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Solar Charging Station

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Major Qualifying Project

Solar Charging Station

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Solar Charging Station

A Major Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

by

Giancarlo Savoy
Akuete W. Sossavi

Date:
6 March 2015

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ABSTRACT

The purpose of this project was to design and develop a proof of concept Solar Charging Station capable of delivering power to up to four cell phones and two laptop computers simultaneously. A custom maximum power point tracker (MPPT) was designed to extract the maximum amount of power available from the solar panels. This MPPT sampled the voltage and current output of the solar panels and executed the “perturb and observe” algorithm to determine the maximum power point.

1 CHAPTER 1: INTRODUCTION

The world, especially the United States, relies heavily on non-renewable energy sources such as coal, oil and natural gas. These come from fossil fuels that are environmentally damaging to retrieve and use, and become more expensive every day. Fortunately, there are many types of renewable energy such as solar power, hydropower, wind power, geothermal power, and biomass. Nowadays, the focus is on researching and developing the use of these renewable energies to make our planet safer, cleaner and enjoyable to inhabit during our brief journey on earth. Solar power is one of the easiest to implement renewable energy technologies. One of the strengths of solar power is its ability to deliver energy in areas where there is not access to the electrical grid.

Utilizing this technology our goal is to design a portable Solar Charging Station (SCS) and build a proof of concept prototype to demonstrate the viability of this idea. To meet our goal, we propose using thin films photovoltaic cells mounted on top of an umbrella. A maximum power of 360W is collected by the photovoltaic cells and tracked by a Maximum Power Point Tracking (MPPT) system. The output of from the MPPT charges a lithium ion battery pack. This battery in turn powers a 5v USB, and 120vAC output. Our product is designed using the components and materials light enough to be semi-portable and easy to move from different location of a patio to another. It is easy to see that application of such a product in areas such as the restaurant and hospitality business, for institutional use such as at schools and universities, as well as for home use.

There is multitude of competitors for powered umbrella used as a charging station. Among others, we can cite Strong Volt, Brookstone, Solpoweror Solprox, Powersol, Gizmodo and even Alibaba. Our design distinguished itself among them by the use of a MPPT to increase efficiency, a large battery capacity to prolong use, and the ability to power and charge laptop computers and other devices.

2 CHAPTER 2: BACKGROUND

2.1 History of Photovoltaic Technology

The first photovoltaic cell was created in Bell Labs in 1954. This fledgling technology only delivered 4% efficiency at its creation. With relatively low efficiency PV cells were slow to be introduced into the retail and industrial markets. Their first major uses were in the early satellites such as the Vanguard I and the Sputnik-3 in 1958. Throughout the 1950's and 1960's PV based solar power began to pick up steam as efficiencies rose to levels which were viable for more and more technologies. In the 1970's large breakthroughs were made by Dr. Elliot Berman which reduced the cost of PV panels from \$100/W to about \$20/W. In 1976 RCA laboratories creates the first amorphous PV cells. This is one of the technologies used in flexible thin film panels.

In 1978 a 3.5kW PV system was installed on the Papago Indian reservation. It was used to provide power for water pumping and 15 homes from 1978 to 1983. The first MW power station was turned on in 1982 in California, and the same year the first solar powered car was used to travel from Sydney to Perth Australia. In 1994 the National Renewable Energy Laboratory develops a PV cell that exceeds 30% efficiency, and in 1999 developed a thin film solar cell capable of 18.8% efficiency [5].

Today the total PV installed capacity of the world is over 38.4 GW and growing. The largest market for PV solar power is currently China with a total installed capacity of over 11.8 GW [6]. The solar power industry continues to grow and expand as the PV technology evolves and matures. As the efficiency and ease of use of this technology expands so too does its applicability. With every advance in this field more markets open up as viable areas where PV solar panels can compete.

2.2 Solar Panel Technologies

In order to determine the relative merits of the various solar panel types we must examine the differences in capabilities between these types of panels. The methodology of this process will use data collected from the "real world" specifications and qualitative description of solar panels available for purchase at the time of this review. While the efficiency and possible cost of cutting edge technology presented in academic papers will certainly be better than what this review will find this technology will still be confined to laboratories and small scale tests. This is unsuitable for our application where panels that are easily sourced and have “backup” secondary sources are necessary. We will use the Topoint 245W JTM 250-96M Solar Panel, Topoint 225W JTM225-60P Solar Panel, and Uni-Solar Laminate 136 Watt PVL-136 as references as research has shown they seen to be reasonably representative of what is available. We can use their product specifications to determine some figures of merit for comparison purposes.

2.2.1 Solar Panel Specifications

Panel	Max Power at STC (W)	Size (m^2)	Cost ($)
Topoint 245W JTM 250-96M Solar Panel, Mono[1]	245	1.704	119.10
Topoint 225W JTM225-60P Solar Panel, Poly[2]	225	1.636	139.50
Uni-Solar Laminate 136 Watt PVL-136, Thin Film[3]	136	2.160	63.92

Table 1: Solar Panel Specifications

The following figures of merit are used to compare important characteristics of each panel type. These values are derived from the specifications in the above table. All figures are based on the panel performance at STC.

- Cost per Watt: This figure determines how costly it is to supply each Watt of power. Lower is better.
- Power Gathered: This metric shows how much power each square meter of panel is expected to gather per square meter. Higher is better.

2.2.2 Solar Panel Figures of Merit

Panel Type	Cost Per Watt ($/W)	Power Gathered (W/m^2)
Monocrystalline	.78	143.77
Polycrystalline	.62	137.53
Thin Film	.47	62.96

Table 2: Solar Panel Figures of Merit

The dollars per Watt ($/W) metric shows how efficient panels are in terms of their cost per amount of power delivered. This metric takes into account the efficiency a panel has when converting light to electricity as well as the cost of the technology. The Watts per square meter (W/m^2) metric show how space efficient panels are. This can help determine the space required for a given panel for a certain delivered power.

These figures of merit show that Monocrystalline panels are the most efficient in terms of how much power they provide per amount of space they take up. This is offset by their high cost. Polycrystalline panels are a close second showing that in all but the most space conscious applications polycrystalline is superior to monocrystalline. Trailing far behind in space efficiency are flexible thin film solar panels. These are very inefficient in terms of space but are very cheap, even when factoring in their inefficiency. Thin film technology has another benefit not shown in these tables. The ability to flex, fold, and even be rolled up is a material property which other more efficient panels do not have. This can be very useful when designing products. Portability, ruggedness, integration into textiles, and other “real world” factors are improved by using flexible panels. To some extent mono- and polycrystalline panels can be made to be slightly flexible, but this somewhat impacts their efficiency and these panels do not flex nearly as much as true thin film panels [4].

To extend our analysis further we must examine our application more closely. Typical laptops (excluding the uncommon power hungry “gaming” laptops and similar) will draw about 60W when in use and charging the battery. Mobile phones will consume about 6W when charging. If we use the assumption that two laptops and four cell phones are charging at once we get a total power draw of 144W. If we assume that converting the DC power from the solar panels to 5v DC and 120v AC will have approximately 80% efficiency the total draw is 180W.

Solar power specifications are tested under “STC”, Standard Test Conditions, which is a set of standards including the assumption of 1000W/m^2 energy from the sun. This is close to the maximum amount delivered to the earth. A more typical amount of energy is around 500W/m^2. Thus the panels must be *rated* at 360W total to deliver 180W under typical conditions. This is the amount of power a Solar Charging Station will need from the solar panels and battery backup under “worst case” conditions.

We can use this number to determine some more specific info about the cost and size of the solar panels needed.

Panel Type	Cost ($)	Size (m^2)	Diameter of a Circle of the Required Size (m)
Monocrystalline	280.80	2.5	1.8
Polycrystalline	223.20	2.6	1.8
Thin Film	169.20	5.7	2.7

Table 3: Solar Panel Cost Analysis

Patio umbrellas are typically 9 to 12 feet (2.7m to 3.6m) in diameter. This range is large enough for all three common panel types to provide the necessary power. This means that when it comes to power generation all panel types are viable for use. With this in mind we must consider other avenues of differentiation between the panel types. The first is cost: thin film panels are the cheapest of the three panel technologies. The second is the physical and mechanical properties of the panel technologies. The thin film technology has the obvious advantage here with its flexibility allowing it to more easily conform to the existing umbrella fabric. Ease of use will be important with this product. The more closely the operation of this charging station mimics that of a traditional patio umbrella the more likely it is to be a viable product. With these attributes in mind it is clear that thin film technology is the most useful panel type for this application.

2.2.3 Modelling of Solar Cell

A photovoltaic solar cell is a complex device whose electrical properties that cannot be reduced to one single component such as an ideal voltage or current source. The physical realities of the solar cell necessitate a more complex understanding of the device. Thus in order to describe and simulate the properties of a solar cell one must build up a model which behaves in a similar way. A solar cell at its most basic has current source properties as it operates by using light to forcefully separate a set amount of charge. Furthermore, when short circuited a solar cell will produce a certain I_{sc} which is characteristic of the cell at a particular light level. Thus at the center of our model is a current source. In addition to the I_{sc} the solar cell has a certain V_{oc} which is the voltage measured across its terminals when they are open circuited. We can model this behavior by placing a component in shunt with the current source. In addition to these components there are losses in the system which we can model as series and shunt resistances. This model is shown below.

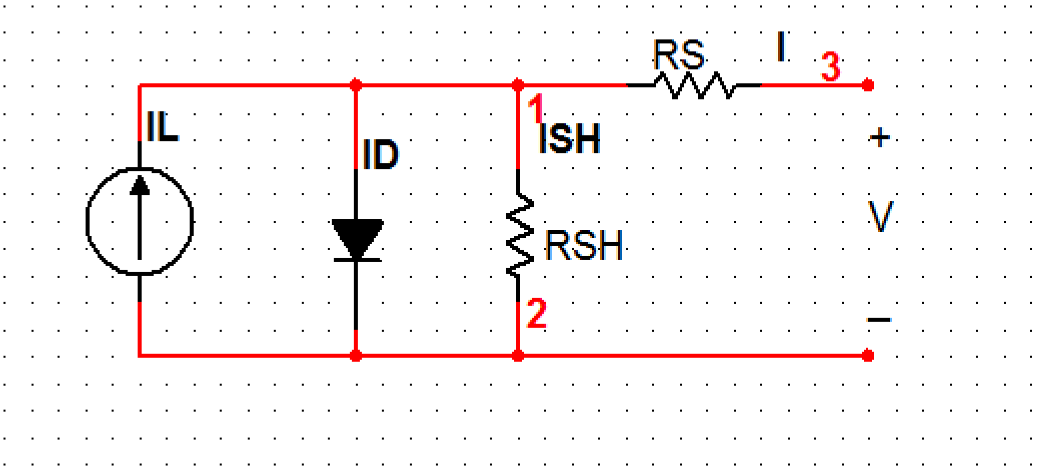


Figure 1: Solar Panel Model

Here we see that the total current flowing out of the cell can be calculated by the following formula

$$I = I_L - I_D - I_{SH}$$

Where I_L is the current generated from the incident light, I_D is the current flowing through the equivalent diode of the junction, and I_{SH} is the current wasted in R_{SH}.

The output voltage from this device can be found through the following equation where V_J is the voltage at node 1.

$$V = V_J - IR_S$$

In these equations the current I_D is found through the standard Shockley diode equation. With these parameters this circuit can be fully simulated and characterized. It should be noted that due to the presence of the diode this is a transcendental equation which makes hand simulation difficult, as there are no analytical solutions to solving these equations. Fortunately the equations are simple and are easily simulated on a computer.

2.3 Battery Technologies

There are a variety of battery technologies available at the present and as such we will use a method similar to that used to determine the proper solar panel technology, along with a pro/con list to determine the optimal battery type. The following batteries were chosen as a representation of the current state of the industry for each battery type.

2.3.1 Battery Specifications

Battery	Voltage (V)	Charge Storage (Ah)	Mass(kg)	Volume(m^3)	Price($)
LEAD ACID 12V 120AH BP120-12-ND [7]	12.0	120.0	39.500	.01682000	289.26
BATT NIMH 1.2V D 6500MAH [8]	1.2	6.5	.175	.00005380	10.82
BATT NICAD 1.2V F 7000MAH [9]	1.2	7.0	.224	.00007374	13.62

Tenergy Li-Ion 26650 3.7V 4200mAh [10]	3.7	4.2	.094	.00003630	9.99
Polymer Li-Ion Cell: 3.7V 10Ah [11]	3.7	10.0	.196	.00008280	26.96

Table 4: Battery Specifications

The following figures of merit are derived from the specifications in the previous table. These are used as a simple way of comparing important capabilities of the batteries.

- Energy Storage Cost: This metric determines how costly it is to store energy is each battery type. Lower values are better.
- Specific Energy: This metric determines how much energy is stored for an amount of weight in each battery type. Higher Values are better.
- Energy Density: This figure determines how much energy is stored for an amount of volume in each battery type. High values are better.

2.3.2 Battery Figures of Merit

Battery Technology	Energy Storage Cost ($/Wh)	Specific Energy (Wh/kg)	Energy Density (Wh/m^3)
Lead Acid	.20	36.460	85612.4
NiMH	1.39	44.570	144981.4
NiCAD	1.62	37.500	113913.8
Li-Ion	.64	165.320	428099.2
Li-Polymer	.73	188.775	446859.9

Table 5: Battery Figures of Merit

2.3.3 Battery Pro/Cons

Battery Technology [12]	Pros	Cons
Lead Acid	-Inexpensive -Low Maintenance -Low Self Discharge	-Low Energy Density -Should not be deeply discharged
NiMH	-Higher Capacity than NiCd	-High Maintenance (Periodic Full Discharge) -Not as Rugged as NiCd (Temperature, More Complex Charging) -Limited Deep Cycle Life
NiCd	-Very Rugged (Temperature, charge cycle, Shelf Life etc.) -Fast Charge	-Low energy Density -High Self Discharge
Lithium Ion	-High Energy Density -Low Self Discharge -Low Maintenance	-Cost -Protection circuitry required
Lithium Polymer	-Lightweight -Similar to Lithium Ion in characteristics	-More expensive than Lithium Ion

Table 6: Battery Pro/Con

With this data in hand we must construct a set of requirements to judge these batteries on based on our specific project parameters. Our battery must be able to have a high capacity, a “set and forget" maintenance schedule, and be reasonably light. The capacity must be enough to run the charging station for at least 12 hour with no help from the solar panels. This does not mean that the charging station must run at full draw for 12 hours. At a full draw of 180W for 12 hour the battery must have 2160Wh of energy storage. This is the "worst case" scenario for our product, and an unreasonable requirement for any battery storage system of this scale. More realistically the charging station will not be in full use for a complete 12 hours. We will use an "average use case" of charging one laptop and one cell phone per two hour. We will assume about 7Wh of energy for the cell phone and 60Wh for the laptop. This totals to 402Wh total for our goal.

Using the 402Wh figure we can determine the specifications for the battery we will require.

Battery Technology	Cost ($)	Weight (kg)	Volume (m^3)
Lead Acid	80.4	11.02	.00470
NiMH	558.78	9.02	.00280
NiCAD	651.24	10.72	.00350
Lithium-Ion	257.28	2.43	.00094
Lithium-Polymer	293.46	2.13	.00090

Table 7: Battery Cost Analysis

If we look only at the cost the lead acid technology seems to win out with a cost many times lower than the competition. The lead acid technology is however the largest and most heavy out of all the contenders. At 11kg and almost 5 liters it would be difficult to elegantly integrate into the design of the charging station and still allow a reasonable degree of portability. The NiCAD and NiMH technologies are immediately out of the running as their metrics are worse in every way compared to the lithium technologies. There is a small benefit to the lithium polymer technology over the traditional lithium ion; however in this application the difference is too small to justify the increased cost. Thus the lithium ion technology is the correct choice for this application.

2.3.4 Selecting a Lithium Ion Battery and Protection Circuits

There are a few things to think about when selecting a battery or set of batteries. The main considerations are capacity and maximum discharge current. Our application requires both high capacity and high current.

We expect the power draw of the loads to be about 144W to place a buffer on this value we will design for a maximum value of 180W. Lithium Ion cells typically have a voltage of 3.7v per cell. One cell delivering this power would mean that the total current draw from the battery would be 48.6A. This high value is due to the very low cell voltage. A typical “Fast Discharge” value for a lithium ion cell is about 2A. To lower the required current these cells can be placed in series increasing the total voltage. The minimum number of cells used in this way can be calculated by $\frac{180W}{2A} = 90V,\ \frac{90V}{3.7V} = 24.3$

This means that if connected in this way at least 25 cells must be placed in series at the input of the DC/DC and DC/AC converters. This is not the only method do decrease the current draw through the individual cells. Multiple parallel stacks of cells can divide the required current between them. It is important to note that when dealing with individual lithium ion cells that the output must run through protection circuitry. Lithium ion chemistry is delicate and can be easily damaged by overcharge or over discharge. Another consideration that the protection circuitry prevents is the discharge of one cell into another. If one cell happens to be at a higher voltage than another it may discharge to equalize the voltage. If the batteries are being used to power something at the time the total current from the individual battery could rise to very high levels. The protection circuitry prevents this by monitoring the current through each stack of cells.

A review of the available options for lithium ion batteries revealed that the LiFePO4 chemistry is ideal for out project. LFP (Lithium Iron Phosphate) cells are much safer than standard LiCoO2 cells with a much smaller chance of combustion when mishandled. LFP cells have an extremely long cycle lifetime compared to LiCoO2 cells (LFP cells have a lifetime of higher than 2000 cycles, while LiCoO2 cells have a lifetime of around 500 cycles). The Solar Charging Station will be more economical for consumers if the batteries don’t need to be replaced, so this metric is very important. In addition LFP cells have a much higher power density when comparted to other Lithium chemistries. With the high peak amount of power out product needs to deliver when “fully loaded” this is a very important consideration.

The disadvantage of LFP cells comes from their energy density which can be up to 40% less than LiCoO2. While the weight and size of our product is very important the difference between these two chemistries is not enough to outweigh the advantages of LFP cells. LFP cells still are more energy dense than any other battery type outside of lithium ion.

With a necessary minimum fully charged energy of at least 402Wh we selected a set of four LFP cells which with 128Wh for a total of 512Wh. At a cost of $240 with set comes to $0.47/Wh, which is actually under our initial estimates for the total cost and cost per Wh of a LiIon Battery Solution. In fact $0.47/Wh approaches the $0.20/Wh of the lead acid technology.

Figure 2: LiFePO4 Battery

This particular set of cells has a recommended battery protection unit which meets all of our specifications. This protection unit has over and under voltage protection for each individual cell, as well as overcurrent protection which is even more conservative than the recommended maximum current specification of the cells, yet still meets the maximum current needs of our application. The price point of $29.95 in addition to the four LFP cells puts the total cost of the battery system at $270. This is within the expected values for this portion of the Solar Charging Station.

Figure 3: Battery Management System

2.4 DC/AC Converter

2.4.1 History of DC/AC Inverter

Figure 4: Inverter

The conversion of DC to AC power dates back to the late nineteenth. In the past DC to AC power conversion was done now outmoded types of converters such as rotary converters or motor-generator sets. This rotary converter is an electrical machine that works as a mechanical rectifier or inverter and is capable of not only converting alternating current (AC) to direct current (DC), but also DC to AC. This invention was a big development in providing AC to DC conversion for commercial industries and railways. This method of conversion was used throughout the entire 19th century until a new method of conversion was discovered using vacuum tubes and gas filled tubes in the early twentieth century. In 1928 the Thyratron, another type of gas filled tube, was invented and was widely used as electrical switch and controlled rectifier. In 1977, Fuji Electric created and built the word's first general purpose inverter, built with a bipolar junction power transistor. Other inverter topologies were developed and the field continued to develop to meet the demands of smaller size and an increase in performance. Today, we have a large variety of DC/AC inverters that can be used in different applications according to the purpose of the project. Figure: 2 below shows different types of inverters with distinct characteristics.

Our project needs an inverter capable of converting 12V DC into a 120V AC to power up and charge two laptop computers. All the inverters described in the below sections could be used to power up and charge our device. Not all are perfectly suited to the requirements of our project however. The choice of the best inverter specific to our project depends on certain factors. With an elimination process, we will chose the inverter that is best suited for our project.

2.4.2 Selection of the DC/AC inverter

All three of these devices meet the requirements we have for the DC/AC converter. The PV140 has both the lowest cost as well as the lowest weight, and thus is the best choice for the AC output stage of the Solar Charging Station. Unfortunately this inverter was not in stock at the time of this project, so an alternate was used for low power testing purposes.

DC/AC INVERTERS	INPUT VOLTAGE(Vdc)	OUTPUT VOLTAGE(Vac)	OUTPUT POWER(W)	INVERTER WEIGH(Kg)	PRICE ($)	AC OUTLETS	CONNECTOR
PV140	12	120	140	0.5443	33.49	1	Cigarette Lighter Plug
PV150	12	120	150	0.5897	44.34	1	Cigarette Lighter Plug
PV375	12	120	375	1	64.16	1	Cigarette Lighter Plug

2.5 DC/DC Converter

2.5.1 Background

DC to DC converters are essential in applications designed specifically for the use of portable electronic devices such as cellular phones and laptop computers whose primary source of power is a battery. The conversion from one voltage to another typically uses either a linear regulator or switched-mode conversion device. The linear method has its benefits but is very inefficient when there is a large voltage drop between the output and the input. This is due to the regulator essentially being a variable resistor which "burns off" the excess power. In addition this method can only output a lower voltage from the input. The switched-mode DC to DC converters on the other hand convert one DC voltage level to another by storing the input energy temporarily and releasing it to the output at different voltage. The storage system uses magnetic field storage components (inductors, transformers) or electric field storage components such as capacitors. Switched-mode conversion has proven to be extremely efficient (between 75% and 98%).

Our project requires two different types of DC to DC converters, which will be used for two different purposes. The first will be used in the MPPT to regulate the output voltage as well as regulate the power delivered by the solar panels. A detailed summary of the design of this converter is found in section 3.1.1. The second converter needed will take an input voltage of 12V DC and convert it to a lower output voltage of 5V DC that will be used to charge four cellular phones. Our choice of an inverter depends on the power consumption of a cellular phone. Most cell phones use between 2W and 6W when charging. We will use this range when determining the DC/DC converter to use in our project. The table below shows different DC to DC converters that we considered for use in our project.

2.5.2 Types of DC/DC Converters

There are many different types of DC/DC converters and the choice between them depends on the application they are used for. For our project, we are using a Buck Converter and a Flyback Converter. The various types of DC/DC converters are explained below.

Buck Converter:

The buck converter is a voltage step down and current step up converter. It takes in a higher voltage and converts it to a lower voltage while stepping up the current. In order to understand the basic operation of the buck converter, we refer to the buck converter circuit diagram in Figure 6: below. The circuit is built with a voltage source V, an open and closed switch S, an inductor L, a diode D, a capacitor C and a load resistance R. In an ideal situation, where all elements of the circuit are considered perfect, the switch and the diode have zero voltage drop when on and zero current flow when off. At the same time, the inductor L has zero series resistance.

When the circuit is opened (switch is in off position), there is zero current in the circuit (I = 0A). As soon as the switch is closed, the current starts to flow and increases through the circuit; the inductor L produces an opposing voltage across its terminals. Initially this voltage is quite large and cancels out the voltage V entirely. As the current through the inductor increases the voltage across it decreases. This results in an increasing voltage over R.

When the switch is opened again the inductor develops a voltage opposite the one it developed earlier to attempt to preserve the current flow through itself. This releases energy from the inductor to the capacitor C and load R. The capacitor stabilizes the voltage over R throughout all of these changes in current. In this way the voltage over R can be decreased from voltage source V's value by only sourcing power from the V during part of its operation.

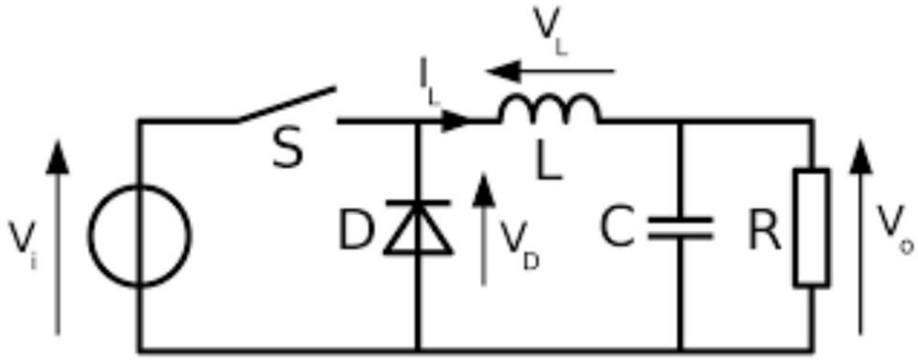


Figure 5: Buck Converter Circuit [25]

Boost Converter:

A boost converter also called a step-up converter is a DC-to-DC power converter that takes a small input voltage and converts it to a greater output voltage. The boost converter circuit is composed of an inductor L, an open and closed switch S, a Diode D, a capacitor C and a load R. There is an input voltage Vin that will be stepped up (boosted) to become Vout across the load R. One of the principal characteristics of a boost converter is the tendency of an inductor to resist to any change in current by creating and destroying a magnetic field. As the term “boost” indicates, the input voltage is increased by the converter before servicing the load. So, in the boost converter, the output voltage is always higher than the input voltage. This is not the kind of converter that we need in our MPPT design since the input voltage coming from the solar panels is greater than the voltage storage unit which is our lead acid battery of 12V.

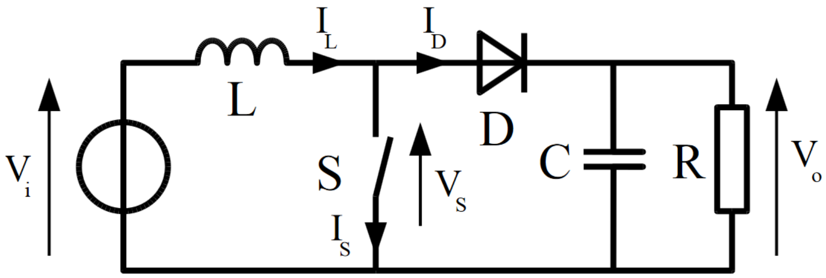


Figure 6: Boost Converter Circuit [26]

When the switch S is closed, the current flows only through the inductor without any going through the diode D, the capacitor C and load R. During this stage the inductor is storing energy. The current slowly ramps up through the inductor as time passes.

When the switch is opened the magnetic field previously created when the switch was closed creates a voltage attempting to preserve the large current that previously when through the inductor. This voltage adds with the voltage of the source to create a higher voltage at the load.

2.5.3 DC/DC Converter Requirements

Our project needs two DC/DC converters: one on the output of the battery, used to charge up to four cell phones through USB ports, and one at the input side of the battery that is part of the MPPT tracking system. The output converter will be purchased and its selection is shown here. Our choice of the converter depends on the output voltage that it will provide.

The power consumption of typical cell phone is less than 6 watts, and all charge from 5v USB. Due to the output voltage of the battery being around 12 volts we need a converter that will stepdown the output voltage from the battery to a lower voltage of 5v to use in the charging of cell phones. To attend that goal, we chose to use a Buck Converter which has a voltage stepdown capability. Our second DC/DC converter is called a flyback convert that will take a 30 V from the solar panel and step it down to an approximate voltage of 15.8 V at the input of the battery. Our flyback converter requires a transformer of 2.05:1 ratio to step down the input voltage from the solar panel. Detailed design of the flyback converter is shown in section 3.1.1.

2.6 Existing products in the market

Knowing the cost of existing product in the market is one of the most important step in the design and manufacturing of particular and unique product. This step allows designers to know the marketability, the interest of target customers, and margin of profit of the product. After researching the existing product available in the market, we find that the price of powered umbrellas range from $254.98 to $649.99 for umbrellas that are equipped with solar panel, battery and LEDs. The price gets higher, starting at $399.99 (Brookstone's price) if the purpose of the umbrella is to be used to charge mobile devices such as cellular. Our project's goal is to use thin film solar panels on an umbrella to collect energy from the sun and use it to charge up to four cellular phones and two laptop computers at the same time. Our product will be on the absolute high end of this spectrum. Although our product will also be on the cutting edge of features for such a product this price still appears to be high for an umbrella set. This sets a challenge in our choice of the prices of the accessories such as PV, the battery, the DC/DC converter, the DC/AC inverter and the microcontroller for the MPPT system.

It is of note that while these umbrellas exist in the market place with such high price tag, they are not equipped with MPPT tracking system like our product will, nor are they capable of charging high power devices such as laptops. This system will make our product more attractive and competitive.

Below are some umbrellas that are built using solar panels to power up LEDs or charge mobile devices. According to Hayneedle Inc, the cost of the umbrella in figure1 is $649.99. This unbrella uses solar cells to power LED lights installed on adjustable umbrella.

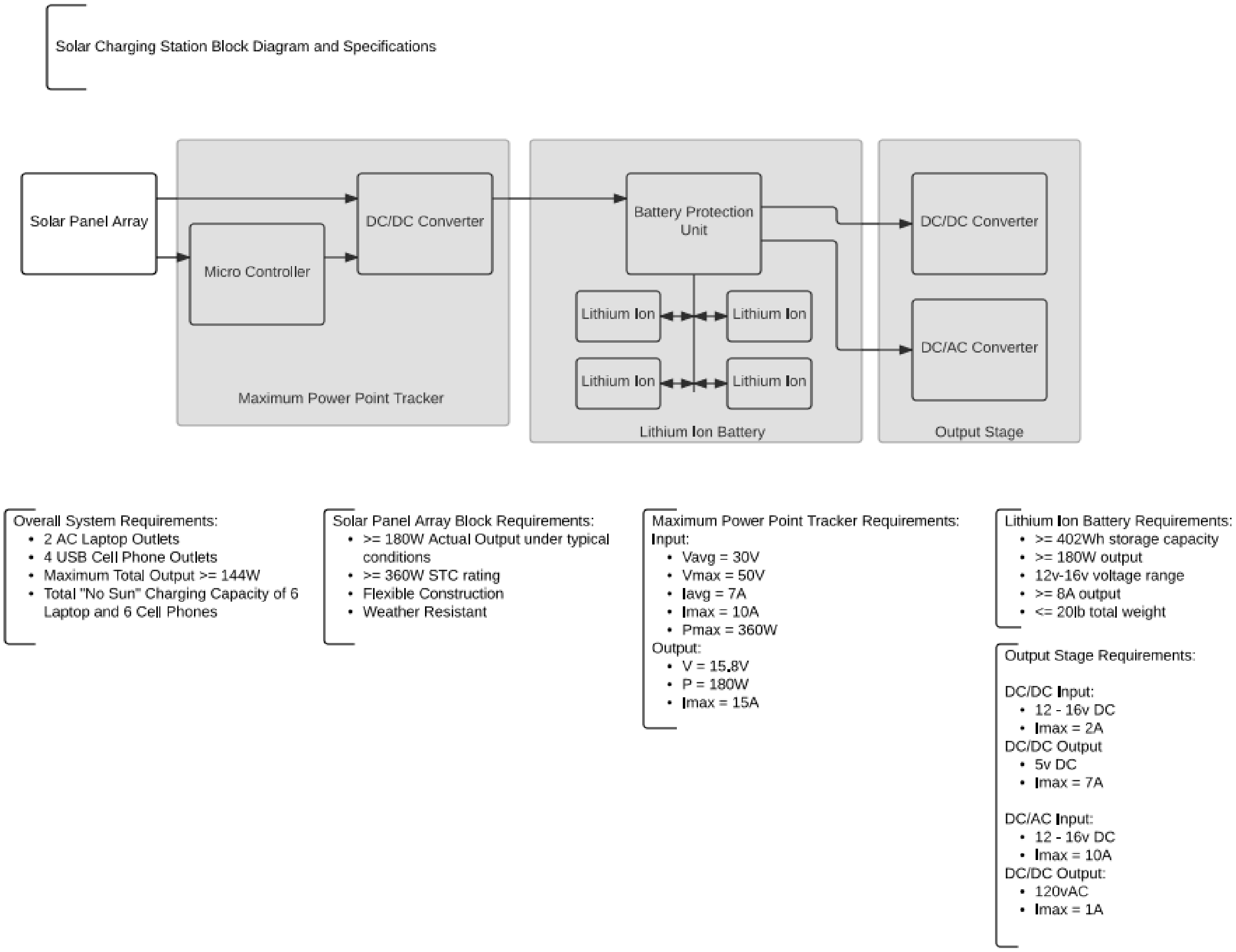
Figures 2, 3, 4 show the same technology with the sole difference that the solar cells are used to charge mobiles devices such as cell phones and laptop. According to Brookstone, the starting price is $399.99 [14][29].

Figure 7: Umbrella with built in LED system [29]

Figure 8: Existing product on the market [14]

3 CHAPTER 3: METHODOLOGY

Our methodology involved building and testing each block in the system individually and then combining them into a whole. Below is a block diagram of The Solar Charging Station along with the system requirements for each section:



Overall System Requirements:
- 2 AC Laptop Outlets
- 4 USB Cell Phone Outlets
- Maximum Total Output >= 144W
- Total "No Sun" Charging Capacity of 6 Laptop and 6 Cell Phones

Solar Panel Array Block Requirements:
- >= 180W Actual Output under typical conditions
- >= 360W STC rating
- Flexible Construction
- Weather Resistant

Maximum Power Point Tracker Requirements:
Input:
- Vavg = 30V
- Vmax = 50V
- Iavg = 7A
- Imax = 10A
- Pmax = 360W

Output:
- V = 15.8V
- P = 180W
- Imax = 15A

Lithium Ion Battery Requirements:
- >= 402Wh storage capacity
- >= 180W output
- 12v-16v voltage range
- >= 8A output
- <= 20lb total weight

Output Stage Requirements:

DC/DC Input:
- 12 - 16v DC
- Imax = 2A

DC/DC Output
- 5v DC
- Imax = 7A

DC/AC Input:
- 12 - 16v DC
- Imax = 10A

DC/DC Output:
- 120vAC
- Imax = 1A

Figure 9: System Block Diagram

The final schematic of the design is reproduced below. From this schematic and block diagram it can be seen that there are four main sections to this design: The solar panel, the maximum power point tracker, the battery system, and the output system. The main design portion of this project focussed on the maximum power point tracker. The output system consists of a DC/DC converter outputting 5v for USB and an inverter outputting 120vRMS. These parts of the design were purchased “off the shelf”. The battery management system was also purchased as the specifics of lithium ion charging is not the focus of this project and there are dangers associated with the incorrect charging of lithium ion cells.

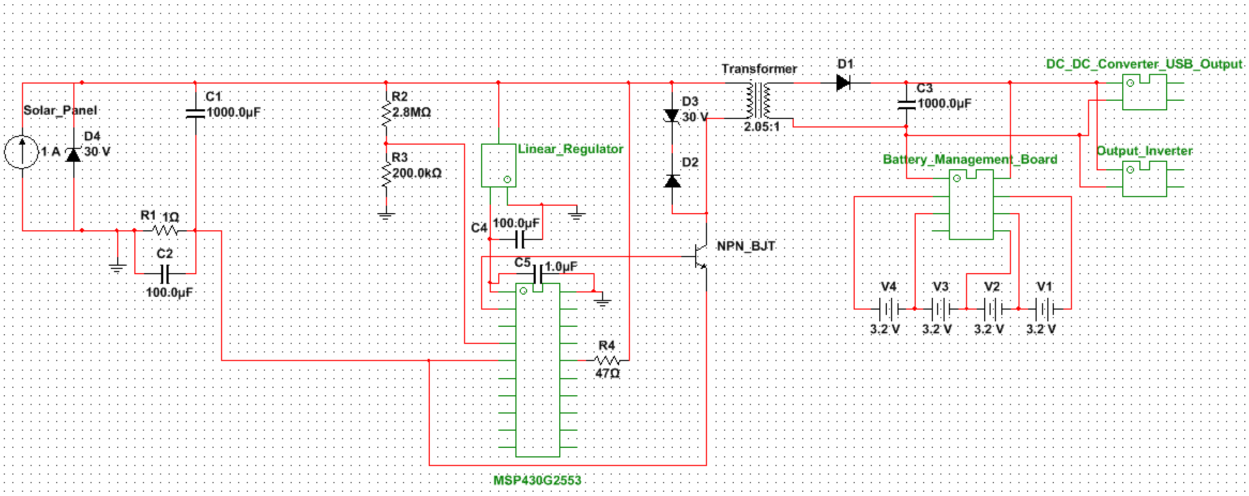


Figure 10: System Schematic

3.1 Maximum Power Point Tracking

With such an inconsistent and often low power source of energy as solar one needs to extract all the power available from a solar panel to truly make it economical. This is difficult to achieve with simple methods due to the electrical nature of Photovoltaics. PV cells are not simple voltage or current sources and thus must be modelled in a more complex way. In section 2.2.3 the modelling of a solar panel is discussed. From this modelling we can find that for any given solar panel there exists exactly one combination of voltage and current that output the maximum amount of power.

Shown below is a graph of the I-V curves of a solar panel in various amounts of sunlight. Additionally there is a line showing the maximum power point on each line. As you can see the solar panel has a nonlinear output. The simple equation for electrical power tells us P = IV. We can see that this attribute is maximised somewhere on the “elbow” of the I-V curve. Thus to extract the maximum amount of power from a solar panel the load must be such that the solar panels voltage and current output sits at this point. As this point changes with a change in sunlight we must create an active load which can change its effective impedance.

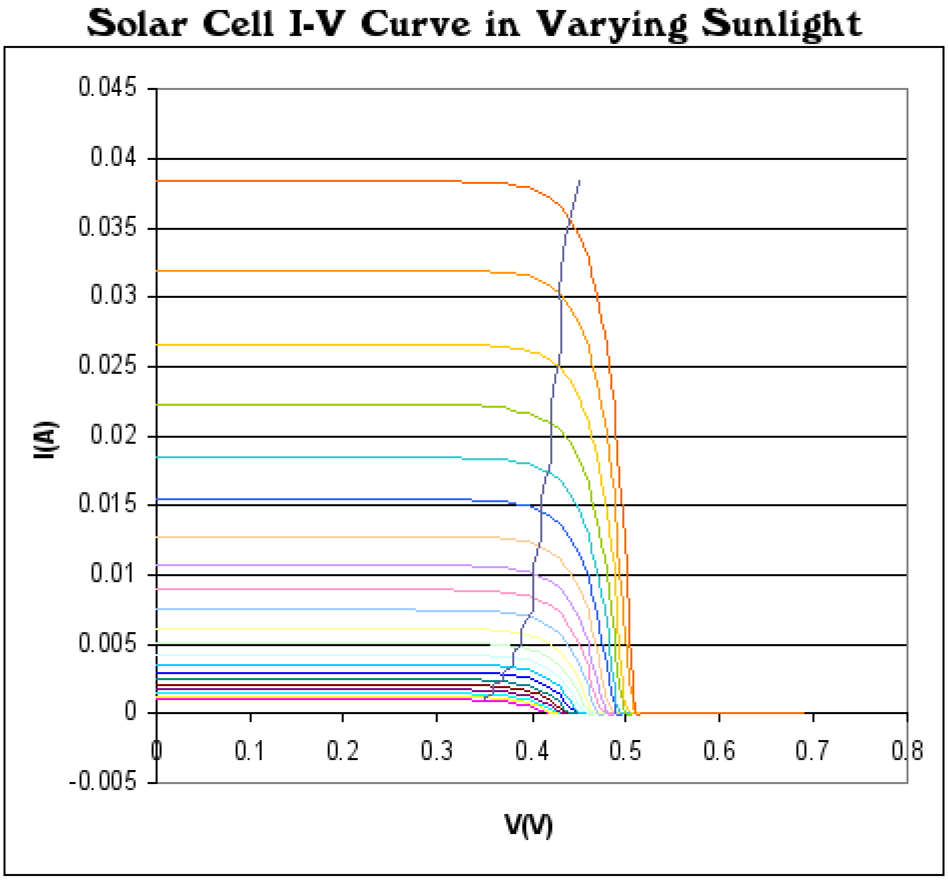


Figure 11: Sample Solar Panel Maximum Power Curve Under Various Conditions [22]

We can construct this active load by using a DC/DC converter. The I-V curve of a DC/DC converter can be changed depending on the frequency and duty cycle at which it operates. If the voltage and current output from the solar panel is monitored, and the resulting information used to modify the operation of a DC/DC converter, thus ensuring the solar panel is operating at the maximum power point.

3.1.1 MPPT DC/DC Converter

Our goal is to design a DC-to DC converter to produce a maximum output voltage of 15.8Vdc with an input voltage of 30Vdc.The output voltage ripple of our converter must not exceed 0.5 percent. Base on the characteristic of the device that we are designing, two converters are the most appropriate to choose from. A Buck-boost converter and a Flyback converter. In order to carefully choose the right converter for our application, it seems important to define both converters. Indeed, the **Buck-boost converter** is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is equivalent to a Flyback converter using a single inductor instead of a transformer." At the same time, **Flyback converter** is defined as "a Buck-boost converter with the inductor split to form as transformer, so that the voltage ratios are multiplied with and additional advantage of isolation."

As we can see from the definitions of the two converters, there is no significant difference from the two except a major difference which is a galvanic isolation. A table below explains some of minor differences for better understanding and better choice of converter for our application.

Buck-boost Converter	Flyback Converter
Buck-boost uses a simple solenoid to store the energy. When the circuit is open, it releases the energy to a capacitor	Flyback has a transformer to store the energy and has a secondary to release the energy to the output capacitor.
Buck-boost converter uses an inductor to store the current and then discharges through the capacitor when the switch is on or off. Less freedom for the adjustment of the output voltage level.	Flyback has the advantage that is uses a transformer, so more freedom is available to adjust the output voltage level (turn ratio).
Buck boost can operate in 2 modes: First as in a buck mode and second in boost mode	Flyback operate in single mode
Buck-boost converter is used for low power operations.	Flyback converter is used for high power operations.

Less complex to design and less expensive	transformer is more complex and more expensive than a single solenoid
Has no isolation	Has galvanic isolation

Table 8: Buck-Bosst and Flyback Converter Comparison

With this understanding of both converters, we choose to design and use Flyback converter (which is derivate from a Buck-boost converter) for our application. The isolation that the flyback converter provides will provide safety to the operators of our system as the solar panels we use can output potentially harmful amounts of voltage. There will be four steps in the design process of this Flyback converter. We start the design with Buck-boost converter to end up with a Flyback converter.

Buck-boost converter:

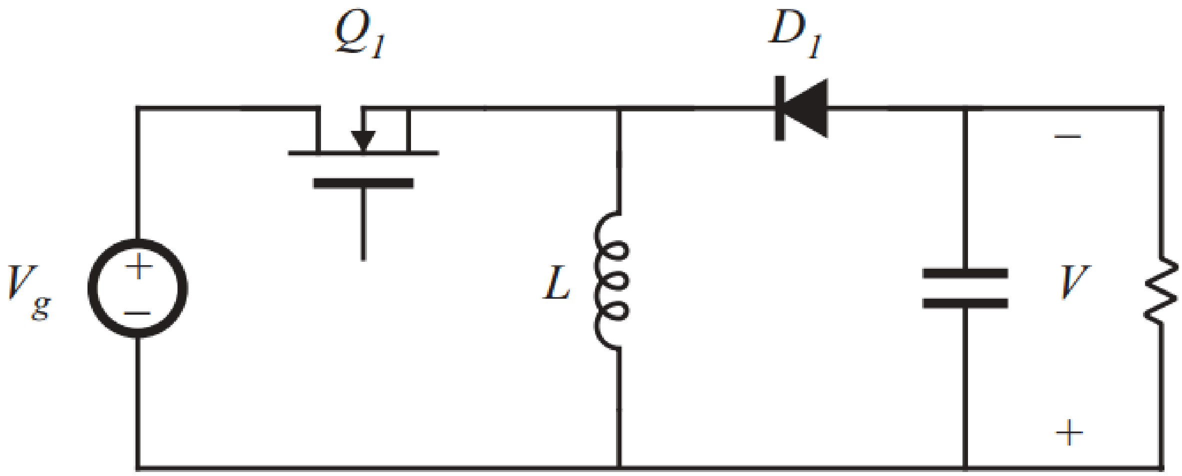


Figure 12: Buck Boost Converter [27]

The figure above is a Buck-boost converter realized using a MOSFET Q1 and a diode D1 as switches. Vg is input voltage of 30Vdc. The voltage V is the expected output voltage of 15.8V that will be used to charge the battery.

Buck-boost converter: Inductor L and two parallel wires: Figure 1b

Using the same Buck-boost converter, the inductor L is wire wound with two parallel wires with 1:1 turns ratio.

$$\text{Turns ratio} = \frac{N_P}{N_S}$$

Where:

Np is the number of turns on the primary coil which is equal to 2.5

Ns is the number of turns on the secondary coil which value is 1.

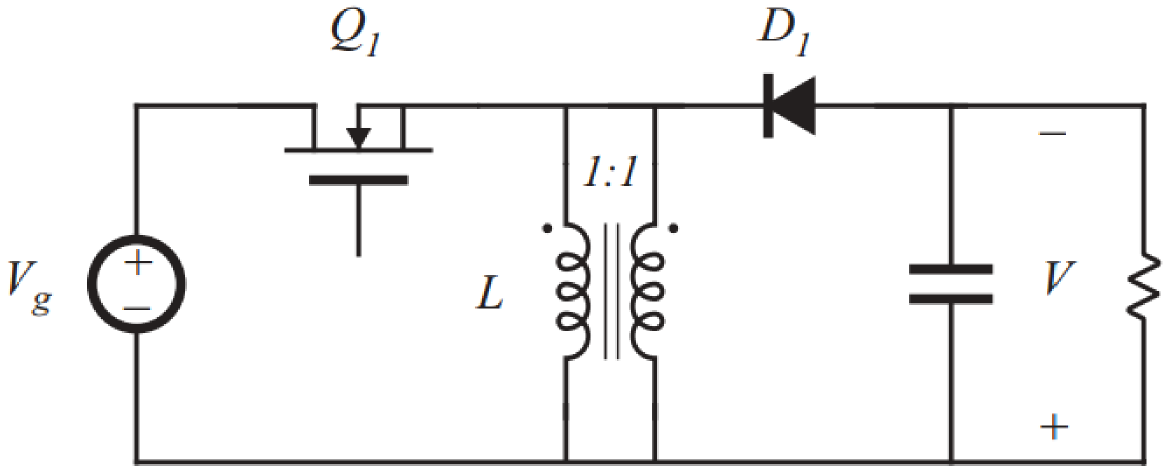


Figure 13: Buck-Boost to Flyback - Change the inductor to a transformer [27]

The next step of the design of our Flyback converter is to take the Buck-boost converter and isolate inductor windings. At this point, the windings are used independently. When the transistor Q1 is conducting, one winding is used and when the diode D1 is conducting, the other winding is used. The total current flowing from the voltage source Vg is the same but is distributed between the windings.

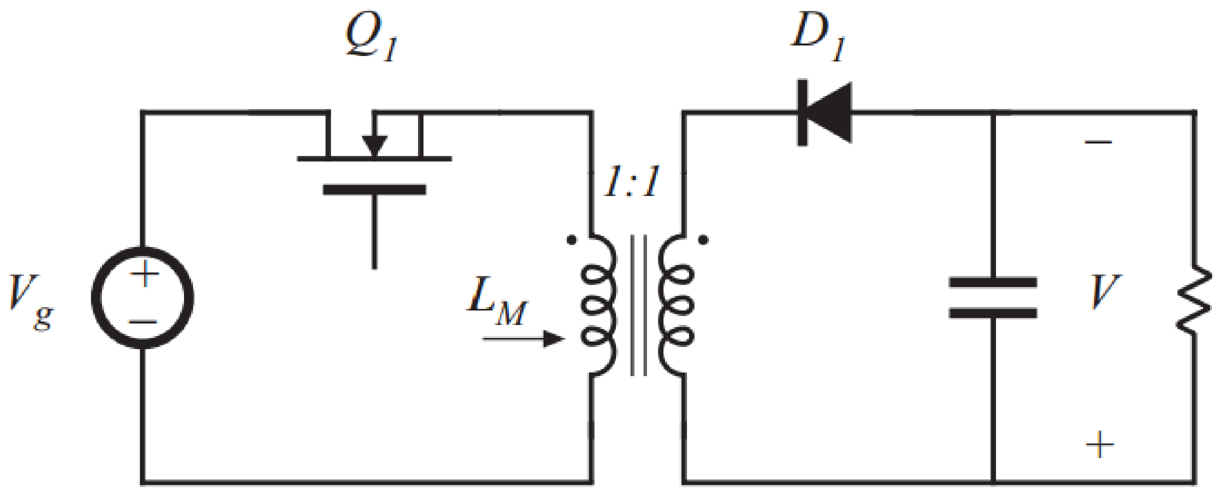


Figure 14: Buck-Boost to Flyback - Split the transformer [27]

With the isolation introduce in the converter in the figure 1c, the converter becomes a Flyback Converter(shown in Figure 1d) with a ratio r = 1:n with n equal the number of turn on secondary coil. This ratio is a factor of having the converter to step up or step down the input voltage to the output.

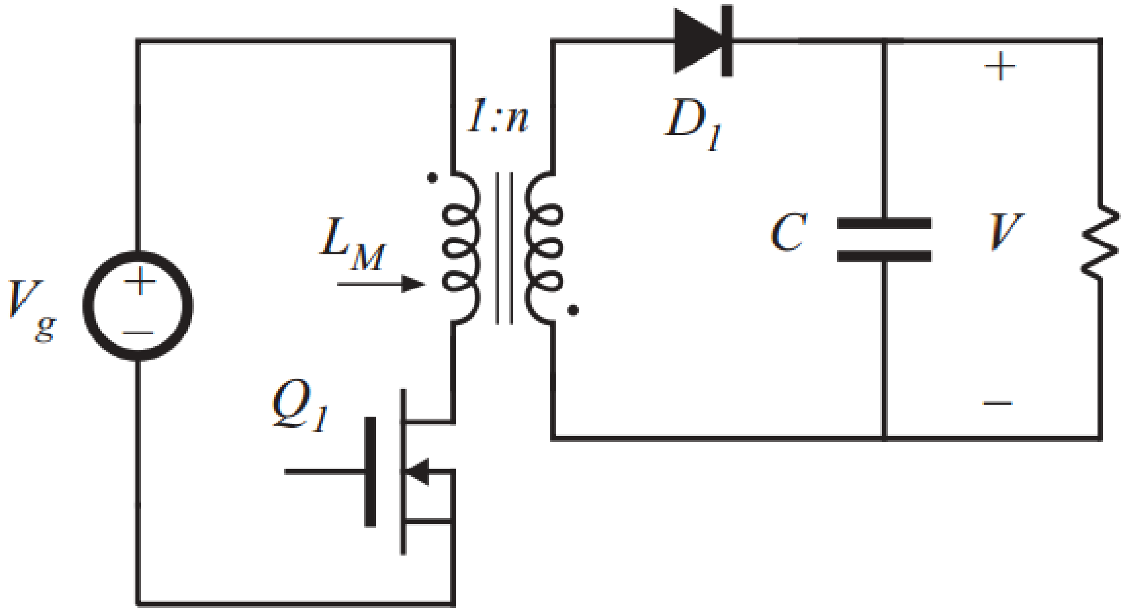


Figure 15: Buck-Boost to Flyback - Change the turn ratio [27]

As we note earlier, the design of the Flyback Converter is typical the same as the Buck-boost converter with the major difference that a transformer of a ratio 1:n is introduced to make the converter as a step up or step down device. In our case, we want to step the voltage from maximum of 30Vdc to 15.8Vdc. Therefore, the specifications of both converters are the same.

Minimum input voltage	30V
Maximum input voltage	50V
Minimum input current	1A
Absolute Maximum input current	10A
Output Voltage	15.8V
Minimum input power	216W
Maximum input power	360 ~ 500W
Switching frequency	40KHz
Inductor current ripple	30%
Output Power	180W
Duty Ratio D	0.6266
Battery Internal Resistance	4.1 Ω
Inductor L Value	46.625 uH
Capacitor value	1810 uF

Table 9: Flyback Converter Specifications

The choice of the switching frequency and the inductor L size depends on the mode of operation. In our case, the frequency and the inductor size are selected for continuous-current operation. This frequency is 40 KHz. Since the buck converter will have 12V battery as load R, we must calculate the equivalent resistance of the load. As the output of the DC/DC converter will be 15.8v and the maximum current output is rated at 2A we can use V/I=R to calculate the equivalent load resistance.

$$R = 15.8/2 = 7.9\Omega$$

The duty cycle ratio is the scalar called D which is the ratio between the output voltages Vo over the input voltage Vi. This defines the proportion of time during which our device operated based on the input and output voltage. The duty cycle ratio must never more than 1. The formula to calculate this duty cycle ratio is giving by D = Vo/Vi. For our specific case the duty cyle will change based on where the maximu power point of the solar panel is.We will use the standard duty cycle calculation for the flyback converter to find the starting point for our MPPT duty cycle. The starting duty cycle is 15.8V/30V which gives D equal to 0.6266 or D = 0.63. Operation with the maximum voltage, this duty cycle becomes 15.8V/50V which gives a value of 0.316 as Duty Cycle.

Knowing the equivalent resistance of the load and the duty cycle ratio, we find the minimum size that our inductor should be using the following formula: L =(1-D)*R/2f . In our case, L = ((1-0.63)*7.9)/2*(40000). This give us a minimum inductor's size of 36.5 uH.

As we note above, our Buck converter is operating at a continious current through the inductor. To make sure that the inductor current is continueus, we choose the inductor that is 25% larger than the minimum. This means that the inductor used in our Buck converter design is 1.25*(36.5 uH) which is equal to 46.625 uH.

The inductor current in continuous mode operation of our DC-to-DC converter has a graph similar to the one below.

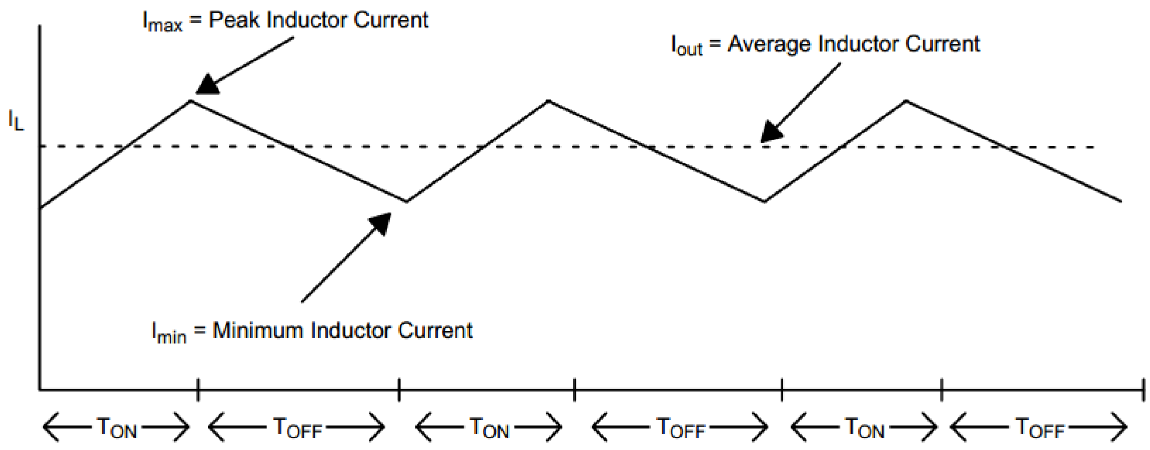


Figure 16: Flyback Converter Continuous Operation [28]

In a buck converter, the switch controls the energy in the inductor. The average of the square wave applied to the filter(inductor plus capacitor) is a DC output level (30V at a duty cycle ratio of 31.6%). At this point, the inductor acts as a current source to keep the the output capacitor charged.The buck converter is operating in a mode called CCM(Continuous Conduction Mode) and the inductor current never goes to zero; the frequency is fixed and the current is high.However, this converter could work in a different mode called DCM(Discontinuous Conduction Mode) with PFM (Pulse Frequency Modulation)'s at low current.

The capacitor filters the inductor's current ripple and delivers a stable output voltage to the load, a voltage that was stored in it during the CCM operation mode. It also ensures that load steps at the output can be supported before the regulator is able to react. The choice of the capacitor is made based on the value of the duty cycle ratio, the inductor size, the output voltage variation (ΔVo), the output voltage Vo itself and the frequency f. The relationship of the capacitor to these elements id giving by:

$$C = (1 - D)/[8L(\Delta Vo / Vo) * f^2]$$

Where:
C is the capacitor
D is the Duty Cycle ratio (0.316)
L is the size of the inductor (46.625 uH)
Delta Vo is the output ripple voltage (0.005)
Vo is the output voltage (15.8V)
f the frequency of the system (40KHz)

Knowing the value of the entire element except the capacitor, we determined the the capacitor value to be 1810 uF. The maximum voltage across the switch and the diode which is operating in forward bias or reverse bias depending in the mode of operation is equal to the input voltage (30V). When the switch is closed, the inductor voltage is equal to the difference of the input voltage Vi and the output voltage Vo. This give us (30V – 15.8V) = 14.2V at maximum. This voltage of the inductor becomes 15.8(equal to the output voltage) when the switch is opened. The inductor must withstand 14.2V and the capacitor must be rated for an output voltage of 15.8V.

3.1.2 Component Selection

The components used to prototype this design are not necessarily what would be used in a production run of this product. They were selected partially based on the ease of procuring them. Together they make a prototype that can properly operate at low power. While not able to withstand the high power necessary for a final product they are adequate to demonstrate a “proof of concept” which was the goal of this project.

Transformer:

Figure 17: Transformer

It was determined that the optimal value for the turn ratio of the transformer in this application was about 3.16:1 to account for the maximum input voltage expected. Common transformer values necessitated using a 2.05:1 transformer. This ended up working very well in our experimental setup. We chose to use the F56-220-C2 transformer from Triad Magnetics. This transformer offers to separate secondary windings that can be operated in series or parallel. In series they offer a 2.05:1 ratio and in parallel they offer a 4.1:1 ratio. This offered us the ability to test using different turn ratios [18].

Diodes:

The diodes used in this project will be handling most of the current flow through this system. For the actual production design they should be selected to be able to handle the full maximum current going through the system. For testing purposes we used the common low powered 1N4004 diode.

Battery:

Figure 18: LiFePO4 Battery

The battery we selected was specified to be able to support two cell phone charges and one laptop charge every two hours for 12 consecutive hours with no input from the solar cells. This equates to at least 402Wh of energy storage. More detail on this calculation can be found in section 2.3.3. The particular battery we selected, from AA Portable Power Corp, consisted of four 3.2v LiFePO4 cells, each 128Wh. The LiFePO4 chemistry can support the high currents needed to supply laptops with power, and is a safer alternative than the standard LiCoO2 chemistry. Purchased together they were cheaper than any comparable 402Wh options. In addition this purchase came with the end plates and tension brackets that some lithium ion batteries need in order to prevent expansion of the batteries during charging [17].

Battery Management System:

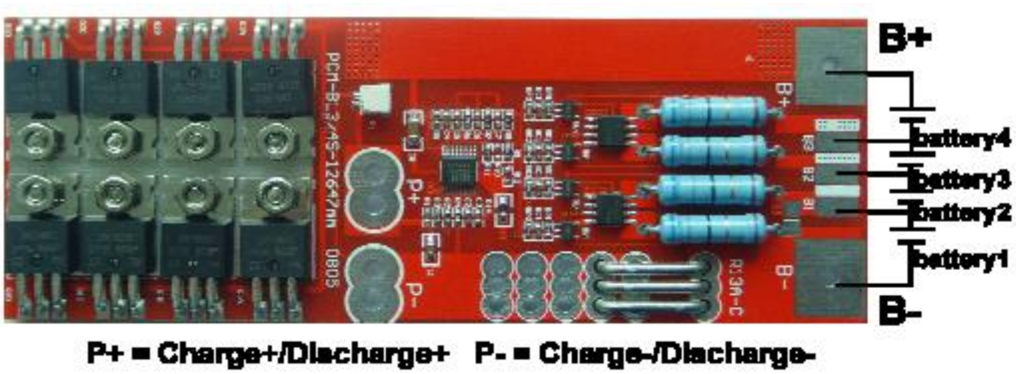


Figure 19: Battery Management System

Lithium ion batteries require some sort of management system to prevent overcharging, over discharging, and other damaging use cases. We selected the recommended battery management system corresponding to the LiFePO4 battery chemistry. This system cuts off discharging of each cell at 2.3v, cuts of charging of each cell at 3.9v, restricts discharge to 16A, and rebalances each cell if there are different voltages on them [19].

Output DC/DC Converter:

We chose to use a simple 12v to USB adapter for this component. As this was an off the shelf purchase the “cigarette lighter” port based converter market was ideal for our application. The output from the 12v rail in cars is sometimes noisy and unreliable, so the adapters can handle up to 24v input. As the voltage of our battery will change slightly due to charge state this flexibility is important.

Output Inverter:

Like the USB output we chose an automotive inverter for our project. This inverter is equipped with only one AC output port which is all that is needed to test the systems functionality. A production model would have two AC outputs for two simultaneous laptop charges.

Wires and Perf-Board:

Our prototype was built using perf-board and 20 gauge wire. Such a construction would not meet the current requirements that the solar charging station needs for full power operation. In future construction of this design at least 14-guage wire should be used for the connections which will carry power. The “data” connections for the microcontroller and anything that does not carry the current to the battery may remain small. Future construction should also use PCB construction to avoid shorts between parts of the board and unnecessarily long wires.

Microcontroller:

Figure 20: MSP430g2553 on MSP430 Launchpad Development Board

We selected the MSP430 microcontroller to control the switching, voltage and current sensing, and power calculations that were needed to control the MPPT. More on this selection can be found in section 3.2.

3.1.3 Methods of Operation

There are a variety of different algorithms that can be used to extract the most power out of a solar cell. These range from the very basic (constant voltage technique) to the complex (incremental conductance technique), and a selection are described below.

Constant Voltage

Also called the “Fixed Duty Cycle” method this technique simply adjusts the duty cycle of the DC/DC converter once to reach the maximum power point of the PV cell at a particular level of insolation. This is the simplest method, but does not take into account any variation in insolation. This method should only be used in places where maximum power is only needed at a particular time of day.

Perturb and Observe

Also called the “Hill Climbing method” this algorithm involves starting the DC/DC converter at a certain point and recording the voltage and current and calculating the power output. The duty cycle or frequency of the DC/DC converter is then changed to change the voltage or current the PV cell output, which in turn changes the other quantity in question. The power at this new point is then calculated. If the power is greater than the previously recorded power this step is repeated. If it is less, than the step is repeated, but the changes made to the duty cycle or frequency are made in the opposite direction. This method in effect “climbs” the hill of the power curve until it reaches the top. At that point it oscillates around the maximum power point.

Incremental Conductance

This technique involves calculating the derivative of the power, and then acting in a similar manner to the “perturb and observe” method. This method relies on the fact that the derivative of the power output of the solar panel is zero at the maximum power point. This method changes the DC/DC converters operating point until this point is reached. Its name comes from the fact that the instantaneous power of the solar panel is the negative of its conductance at the maximum power point.

Current Sweep

This technique essentially does a sweep of the entire range of output powers of the solar panel to create a graph of the entire power curve. It then selects the maximum power point from that graph at sets the DC/DC converter to act at that point. Periodically the current sweep is repeated to reflect any changes that happened since the previous sweep.

Fractional Open Circuit Voltage

The connection to the solar panel is periodically severed in this method and the open circuit voltage of the solar panel is measured. The DC/DC converter is set such that its operating voltage is at a certain fraction of the open circuit voltage. This does not actually track the MPP exactly, but uses a fraction of the open circuit voltage that should be as near the MPP as possible for many levels of insolation.

There are a large number of other algorithms that have been proposed for this problem. Some are entirely new methods, and others are modifications of the ones shown here. The algorithm to be used in this project will be the **"perturb and observe"** method. This method is advantageous in that it is a very simple algorithm to implement as well as giving a fairly good approximation of the maximum power point. Other algorithms such as the current sweep spend too much time not near the maximum power point, while others such as the fixed duty cycle approach are the simplest, but do not give adequate results.

3.2 Microprocessor Control

The MPPT design requires a PWM signal to switch the current through the transformer. The duty cycle of the PWM signal must change based on the power being extracted from the solar panel. Thus we need a way to generate this signal, sense the power generated by the solar panel, and change the duty cycle of the signal accordingly. The simplest way of doing this is to employ a microcontroller to do all these tasks.

Due to the MSP430's low cost (<$1), ease of use, and the MQP teams familiarity with it this microcontroller was selected for this task. The MSP430 microcontroller family includes several features useful to this design. A fast internal clock and integrated timers allow the microcontroller to generate an appropriate PWM signal. The included 10 bit analog to digital converter can be used to sense voltages, and the integrated multiplier can be used to quickly compute power values. The specific model we are using in this project is the MSP430g2553. This model contains all the features we =need and is included in the MSP430 Launchpad kit which includes a JTAG programming board for program loading and debugging.

3.2.1 Microcontroller Circuit Layout

The MSP430g2553 microcontroller has the following pinout:

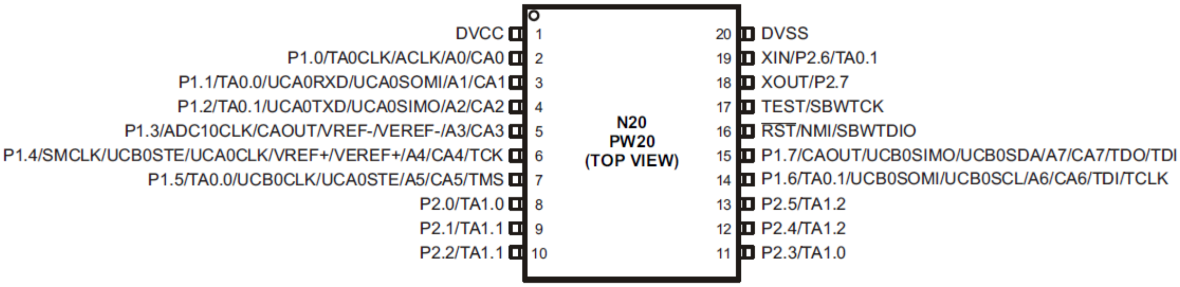


Figure 21: MSP430g2553 Pinout [23]

The pins which we are concerned with are pins 1, connected to power, pin 20, connected to ground, pin 2, which is the PWM output, pin 4, which is the ADC input for voltage sensing, pin5, which is the ADC input for current sensing, and pin 16, which is the reset pin which must be pulled high.

Pin 1	V_{CC}
Pin 2	PWM output
Pin 4	ADC input for voltage sensing
Pin 5	ADC input for current sensing
Pin 16	Reset Pin
Pin 20	V_{SS}

Table 10: MSP430 Pinout

There are a few considerations to take into account when using this microcontroller. The most basic deals with power it. This microcontroller runs on an input power of around 3.6v. Most microcontrollers are quite sensitive to fluctuations in their power inputs. Our microcontroller will be run off of a voltage regulator supplied with power from the output of the solar panel. This may introduce noise into the power signal. Thus it is always best practice to insert a capacitor between V_{CC} and V_{SS}. As the wires or traces between the microcontrollers inputs and the capacitor may pick up stray electromagnetic signals it is always advised to physically locate the capacitor as close to the pins as possible.

The power for the microcontroller is supplied by a linear voltage regulator. We chose the LD33V regulator which recommends a capacitor on both the input and the output for the most stable operation. In this case the input capacitor is unnecessary as there is a very large capacitor on the input to the regulator which we use to hold the voltage of the solar panel. An additional capacitor in parallel with this one is unnecessary. The capacitor on the output is in parallel with the capacitor on the microcontroller input, but as the physical location of this capacitor was important having two capacitors here is not redundant.

Another consideration when running this microcontroller is the sensitivity of the ADC inputs. The maximum voltage applied to any pin must be at most V_{CC}+0.3v. The ADC can sample with a max voltage reading of either an external voltage, V_{CC}, or an internal reference voltage of 2.5v. The internal reference voltage is the most likely to be stable, accurate, and precise so we chose that as out ADC reference voltage. The values that the ADC will be sensing are quite high (up to 30v) so the voltage is brought down to a lower level for sensing.

The output from this system is the PWM signal from pin 2. This signal is used to drive an NPN BJT. The max output current from the digital output pins of the MSP430 is 20mA. This is more than enough to drive a BJT even with the high currents expected from this application.

Finally the MSP430 microcontroller must have its reset pin brought high during operation. It is recommended that this be done by attaching it to V_{CC} through a 47Ω resistor. Below is a schematic of the microcontroller circuit used in the MPPT.

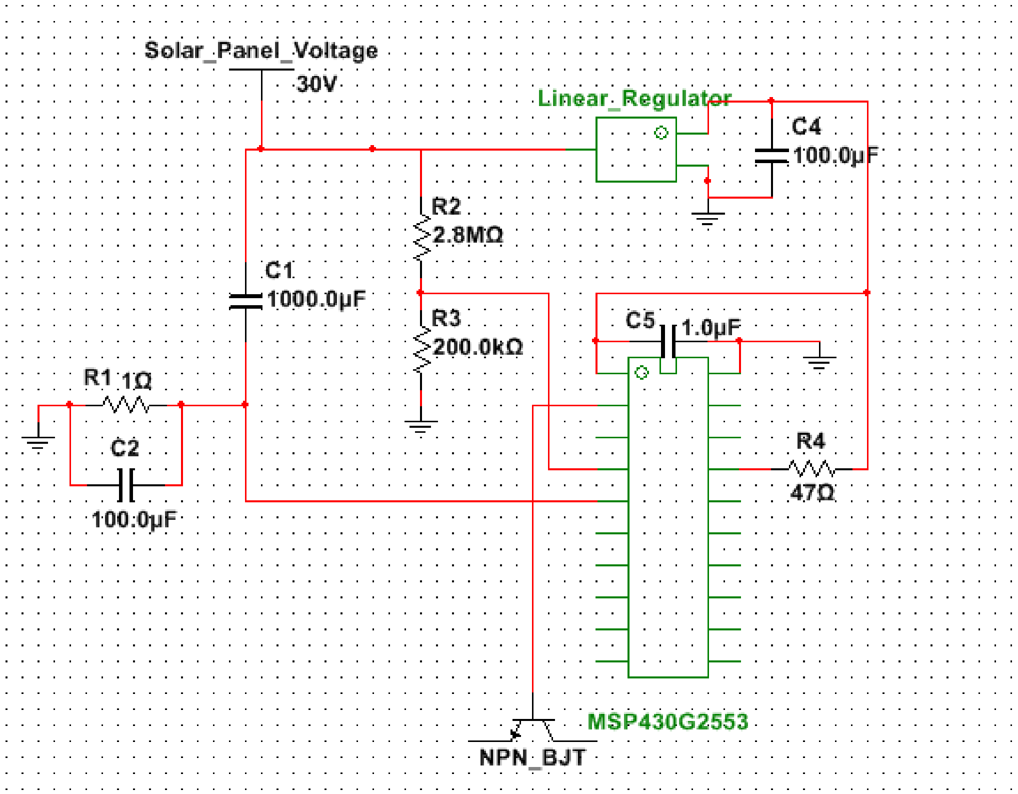


Figure 22: Microcontroller Circuit

3.2.2 Voltage and Current Sensing

In order to determine the power supplied by the solar panel the voltage and current it is supplying must be sensed. As the MSP430 has no current sensing capability the current must be turned into a proportional voltage and then be sensed. The solar panel's voltage must be attenuated to a smaller proportional voltage to both protect the microcontroller and keep the voltage within the ADC reference voltage.

The voltage sensing was accomplished with a simple voltage divider. The max voltage of 30v was set to an output voltage of 2v. We assumed that 3MΩ of resistance would be sufficient to reduce the energy losses of the voltage divider. A voltage of 30v over 3MΩ develops a power of .3mW using V^2/R. With this total resistance we can use the voltage divider equation of (R1/R1+R2)*V = Vout to determine the values of the two component resistors. These values are 2.8MΩ and 200KΩ. The pin used to sense this value is pin 4.

The current sensing was accomplished by placing a 1Ω series resistor between the solar panel and the rest of the circuit. As the maximum current from the solar panel is around 2A the maximum voltage developed over the resistor will be 2v. This can be sensed directly be the microcontrollers ADC. The pin used to sense this value is pin 5.

3.2.3 Microcontroller Code

This project used C as the language to program the MSP430 microcontroller. This is the standard language used for this family of microcontrollers. There are a wide array of compilers and IDE's compatible with C and the MSP430. A combination of the Code Composer Studio and IAR Kickstart IDE's were used in this project.

3.2.4 Program Flow

The following flowchart illustrates how the program operates.

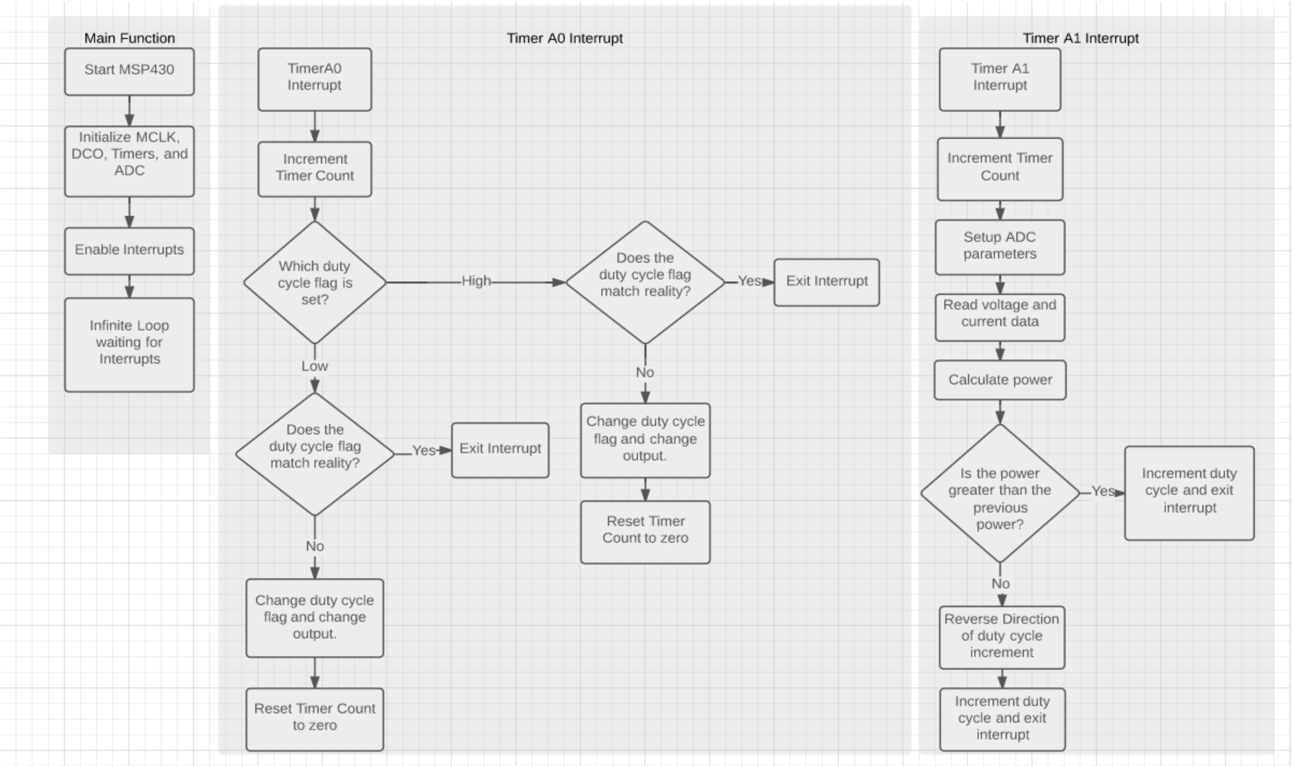


Figure 23: Code Flowchart

This program operates by first initializing the timers, clocks, and ADC and then entering an infinite loop waiting for the interrupts to fire. The interrupts are based on two timers. Timer A0's job is to produce the correct output waveform. Timer A1's job is to determine what the duty cycle of that waveform should be. More detailed information about the program can be found in the comments within the code used. This can be found in Appendix B. The MSP430 Datasheet [23] is a valuable resource on the physical specifications of the microcontroller, while the MSP430x2xx Family User Guide [24] is an excellent resource for any software side information.

3.3 Storage Stage

The storage stage of this project is fairly simple. The battery management system is connected to the positive and negative terminals of each cell. The only interaction with the outside world the cells have is through the battery management system. This allows the system to prevent charging and discharging from damaging the batteries. The connections to each individual cell allows the system to selectively charge or discharge cells to balance the overall battery. Otherwise the cells may become unbalanced and damaged. Unbalanced cells can also effect the storage capacity of the battery.

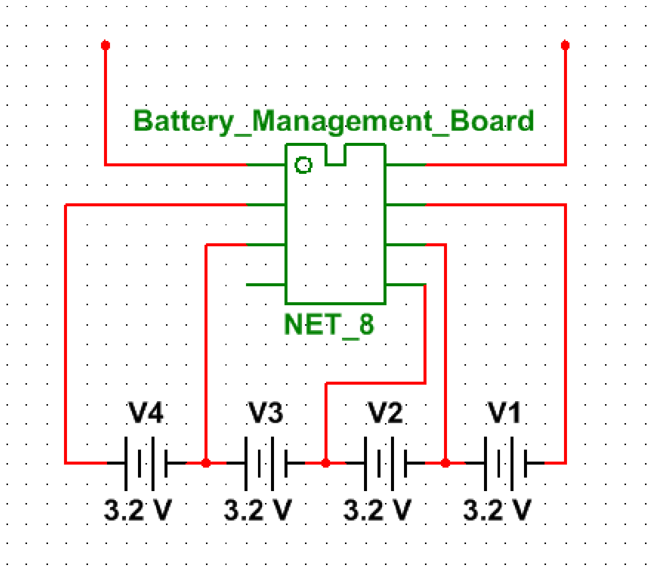


Figure 24: Storage System Schematic

3.4 Output Stage

As we used off the shelf parts for the output stage the circuit is extremely simple. The two converters are simply connected to the output of the battery and their outputs become the overall output of the system.

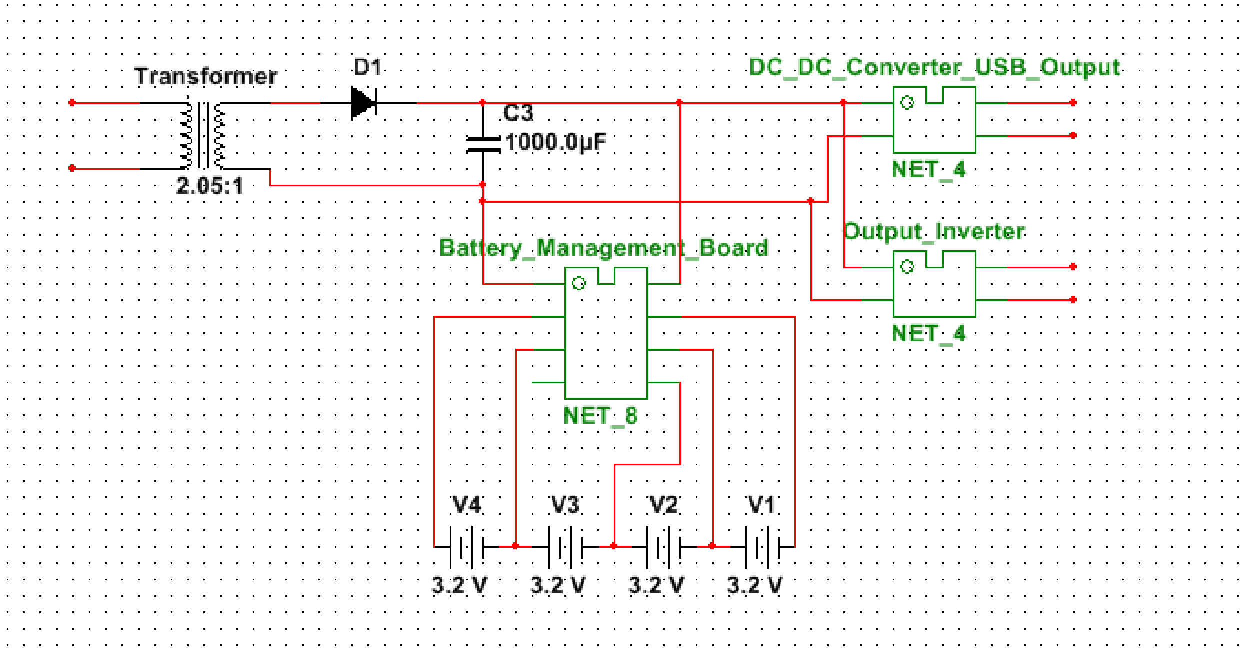


Figure 25: Storage System and Output System Schematic

4 CHAPTER 4: RESULTS

There are a few pieces of data that must be verified in order to determine the functionality of this design. The operation of the microcontroller, the flyback converter operation, and whether the system actually hold the solar panel at the maximum power point. These measurements were taken with the MPPT system active and powering the USB DC/DC converter.

4.1 MPPT Internal Operation

4.1.1 Microcontroller Output

Verifying the functioning of the microcontroller is simple. The PWM output of the microcontroller was measured. The results are shown below in Figure 26: Microcontroller PWM Output . As you can see the microcontroller is outputting a square wave at high frequency.

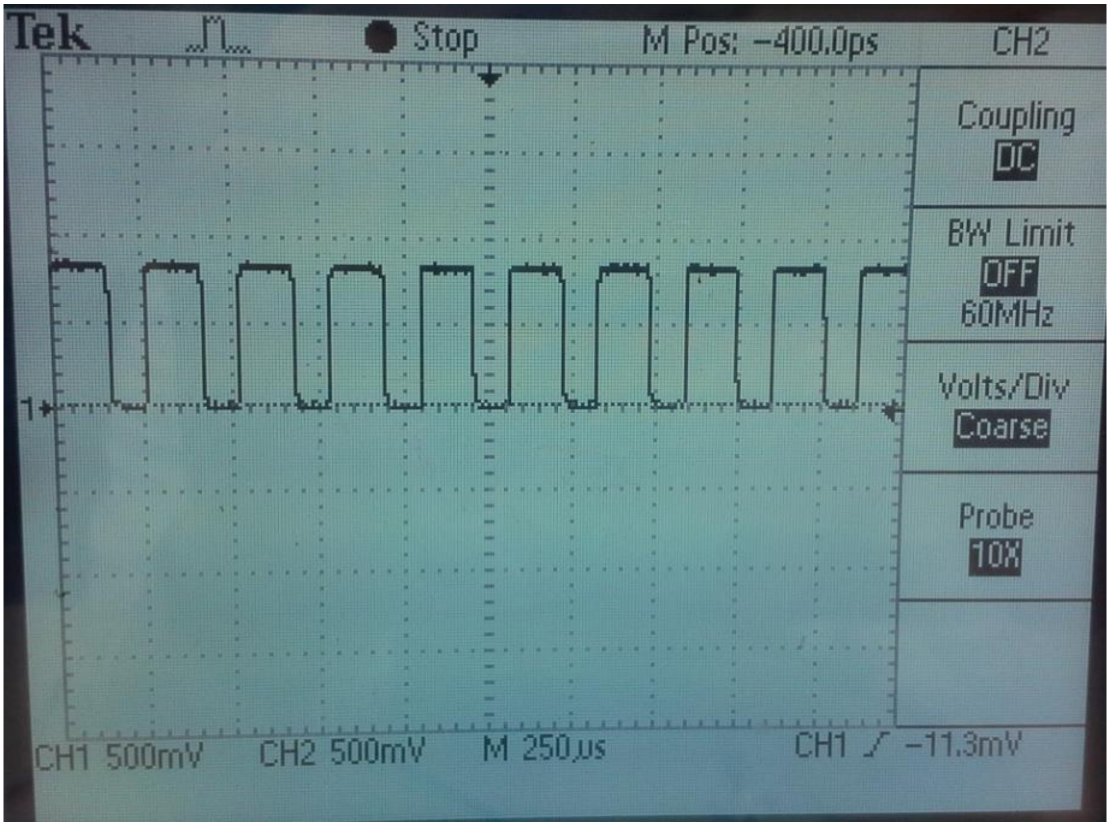


Figure 26: Microcontroller PWM Output

4.1.2 BJT Voltage

The next piece of data to verify is the voltage over the BJT which controls switching. Shown below in Figure 27: BJT Voltage the inductive effects of the transformer produces spikes of voltage over the BJT, distorting the square wave. This is the expected behaviour of this part of the circuit.

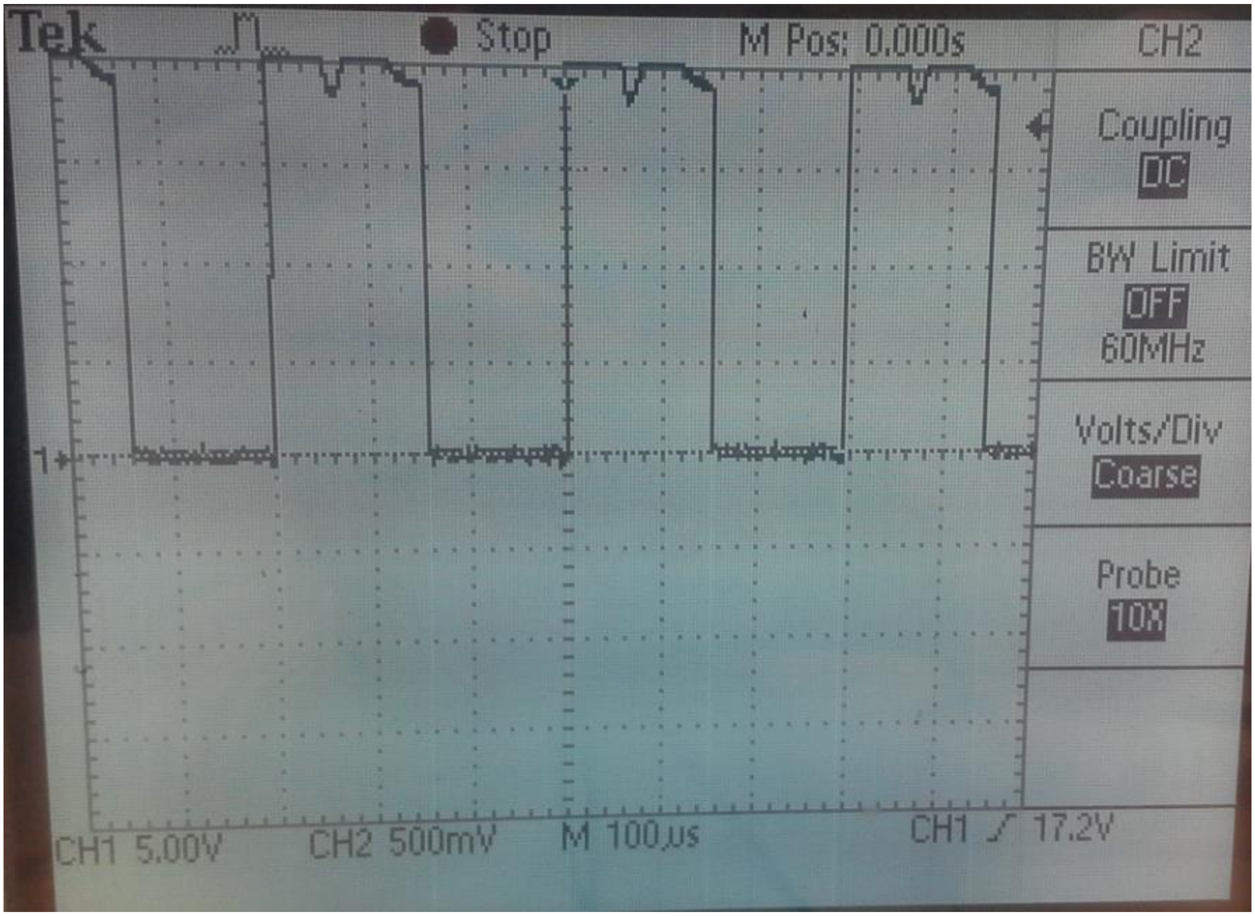


Figure 27: BJT Voltage

4.2 Indoor Test Results

4.2.1 Maximum Power Point Calculation

In order to determine whether our prototype is actually holding the solar panel at the maximum power point the power curve of the solar panel must be calculated. Unfortunately weather conditions forced all solar panel tests to be done indoors. High powered artificial lights were used to simulate the light from the sun. The voltage over the solar panel was measured with resistors of varying values as the load on the solar panel. The voltages and resistances were recorded and the current output and power output of the solar panel were calculated. The schematic of the simple test setup is shown below in Figure 28: Maximum Power Point Test Setup.

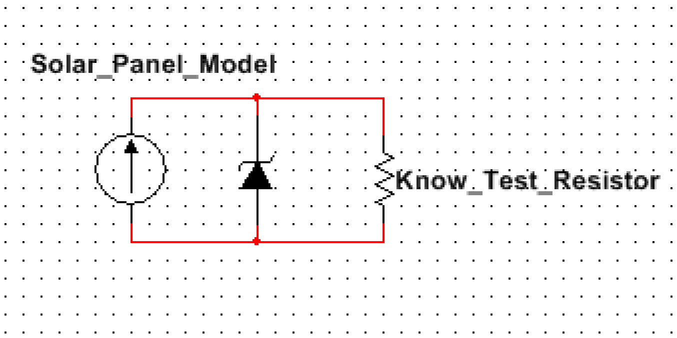


Figure 28: Maximum Power Point Test Setup

The results from this test are shown below in Figure 29: Solar Panel Power and V-I Curves Under Test Conditions. The raw data is shown in Table 11: Solar Panel Maximum Power Point Test in Appendix A.

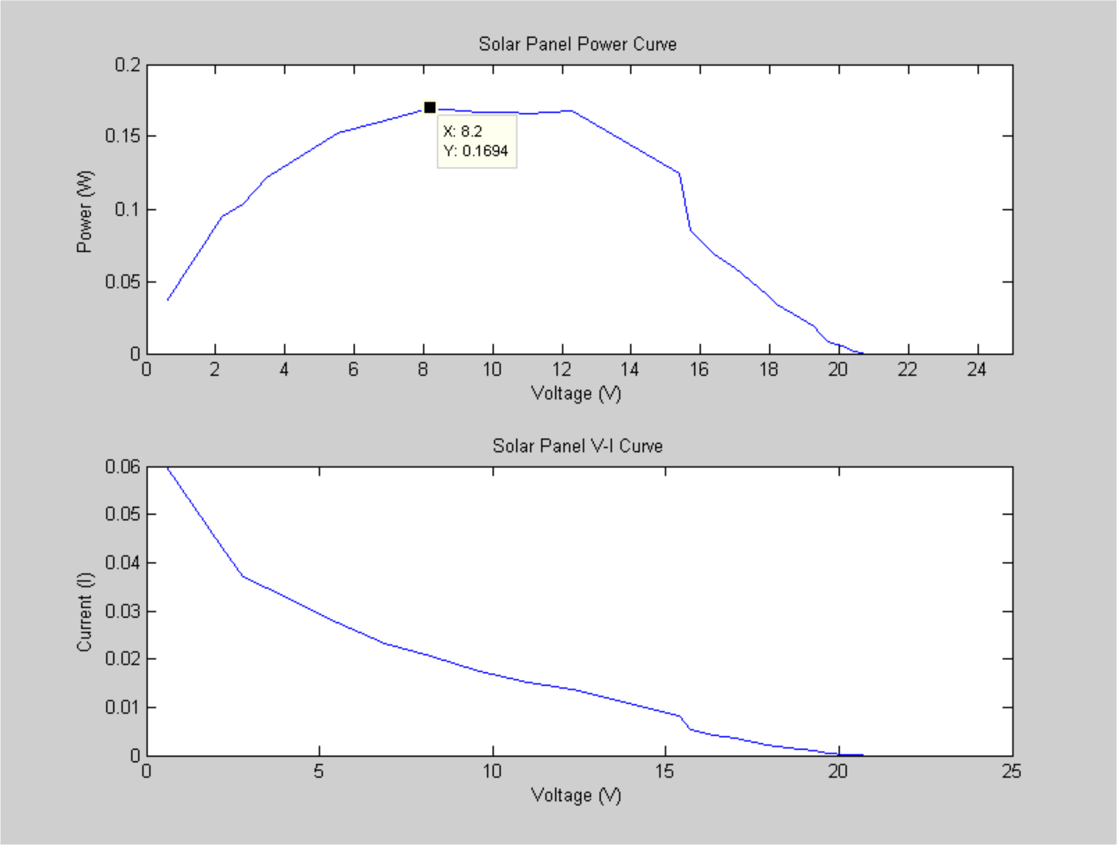


Figure 29: Solar Panel Power and V-I Curves Under Test Conditions

The results of this test are slightly surprising, though not unexplainable. The power curve follows the expected shape, but the V-I characteristic deviates from the canonical solar panel shape. This can be explained by non-ideal elements in both the solar panel and the test setup. The test setup resulted in uneven levels of light being shown on the various parts of the panel. Indeed a small portion had to remain rolled up due to size constraints. This could change the characteristic of the V-I curve to what we see in figure. Nevertheless this does not affect the performance of the MPPT, as there is a clear peak for the tracker to attempt to keep the solar panel at. In the figure this is noted as being at 8.2v.

4.2.2 MPPT Results

To check the effectiveness of the maximum power point tracker the same setup used to measure the maximum power point in the previous section was preserved. The solar panel was attached to the input of the MPPT system and the voltage over the solar cell measured. It was found to oscillate between 8.8v and 7.1v. This indicates that the MPPT is detecting the power delivered by the solar panel and oscillating around the power peak. With the "perturb and observe" algorithm employed by the MPPT this is exactly the effect that should be occurring. Oscilloscope readings of the voltage are shown below.

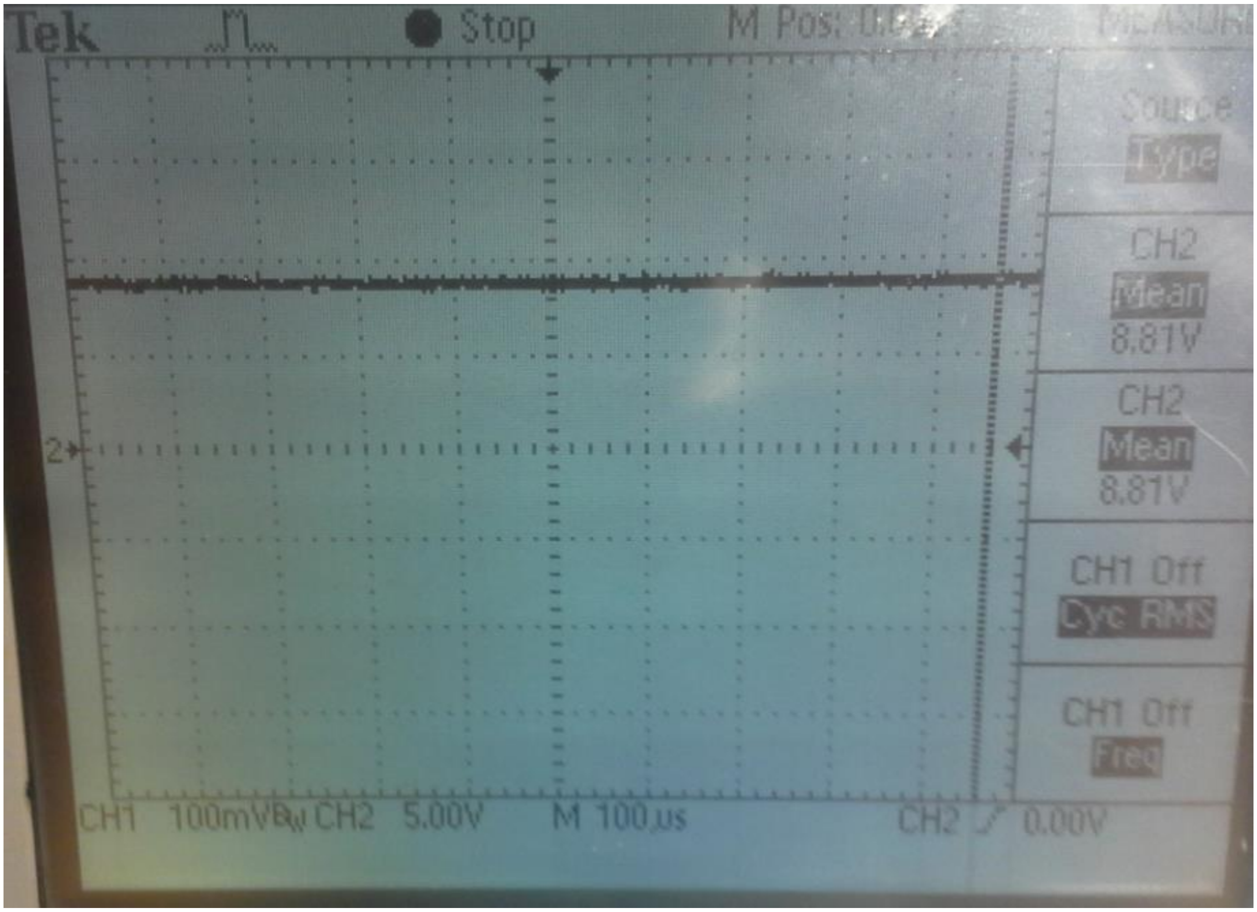


Figure 30: Maximum Voltage Observed During MPPT Test

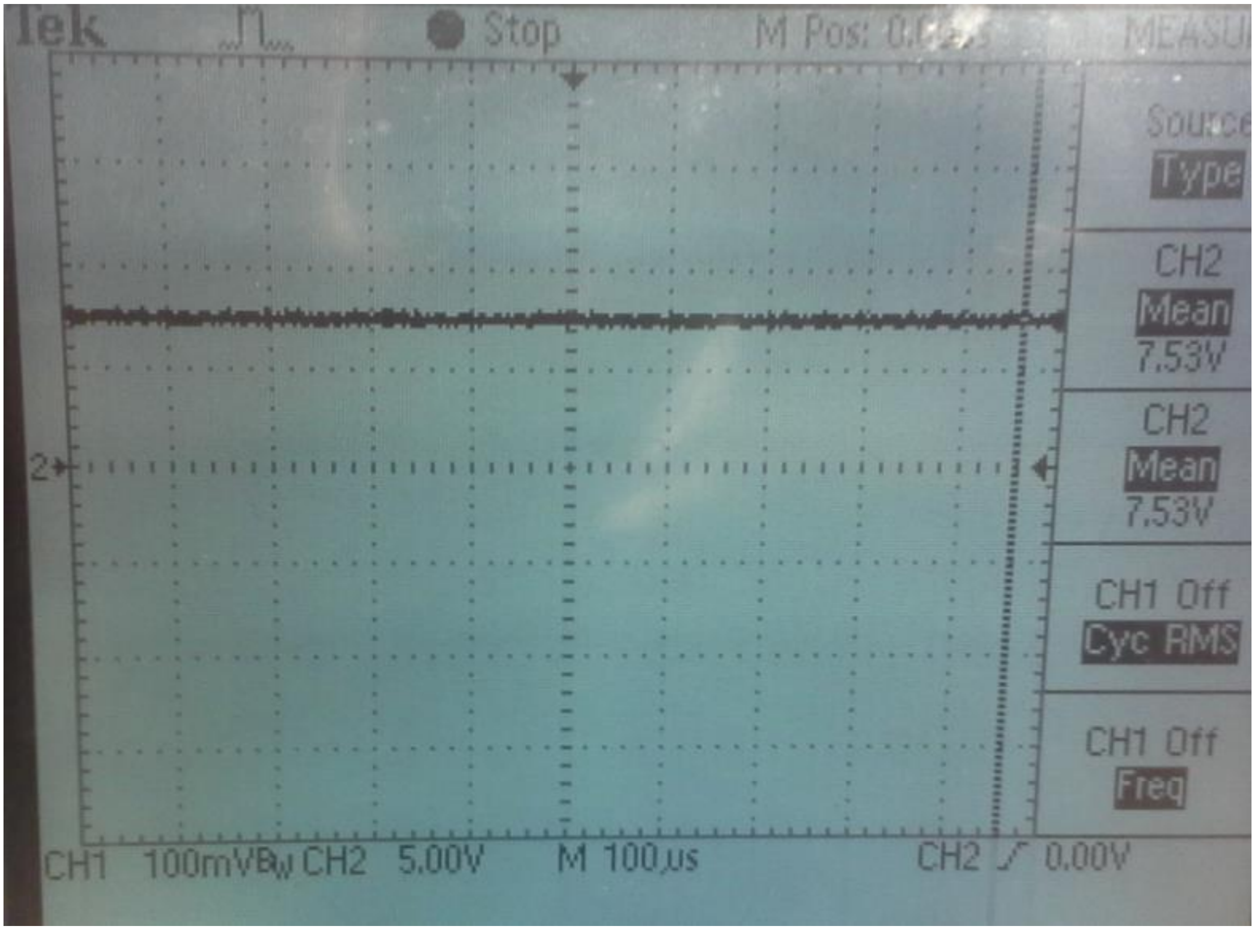


Figure 31: Close To The Minimum Voltage Observed During MPPT Test

Overall these results speak to a design that is functioning exactly as intended. The Solar Charging Station prototype is capable of maintaining the maximum power point of a solar panel while outputting power through both USB and AC.

5 CHAPTER 5: FUTURE WORK

There are many areas in which this project can be expanded upon. The build quality, part selection, and design can all be improved upon. Future features may include charge state monitoring as well as notification to the user of low battery state. Output cut-offs could be implemented so that when the battery charge is low the AC output is disabled to allow the more low power phones to charge.

5.1 Build Quality

As this was a proof of concept project the prototype was not built to production standards. The circuit was not built on a PCB and there is no enclosure around the device. In addition to this the unit was not actually mounted on any sort of umbrella. Future projects which include a mechanical engineering student could improve on many of these areas by designing and building an enclosure that attaches to an umbrella, as well as mounting the solar panel on the umbrella. The high power nature of this design necessitates that anything farther than a proof of concept must be built on a well-designed PCB. This would improve the electrical characteristics of the device.

5.2 Part Selection

As our project was not going to be submitted to the rigors of a full power use case the parts used in our projects construction were limited in their capability. The part selection for our project was mainly based on availability and how appropriate they were for a small scale proof of concept prototype. The transformer, diodes, and wiring were suitable for using this device at low power levels, but would quickly fail if tested under a full load condition. It would behove future projects to use more appropriate parts.

5.3 Design

The actual design of this project is quite functional but lacks refinement and additional features. The simplest algorithm for the MPPT was used as it can be implemented easily and produces good results. A more thorough testing procedure that tests multiple algorithms in the finished product to determine the optimal choice is one way the design could be improved. In addition the current implementation increments the duty cycle by 10% each cycle. A more thorough testing would reveal the optimal value for incrementing that takes into account both speed and accuracy. The project could be expanded to provide information on the operating condition of the system i.e. Battery charge level and load. A warning could be given to the users of when the battery is about to run dry.

5.4 Safety Standards

The nature of our low powered proof of concept means that the standards of safety that a production item must have to be sold were not considered. Any future work that expands on this project must incorporate more stringent safety standards into their design. While the lithium ion cells used are not of the most dangerous type and are protected by a battery management system there are certainly industry standards on the use of lithium based batteries that must be followed in any production design. In particular the IEC 62133 and IEEE 1725 standards are applicable to our project. These standards include requirements for unusual temperature rise protection, overvoltage protection, and terminal contact material and marking. Other standards such as UL 1642 and UL 2045 deal more with the construction of the individual cells than how they are used in consumer devices [20][21].

6 CHAPTER 6: CONCLUSION

The capabilities and price point of solar technology have reached a place where innovative new uses for this energy resource are coming to the fore at a fast clip. The cost, both environmental and monetary, of traditional carbon based energy sources is beginning to decrease the attractiveness of such limited resources. With the lowering cost and rising capabilities of solar technology there is no excuse not to incorporate it into the design on new products.

The Solar Charging Station proof of concept developed in this project has proved to be a very viable concept for a product. The delivered product is a functioning prototype of an interesting concept that has high potential in the marketplace. Future work and improvement on this design could turn it into an impressive product, and we encourage any future teams to take on this task. The demand for products that utilize solar energy is rising every day and the number of portable devices that require electricity is rising with it. These two factors make the need for such a product clear. Within the last few years similar products with fewer capabilities have begun to be brought to market. Now would be a perfect time to bring a more fully featured Solar Charging Station into the market.

As a major part of the WPI curriculum the Major Qualifying Project has proven to be a valuable tool in broadening the experience of students. Our team has learned how to work through both practical and theoretical problems during this project. Time management and group dynamics went hand in hand with the engineering design process to challenge our abilities. These along with many other skills were tested and honed during this process, and resulted in a worthwhile project experience.

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APPENDIX

Appendix A (Solar Panel Measurements)

Solar Panel Voltage (V)	Test Resistance (Ω)
20.7	Open Circuit
20.4	401000
20.2	98000
19.7	49000
19.5	29000
19.3	19400
18.9	14700
18.2	9800
17.9	7900
17.0	4900
16.4	3900
15.7	2900
15.4	1900
12.3	900
11.0	730
10.5	660
9.6	552
8.2	397
6.9	296
5.5	199
3.49	100
2.79	75
2.2	51
.6	10

Table 11: Solar Panel Maximum Power Point Test

Appendix B (MSP430 Code)

```
//************************************************************************************
****
// MSP430 Maximum Power Point Tracker - MQP - Giancarlo Savoy
//
// Description: This code is designed to be run on the MSP430 G2553 microcontroller.
The purpose
//                        of this code is to sense the voltage and current
characteristics of a solar panel
//                        and use this information to output the controll signal to
a Flyback converter.
//                        By changing the duty cycle of the output the maximum power
point of the solar
//                        panel can be reached.
//
// MSP430G2553
// WPI 2015
// Note: Make sure optimizations are off when compiling unless you change the main
function.
//            There is an empty loop in main whcih will get optimized away.
Alternatively you may
//            want to send the uC into low power mode instead of including this loop.
//
//
//
//
//
//
//
//
//************************************************************************************
****
```

```c
#include <msp430g2553.h>


#define LED_0 BIT0
#define LED_1 BIT6
#define LED_OUT P1OUT
#define LED_DIR P1DIR



float timerCount = 0;//How many times the timerA0 has interupted. Used to increase or decrease the output frequency based.
unsigned int timerCount2 = 0;//How many times Timer A1 has fired. Controls the granularity of the duty cycle.
float dutyCycle = .5;//Starting duty cycle
unsigned int whichSideOfDuty = 0;//denotes whether the duty cycle is currently on the poitive or negative swing. 0 is positive, 1 negative.
float current = 0;//Sensed current.
float voltage = 0;//Sensed voltage.
float power;//Calculated power.
float powerLast;//Previous calculated power
unsigned int incOrDec = 1;//1 is increase 0 is decrease
//float vmod = .0386;
//float cmod = .00244;
unsigned int busy = 1;//Used in waiting for the ADC.



/*
unsigned int bToD(unsigned int binary){
int i =1;
unsigned int dec = 0;
unsigned int remainder;

while(binary !=0 ){
remainder = binary%10;
```

```
dec = dec + (remainder*i);
i=i*2;
binary = binary/10;
}

return dec;

}
//Unused code, may be usefull if you want to modify how the power calculations are
done. Binary to Decimal.
*/

void main(void)
{
WDTCTL = WDTPW + WDTHOLD; // Stop watchdog timer
LED_DIR |= (LED_0 + LED_1); // Set P1.0 and P1.6 to output direction
LED_OUT &= (LED_0 + LED_1); // Set the output on

//Set Port 1 to Analog
P1SEL |= BIT3+BIT2;
//Configure ADC parameters 2.5v reference
ADC10CTL0 = SREF_1 + REFON + REF2_5V + ADC10ON;
//Use P1.2 and P1.3 for input
ADC10AE0 = BIT3 + BIT2;

//Set MCLK speed
DCOCTL = 0xe0;
BCSCTL1 |= RSEL0 + RSEL1 + RSEL2 + RSEL3;

//Start TimerA0 and Timer A1 in up mode
TACTL = TASSEL_2 + MC_1;
TA1CTL = TASSEL_2 + MC_1;

//Timer interupt enabled
CCTL0 = CCIE;
TA1CCTL0 = CCIE;
//Timer count
```

```
CCR0 =  0x0001;
TA1CCR0 =  0xFFFF;

__enable_interrupt();


//Goes into loop waiting for interrupt
while(1){
}

}



// Timer A0 interrupt service routine
// Outputs the main signal
#pragma vector=TIMER0_A0_VECTOR
__interrupt void Timer_J (void)
{



//increment the timer count
timerCount = (timerCount + 1);

//Check to see if we are on the high or low part of the duty cycle
//0 is high, 1 is low
if(whichSideOfDuty == 0){
//If we have passed to the low side of the duty cycle change the output
//and record the change in whichSideOfDuty. Reset timerCount.
if(timerCount > 10*dutyCycle){
P1OUT ^= (LED_0 + LED_1);
timerCount = 0;
whichSideOfDuty = 1;}

}
else{
//If we are on the low side of the duty cycle check to see if we have
//passed to the other part of the duty cycle.
```

```
if(timerCount > 10*(1-dutyCycle)){
P1OUT ^= (LED_0 + LED_1);
timerCount = 0;
whichSideOfDuty = 0;
}
}


}




// Timer A1 interrupt service routine
// Fires less frequently and records power readings and changes the duty cycle
parameter
#pragma vector=TIMER1_A0_VECTOR
__interrupt void Timer_A1 (void)
{
timerCount2 = (timerCount2 + 1);

if(timerCount2 == 15){
//Reset Timer
  timerCount2 = 0;
  //Update all ADC settings.
  P1SEL |= BIT3+BIT2;
  ADC10CTL0 = SREF_1 + REFON + REF2_5V + ADC10ON;
  ADC10AE0 = BIT3 + BIT2;
  ADC10CTL1 = 0x2000;//Selects ADC input
  ADC10CTL0 |= ENC + ADC10SC;//Start conversion
  //Wait for ADC to finish.
  while (busy != 0){
    busy = ADC10CTL1 & ADC10BUSY;}
  //Record voltage reading
  voltage = ADC10MEM;
```

```
//Repeat for current reading
//ADC wont change input port if any of this is not reset.
P1SEL |= BIT3+BIT2;
ADC10CTL0 = SREF_1 + REFON + REF2_5V + ADC10ON;
ADC10AE0 = BIT3 + BIT2;
ADC10CTL1 = 0x3000;
ADC10CTL0 |= ENC + ADC10SC;

while (busy != 0){
  busy = ADC10CTL1 & ADC10BUSY;}

current = ADC10MEM;




//Scale voltage and currents to approapriate size.
voltage = voltage*.03858;//(30/1.9)*(2.5/1023)

current = current*.002443;//(2.5/1023)

//calculate power
powerLast = power;
power = voltage*current;

//Algorithm: If power is greater than previous power keep going in that direction.
//             If it is less than previous power change direction
if(power > powerLast){
  if(incOrDec){
     if(dutyCycle <= .91){
    dutyCycle = dutyCycle + .1;
     }
  }
  else{
     if(dutyCycle >= .6){
            dutyCycle = dutyCycle - .1;
     }
  }
```

```
    }
    else{
      if(incOrDec == 1){
        incOrDec = 0;
      }
      else{
        incOrDec = 1;
      }
      if(incOrDec){
         if(dutyCycle <= .91){
        dutyCycle = dutyCycle + .1;
         }
      }
      else{
         if(dutyCycle >= .6){
               dutyCycle = dutyCycle - .1;
         }
      }
    }



  }


  }
```