added benefit is that all of the ports are bidirectional. Two PIC microcontrollers were going to be set up directly to two of the ports. These PIC microcontrollers will calculate the power that is being generated and the power that is being consumed by the load, but instead only one microcontroller was used and a voltage divider.

The second primary function of the microcontroller is to measure the power of battery bank. Connecting the voltage shunt regulators to the microcontroller directly, it would be able to know the status of the battery bank’s charge and manipulate the switches accordingly. There will be two voltage shunt regulators from each battery, which would send a signal to the microcontroller, to tell it if the battery has a 50% discharge or a 100% charge. The battery bank all together will use six pins of the microcontroller’s input/output ports to check the battery bank’s status.

Knowing the input power and the power being used, in conjunction with the charge of the battery bank, would allow the microcontroller to make a decision of where to direct the power and manipulate the switches. The key benefit to use this microcontroller is the amount of input and output it is able to handle.

To read in the values from the two PIC controllers there will be eight 2-1 multiplexers. The two controllers will be connected to the 2-1 multiplexers and they will be connected to the port of the TMP89FS60 microcontroller. When the multiplexers select zero they power input PIC controller will be selected to be connected to the port of the TMP89FS60 microcontroller, conversely when zero is selected the power consumed PIC controller will be connected to the TMP89FS60 microcontroller. This would allow the two PIC controllers to share a port. The pin configuration for the Toshiba microcontroller is shown below in figure 29.

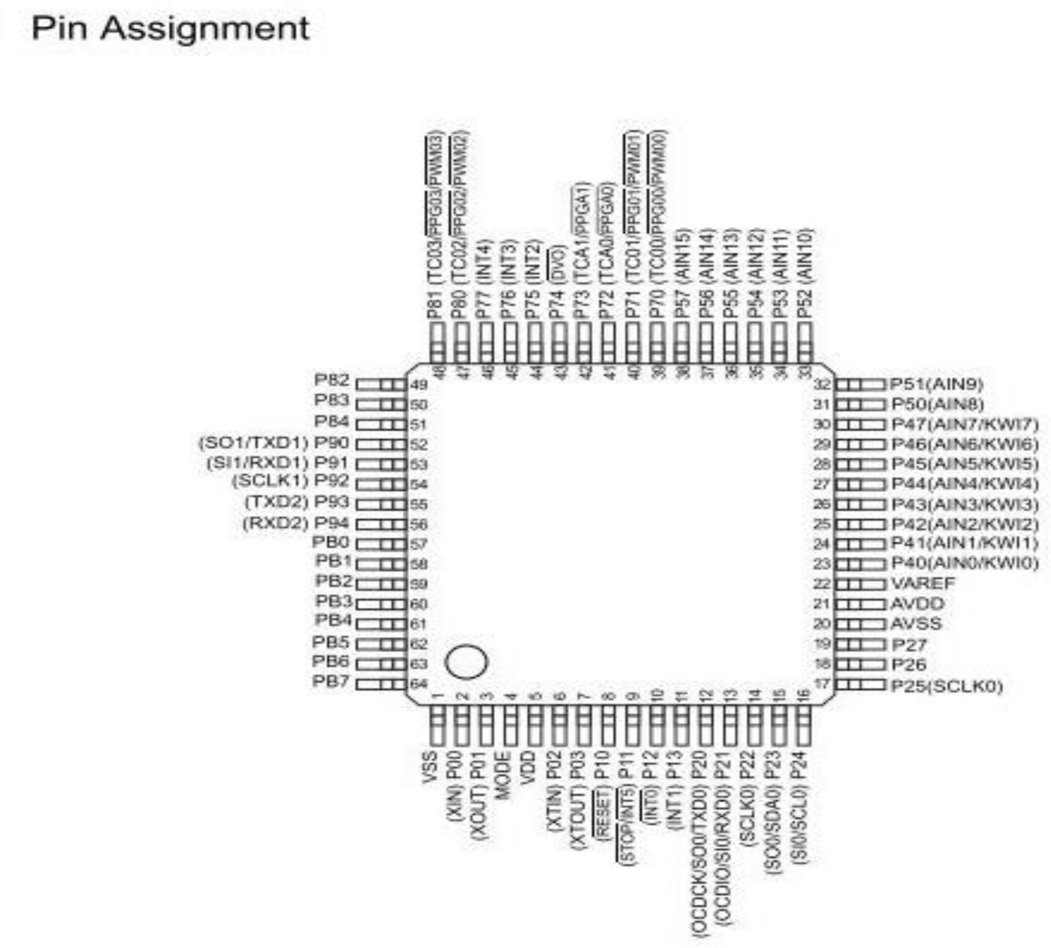


Figure 29 Pin Assignment of the Toshiba TMP89FS60 Microcontroller

The next microcontroller is the Atmel ATmega32. This was a viable option because it would be able to handle the amount of inputs and outputs that are part of our original design. There are 32 programmable input/output lines and only 16 of them will be needed. Another benefit to this microcontroller is the large amount of programmable space that is available, much more than what is needed, over 32Kbytes. There is also a large cache, which helps run the microcontroller more smoothly. This microcontroller would also be able to withstand the climate for years to come; it has a data retention rate of 20 years at 85°C and 100 years at 25°C. This microcontroller has over 131 instructions in its advanced RISC architecture that will make coding a little bit easier have fewer instructions to choose. This microcontroller also comes with software security, so the code can be locked. There is also a 10-bit analog digital converter.

The next microcontroller is the Texas Instrument MSP430. It is an ultra-low power consumption microcontroller, using only 1.8 V to 3.6 V. It is a 16-bit RISC architecture system. MSP430 has an 8-bit input/output port and a 2 bit input/output port. This system's processor runs at 16MHz. Having only one 8-bit input/output port a multiplexer would need to be implanted in order for the microcontroller to read in all the data that the charge controller needs to know to make necessary decisions.

Lastly, the PIC16F887 is a viable option. This microcontroller has 14 analog to digital converters and a 10 bit resolution. It comes in a 40 pin DIP package so soldering was easily done. It consumes minimal power to run. It has an 8MHz internal clock, but an external 16MHz clock was used. This PIC has 35 instructions that are easy to use. This was the best choice for the microcontroller because of all of the resources that was found for programming and other senior design projects. Another reason why this microcontroller was chosen was the cost and microchip gives free samples of this product which made the prototyping easier. The programming will be done using the C programming language

Section 4.2.5 – Method of Charge

A three-stage charge controller was going to be implemented to charge the battery quickly and efficiently. A benefit to this methodology is the bulk of the charging is done quickly and the last 25% or so charges slowly to store the most amount of power into the batteries. This ideal is great for solar applications because the amount of sunlight that can be harvested is limited, so the batteries need to charge rapidly. A quickly charged battery would also quickly discharge, but this method allows the battery to restore most of its capacity.

The first stage of the charge will be the bulk charge section. This time in the charging sequence, the current will remain constant while the voltage increases. This is especially useful for when the battery is at a deep depth of discharge.

The second stage of the charge will be the absorption stage. During this time, the voltage peaks out and the current will reduce according to the power that the battery already has stored. The current will taper off because the input current will receive more resistance as the battery stores more current.

The third stage of the charge will be the float charge stage. This will keep the battery at full power. The float charge puts the same amount of charge that the battery is self-discharging. The float charge also helps reduce the amount of gas that is generated from charging because the battery is at a lower temperature. Since the battery will be at a cooler temperature, it will be able to reach max storage capacity.

The three stage charge is one of the better charging methods, but our design used a constant voltage charge which was easier to implement and still able to charge the battery. A constant voltage charge, charges the battery at a constant voltage until the battery becomes fully charged.

Section 4.2.6 – Problem Identification

The condition of the different components will be indicated by a stack of LED lights. The stack lights will be attached to shunt regulators that will trip at different voltages. The indicator lights will be assigned accordingly to follow a high to low pattern. This was going to be used, but instead using a voltage divider to the microcontroller eliminated the use for the shunt regulator. The other downside to using the shunt regulator is the amount of space that would have been needed to implement it in the PCB.

The voltages would range from 5.2 volt to 6.7 volts for the batteries with an increment of 0.15 volts. The stack light would have 12 lights, the top 10 would be for voltages that would be in the operating range of the batteries and the last two would be for identifying batteries that need to be charged and bad batteries, respectively. The color coordination for the stack light would be a green to yellow to red scheme. Green would be the top two LEDs that are indicating fully charged. Then the yellow would populate the next eight LEDS that indicate a moderate charge. Once the last yellow LED is turned off the microcontroller will identify this and know that battery needs to be charged. The red LEDs would have been used to identify dead batteries and damaged batteries. The top red LED would identify that the battery is dead, but if the last LED is the only LED lit the battery is damaged and not storing its charge properly.

The same method would have been used for the solar panels. The stack of LED lights would have to be larger because the voltage range is larger for the solar panels. Also, just because a solar panel is not producing a voltage does not mean that it is malfunctioning. The stack lights will have to be manually compared because at night the panels should not be producing power, but during the day the panels should be producing power and the stack lights will indicate if one of the panels is not producing power. If it is not producing power it can be identified as a bad solar panel. Since the panels are in a parallel combination the use of shunt regulators with this design is useless, unless monitoring the solar panel array is important.

Identifying bad components would be very beneficial because it would increase down time because repairs can be made in a timely manner. This would also reduce damage to the systems by preventing a guess and check method of problem solving.

Section 4.3 – Inverter

The design of a sine wave inverter is complex and there are several things that need to be considered in the design. The requirement for this design is to build an inverter that takes 12VDC input and converts it into 220VAC output. The frequency should be 50Hz and it should be capable of delivering at least 1kW.

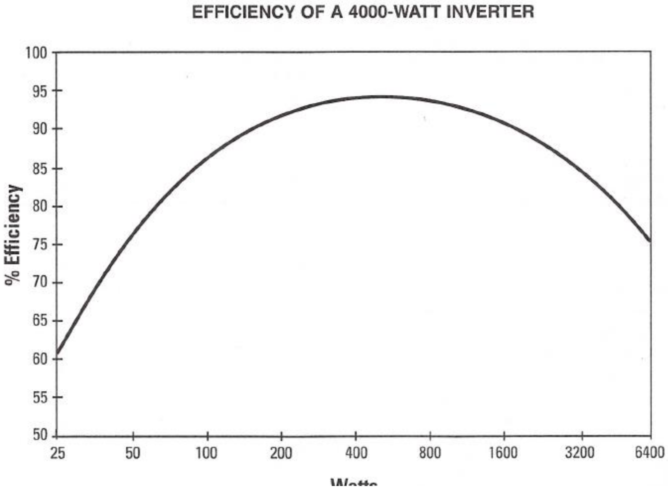
The wattage output of the system is the amount of watts the inverter can deliver during standard operation. The inverter has to have the capability to power all the alternating current loads operating at one time.

The input voltage of the inverter is the figure that the inverter is required to run on. The input voltage of the inverter must match the voltage coming in from the battery bank. As the inverter's power output increases by load consumption, the direct current input voltage increases as well. Designing voltage units higher than 24 volts will allow less amperage to pass through the inverter and reduce the size of wires and components.

The frequency shows how often electricity alternates or cycles. In the United States the standard is 60Hz. In other countries, such as South Africa uses 50 Hz. Frequency regulation is important to protect the life of the equipment used as loads.

Voltage regulation is important since it is the variation that will occur on the output voltage. Inverters that are well designed will produce a near constant output voltage.

The efficiency of an inverter is critical in the design. Inverters have different levels of efficiency at different power outputs. The inverter should be design to power loads at less than its rated capacity. With that in mind, it is wise to design a unit rated at a high efficiency over a wide range of loads. To illustrate the idea, Figure 28 shows a sample of the efficiency curve on a 4kW inverter. In this example it is easy to observe that its maximum efficiency stands at 400 watts with a 93% efficiency rate.



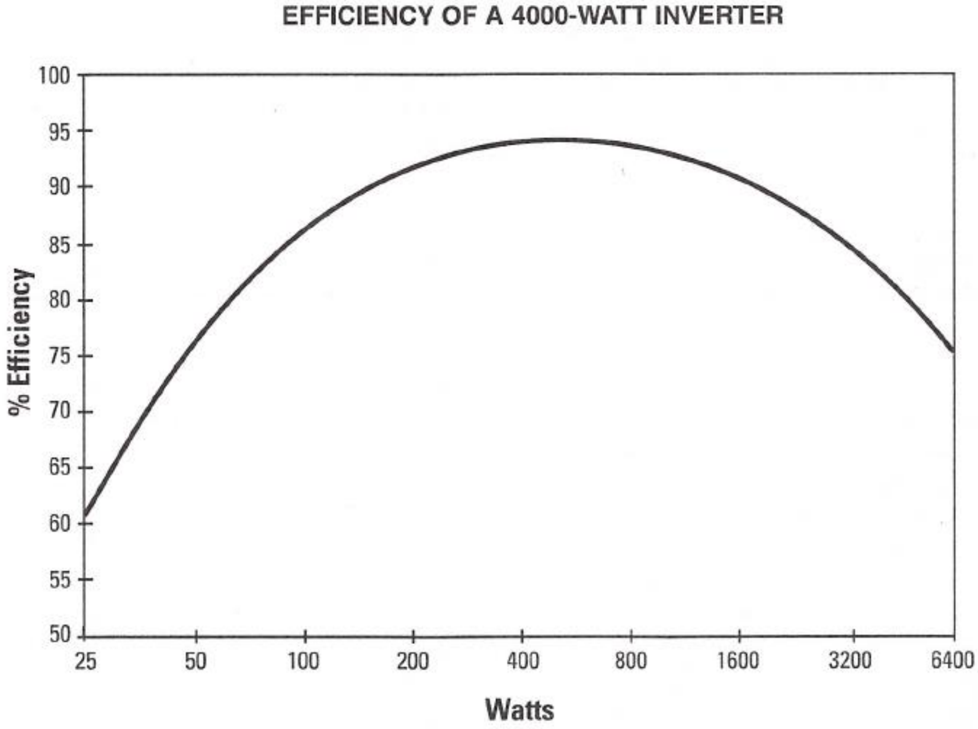


Figure 30 Common Waveforms Produced by Inverters. Adapted from by "Photovoltaic Photovoltaic Design and Installation Manual," by Solar Energy International, p.83. Copyright 2004 by Solar Energy International. Adapted with permission pending.

In order to accomplish the desired parameters, a general introduction of the inverter analysis had to be presented. To meet these strict parameters, a detail description of the components will be discussed. The following components such as the sinusoidal pulse width modulation (SPMW), full wave bridge inverter,), LC filter, and high stage voltage are primordial for well-designed inverter.

Section 4.3.1 – Sinusoidal Pulse Width Modulation (SPWM)

Pulse Width Modulation techniques are commonly used on DC to AC inverters. This very advance technique is used to maintain a steady voltage rate, regardless of the load. This is accomplished by correcting the width of the pulses to obtain the desired output voltage. To create a PWM, a reference and a carrier signal must be generated to compare them using a comparator to obtain final output. The reference signal can be a sinusoidal or square wave and the carrier signal can be triangular or saw-tooth wave form that must be much greater than the reference signal. The three basic types of PWM techniques that will briefly be discussed are based on cost, noise, and efficiency. These basic types are single pulse width modulation, multiple pulse width modulation, and sinusoidal pulse width modulation (B. Ismail, 2006).

In single pulse width modulation there is only one output for every half cycle. To generate the gating signals, a comparison of the rectangular and triangular reference must be done. The frequency of these two signals is similar to each other.

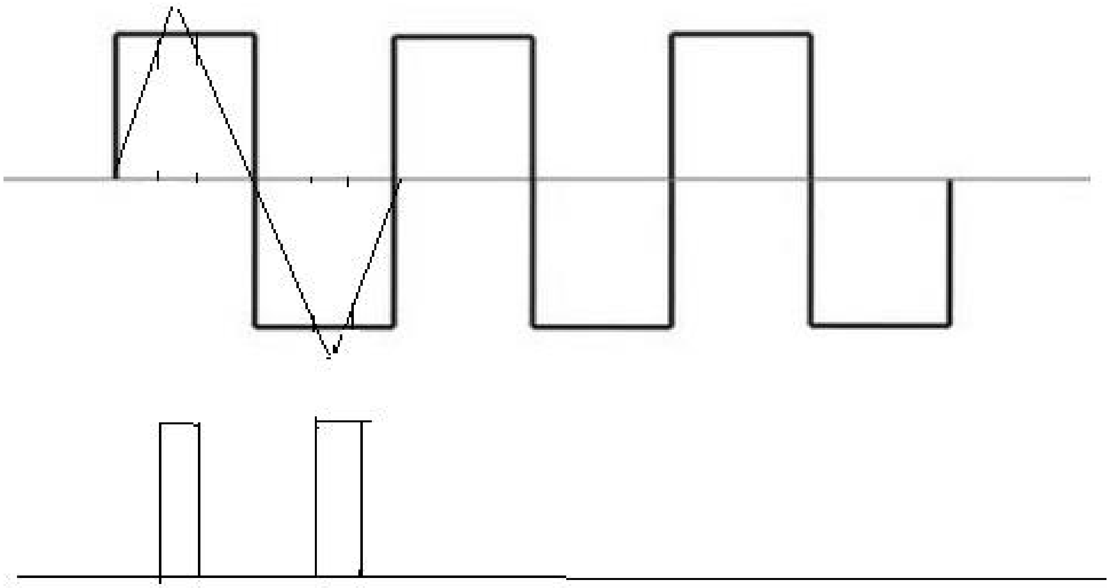


Figure 31 Single Pulse Width Modulation, permission pending from Majhi

In order to determine the values for the rms, delta (duty cycle), and Modulation index the following formulas may be used.

$$V_o = V_s\sqrt{\frac{2*t_{ON}}{T}} = V_s\sqrt{2*\delta}$$

$\delta = \frac{t_{ON}}{T}$

MI = $\frac{V_r}{V_c}$

Where,

δ = Duty Cycle

MI = Modulation Index

V_r = Reference signal voltage

V_c = Carrier signal voltage

The second type of modulation is a multiple pulse width modulation, where there is multiple numbers of outputs per half cycle and their width are equal. The output signal is generated by comparing a rectangular reference signal with another triangular reference signal. The output frequency and the carrier frequency are determined by the reference signal. To determine the number of pulses (p) per half cycle the use of the following formulas is essential. (Majhi, 2012)

p = $\frac{f_c}{2f_o}$

V_o = $V_s\sqrt{\frac{p\delta}{\pi}}$

δ = $\frac{t_{ON}}{T}$

Where, delta is the duty ratio and V_o is the rms AC output.

The modulation index varies from 0 to 1 which then varies the pulse form 0 to π/p and the output voltage from 0 to $V_{s.}$

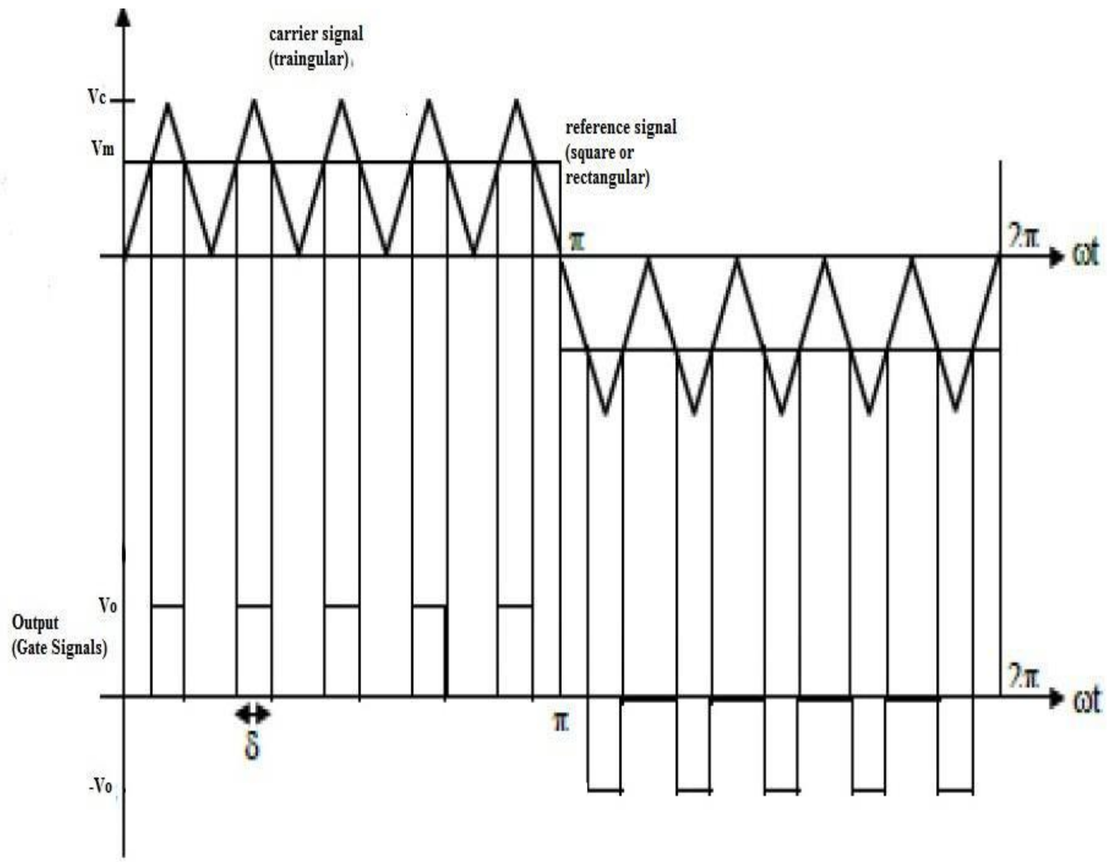


Figure 32 Multiple Pulse Width Modulation, permission pending Majhi

The third type is a sinusoidal pulse width modulation. This technique uses multiple numbers of output pulses per half cycle that have a different width. The pulses are varied in with proportional to the sine wave. A triangular reference waveform at a high frequency is used and compared it to a sinusoidal reference waveform to obtain the output signal.

$$V_o = V_s\sqrt{\frac{p\delta}{\pi}} = V_s\sqrt{\sum_{m=1}^{2p}\frac{\delta_m}{\pi}}$$

Where, p is the number of pulses and δ is the pulse width

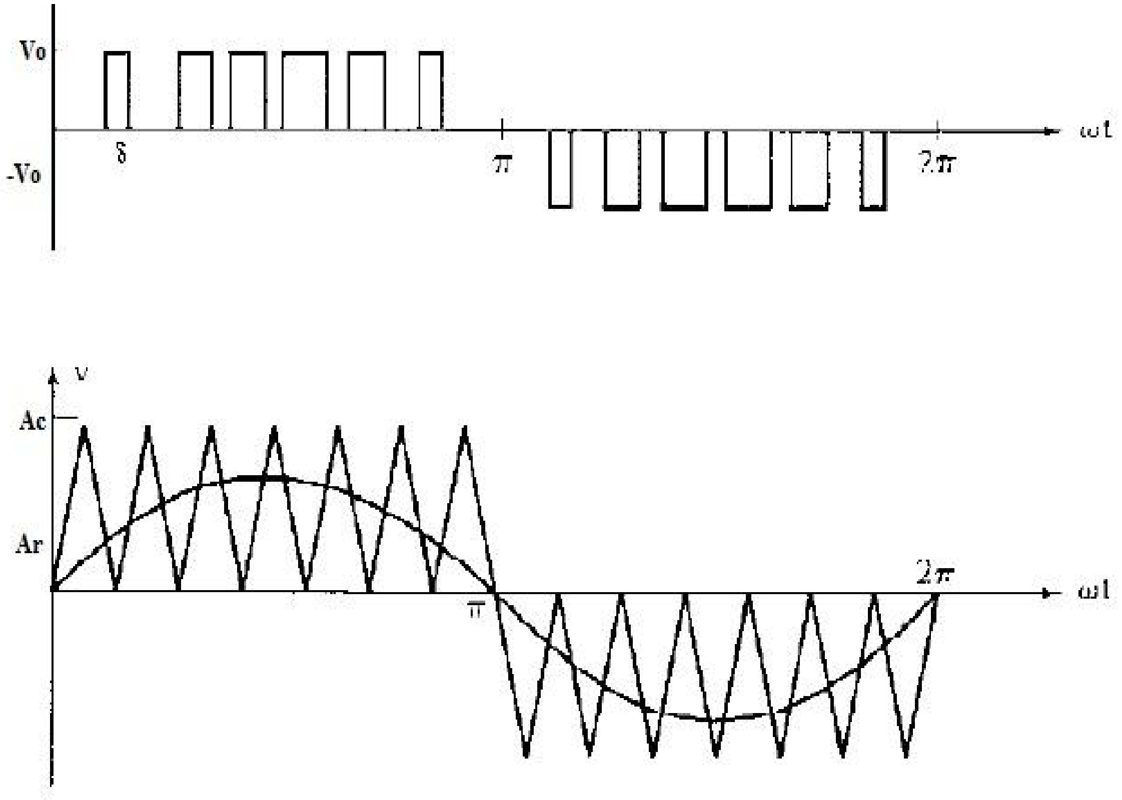


Figure 33 Sinusoidal Pulse Width Modulation, permission pending from Majhi

In order to create a true sine wave inverter, the best technique to use is the sinusoidal pulse with modulation. A digital waveform needs to be created using this method and the duty cycle needs to be modulated so the average voltage corresponds to a pure sine wave. To obtain a sinusoidal pulse width modulation signal, a low power sine waveform needs to be produced and compared to a high frequency triangular wave. The generated signal can be used to control switches such as an H-bridge that will be discussed further in section 4.3.3. After the signal goes through the H-bridge, the output signal needs to be filter by an LC filter in order to obtain a signal approximately equal to a sine wave. The SPWM technique produces a much more similar AC sine wave than the other techniques. Harmonic signals are still present at this point and they are relatively high. Later in this section the elimination of harmonic signals will be discuss in further detail. (Majhi, 2012)

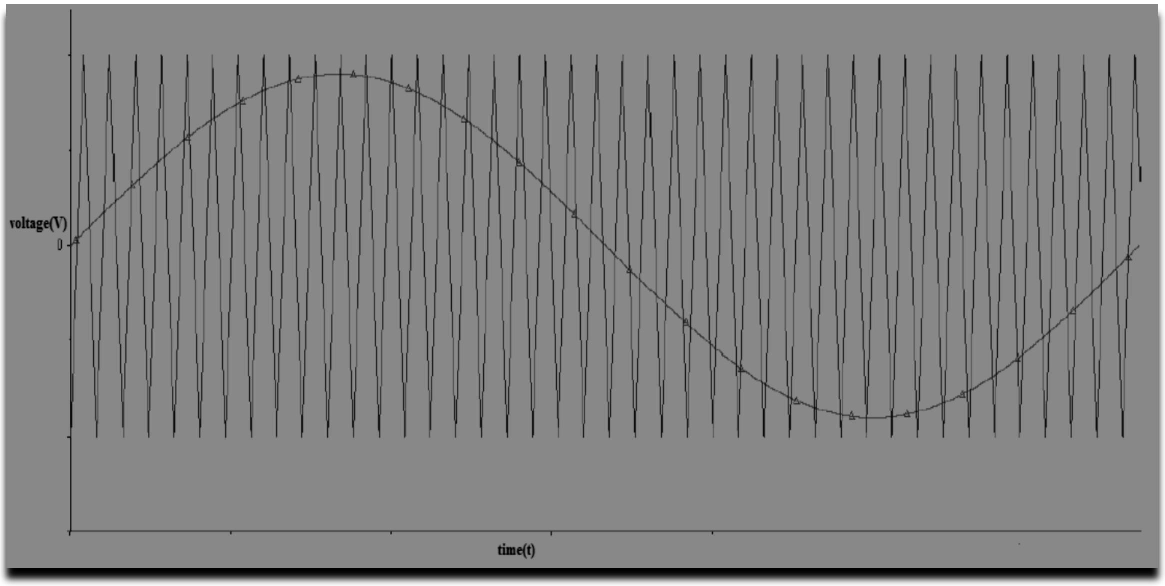


Figure 34 SPWM comparison Signals, permission pending from Majhi

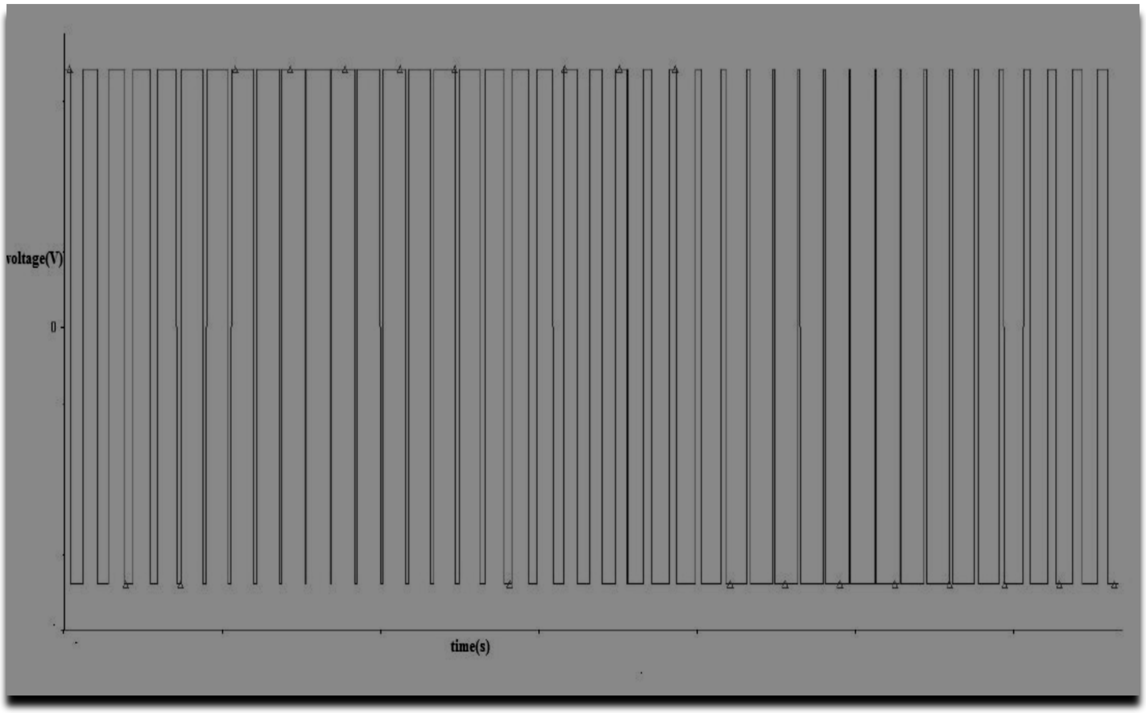


Figure 35 Unfiltered SPWM output, permission pending from Majhi

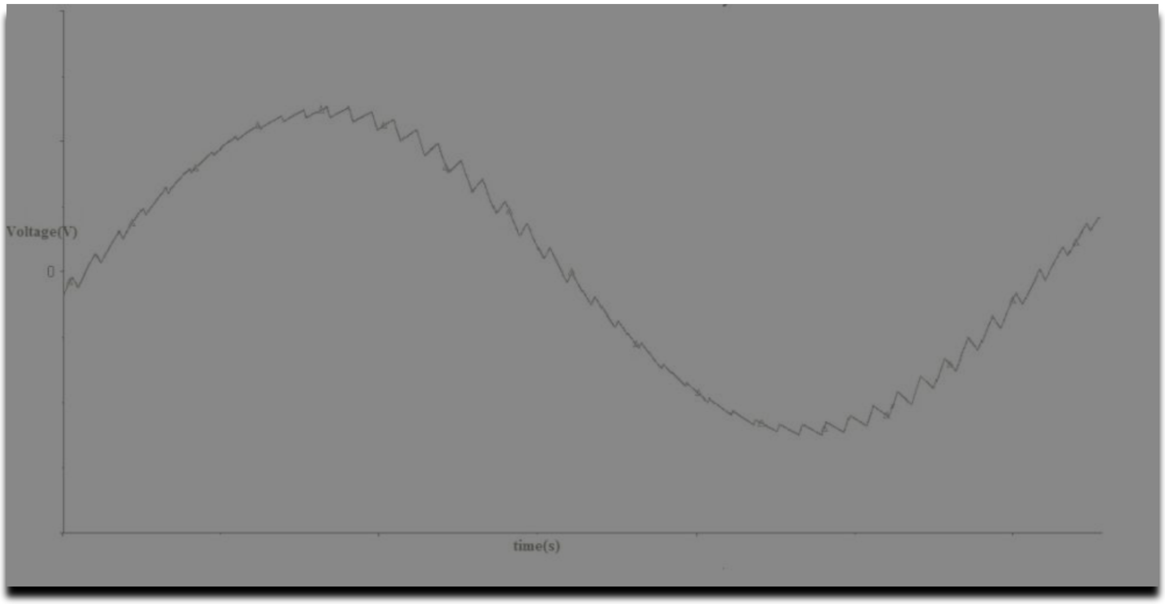


Figure 36 Filtered SPWM Output, permission pending from Majhi

The modulation index of this signal (MI) is the ratio of the amplitude of the sinusoidal reference signal (Am) and the amplitude of the triangular carrying signal (Ac). The modulation index controls the amplitude of the output voltage. Therefore, the triangular carrier amplitude must be greater than the sinusoidal amplitude to achieve a ratio smaller than one. The advantage of having a ratio smaller than one is that a clean sinusoidal waveform can be produced. The down side of having a ration smaller than one is that power loss will increase due to the large amount of switching per cycle. On the other hand, if the triangular carrier signal is not greater than the sinusoidal reference signal, over modulation will occur. This phenomenon causes less switching per cycle and as a consequence a large AC voltage can be obtained. The tradeoff for obtaining a higher voltage will be a degraded sinusoidal output signal. For this reason, it is important keep the modulated index ratio slightly smaller than one to achieve the highest efficiency for the generated sinusoidal signal. (Crowley & Fong Leung, 2011)

Section 4.3.2 – Selective Harmonic Elimination (SHE)

Harmonic signals are produced when generating a sinusoidal pulse width modulation signal. As the harmonic spectrum generated becomes bigger, the wave form acquires a more complex appearance, which points out a deviation of the generated sinusoid compared to its original appearance. This new complex harmonic spectrum obstructs the fundamental frequency sine wave causing difficulty when analyzing it, or even making it impossible to be recognized. In a situation where the magnitude and order of the harmonics are given or known, the process of reconstructing the original wave form is fairly simple. On the contrary, decomposing a distorted waveform into its harmonic components is far more challenging. To be able to find its harmonics we must use the following Fourier Equations (Du, 2005).

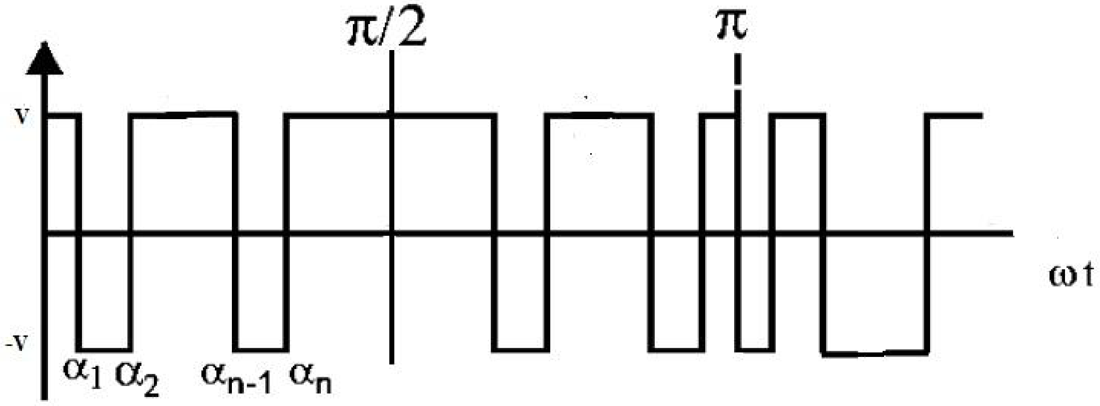


Figure 37 SPWM wave with odd and half wave symmetry, permission pending from Majhi

$$h_1 = (4\left(\frac{V}{\pi}\right)\lceil 1 - 2\cos(\alpha_1) + 2\cos(\alpha_2) - 2\cos(\alpha_3) + \cdots 2\cos(\alpha_n)\rceil$$

$$h_3 = (4\left(\frac{V}{3\pi}\right)\lceil 1 - 2\cos(3\alpha_1) + 2\cos(3\alpha_2) - 2\cos(3\alpha_3) + \cdots 2\cos 3(\alpha_n)\rceil$$

$$h_n = (4\left(\frac{V}{n\pi}\right)\lceil 1 - 2\cos(n\alpha_1) + 2\cos(n\alpha_2) - 2\cos(n\alpha_3) + \cdots 2\cos(n\alpha_n)\rceil$$

Where,

h_n = Magnitude of the nth harmonic component.

α = Primary switching angle.

n = Harmonic order.

The Fourier sine and cosine coefficient formulas are (odd symmetry and quarter symmetry).

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} f(\theta)d\theta$$

$$a_k = \frac{1}{\pi}\int_0^{2\pi} f(k\theta)\cos(k\theta)d\theta$$

$$b_k = \frac{1}{\pi}\int_0^{2\pi} f(k\theta)\sin(k\theta)d\theta$$

$$b_k = 4\frac{V}{\pi}\left[\int_0^{\alpha 1} \sin(k\theta)\,d\theta - \int_{\alpha 1}^{\alpha 2} \sin(k\theta)\,d\theta + \int_{\alpha 1}^{\alpha 2} \sin(k\theta)\,d\theta - \cdots \int_0^{\frac{\pi}{2}} \sin(k\theta)\,d\theta\right]$$

$$b_k = 4\frac{V}{n\pi}[1 - 2\cos(\alpha_1) + 2cos(\alpha_2) - 2\cos(\alpha_3) \ldots - 2\cos(k\alpha_n)]$$

(Du, 2005)

The harmonic equations presented before are very transcendental equations. While they are complicated to solve without a numerical iteration technique, they can be simplified to simpler polynomial equations. These equations are utilized to find the solutions for the harmonic equations.

While the SPWM and the SHE techniques do have their drawbacks such as increases in the switching frequencies, or high frequency harmonic generation. The SPWM technique combined with the SHE technique is considered the best choice for the inverter for a couple reasons. It consumes very low power; it has an efficiency of 90%, it can operate at high power levels, does not get affected abruptly by temperature changes and is easy, controllable and compatible with today's microprocessors. (Du, 2005)

Section 4.3.3 – Gate Drive

In order to protect the low side voltage from the high side voltage an optocoupler is required to isolate the circuit. Another part that is required to drive the H-bridge is a gate drive. A new technology that has both parts integrated into one component has been chosen for the design of this inverter. The integrate gate drive Optocoupler ACPL-H312 has been selected for the features that it provides.

Through this device the interface between the power stage and the control circuitry is possible. This device is capable of driving IGBTS with rating as high as 1200V and 100A. Another great feature of this component is that it has the ability to suppress common-mode noise transients. In an H-bridge there is a safety risk that if the switches are not synchronized properly a short circuit can occur. The switches should be synchronized in a manner that when two switches are closed, they should be across the load. If the switches close on the same side of the load a voltage discharge will occur. Common-transients can cause an erroneous turn on to one of the IGBTs which can cause permanent damage to the IGBT driver. The ACPL-H312 that has been selected for the inverter, it outperforms other technologies when it comes to common-mode rejection (Power Electronics Europe, 2008). The great design of this optocoupler minimizes the adverse effects of leakage currents that pass through the isolation barrier.

In optical coupling technology, the physical separation distance of the signal coupling interface is kept as wide as possible. This separation along with the packaging technology will have a low parasitic capacitance on the device. Parasitic capacitance is the internal capacitance of a component that can affect the ideal behavior of that part. The gate drive optocoupler has the advantage of a grounded Faraday shield that can be deployed to protect the drive isolation circuit. The purpose of the Faraday shield is to divert the transient currents that flow from the input directly to the output ground in order to ensure the gate drive isolation circuit does not turn on the IGBT in case of current leakage from the isolated side. This component will provide confidence in the design of the inverter since it provides many safety features. It is important to consider these details in the design because it will provide maximum safety features and it will also protect the inverter from being damage.

After the prototyping phase was completed it was noticed that the optocoupler was not the best option for the project. Compatibility issues with the other devices were the main reason to switch to a similar component with not only the same, but even higher capabilities. The device that was chosen is the IR2110 from microchip. This type of component is actually the most popular in the market and plenty of information was found for its proper operation. It counts with the same characteristics the optocoupler was chosen for, but it has two more characteristics that gives it the edge compared to any other device in the market. After testing the original components it was noticed that the gate driver device needs to handle as much current as possible in case a short circuit occurs. The IR2110 handles a bigger short circuit current than any other gate drivers. Another important requirement for this drivers is to have fast dead on times, and fast dead off times. The dead time of the optocoupler devices is slower than the IR2110, this feature is also critical for the device so it can prevent any short circuit to happen.

Section 4.3.4 – DC Boost Converter / Transformer

A DC-to-DC converter is an electronic circuit capable of converting a source of direct current from one voltage level to another. To be more specific, a DC Boost converter must be used in order to convert an output voltage greater than its input voltage. This type of converter is also called a step-up converter and is going to be used in the battery source, because the voltage needed to operate in the H-bridge, high voltage, does not correspond with the voltage supplied by the battery, low voltage. The main principle that drives the converter is the fact that the inductor will resist changes in the current. In the following circuit a schematic of the boost converter is introduced. (Erickson)

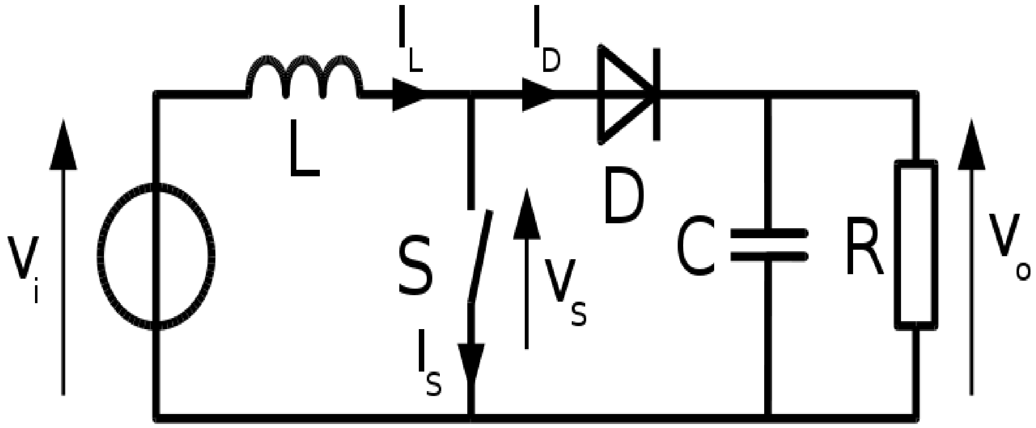
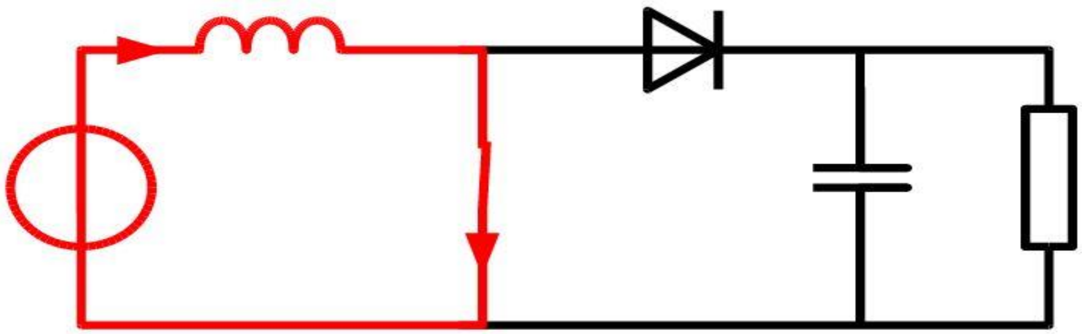


Figure 38 Boost Converter Circuit, permission received from Linear Technologies

As it can be seen a switch component is part of the boost converter circuit. When this switch is closed, the current will flow through the inductor (clockwise direction) and the inductor will store energy because the inductors polarity is positive. On the other hand, when the switch is open, the current will decrease as the impedance becomes greater; this means that the impedance inversely controls the change in the current (the polarity of the inductor is now negative). This leaves the two sources in series creating a higher voltage in consequently charging the diode. To be able to avoid the inductor from completely discharging between every charging stage, the switch must be cycling at a rapid rate. While the switch is open the load on this inductor will be bigger than the load of the input source. When the switch is closed the capacitor will be able to provide enough voltage and energy to the load. While this happens the diode will prevent the capacitor from discharging from the switch. In the figure below a representation of the basic operation of a boost converter is shown. (Erickson)



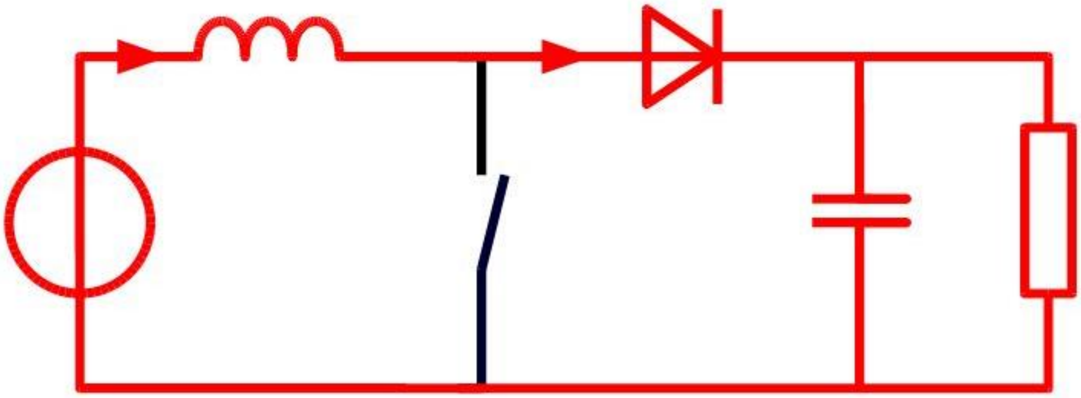


Figure 39 On and off state boost converter, permission received from Linear Technologies

On the ON state, the switch is closed; resulting on the inductor's current to be increased. In the OFF state, the switch will be open and the only path the inductor can use is through the diode, the capacitor and the load. This results in an accumulation of energy on the capacitor while it was transferred during the ON state. When the input current is the same as the inductor current the boost converter will be working in continuous mode. If a boost converter is operating at continuous mode it is because the current through the inductor will not be able to fall to zero. The figure below shows the waveforms of a current and voltage in a boost converter operating in continuous mode. In ideal conditions the output voltage can be calculated with the use of the following formulas. (Erickson)

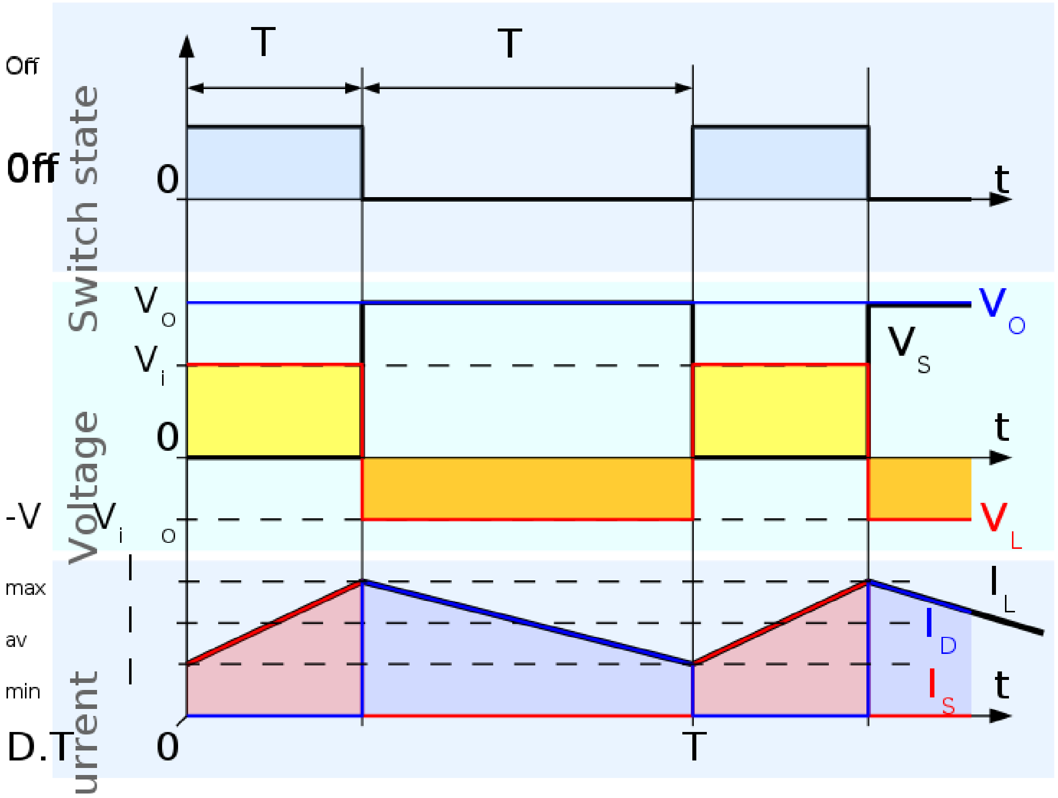


Figure 40 Continuous Mode waveform, permission from Linear Technologies

$$\frac{\Delta I_L}{\Delta t} = \frac{Vi}{L}$$

At the beginning of the ON state

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} Vi\, dt = \frac{DT}{L} Vi$$

At the end of the ON state

D is the duty cycle, and it represents the fraction of time on which the switch is ON. So it can range from 0 (OFF) to 1 (ON).

$$Vi - Vo = L\frac{dI_L}{dt}$$

At the beginning of the OFF state

$$\Delta I_{L_{Off}} = \int_{DT}^{T} \frac{(Vi - Vo)dt}{L} = \frac{(Vi - Vo)(1 - D)T}{L}$$

At the end of the OFF state

When the boost converter is operating in continuous mode, the amount of energy stored in each of the components bas to be equal at the beginning as of at the end of every cycle.

$$E = \frac{1}{2} L I^2{}_L$$

Energy stored in the inductor.

The current in the inductor has to be the same at the beginning and end of the cycle.

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{ViDT}{L} + \frac{(Vi-Vo)(1-D)T}{L} = 0$$

$$\frac{Vo}{Vi} = \frac{1}{1-D}$$

$$D = 1 - \frac{Vi}{Vo}$$

This last equation is the Duty cycle equation. This one shows that the output voltage must be higher than the input voltage, increasing as the duty cycle increases starring from zero and getting closer to 1. This is the basic reason why this booster converter is also known as the step-up converter. (Walter)

The prototyping phase for the DC Boost Converter revealed that it was not convenient to work with this circuitry. A combination of time frame, device compatibility, and money constraints made this DC Boost Converter not a viable choice. This is why after the prototyping phase was at its mid-range a redesign was the best choice for the step up procedure. The DC Boost converter tends to be the de facto market choice for an inverter design, due to its purpose of stepping up the voltage before it goes into the H-bridge, this procedure will decrease the amount of current inside the H-bridge, creating a safer circuit due to the fact that the current is lower. This advantage will also decrease the price of the PC board and in general of all the components on the board. Finally, based on the theory and calculations it will also be able to create a much better output sinusoidal signal.

The problem we found with this device was the ability to operate with it properly. After a couple of days of prototyping and testing, it was concluded that due to the fact that this DC Boost converter operates with switching devices it conflicts with the operation of the H-Bridge that also operates with switching devices. Once again, this problem accumulated with time constraints was a good enough reason to conclude that another approach was needed. This is where the transformer was welcomed into the project.

The transformer PH1000MLI was the best option for the project due to the following facts. This is a step down transformer that can be inverted and then used as a step up transformer. As it was stated in the beginning of the project description, the inverter needs to be able to step up voltages to a final voltage that fits the European standard which is 220V at a frequency of 50 Hz. This transformer meets these minimum requirements. Some of the problems that it may present when operating is a distortion of the signal when the voltage is step up, and an apparent modification of the LC filter configuration that also interferes when filtering the signal. At the end, these problems where improved as much as possible and made of the transformer the component that fit due to its simplicity.

Section 4.3.5 – H-Bridge

An H-bridge also known as a full wave inverter is composed of four switches that are arranged in an H shape. These switches are semiconductor based, such as MOSFETs, BJTs, Thyristor, or IGBTs. The selection of the correct type of switch is based on the requirements of the system. The switches most commonly used are the MOSFETs and IGBTs.

MOSFETs are generally used for high frequencies, low power consumption, low voltages, and low currents for small power loads. On the other hand, IGBTs are capable of handling high voltages, high currents, and frequencies lower than 29 KHz. Since this project requires a 1 KW power, then IGBTs are the most appropriate choice for the H-bridge.

When selecting an IGBT power losses need to be consider to avoid consuming too much power. The H-bridge can be divided in two sections which are a low side and a high side. The switches at the high side will be operating at 20 KHz and the switches on the low side will operate at 50Hz. Two different types of IGBTs will be used for the high side and the low side. For the high side an ultrafast IGBT will be required and for the low side a standard IGBT will be used to reduce power dissipation (Chou, 2008).

On the high side of the H-bridge two IRGP4063DPBF that are capable of handling 600V and 48A will be used. The reason for selecting this particular IGBT is that it has low power dissipation. For the low side of the H-bridge two IRG4PC40SPBF that is capable of handling 600V and 31A will be used. The IGBTs will be set up in a way that the switches alternate from each other. This is done to avoid having the switches operating on the same mode. Switch Q1 is pulse width modulated and Q4 stays on during the positive half-cycle. Switches Q2 and Q3 will remain off during the positive half-cycle. For the negative half-cycle Q3 is pulse width modulated and Q2 is kept on. Switches Q1 and Q4 will remain of during the negative half cycle. Table 4 shows the state for switches Q1, Q2, Q3, and Q4. (Eggleston, Doucet, & Shaw, 2007)

Q1	Q2	Q3	Q4
CLOSE	OPEN	OPEN	OPEN
CLOSE	OPEN	OPEN	CLOSE
CLOSE	OPEN	CLOSE	OPEN
OPEN	CLOSE	OPEN	CLOSE
OPEN	CLOSE	OPEN	OPEN
OPEN	CLOSE	CLOSE	CLOSE
OPEN	OPEN	OPEN	OPEN
OPEN	OPEN	OPEN	CLOSE
OPEN	OPEN	CLOSE	OPEN

Table 4 Switching States

To have a better understanding a circuit of an H bridge is illustrate on figure 39. Using this diagram along with the switching state table to trace the switching stages will explain the functionality of the circuit.

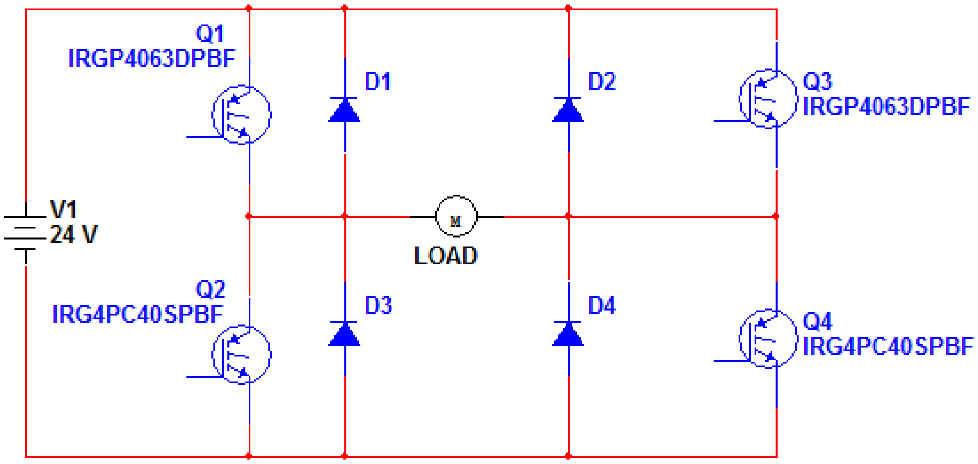


Figure 41 H-bridge circuit

The H-bridge circuit is an important subsystem in the inverter since it is going to create the sine wave through a switching method. The output voltage coming out of the H-bridge will be unfiltered and a low pass filter is required to clean up the signal. After the low pass filters the signal, the pure sine wave is generated.

The final design of the H-bridge circuitry also presented some modifications. While it was calculated that the operation of the H-Bridge would have been better with the use of IGBTs as the switching devices, it was concluded that in practice this was not applicable. The IGBTs were expected to manage the fast switching requirement in order to create the desired set of numbers required to create the sinusoidal signal, but this was not the case. The IGBTs were not switching fast enough, and as consequence, the output signal of the H-Bridge had a lot of distortion.

After more research was done, it was concluded that the perfect replacement for the IGBTs was the IRFPS3810. This component is a MOSFET that was recommended to work perfectly with our circuit design. Its switching speed is larger than the IGBTs that were selected before and its price was lower. After these devices replaced the old IGBTs the difference on the sinusoidal output signal was abysmal. It was found that this was the solution for the distortion created by the IGBTs, and the MOSFETs were not creating any other unexpected problems. Finally, it is good to mention that no other components on the H-Bridge were changed or required further testing on the circuit. After this modification was applied, the H-Bridge worked as it was expected.

Section 4.3.7 – Microcontroller PIC16F684

The most important component of the inverter is the microcontroller. The microcontroller is going produce the sinusoidal reference signal, which is the signal that determines output signal, and triangular carrier signal to control the switching of the bridge. It is also going to be responsible for monitoring the output voltage and making necessary adjustments to maintain a constant output. The Microchip PIC16F684 has been selected for the inverter on this project. The reason for selecting this approach was to have the flexibility to store the commands to create the required waveforms to control the frequency of the inverter using switching pulses. This is also a low cost, very efficient, and it will occupy less space than traditional inverters with analog components. The advantage to this method is that it can be operated at higher switching frequencies of the inverter voltage, which makes the output filter smaller, reduces cost, and makes it easier to implement. The sinusoidal pulse width modulation signal that is generated will need to be oscillated for circuit protection and safety. Two integrated circuit drivers (IR2110) will be used to isolate the high voltage from the low voltage.

Section 4.3.4 – LC Filter Design

It is fundamental to have a low pass LC filter right at the output of the H-bridge circuit. This component reduces the amount of harmonics generated by the sinusoidal waveform. The design of this LC filter must be capable of eliminating most of the low order harmonics of the system, and should operate without creating any additional voltage distortion, so the output of the inverter can be kept without interference from this component. It must be taken in to account that the values of these components must be wisely chosen to have a fairly priced LC filter design. By having this component parts properly chosen the voltage waveform of the inverter will be a clear sinusoidal wave because the output impedance is zero. In the case of not having the correct values the sinusoidal will be distorted because the output response will not be zero.

The figure 40, below, will illustrate a single phase PWM-VSI circuit. As it is noticed in the figure the low-pass filter satisfies linear property which makes it possible to represent the system. (Majhi, 2012)

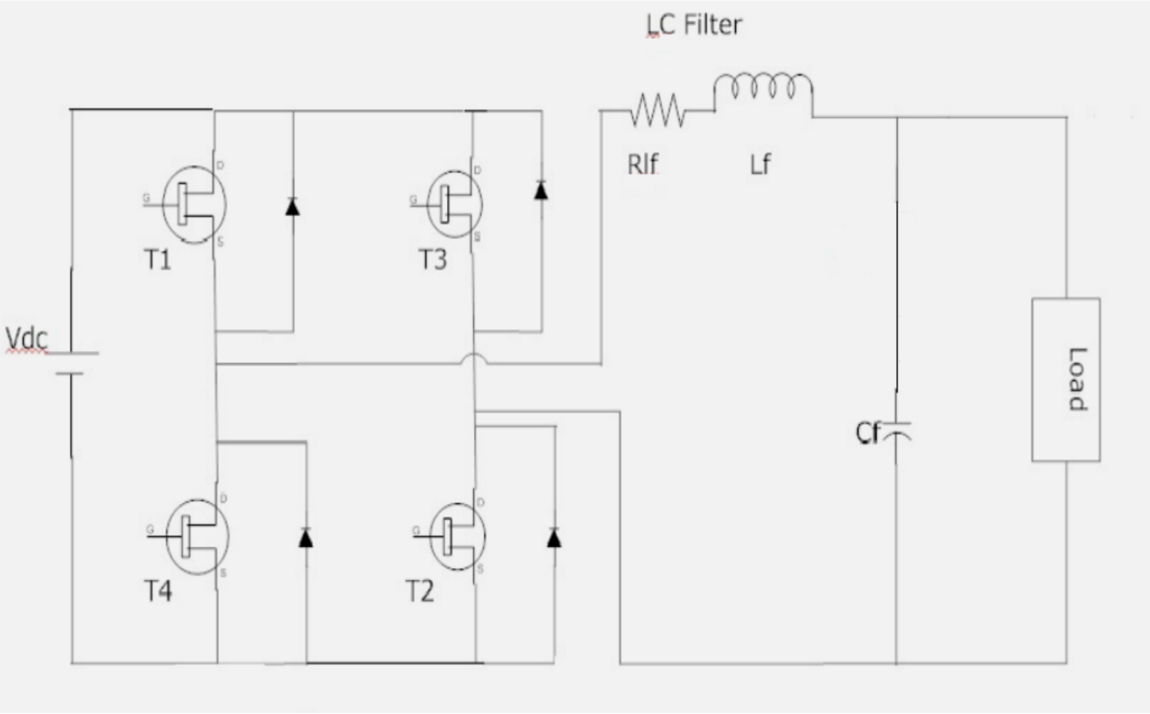


Figure 42 PWM LC Filter Circuit, permission pending from Majhi

To be able to calculate the values for the capacitor we must find the relation between the filter capacitor value and the time constant of the system. It is possible to analyze the voltage distortion of the system in case of a nonlinear load and the effect of the load current from the closed loop form. The following block diagram will give a clear example of the closed loop form with its corresponding input and output transfer functions.

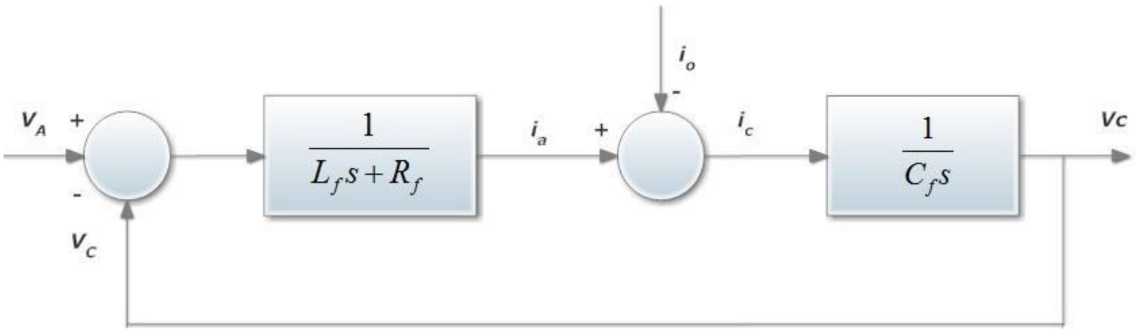


Figure 43 Block Diagram of single phase PWM-VSI

From this diagram we can derive the transfer function equations that will help us find the proper values for the LC filter. (Majhi, 2012)

$$V_c(s) = \frac{1}{L_f C_f s^2 + jR_f C_f} V_A(s) - \frac{L_f s + R_f}{L_f C_f s^2 + jR_f C_f s + 1} I_o(s)$$

$$V_c(j\omega) = \frac{1}{1 - L_f C_f \omega^2 + jR_f C_f \omega} V(j\omega) - \frac{L_f s\omega + R_f}{1 - L_f C_f \omega^2 + jR_f C_f \omega} I_o(j\omega)$$

$$Va(s) - sL_f Ia(s) - R_f Ia(s) - Vc(s) = 0$$

$$Va(s) - Vc(s) = Ia(s)\left[sL_f + R_f\right]$$

$$\frac{Va(s)}{Vc(s)} = 1 + \frac{Ia(s)\left[sL_f + R_f\right]}{Vc(s)}$$

$$\frac{Va(s)}{Vc(s)} = 1 + \frac{Ia(s)\left[sL_f + R_f\right]sC_f}{Ic(s)}$$

If:

$$i_a = i_b + i_o$$

$$Ia(s) = Ic(s) + \frac{Vc(s)}{Z_L}$$

$$\frac{Ia(s)}{Ic(s)} = 1 + \frac{1}{sC_f Z_L}$$

$$\frac{Va(s)}{Vc(s)} = 1 + \left(1 + \frac{1}{sC_f Z_L}\right)\left(sL_f + R_f\right)sC_f$$

$$\frac{Va(s)}{Vc(s)} = 1 + \left(1 + \frac{1}{sC_f Z_L}\right)(sL_f + R_f)sC_f$$

$$\frac{Va(s)}{Vc(s)} = \frac{s^2 L_f C_f + sL_f + R_f C_f s Z_L + R_f + Z_L}{Z_L}$$

$$\frac{Vc(s)}{Va(s)} = \frac{Z_L}{s^2 L_f C_f + sL_f + R_f C_f s Z_L + R_f + Z_L}$$

(Majhi, 2012)

With this transfer function it is possible to find the step response, the cross over frequency from its bode plot and its stability applying root locus method. To calculate the amplitude for the voltage in the harmonics we must sum the harmonics caused for both the inverter output voltage and the load current. We can also simplify the initial equation on the frequency domain even more, if we neglect the imaginary part and realize the fact that the resistance of the inductor is very small. The equation will be simplified to the following. (Majhi, 2012)

If,

$$\left|1 - L_f C_f \omega^2\right| \gg \left|R_f C_f \omega\right|$$

Then,

$$Vc(j\omega) = \frac{1}{1 - L_f C_f \omega^2} V(j\omega)$$

By analyzing this result it should be noticed that in a conventional output filter design method, the current load can be neglected because it is treated as a disturbance. However, if the load is nonlinear its current load cannot be neglected because it is causing an increase in the harmonics. Because of this fact, if the purpose is to be independent of the load current, the value of the capacitor should be maximized and the inductor value should be minimized at the same cut-off frequency. By doing so, the zero output impedance will be accomplished and the LC filter will work as an ideal voltage source.

At Cut-off frequency

$$\frac{Vc(j\omega)}{V_A(j\omega)} = \frac{1}{1 - L_f C_f \omega^2}$$

The ratio of these two voltages must me less than 3%

$$\frac{Vc(j\omega)}{V_A(j\omega)} = 3\% = \frac{1}{1 - L_f C_f \omega^2} = 0.03$$

Then,

$$\left|\frac{1}{f^2 \frac{X_L}{X_C} - 1}\right| \leq 0.03$$

$$\frac{X_L}{X_C} \geq \frac{34.2}{f^2}$$

Where,

f = Cut-off frequency.

X_L = Value for the Inductor.

X_C = Value for the resistor.

With this last equation the values of the capacitor and inductor can finally be found and put on the LC filter. (Majhi, 2012)

Section 4.4 – Power Storage

When designing a photovoltaic system there are many variables to consider in the specification and installation of the battery bank in a stand-alone system. Since batteries are very expensive for a photovoltaic system, it is recommended to do a complete analysis to avoid overspending.

Section 4.4.1 – Days of Autonomy

This is referred to the number of days a battery bank will be able to supply power without being recharged by the solar panels or any other source of energy. In order to determine the number of days of autonomy the location, total load, and types of loads are required. Since the design of this project is limited by a strict budget the days of autonomy will be limited.

Section 4.4.2 – Battery Capacity

The capacity of a battery is measured by amp-hour (AH). Looking at the overall AH capacity will determine amount of power that it can provide and for how long it will provide it. If a battery is rated to provide 100 AH, the battery in theory will provide two amps of current for 50 hours before being fully discharge. If the system is required to provide 4 amps for 50 hours then the batteries can be wired in series. That will provide 215AH at 24 volts. If the voltage needs to be increased then four 6 volt batteries can be wired in series to obtain 24 volts. One thing the user should never do is to add new batteries to an old battery bank. Reason being is that old batteries will degrade the performance of new batteries. The increased internal cell resistance of the old batteries causes this. When selecting batteries a slightly larger battery capacity then what is needed is recommended since batteries lose their capacity as they age. On the other hand, do not oversize the battery bank since it can remain at a state of partial charge. In a partial charge state the battery life can decrease, reduce capacity, and increased sulfating.

Section 4.4.3 – Rate and Depth of Discharge

The battery capacity is directly affected by the rate at which is discharged. If batteries are discharge at a fast rate, the battery will have a lower capacity. If batteries are discharged at a slower rate, then the battery will have greater capacity.

A battery specification that is normally use is the ratio of the battery capacity over the number of hours that it will be discharged. For instance, if a battery discharges for a period of 15 hours then C/15 is the capacity rate. Notice that if a battery discharges in fewer amounts of hours then it will discharge faster. The majority of batteries are rated a C/20 rate. On the other hand, batteries should not charge at a rate higher suggested by the manufacture.   Gel cell batteries should not charge at a rate higher than C/20 rate (Solar Energy International, 2004).

Depth of discharge of a battery is referred to the capacity that is drawn from the battery. The life of the battery is directly related to the percentage that the battery is cycled. For instance, if battery is discharged to 50% on a daily basis, it will last twice as much than if the battery is discharged to 80% on a daily basis. Discharging batteries completely it is not recommended. Although Nicad batteries can be totally discharged without harming the battery, lead-acid batteries will gradually lose their voltage. Even though Nicad batteries do not get damaged when fully discharged, it may reserve polarity that can potentially harm the load (Solar Energy International, 2004).

Batteries can also be discharge using a shallow cycle method. The benefit of this method is that it can expand the battery life span up to five times more than fi the battery is discharged at 50%. Another benefit is that a higher amp hour capacity will be reserve in the system for extended cloudy days.

Section 4.4.4 – Battery Life Expectancy

The life expectancy of a battery is measured in terms of quantity cycles. When batteries lose 20 percent of their original capacity, they are considered to be at the end of their service. Depending on how the system is set up, deep cycle or shallow cycle, the life time of the battery can be estimated. If a battery is estimated to have 3000 cycles at 20 percent daily depth of discharge, than the battery can be estimated to service for 8.22 years. If the same battery will give you 1100 cycles at 50% daily discharge, than the battery will only service for 3 years. This can have a deciding factor on how to set up the system. If budget is an issue, a shallow cycle system would be more suitable to maximize the life span of the battery (Solar Energy International, 2004).

Section 4.4.5 – Environmental Conditions

Battery performance is affected by high and low temperatures. Batteries are normally rate by the manufacture at 77°F. If the temperature reaches freezing point, than the battery only perform 65 to 80 percent of its full rated capacity. The opposite is true when temperatures are higher. An interesting point is that the battery life increases at lower temperatures. The opposite effect takes place at high temperatures. Batteries should be contained in a sturdy enclosure that is well ventilated. When batteries are recharging they release a hydrogen gas. This gas can be very explosive and a good measurement is to keep the gasses contained. If a battery were to burst than the container will keep the acid contained. For this reason, it is important to keep electrical components at a reasonable distance. This can prevent an explosion in case of an accidental discharge. Another good reason to keep components at a reasonable distance is that the gas is corrosive. System component may be attack by corrosion if placed too close (Solar Energy International, 2004).

Section 4.4.6 – Battery Safety

In photovoltaic systems the battery bank can be the most dangerous subsystem if installed, handled, or maintained improperly. The combination of dangerous chemicals, high voltages and currents can result in potential hazards of electric shock, burns, or even explosions. That is why it is important that the designer chooses the correct type of battery and size. The following safety rules should be utilized in to order to properly insure the safe handling, installing, maintaining, and replacing of batteries. The first thing is to choose the location of the battery bank. Always wear the proper protection equipment when working with batteries and discharge body static electricity before touching battery terminals. No open flames or smoking should be permitted in the area. Have baking soda available to neutralize the acid in case of a spill. Keep plenty of water available for rinsing in case of being splashed by electrolyte. Always disconnect batteries any charging/discharging sources before working on them. Use carrying straps to lift batteries and avoid injuries. Last but not least, never use tools that are not well insulated to avoid shock (Solar Energy International, 2004).

Section 4.5-Power Supply

Solar panels have a great life expectancy. Properly maintaining the solar panels can give them a life expectancy of up to 40 years. Most panels have an economic lifetime of 25 years (CAT). The panels tend to lose no more than 1% of its efficiency every year; so after about 20 years the panels will have about 80% efficiency of their peak performance (CAT). When choosing an alternative energy source it is important to pick something that will not leave a carbon footprint. Depending on the area the solar panels are installed the solar panels will pay back the energy cost and resources it took to make them. This makes it an excellent investment because in sunny locations it would take less than five years to pay back the cost of the panel. Assuming the panels will last more than 20 years means the panels will pay back themselves multiple times over. In the South African village where this project will be installed, has really sunny conditions, which resulted the group to conclude that a solar system would be beneficial and optimal as an alternative source of energy.

Section 4.5.1 – Solar Panels

The solar panels will each produce 235 watts at peak production time. The solar panels have a maximum output of 30.20 volts DC and 7.92 amps each. These solar panels are a great choice because there is limited space available to install this kilowatt system. With only four panels to install, these panels are better than some others that may only produce 100 or 150 watts in which 10 or 7 panels respectively would need to be installed to get generate the same amount of power.

These panels must be able to survive the rugged conditions of South Africa. The solar panels have a guaranteed efficiency of 90% for the first ten years and greater than 80% efficiency for the next 15 years. This will help with the strong solar radiation that can be felt in South Africa.

The high quality panel is composed of polycrystalline and contains 60 cells. The dimensions of the cells are 15.24 cm at 14.8% efficiency. The cells are encased in a silver anodized aluminum frame. To protect the cells from the elements of the climate the glass pane is 3.2 mm of glass. The weight, at 18 kg, will prevent them from being blown around in the wind. The dimensions of the solar panels are 165.2 x 99.4 x 4.5 cm. (length x width x height).

The operating range for the solar panels is -40°C to 85°C. This is well within the temperature range of South Africa, with a range of 27°C in the warm summer months and 2°C in the cold winter months.

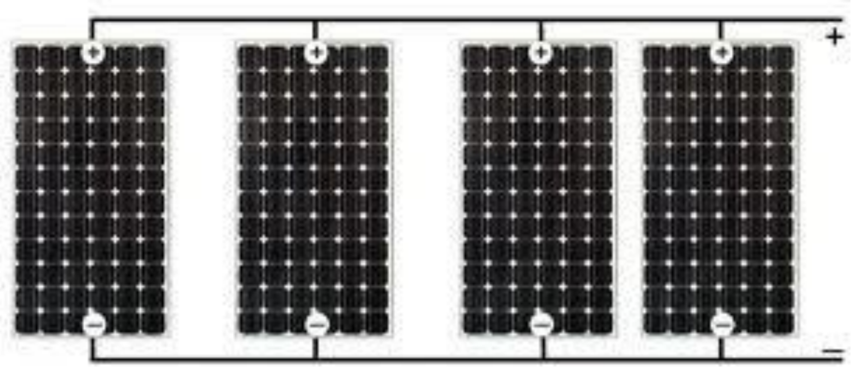


Figure 44 Four solar panels in parallel after regulation, permission pending from cleanenergyzone.com

Section 4.5.2 – Wiring of Panels

The solar cells within the panel are connected in a parallel-series combination, so the whole solar panel acts like a battery. Connecting the solar panels in series would cause a lot of variation on the input voltage to the charge controller. The best way to get the same effect is to connect the four solar panels in parallel. This will allow the currents to merge and the voltage across the four panels to be equal. Each panel could potentially produce different potential voltages and those voltages will not merge safely unless they are the same. Four solar panels are fitting for the project, given the budget restrictions and what is needed to create a one-kilowatt system. Four solar panels times the maximum power they are able to produce, 235 Watts, equals 940 Watts. At peak production time, the solar panels are able to produce over 900 Watts, with some inefficiency, of power to charge the batteries or to be delivered straight to the load through the batteries.

Section 4.5.3 – Regulation

The reason the solar panels will be separated before going into the charge controller, is because to keep the cost of the board lower by splitting the currents to several switching regulators. The panels of choice output a peak of 30.20 Volts DC, so if two of the panels are at 20 Volts, another at 17 Volts, and another at 13 Volts. If this were the case, then when connected in parallel the voltage of the lowest panel takes precedence and the output power will be the sum of the currents times the 13 Volts. This configuration acts as a single power supply and splitting the currents before entering the charge controller kept the cost of the PCB down because it met the specifications for the student discount.

In order to achieve these requirements the Linear Technologies LTC3862 buck boost voltage regulator was chosen. The LTC3862 has a minimum input voltage of 4 volts and a maximum input voltage of 36 volts. The output is adjustable up to 60 volts and has a switching current of 1.80 milliamps. These requirements do not fall within the 30 volt output at 8 amps for a maximum power generation of the solar panels, like previously thought. The 4 volt input allows for the panels to be producing a low amount of power, but still regulate the input to 30 volts. If a proper integrated circuit was selected then this would be fine.

The more power that is being generated the more efficient the regulator is. The efficiency of the regulator is based on the input voltage. As the solar panels are able to produce more power the higher their output voltage will be creating a more efficient situation for the voltage regulator. Figure 45 compares the efficiency and output current for a regulator circuit that outputs 48 volts.

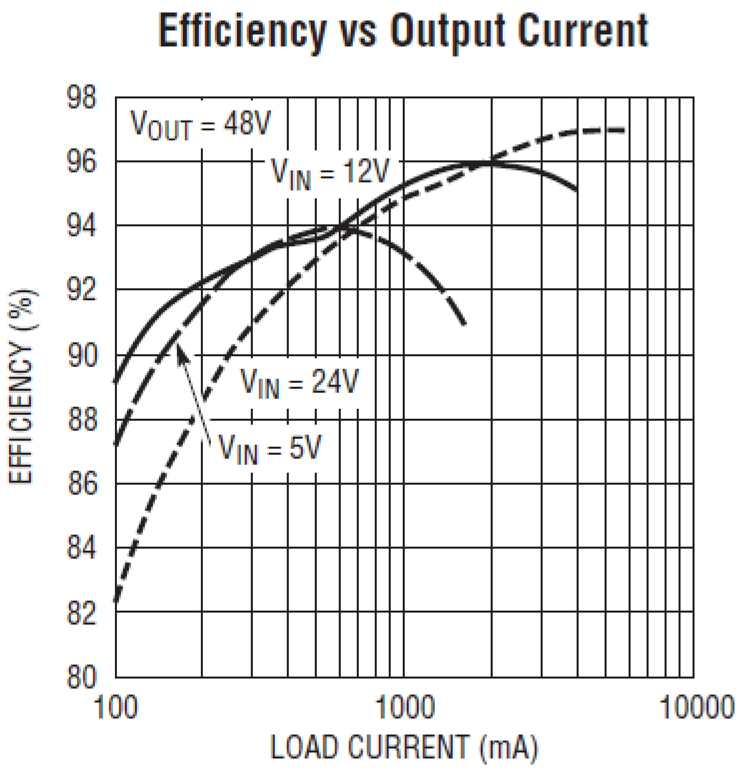


Figure 45 Efficiency graph from Linear Technologies datasheet.

The design still needed a way to regulate the voltage either to step up the voltage or to step down the voltage. So a buck boost dc dc converter was still used. The design of the buck boost was not a simple task and it is not as efficient as an integrated circuit.

The voltage regulator is efficient, which is an important feature, because the power being generated cannot be wasted. Another application to the voltage regulator is the case where the power will use the batteries as a capacitor and be sent directly to the inverter. The regulated output voltage of the solar panels will be set to 20 volts and the inverter takes in a 18 volt input. The reason the solar panels are regulated to 20 volts is the case where the batteries need to be charged, a higher voltage than 18 is needed to charge the batteries. There is no need to have an integrated circuit that will step down the voltage to 18 volts before the input gets to the inverter when the batteries are used as a capacitor.

Section 4.5.4 – Shunt Regulator

The shunt regulator that will be used to monitor the solar panels was the Texas Instrument TL431QPKG3, which is in the TLXXXQ family. It is a military grade product, which can withstand the extreme temperature swings during the day and the seasons, where temperature throughout the year changes between 2°C - 27°C. The part is able to operate with a large range of temperatures from -40°C - 125°C.

The shunt regulator has a voltage reference between 2.5 – 36 volts, which fits with the maximum output of the panels at 30.20volts. The shunt regulator will be an integrated circuit using an LED. There would have been a stack of five LEDs per panel. The idea is to show the user which solar panels are producing power and which are not. The LED stack would allow the user to identify which solar panel is bad. In the case where all of the solar panels are facing a strong sun, but one of the panels is significantly less than the other three, the user will be able to check to see if there is a problem with the solar panel or if there is an outside obstruction blocking the sunlight.

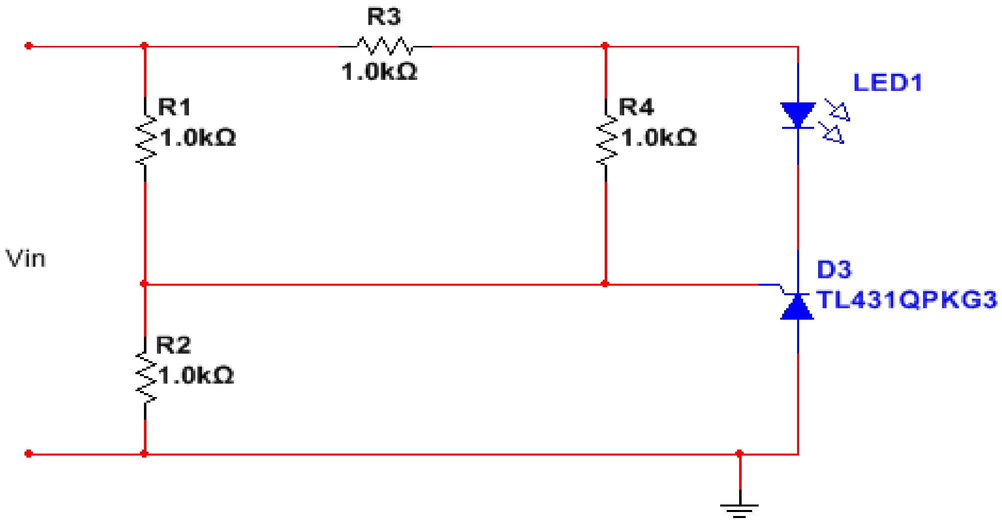


Figure 46 Circuit for the shunt regulator

The shunt regulator is a small signal circuit, above in figure 46, that will measure the input voltage by using a voltage divider, referencing R2. The voltage across

R2 will be the reference voltage that will cause the shunt regulator to be tripped. The LED is used as a symbolic symbol that represents a signal. When the shunt is tripped allowing current to flow the LED will turn on. When the reference voltage is 5 volts, the full capacity is 29 volts, and R1 to 1M ohms makes R2 to equal to 200k using the formula below.

$$Vlimit = Vref * \left(1 + \frac{R1}{R2}\right)$$

The resistance must be high in order to prevent a high current from flowing through the circuit. The purpose of the circuit is to check the voltage not draw power.

The shunt regulators are no longer used or needed in the final design of the system. A simple voltage divider to an analog to digital pin was used instead. Realistically with how long the panels last the shunt regulator is not needed.

Section 5 – Design Summary of Hardware and Software

In this chapter all the different subsystems and their integration will be discussed. It will be described in the order starting from the input and ending at the output. The solar panels are the input stage for the system and they provide the power to the batteries for storage. Before the power gets sent to the battery bank, the voltage needs to be regulated. This voltage will be regulated by a charge controller to ensure a constant output. This constant output will be distributed either directly to the battery bank. From here the battery bank will serve the system as storage to stay operational while the sun is not powering the system. The next stage of the system is the inverter where its input can be taken from the charge controller or the battery bank. The inverter converts the DC voltage to AC voltage to power up the load. These subsystems will be discussed in further detail in the following section to have a better understanding of the functionality of the system at its different stages.

Section 5.1 – Power Supply

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.

The power supply are four STP 235/ 20-Wd solar panels 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 7.92 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 6.57 meters squared. The temperature and climate of Pomolong is well within the range of operating temperatures for the solar panels, - 40°C to 85°C. 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; after all of the voltages are regulated, the currents will merge. This will allow the panels to produce 940 watts of power at peak production time.

The voltages coming into the system will have to be regulated in order to get the appropriate output. If they were to merge unregulated the panels would get damaged. The design called for a buck boost voltage regulator from Linear Technologies, LTC3862 that is able to withstand the maximum output voltage of 30.2.54 and the maximum output current of 7.92amps. The LTC3862 needs a minimum of 4 volts to operate which will help on cloudy days. Instead of using the LTC3862, the group designed their own dc dc converter.

There would have been a shunt regulator from Texas Instrument to monitor the panels. The regulator is a military grade product, which would have been able to withstand the range of temperatures that are experienced by the Pomolong Township. The shunt regulator will be able to handle the large voltage from the solar panels. The shunt regulator is an integrated circuit using an LED. There would have been a stack of five LEDs per panel. Each LED would have denoted about a 5 volt increment that the panel is producing. This is to show the user which solar panels are producing power and which are not. The LED stack will allow the user to identify which, if any of the solar panels are bad. In the case where all of the solar panels are facing a strong sun, but one of the panels is significantly less than the other three, the user will be able to check to see if there is a problem with the solar panel or if there is an outside obstruction blocking the sunlight. To maximize the power coming from the panels, a charge controller will be required to maximize the efficiency of the system.

Section 5.2 – Charge Controller

The charge controller is an intricate system that will watch over the battery bank to make sure they receive charge efficiently. The charge controllers job is make sure not to overcharge the batteries and monitor the incoming and outgoing power to make decisions. There will be four conditions that the charge controller will be looking for to make a decision of how to divert the power being generated.

The first situation is where the batteries need to be charged and there is power being generated. The output will be set to 20 volts and based on the input the microcontroller will be set to buck or boost mode. If the voltage is above the 20 volts then the microcontroller will be set to buck mode to bring down the voltage to 20 volts to charge the battery bank. If the solar panels are not producing the 20 volts necessary then the microcontroller will be set to boost mode to step up the voltage to 20 volts.

The second condition is when the batteries are charged and there is enough power being generated. Enough power includes excess power being generated and the exact amount of power being generated that is needed to supply the consumption load. The excess power, if there is any, will be directed to the dump resistor.

The third condition is when the batteries are charged and there is an insufficient amount of energy being produced. The batteries will need to be utilized. The power will be directed across the batteries. The batteries will be losing charge even though the batteries are being charged because the draw will exceed the charge.

The fourth condition is when the batteries have a low charge and there is an insufficient amount of power being generated. This situation is the extreme condition of the previous condition. When the situation becomes extreme enough the system will need to be shut down.

The shutdown process will need to start with alerting the users that the power is low. This will give them an appropriate amount of time to shut down the devices that are being used. After the alerts have been given, the system must set its self into a “default” state. That will allow for a re-initialization of the system, when power is introduced back into the system. The initialization will also need to done when the system is first assembled.

The shunt regulators would help identify any batteries that are not charging properly. This would have been achieved by comparing all the batteries to each other. If there is a battery that is not charged and all the other batteries are charged then it will be identified as a defective battery. The microcontroller will be able to notify the users that there is a defective in the battery bank, allowing for timely repairs.

In order to prevent the battery bank from discharging at night when there is no sunlight, the microcontroller will open the switches to prevent the power from the battery bank going to the panels and damaging the voltage regulators. The microcontroller will have to sense if power is being generated. The microcontroller will also have a start-up sequence for when there is a total power loss or the microcontroller is reset.

The Texas Instrument TL431QPKG3 shunt regulator was chosen to be implemented in the system. It is military grade and has a wide operating temperature range of - 40°C - 125°C. This part also has a wide voltage input range of 2.5 volts to 36 volts, which will be sufficient for an adaptive battery bank.

The shunt regulator is an integrated circuit and there will be a stack of LEDs for each battery to know how charged the batteries are individually. There would have been a high and low shunt regulator that are connected to the microcontroller to let it know when the battery bank is at full charge or when the battery needs to be charged again. The high shunt regulator lets the microcontroller know when full charge is reached; likewise, the low shunt regulator lets the microcontroller know when maximum depth of discharge is allowed. Instead a voltage divider took the place of the shunt regulator and the reference voltage was sent to the microcontroller where based on the reference it knew how much power was stored in the battery bank.

Two PIC microcontrollers were going to be used to calculate the power input and output of the system. A reference voltage and current were going to be chosen as not to burn the microcontroller. The PIC microcontrollers would have been used as an analog to digital converter and send the signal to the general microcontroller. The PIC microcontrollers will need to be programmed using a programming board. They are also programmed using C programming language. The programming board will need to interface with the computer using a USB to download the program to the microcontroller.

Instead of three microcontrollers being used two for power output and input and one for the general processing only one microcontroller was sufficient for the project.

The brain behind the charge controller would have been the Toshiba TMP89FS60 8-bit microcontroller. The microcontroller will be able to operate in ambient temperatures from - 20°C to 85°C. It is highly efficient and only uses a 93.5mW of power. This microcontroller would have also been programmed using C and has plenty of space to store the program that will be installed.

The first primary function is to control the direction of the power that is being generated. This microcontroller takes the inputs from the PIC microcontrollers and tells the power to charge the battery bank or to divert to the inverter. The PIC microcontrollers will be connected to the bidirectional ports of the Toshiba microcontroller.

The second primary function is to measure the power that is stored in the battery bank. The voltage shunt regulators would have been connected to the Toshiba microcontroller to allow the microcontroller to make a decision of whether to charge the battery bank or not. The battery bank would have used eight pins to tell the microcontroller the status of it. The first two pins will be for battery one, the second two pins will be for battery two and so on to battery four. Each battery only has two shunt regulators communicate with the microcontroller resulting in eight pins used.

As previously mentioned since only microcontroller was used and the shunt regulators were not used the PIC microcontroller was able to sense the voltage input and output using a voltage divider and measure the voltage of the battery bank based on the voltage divider of the output.

Since the Toshiba microcontroller will be aware of the input and output power and the battery status, the microcontroller will be able to make a decision of which switches need to be on and off to divert the power appropriately.

The charge controller was going to implement a three stage charging algorithm to charge the battery bank quickly and efficiently. The first stage is the bulk charge, this is the quickest part of the charging cycle. The bulk charge, constant current charge, supplies the battery bank with a constant current and an increasing voltage to put life quickly into the battery bank and have the battery bank about 80% charged. The next stage is the absorption stage, constant voltage charge, this is where the current tapers off while charging at a peak constant voltage until the battery bank is about 98% charged. The final step keeps the battery at full charge doing a float charge, trickle charge, which has the same voltage as the battery and puts in a little current to counter the self-discharge. Due to lack to time only a constant voltage charge was used.

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.

Section 5.3 – Power Storage

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 will have 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. They system will only discharge 50% to maximize the life of the batteries

The batteries will be placed in a series combination to increase the battery bank voltage to 24 volts. Using three 6-volt batteries in series will allow the battery bank to output around 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 SLIGC10, which costs a mere $0.13/Wh to store the power. The SLIGC110 is a golf cart sized battery that is able to hold 215 ampere-hours. 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 or branch will be charged and the other not which will greatly decrease the life expectancy of the batteries.

A battery will also have different life expectancies based on the amount of daily discharge as this affects the cycle count. If a battery were to have a depth of daily discharge at 20% and the battery is rated for 3000 cycles then the battery will last over 8 years. In contrast, if the same battery were to have a daily depth of discharge at 50% then the battery will last around three years.

The environmental conditions also play a very important role in the design of the power storage. Batteries are typically rated by the manufacture at 77°F; the battery's performance will drop to 80% - 65% of its capacity when the temperature is below freezing. All the while, the opposite is true for a battery in hot temperatures. The battery will have a shorter life due to the extreme heat.

Batteries should be in a contained enclosure to minimize the leakage current through the batteries. Among containing the batteries, they need to be in a well-ventilated area as they release hydrogen gases from the charging state. It is a good measure to contain the batteries just in case they explode the corrosive sulfuric acid will not spread to the electrical components or the other batteries.

When working on the batteries it is best to keep water nearby to add to the cells if needed to keep the batteries operating at peak performance, as well as cleaning them if need be. In addition to the water, baking soda should be kept close by to neutralize the acid. The batteries should be disconnected from the system before working or replacing them.

Section 5.4 – 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 50 Hz sinusoidal wave with 220VAC capable of delivering at least 1 kW. 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 way 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 is going to be two switching frequencies that will be used to control the gate drives. A high frequency of 20 kHz and a low frequency of 50 Hz will be used. At this point the gate drive 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. That is why it is important to select a reliable gate drive that offers additional features to protect the circuit and ensure minimal error. At this point the low voltage side of the circuit has completed its duty of controlling the circuit.

There is also a high voltage section of the circuit, where the 18V coming from the battery or the charge controller output will be stepped up to produce 220V. If the voltage is coming from the charge controller, then the voltage needs to be controlled in order to meet the inverter's 18V requirement. This is because the charge controller needs to deliver 30V in order to charge the batteries. On the other hand, if the inverter receives power from the battery bank, then in will take its normal course to invert the power. 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 MOSFETs switching sequence a pulse signal is generated. This pulse signal is created by the intersections of the sinusoidal reference signal and the triangular carrier signal. Since there is high current going through the MOSFETs and a low voltage controlling it, then an IC driver will be needed to protect the circuit. After the output is properly created, it is required to step up this voltage. As previously discussed, the gate drive has a feature that is integrated. The driver's duty is to protect the circuit from the high side current. It transfers electrical signals using light waves and that is why is able to keep a safe distance to isolate the circuits. After the pulse signal has been created by the MOSFETs, the output signal will be distorted. At this point the pulse signal has to be put through a low pass filter in order to obtain the pure sine wave signal. The purpose of the low pass filter is to reduce the harmonic distortions and be able to select the frequency required to obtain the pure sine wave. Once the signal has been filtered, the power is ready to be step up. This is the final stage of the inverter where the output that is delivered to the load should be a 50 Hz sine wave at 220V.

To be able to achieve the desired frequency and voltage, it is needed to use a step up transformer, more specifically a transformer that is able to step up the voltage from 18V to 220V. This transformer was required to contain unit ratios that will be able to step up this voltage accurately. This unit ratio required by this transformer made its size, prize and availability, greater than other common transformers, more expensive, and rare respectively.

Section 6 – Project Assembling and Coding

In this chapter the construction and code structure will be discussed. A list of materials will be reviewed along with the process that was used to acquire the materials. The implementation of the PCB, steps for the design, software used, and test procedures are explained. Some details of the vendor will be discussed along with the reasons for selecting this vendor. The computer language that was selected to program the components is a critical portion of the project and it will be discussed in further detail. Selecting a computer language that has a lot of resources is essential to be able to program the components efficiently. An explanation of the approach that was used to write the programs along with its respective activity and flow chart diagram will be shown to illustrate the flow of the program and its different stages.

Section 6.1 – PCB Vendor and Assembly

The PCB plays an important role in the design of the circuits for the charge controller and the inverter. In this section the assembly and the vendor that was used will be covered. Once the designs have been finalized, the circuits need to be compiled into one board. The purpose of using circuit boards is to eliminate the clutter of wires that can be pretty messy on a circuit and replace it with a clean organized PCB. Circuit boards are compact design that has no moving parts which reduces the wear and tear of the on components. These boards are made from glass reinforced plastic and the surface track is copper. The surface tracks substitute the wires that would normally go on a circuit.

The PCB needs to be designed in an organized fashion. One thing that needs to be considered when designing the PCB is to layout the components that require a specific location first. It is not recommended to place parts in close proximity to avoid components touching each other. At least a 0.1inch is the minimum distance that parts should be placed when placing parts on the board. It is a good idea to attempt placing the components evenly vertically and horizontally. Ensure that the polarities of the components are all in the same direction. All the parts should be placed at a 0 or 90 degree angle and it should be avoided if necessary to place parts at any other angles. It is also important to minimize the trace length between parts since it creates resistance to the circuit. For the charge controller and inverter Advanced Circuits vendor has been selected.

The reason for selecting this vendor is that they have an Engineering Student Program. This program for students offers competitive prices and fits the budget of this project. This vendor also offers competitive software that according to their website is the best in the industry. The software that this vendor uses is PCB Layout Artist. Some interesting features that their software has to offer is a free wizard tool that includes a schematic symbol, footprint, part, and creation. It also has a library structure that contains the part names by different manufactures. This software has an integrity check for PCB to schematic and schematic to PCB. The website also contains a trace width calculator that will help chose the correct trace width for the circuit. Learning how to use this software is going to be a learning curve for the group, but it will be a good experience. The CadSoft Eagle program was used to draw the schematic and do the board layout of the design for the inverter and the charge controller. This program was then sent to Advanced Circuits Gerber file checker for any errors.

Fortunately, the vendor’s website offers a lot of resources that can ease the process of learning the use of the software. There are video tutorials on how to use the software and they also have technical support. Once the designs were finalized with definite part numbers and component values the circuit board was designed and ordered at this point.

Section 6.2 – Final Coding Plan

The code for the project is the brains of the systems and allows the system to be self-sustaining. The code monitors the system and has to make decisions based on the state of the system. It is vital that the code is complete and thorough. The code makes a decision for all possible states of the system. If the code encounters a state that it does not know how to handle, there can be a substantial amount of damage done to the system.

A potential situation that the system can encounter that will cause a large amount of damage includes; when the solar panels are not producing power, the power can flow back into the panels. This can cause damage to the solar panels and the charge controller. The solar panels and voltage regulators in the charge controller can only have power flow in one direction. Power flowing in the reverse direction can cause extreme damage to the circuits. To prevent reverse flow blocking diodes were used.

In order to program the PIC microcontroller a programming board must be used. The programming board will interface with a computer through a USB port. Once the code is compiled on the computer, the executable file will have to be sent to the PIC microcontroller via the USB port. Programming boards are available in a surface mount board and breadboard plugin interface.

Section 6.2.1 – Charge Controller

For the charge controller the Toshiba and the PIC microcontrollers will be programmed using the C programming language as they are both compatible. MikroC was used to write the programs. The programming language was also chosen because it uses less space than a higher-level language like C# or Java and it is compatible with the PIC microcontrollers.

A few of the methods that will be implemented will be voltageIn function, voltageOut function, and batteryCheck function. The voltageIn function will return the value of the amount of voltage that is coming into the system. This function will communicate with the PIC microcontroller through the input/output port to have a constant reading of the input voltage. The voltageOut function will return the value of the amount of voltage that is being sent out. This function will communicate with the PIC microcontroller that is calculating the voltage output, through the input/output port. Finally, the batteryCheck function will return the status of the battery bank. The function will return a 10 bit number that will be used for the LED stacklight to indicate the charge of the battery. The stack light will indicate values from 50% to 100%. This function will be getting a signal from the battery bank voltage divider to update the status of the battery bank. Figure 47 would have been an activity diagram of the charge controller and how it would divert the power.

The Toshiba microcontroller would first check to see if the battery is full, if it is, and if the Pin is greater than Pout then close the switch to the inverter, open the switch to the batteries, and dump the excess. If the Pin is not greater, then close the switch to the batteries and open the switch to the inverter.

If the batteries have some charge between 50% and 95% and Pin is greater than Pout, close both switches else close the switch to the batteries and open the path to the inverter.

If the batteries need to be charged, has less than 50%, and Pin is greater than Pout close both switches to send power to the inverter and the batteries. Else, if the Pin equals Pout close the switch to the batteries and open the switch to the inverter. Else, close the switch to the batteries, open the switch to the inverter and disconnect the load to charge the batteries.

The PIC microcontrollers will have only one program to figure out the power that is passing through the circuit and sending the digital signal to the Toshiba microcontroller.

This architecture was not used because the system was simplified to using only one PIC microcontroller that was able to monitor the system. The PIC16F887 has enough ports for the voltage dividers to measure the input and output voltages to make the decisions to change from buck or boost mode and to modify the duty cycle to make a 20 volt output.

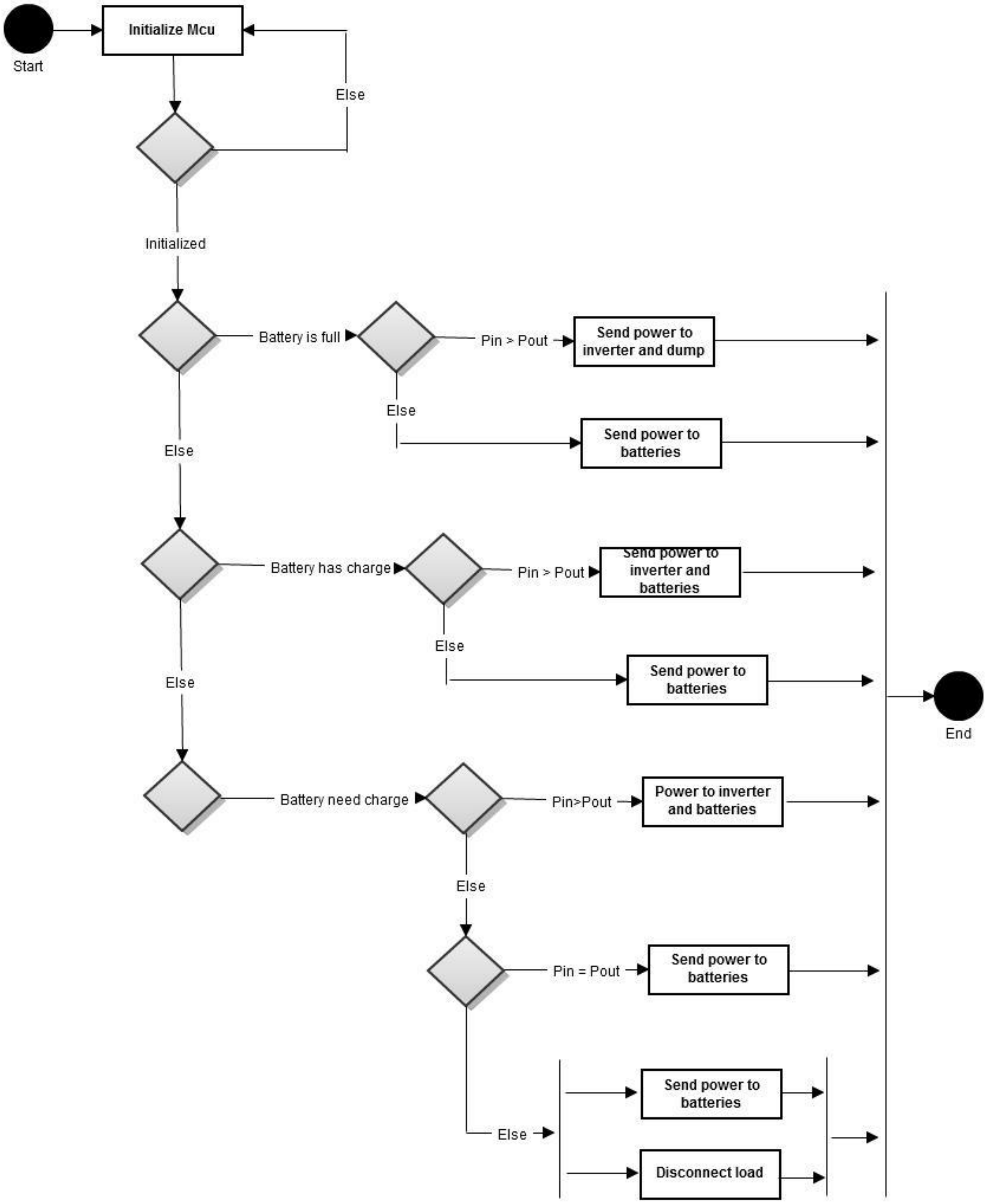


Figure 47 Activity Diagram for charge controller

Section 6.2.2 – Inverter

The inverter needs to be able to receive a DC input, and then convert it into an AC output. To do so, it needs to be able to digitally produce a sine wave signal. In order to produce this signal, it is required to use a fixed number of square wave pulses. The larger this number is the cleaner the sine wave output will be. In the inverter that was designed the number of square wave pulses used were 32, this set of values is enough to achieve an accurate sinusoidal signal. The values produced vary from 0° to 360°; first, they will cover the positive sine wave section of the signal and then they are reversed in order to cover the negative sine wave section of the sinusoidal signal.

Here is an example of how the values are generated, using 10 samples

1. sin(0) = 0 = 0%
2. sin(18) = 0.31 = 31%
3. sin(36) = 0.59 = 59%
4. sin(54) = 0.81 = 81%
5. sin(72) = 0.95 = 95%
6. sin(90) = 1 = 100%
7. sin(108) = 0.95 = 95%
8. sin(126) = 0.81 = 81%
9. sin(144) = 0.59 = 59%
10. sin(162) = 0.31 = 31%

To implement these values we will use the PWM of the PIC. The respective percentage is the equivalent of the duty cycle implemented.

PWM Period = [(PR2) +1]*4*TOSC*(TMR2 Prescale Value)

PR2 = [PWM Period / (4*TOSC*(TMR2 Prescale Value))] - 1

This gives PR2 = 249 making the Period = 250

Now every value calculated from the example above will be multiplied by the period creating the following array of values:

[0, 77, 147, 202, 237, 250, 237, 202, 147, 77]

Now to be able to implement this sine wave we will use the CCPR1L and initialize it to 0. This interrupt will occur whenever the end of a period is reached. Now the calculated array will be assigned to the variable sinval. This variable will act as the array index. In the ISR, ind will be used to determine the current position of the array.

Section 7 – Project Prototype Testing

Testing the project is essential to the goal of the project. The final project will be in a remote area of South Africa. This means that the system should last a long time and have a wide range of operating conditions. The system will have to face the environment and run strong.

In order to meet this goal every component of the system will have to be thoroughly tested.

Everything that is bought has a possibility of being defective. In the goals of the project the system must be functioning at a high quality to ensure longevity of the system. Longevity of the system is essential since it will be in a remote part of the world and will become a vital part of many people's lives. If a component is defective it cannot be used in the system because of these facts.

Section 7.1 – Prototyping

In order to save money and time, by guessing and checking, every component will be prototyped using a bread board. All electrical components will have to be purchased in a package that will interface with a breadboard. Each component will have to be tested down to the node to check the accuracy of the current calculations.

Section 7.1.1 – Shunt regulator

The shunt regulator is an important component that would have monitored the status of several components in the system. The shunt regulator would have to be prototyped for all the voltages that are required for the stack lights. The biggest concern for the shunt regulator is the current flowing through the circuit, since it is a small signal circuit. The current at every node would have to be compared to the theoretical currents in order to assure that LEDs or shunt regulator will not be damaged.

In order to test the shunt regulator a breadboard was implemented. Resistors R1 and R4 will be easily removed to allow the testing of all voltages required in the stack light. The resistors will be chosen so the LED will turn on. The LED turning on signifies that the voltage has been reached in order to clamp the shunt regulator. All the voltage steps for the stack light would have to be tested. A voltage would be applied using a power source provided in the lab. The voltage on the power source would be set below the required voltage. Then the voltage source would be increased over the clamping voltage to test that the shunt regulator will clamp. The process would be repeated again for all the required voltages of the stack lights. In order to test the clamping for all the voltages in the stack light; resistors two and four would have to be replaced in order to change the reference voltage of the shunt regulator.

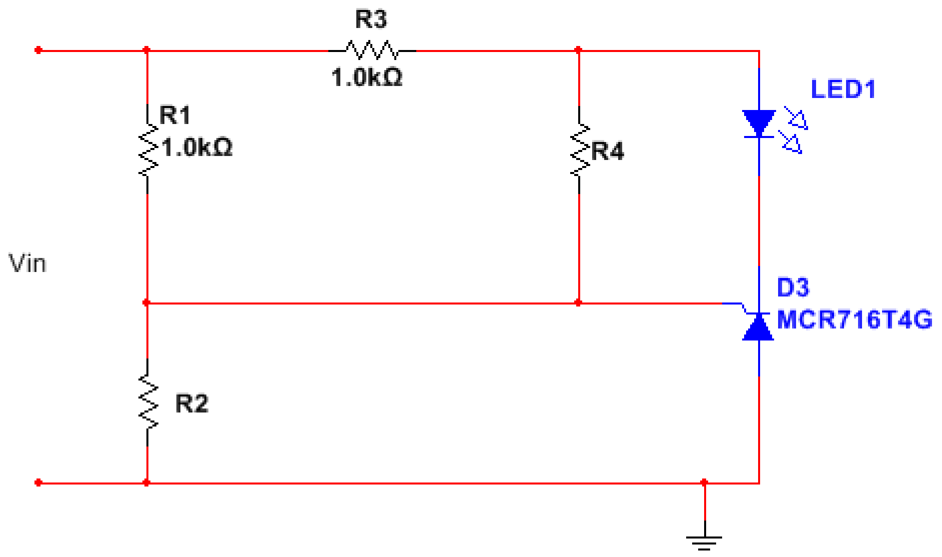


Figure 48 The circuit design for testing the shunt regulator. Resistors R2 and R4 will have to be replaced to clamp the shunt regulator at the different voltages for the stack lights.

Section 7.1.2 – Voltage Regulator

The voltage regulator is responsible for the increase or decrease of the voltage of the solar panels to 20 volts. Since the panels are in a parallel configuration all the currents will be able to merge but the voltage output is unregulated. So stepping up or down the voltage to 20 volts and regulating the charge voltage is a must.

The voltage regulators will be designed and built on a breadboard. To ensure that the voltage regulator is functioning properly a voltage will be applied to the input. The input will be adjusted to make sure that the voltage stays at a constant 20 volts. Merging power at different voltages creates a lot of heat. The potential amount of power that the solar panels can produce, the consequences can be extreme.

The other aspect that needs to be tested is the current. The maximum current that the voltage regulator will need to withstand is 7.92 amps. A high current will have to be inputted to the voltage regulator to ensure that the current is not too high. The voltage regulator must be able to handle an input of 7.92 amps and 30.20 volts.

In order to be able to step up or down the unregulated voltage a buck boost dc dc converter is optimal. A simple buck boost is made of 5 components. There are two transistors, two diodes, an inductor, and a capacitor.

The way the two transistors switch will dictate if it is in buck mode or boost mode. The two diodes where used to make switching from buck and boost mode easier but using four switches is best for efficiency. The diodes make sure there is no reverse flow. The inductor is used to store and release power and makes the voltage increase or decrease based on the switching of the two transistors. Finally the capacitor is used as a filter to minimize the dc voltage ripple at the output.

Section 7.1.4 – DC Boost Converter / Transformer

The DC Boost Converter is an essential piece of the inverter; it increases the output of the battery source into a greater voltage that is necessary in order to run other important devices.

The DC Boost Converter needs to be prototyped in a breadboard so it can be implemented. In this breadboard a DC input supply will be used, this DC input voltage will be changed in order to test the converter in different voltage levels. The breadboard implementation is an easy and handy tool because it allows the easy change of components like inductors, and capacitors which are also going to be used; different components will change the behavior of the circuit. An oscilloscope almost must be ready for use in order to analyze the inductor behavior. Finally, another reason the breadboard is useful is because this converter requires a switch, the most important component. This one can typically be a MOSFET, an IGBT or a BJT. The versatility of the breadboard allows an easy preparation for prototyping this converter with all of these different components, once again different types of switches will affect the behavior of the circuit. The following circuit illustrates how the prototype will be connected on the breadboard, and the different components that can be placed and exchanged for any future testing.

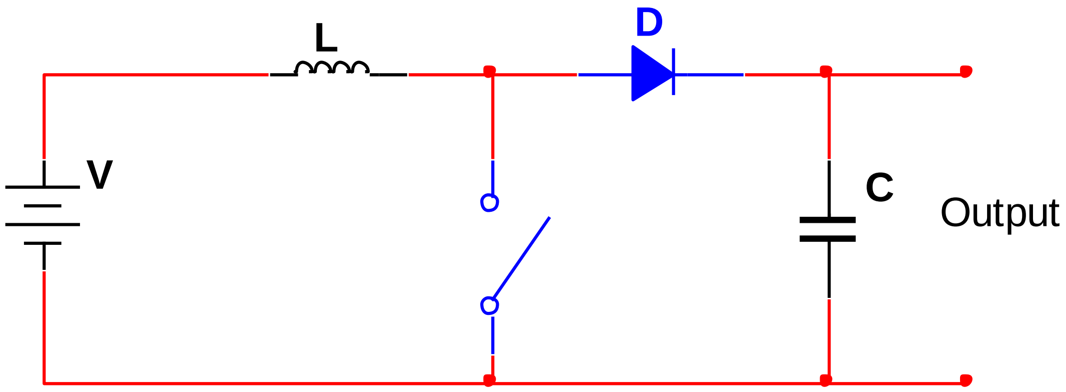


Figure 49 DC Boost Converter

The transformer component was not prototyped by itself, but it was later tested with other components were a couple of unexpected results were found.

Section 7.1.5 – H-Bridge

The H-Bridge can be the most important component on the inverter. This component is in charge of creating the sinusoidal wave output. This signal is the exact reason why the inverter is taking part of the project, and that is why this component is so important inside the inverter design.

A very organized prototype must be done for the H-bridge in order to be able to test every section needed inside the circuit. This prototype circuit will contain four switches; the slots where these will be located must be properly accommodated within the breadboard in order to change the type of switches if necessary. There are different types of switches than can be used such as the MOSFETs. These are used for high frequencies, low power consumption, low voltages and low currents for small power loads. Other type of switches are the IGBTs, these can handle high voltages, high currents, and relatively low frequencies compared to the IGBTS. These specifications require the prototype to use an oscilloscope to measure the changes of frequencies, the amount of power use, the current and the voltage variations for this type of components. As a last measurement the oscilloscope must read the power dissipation of the devices. The breadboard must be properly divided in two sections for the H-bridge; one will be the low side and the other, the high side. This division will help the testing procedures to be more logical because the low side will accommodate the low frequency switches and the high side will accommodate the high frequency switches.

Another important setup that must be made for the H-bridge is the operation of the switches. A multimeter will be needed to read the state of every switch; these readings will have to be made for nine different types of switching state combinations. The multimeter and the oscilloscope will also be used to measure reading from the blocking diodes. Finally, the oscilloscope must be used to measure the input coming to the H-bridge and the output it produced in order to be used for a comparison in future testing procedures. The following circuit, in figure 48, illustrates the setup that will be put into the breadboard.

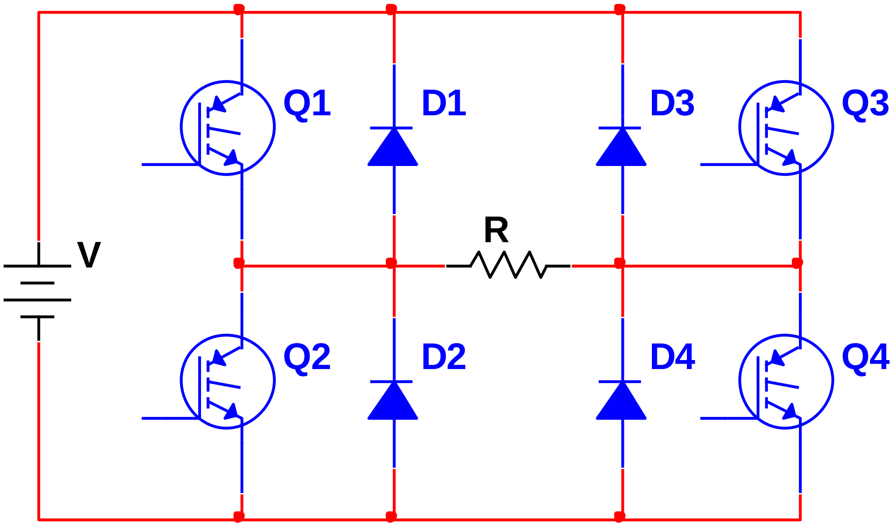


Figure 50 H-Bridge Circuit

Section 7.1.6 – LC Filter

The LC Filter is another important component for the design. Its importance lies on the need for creating a sinusoidal wave output as close as possible to a pure sine wave. To do so, this component reduces the amount of harmonics generated by SPWM so the final sine wave output contains much less distortion. To be able to properly create a prototype we must use a breadboard that connects the output of the H-Bridge circuit into the input of the LC filter. An oscilloscope will be used in order to read the output from the H-bridge, before it is connected to the LC Filter, and it will also read the output of the LC filter. This procedure will allow a comparison between the output of the H-bridge and the output of the LC filter. The use of the breadboard also allows the change of components within the LC filter in case the output is not the desired one. Tools like the multimeter and the oscilloscope will once again be available in order to deeply analyze the behavior of the new components. To correctly choose the proper components such as the inductor and the capacitor for the system, equations have been researched to calculate proper values as accurately as possible. Figure 50, below, illustrates the setup that will be used for the breadboard.

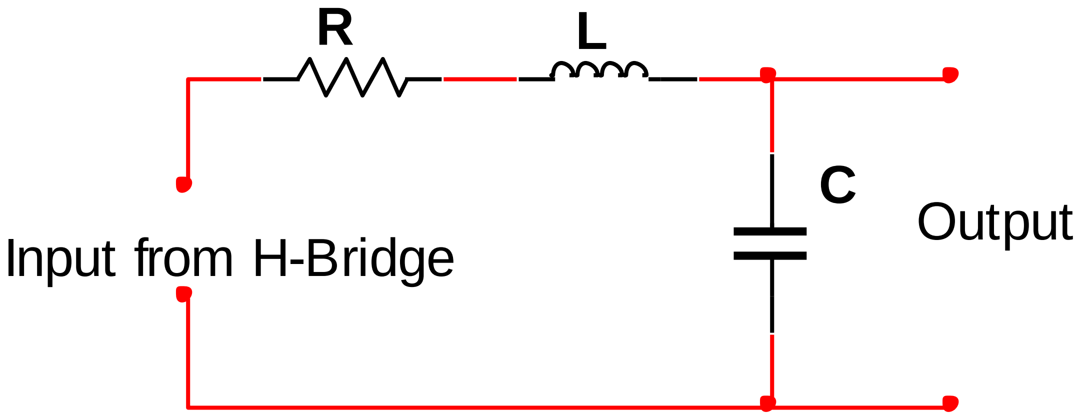


Figure 51 LC Filter Circuit

Section 7.2 – Testing

Testing of the system is a vital part of the design. If the system is not tested then when the system is deployed it could fail. This failure cannot be tolerated. The success of the system is crucial to many people.

All of the final components need to be tested, so they can be integrated into the system. Testing the components individually first will ensure that they take the correct input and output what they are supposed to. If any component does not output the correct output the whole system could fail. In order to prevent the failure of the system all the components will have to be tested.

Section 7.2.1 – Shunt regulator / Stack light

The shunt regulators testing will be less tedious than the prototyping because all the resistors will be mounted to the integrated circuit already. The stack light would be attached to a voltage source and the voltage would be adjusted up and down. When the voltage is varied the LED lights should turn on and off in order of red, yellow, and green or vice versa. Once the voltage is turned all the way up all the lights will turn on. As the voltage drops the lights will turn off in sequence running down the stack. Once the voltage is dropped all the way down, the last light will turn off.

There are four stack lights for the battery bank and four stack lights for the solar panels. Each stack light would have been tested to ensure that they are all functioning properly. Since the stack lights are being used to identify malfunctioning components they cannot malfunction themselves.

Section 7.2.2 – Voltage Regulator

The voltage regulator will be tested in the same manner as the prototype. A voltage will be applied to the input and adjusted. The output will be measured to ensure that the voltage for the output is constant at 20 volts. The current will also have to be tested. The maximum input of current from the solar panel that the voltage regulator is attached to is 7.92 amps. The circuit must be able to withstand such a high current and testing that it can is important.

Section 7.2.3 – Charge Controller

Once all the components of the charge controller were tested then the microcontroller was tested with the components. The charge controller consists of the voltage regulator, the PIC microcontroller, and the LED stack light. Once the voltage regulator was tested then the charge controller as a whole was tested.

The microcontroller will be added for the testing once it has been determined that the voltage regulator will not damage the ports of the microcontroller. The microcontroller will be programmed and the signals from the voltage regulator were tested to ensure that the microcontroller will respond to the input properly.

Section 7.2.4 – DC Boost Converter / Transformer

As stated, the boost converter steps up the input voltage in order to be useful for other devices. This DC Boost Converter will be initially tested with different voltage levels; this procedure will give us a general idea of the range of voltages this converter is allowed to be working with.

Within the circuit itself different inductor and capacitor values will be tested with the purpose of finding the closest match that will provide the best step up voltage. To do so, a check point must be set; this one can be the desired voltage output that will be needed for the other device in order to run properly. The fly back diode is another crucial component on the converter; its job is to maintain the capacitor with enough charge so it does not discharge through the switch. Another aspect that must be tested is the switching component, as it was mentioned before there are different types of switches that can be used within the converter. By testing these different types of devices such as the MOSFETs, IGBTs and BJTs it will be possible to determine not only an optimal match for the set up procedure, but the best match from all the components. Different characteristics of these switches will be taken into account, specially the capability of switching properly in order to keep the system stable.

In the case of the inductor, while the circuit is in the ON state, the oscilloscope must receive a signal where the current must increase in order to meet the expected behavior of the design. Another analysis must be taken for the capacitor, when the switch is in the OFF state, the oscilloscope must show an increase on the voltage of the capacitor. If any of these expected results are not meet, there is a big possibility that the diode or the switch are not working properly. If this happens, the necessary adjustments must be taken and the steps above repeated.

Another component that was tested is the transformer. While this is a component that does one task, while doing so it modified the topology of the circuitry and as consequence the behavior of the system. This is the kind of testing that was taken into account for the transformer. The connection of the transformer with the LC Filter created an undesirable but inevitable LCL circuit that created interference with the final filtering process of the Filter. Another problem presented with the transformer and was tested is the increment of signal noise when stepping up the voltage from the inverter to the final 220V. Proper testing of this two unexpected behaviors was done in order to correct any signal disruption of the system as good as possible.

Section 7.2.5 – H-Bridge

While the datasheets give technical information on the IGBTs, it is better to measure the real maximum and minimum values these components can handle for every distinctive characteristic such as voltage, current, and frequency ranges. These values must be compared to the minimum requirements in order to choose the best fit for the H-Bridge. Another important test that should be done is the measurement of the voltages on every state of the switches; these states should be measured with the purpose of reliability of the components, these switching states are crucial for the optimal functionality of the inverter. Finally, a comparison between the input signal (DC) and the output sinusoidal wave (AC) must be measured on the oscilloscope. While is it expected to have the output sinusoidal wave with some distortion, it should still look like a sinusoidal wave on the screen of the oscilloscope.

Testing of the H-bridge is very essential for the inverter system. This is the component that takes the DC input and converts it into the sinusoidal output waveform needed in this project. The prototype allows us to connect different types of switches into the system. As it was decided after the testing procedure the IGBTs are not the most appropriate selection for the design of the H-Bridge. After testing was done it was found that while these IGBTs based on their specifications were designed to be able to handle high voltages, high currents and relatively low frequencies compared to the MOSFETs, they were not reliable on final design. The MOSFETs were also tested to see if they improved the performance of the system, and they greatly did compared to the IGBTs.

Section 7.2.6 – LC Filter

As stated before, the LC Filter is in charge of minimizing any harmonics that might create distortion in the final output for the sinusoidal wave. This task is crucial for the full functioning of the project, because of this; very detail steps must be taken to avoid any mistake that may disrupt the signal.

The first step that must be taken in order to properly test this circuit is to double check the correct values for the inductors and capacitors that were calculated for the circuit. These will be checked with the use of a multimeter, this procedure will allow knowing the exact value for the components. After these components have been checked, properly positioning them in the breadboard, so they can be connected to the output of the H-bridge. After these two circuits are connected the output of the H-bridge and the output of the LC Filter must be read, this will demonstrate if the LC Filter is filtering any distortion of the sinusoidal wave coming from the output of the H-bridge. If the LC filter output meets the requirements for the sinusoidal wave it produces then the test is completed. If the output is not expected, a detailed inspection of the system must be done. First, the oscilloscope must be used in order to read the behavior of the capacitor and the inductor. If this behavior is not the desired, then the components must be changed in order to get a better output of the LC filter. This procedure must be done repeatedly until the desired sinusoidal output is finally reached.

Section 7.2.7 – Gate Drive Optocoupler IGBT/MOSFET Driver

The Gate Drive Optocoupler is a very essential component in the inverter design. The main reason for its use is because it must isolate the low side voltage from the high side voltage in order to prevent a critical circuit failure. The great feature of this component is that plays the role of driving IGBTs while at the same time protecting the circuit.

The Gate Driver Optocoupler must be able to be tested for different types of voltage variations within the power stage and the control circuit. To do so, a voltage generator with two different voltage supplies will be available in order to compare these voltages and its variations which are the ones that must be taking into account on any future testing. The use of a breadboard will be essential for the manipulation of different components within the H-bridge and the optocoupler. The circuit created on the breadboard must be properly designed in order to be able to change the components of the H-bridge. Different components will be selected in order to reach the most adequate components when the testing procedure is done. In this process, the theoretical ranges of the IGBTs must be tested in order to calculate the real values the optocoupler is actually able to drive. As stated section 4.3.3 the optocoupler has the capability of preventing the H-bridge from having a short circuit, but it is safer to calculate the maximum range at which this component will be able to safely protect the H-bridge. To do so, the optocoupler will be tested from slow changes on the switches and they will slowly be increased until the highest safety margin of protection is reached. These testing procedures must be repeated in case of having significant changes on circuitry.

In the same way, it was found while doing the same testing that was made to the opt couplers that the best choice for driving the MOSFETs was the IR2110. Once again it was proven that when proper testing was done, the initial components chosen were not as reliable as expected. Testing was very important to avoid any irreversible problems that could have happen once the final product was assembled.

Section 7.2.8 – Solar Panels

The solar panels are the heart of the project because without them the rest of the components are not able to be utilized. It is of utmost importance that the solar panels work.

To test the solar panels a power resistor can be implemented along with a multi-meter. A power resistor with low resistance will allow the current to flow between the terminals and be dissipated through heat. Since the voltage will be measured using the multi- meter and the resistance is known the current can be calculated. Using the voltage and current the power can be calculated.

The first controlled variable for the solar panels is sun exposure. In order to ensure that the solar panels are getting the same amount of solar exposure, the panels were lined up next to each other in an open area without shade. All of the panels were tested at the same time to ensure that the sun was a controlled variable. Then shade was introduced to the panel to insure that the power drops. To introduce shade to the solar panels a board was placed over the solar panels to reduce the solar exposure. The boards were moved around to cover different sections of the panel to identify bad cells.

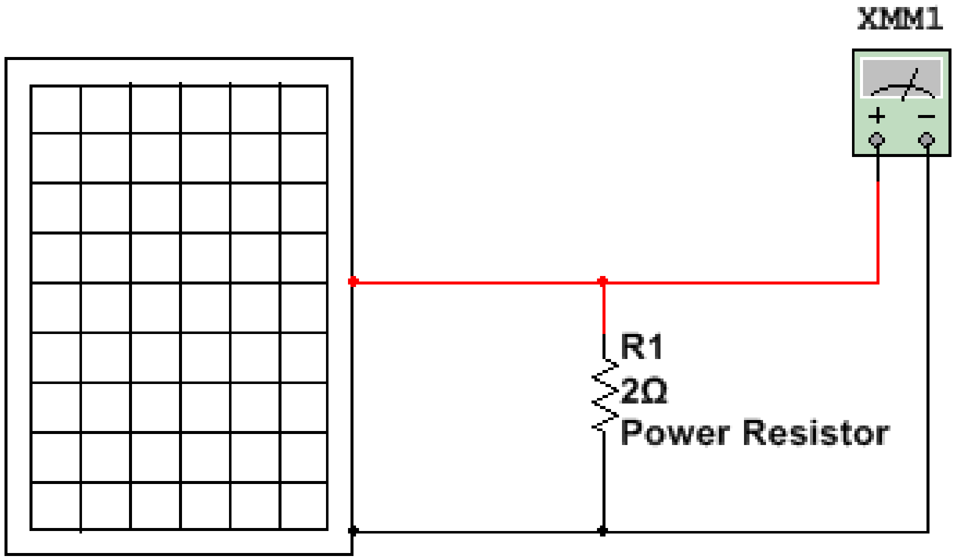


Figure 52 The power resistor is connect to the positive and negative (red and black) of the solar panel. The multimeter is measuring the voltage across the resistor wich allows for power to be calculated.

Another independent variable is temperature. Solar panels have different efficiencies at different temperature. To test the durability with respect to temperature the solar panels were tested in the winter and in the summer. Since the spring semester is from January to May, the temperature range of the climate varies from close to freezing in January, to extremely warm in the spring months. The solar panels were tested over several months for short periods of time to ensure that the power output is consistence across all the panels at the same time. On cold days the solar panels were left outside to create equilibrium between the temperatures of the climate and the solar panels. The panels were also tested on days with poor quantity of sun light.

Section 8 – Administrative Content

Every project has aspects that are necessary. The administrative content is the section that will help keep people on track and help them when needed. The administrative content was a map of the project that guided people and given them an insight to why they are doing what they are doing. By looking at the map of the project designers were able to grasp the concept of the project, the importance of what they were working on and motivate them to see what they are working on.

Section 8.1 – Milestone Discussion

Every project has to have deadlines and milestones. This keeps people honest, focused and is a good time management tool. In order to meet the deadline the whole group has been broken up into 2 subgroups. The first subgroup was responsible for the development of the charge controller and solar panels. The other group was responsible for the development of the inverter and the construction of the battery bank. Each group prototyped the components that they designed to ensure that the design functions properly before the final components are built. Once a subgroup has determined that the component has satisfied the requirements of the project then the component is ready to be built. Then when the final component was received it was tested to ensure that the product is not defective.

Each subgroup had been tasked with a system that was not designed by the group, the solar panels and batteries. The solar panels must be thoroughly tested to ensure that they are functioning to their specifications. The batteries must also be tested to ensure that they charge to their specified charging capacity and the output meets the specifications as well.

Section 8.1.1 – Prototyping

The first milestone that has to be met is testing the components that were purchased. These components have to function properly because they have to be integrated into the design of the entire project. If these components are not thoroughly tested to ensure that they perform within the desired specification of the project the components that are custom designed will not function properly or will be permanently damaged. These components were tested as soon as they were received. The batteries were tested once when they were received and were not used again in order to preserve their life. The solar panels were tested once they were received and also under different weather conditions such as cold temperatures and warm temperatures with varying amounts of solar radiation exposure. Since the weather can be comparable to South Africa here in Florida the solar panels were tested here under every combination of solar radiation and several temperature ranges. This would ensure that the solar panels are capable of handling any weather conditions that South Africa has to offer. The weather was monitored and the specific weather conditions will have to be forecasted watching the weather channel. When a specific weather condition is predicted, plans were made to test the solar panels for that time.

The second milestone that was to be met is prototyping. Prototyping is the foundation for building the system. Without knowing if the conceptual design functions properly the rest of the design becomes a blind guess that could turn out as a failure for the project. All components will have to be prototyped in a timely manner. The prototyping for the components were have to be finished and finalized by the end of March. The main components of the charge controller and inverter were be split up amongst the group members. Two group members prototyped the charge controller and the other two members prototyped the inverter. The two teams had deadlines that needed to be met for the project to go smoothly. Both the charge controller and inverter have individual components that were prototyped.

The components of the charge controller that were prototyped were the shunt regulators, PIC microcontroller and circuits, and external circuits for the PIC microcontroller. The PIC microcontroller must have a voltage divider in order for the analog to digital converter to function properly. To prototype the PIC microcontroller the voltage circuits were prototyped first. Once the circuits were prototyped to ensure that signal will not damage the PIC microcontroller, the circuit was added to the PIC microcontroller, so the PIC microcontroller can be tested.

The shunt regulator were also prototyped until they were deemed unnecessary for the project. The shunt regulator needed to have a lot of time allocated to prototype it. The original stack lights were going to utilize the shunt regulator, so the shunt regulator needed have to be prototyped for many clamping voltages. This will be a tedious task that will take an ample amount of time, so the prototyping of the shunt regulator was planned accordingly and it was prudent that the deadline be met.

Component	Prototypers	Deadline
Shunt Regulator/Stack Light	Patrick and Cory	Jan 25, 2013
Circuit for PIC	Patrick and Cory	Jan 10, 2013
PIC Controller with Circuit	Patrick and Cory	Jan 17, 2013
DC Boost Converter	Pablo and Esteban	Feb 22, 2013
H-Bridge	Pablo and Esteban	Feb 22, 2013
LC Filter	Pablo and Esteban	Mar 8, 2013

Table 5 Detailed list of deadlines for prototyping.

Section 8.1.2 – Testing

After the components were prototyped they must be built as an integrated circuit. Once all the components were built as an integrated circuit they had to be tested in a similar manner as when they were still in the prototyping stage. The voltage circuit was tested to ensure that it functions properly before the PIC microcontroller is placed into its housing. Once it has been verified that the voltage divider circuit are working properly then the PIC microcontroller was added to ensure that it works with the circuit.

The shunt regulators in the stack light needed to be tested. The testing for the stack lights will be straight forward, but will be tedious because there were a lot of clamping voltages that needed to be tested. Testing the stack light will take a lot of time, like the prototyping, and must be completed in a timely manner to meet the deadline.

Component	Testers	Deadline
***Solar Panels**	Patrick and Cory	Jan 20, 2013 – April 1, 2013
Batteries	Patrick and Cory	Feb 20, 2013
Shunt regulator/Stack light	Patrick and Cory	March 10, 2013
Circuit for PIC	Patrick and Cory	March 10, 2013
PIC Controller with Circuit	Patrick and Cory	March 15, 2013
DC Boost converter	Pablo and Esteban	March 10, 2013
H-Bridge	Pablo and Esteban	March 10, 2013
LC Filter	Pablo and Esteban	March 15, 2013
Gate Drive	Pablo and Esteban	March 15,2013

Table 6 Deadlines for when testing will be completed
**Special test case. Must be tested based on weather conditions*

After testing of individual components is completed, the components need to be test as a whole system. Getting the whole system operational does not signify the end of the project. The project was tested as a whole for an extended period of time also. This allowed for the testing of the adaptability of the system. The system experience a fluctuation in solar exposure. This will allow the system to respond to different climate conditions. The system was tested by plugging in a light bulb. This tested the load that the system will experience once it is deployed.

Section 8.2 – Budget and Finance Discussion

All the parts for the controller and the inverter were ordered all at once. The purpose for doing this was to be able to prototype the design that was created for the charge controller and the inverter. It is common knowledge that what works in theory might not necessarily work in real application. Keeping that in mind all the parts that are essential to test the design of the controller and the inverter were ordered. This will allow the integrity of the design to be tested and to be tuned as necessary. There is always a possibility that some parts have to be changed and that could potentially change the design. For this reason, Table 7, has been created to show the budget for the system. Table 7 will illustrate with detail the name of the components and values, its unit price, the total items ordered, the total price for each component, and then the final price for the project.

To help fund research and generate interest of student engineers to study and work with alternative and renewable energy sources Progress energy has chosen to donate money. The project was financed through Progress Energy.

The budget for the project is $1985 about half of the money is allocated for the solar panels, about 20% for the battery bank, and 10% each for the inverter, the charge controller, and miscellaneous. Below are the list of parts that will be used for the charge controller. The parts were quoted through different vendors to compare the price difference. Allied Electronic, Mouser, and Digikey were selected as vendors for their reasonable pricing and their part's availability. Another reason for selecting only three vendors for the integrated circuit part was to save on shipping cost rather than ordering from different vendors.

Here is display a couple pictures of the final design and at the end the final budget Table.

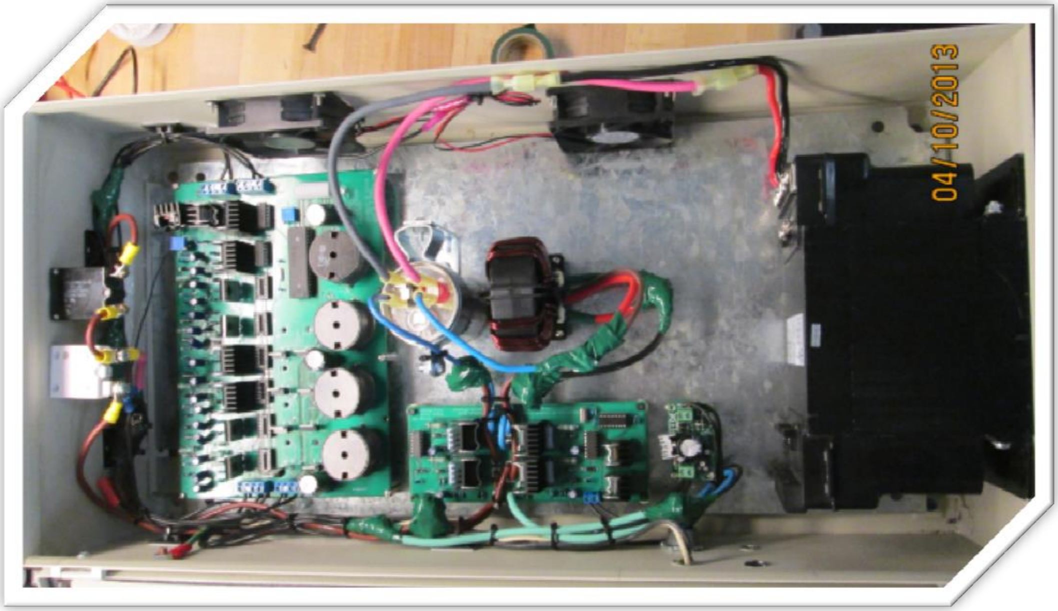


Figure 53. Final Design

COMPONENT DESCRTIPTION	TOTAL ITEMS	UNIT PRICE	TOTAL PRICE
CAP CER 0.1UF 50V 5% RADIAL	66	$0.65	$42.90
DIODE FAST 1000V 1A DO-41	46	$0.43	$19.78
CAP ALUM 47UF 50V 20% RADIAL	54	$0.25	$13.50
IC DRIVER HIGH/LOW SIDE 14DIP	34	$4.26	$144.84
RES 10 OHM 1W 1% WIREWOUND AXL	34	$0.44	$14.96
RES 1.0K OHM 3W 5% METAL OXIDE	12	$0.59	$7.08
CAP CER 15PF 50V 5% RADIAL	14	$0.29	$4.06
CAP CER 0.22UF 50V 10% RADIAL	6	$0.38	$2.28
CAP CER 0.1UF 50V 10% RADIAL	12	$0.20	$2.40
CAP CER 0.33UF 50V 10% RADIAL	10	$0.27	$2.67
16MHz - 18PF	50	$0.35	$17.50
CONN IC SOCKET VERT 14POS TIN	16	$0.22	$3.52
HEATSINKS	12	$1.95	$23.40
ENCLOSURE	1	$35.00	$35.00

Table 7.1 Budget list for the Solar Power Generator

DESCRTIPTION	TOTAL ITEMS	UNIT PRICE	TOTAL PRICE
DIODE MBR1045	25	$0.64	$16.10
LED STACK LIGHT	1	$6.92	$6.92
LED BLUE	2	$0.21	$0.42
RESISTOR 1K	32	$0.06	$1.82
CAP ELEC 1.5mF	10	$1.29	$12.87
INDUCTOR 120uH	8	$7.17	$57.36
SOCKET 40 PIN	2	$0.51	$1.02
TERM BLOCK 2POS	3	$0.63	$1.89
TERM BLOCK 4POS	6	$0.73	$4.38
HEATSINK AND CLIP FOR TO-247	12	$2.07	$24.84
PIC 16F887	5	$2.80	$14.00
SOLAR PANEL	4	$183.00	$732.00
BATTERIES	4	$85.00	$340.00
PCB INVERTER	1	$464.00	$464.00
PCB CHARGE CONTROLLER	1	$66.00	$66.00
EASYPIC 7	2	$140.00	$280.00
CABLES	1	$140.00	$140.00
PIC 16F684	20	$1.96	$39.20
		TOTAL	$2,536.71

Table 8.2 Budget list for the Solar Power Generator