California State University of Long Beach

Solar Panel

Charging Circuit with Battery

Michael Altamirano

EE458
Fall 2011

Table of Contents

1 Abstract

The project consisted of a solar panel powering a battery for charging purposes, using photovoltaic (PV) panel to convert solar rays into electricity (voltage and current) feed into a Buck (Step-Down Voltage) converter. The Buck converter regulates the power to manage the voltage and current to satisfy charging conditions for the battery. The simulation and experimental results are presented and compared. The applications of this technique can be renewable power stations where batteries are used for energy storage.

2 Introduction

In recent years, renewable energy sources have been an important topic due to the challenges on the environment, fuel source, and automotive industries. Solar energy is a clean fuel source when developing electricity and solar power last as long as the daylight hours are available. Simply connecting a solar panel to a battery is not good enough. When the solar panels are not active (meaning no daylight) the panel reverses direction and energy is taken away from the battery. Having a diode between the battery and solar panels in place prevents reverse direction.

We decided on using a 6V 12Ahr Lead Acid Battery for the design of the solar panel charging station. Lead Acid Batteries are very robust, simple to use, and maintain their storage capacity. Using a 12Ahr battery meant the fast charge current had to be limited to 10% of this rating, amounting to 1.2 amps. The design of the circuit would include limiting the voltage to 8 volts and 1.2 amps.

The solar panels used are 40 watt panels. This generates 17.2 volts and 2.32 amps output. Directly charging the battery with this amount of power would damage the battery. Regulating the power would be needed to manage the power to safely charge the battery.

Most consumer available solar panels are not efficient or lack the wattage to provide enough power for battery charging and power regulation. The 40 watt panels worked well in low sun light and were efficient in power conversion of light into electricity.

The solar panel was attached to an aluminum pole and an electrical box enclosure was used to house the circuit, battery, and fan. The fan provides cooling to the circuitry to cool the components and added venting of gas accumulation from charging the battery.

Figure 1. Solar Panel and Enclosure

3 Theory and Design Criteria

Having only eight (8) to twelve (12) hours of sunlight and providing one (1) amp output load at any given time was the goal of the design project. Using the energy from the solar panels to a convertion process and then storage of this energy was central to completing that goal.

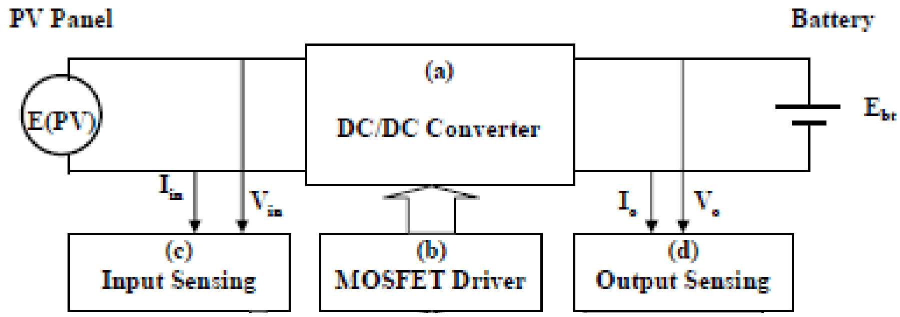


Figure 2. Block Diagram of Solar Charger

Circuit Analysis:

Figure 2 is a block-diagram of the optimal controller, which contains the following components: (a) DC/DC Converter: according to the system specification, a step-down (buck) converter is used, which consists of a power MOSFET, a power diode, an inductor, and a few input / output capacitors. (b) MOSFET Driver: controls the switching of the power into the battery. (c) Input Sensing Circuit: sensors measuring the input voltage (Vin) and current (Iin). Based on the measurement, the input power of PV panel can be calculated as Pin= Vin× Iin. (d) Output Sensing Circuit: sensors measuring the output voltage (Vo) and current (Io). The output voltage (Vo) represents the charge level of the battery, and the output current (Io) is the charging current.

The converted solar power is used to charge the battery, therefore the charged level of the battery, usually the battery voltage, is checked to see if the battery is capable of taking the maximum available solar power. When a fully charged battery voltage is detected, a voltage limit will be given, and then the charging power will be cut off from the battery using the MOSFET. In most of the time during operation, the battery is not fully charged, and the maximum power is applied in the system, allowing charging the battery as fast as possible. Based on the measured input voltage and current, the input power is calculated. The optimal power control is key in trying new current set-point (I*) until the maximum output power is achieved. The measured battery voltage indicates if the battery is fully charged, hence determines whether a limit on the current set point is needed. The measured battery voltage is compared with the set point; the comparator activates and deactivates when the battery needs charging.

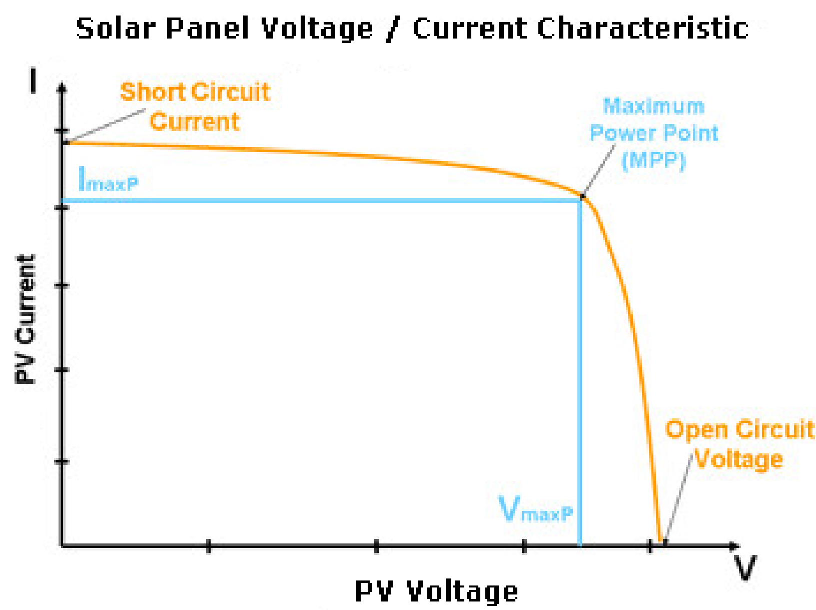


Figure 4. Output Characteristics

In figure 4, the curve indicates clearly that there is a maximum point for the output power. This maximum power is going to vary along with the environment condition. To track the maximum power during the real-time operation is the purpose of the control experiment.

Result for start-up process, at the first moment after the DC/DC converter is powered into the system, both the input capacitor (Cin) and the output capacitor (Co) are charged up by the PV panel and the battery respectively. Both the input current (Is) and output current (Ib) increase significantly at the beginning, and decrease while the capacitors are charged up. The battery current (Ib) is negative since it flows from the battery to the output capacitor (Co). After the capacitors are charged up, the DC/DC converter starts working, stepping down the PV voltage down to the battery voltage level and provides a current to charge the battery. Both input and output current become stabilized.

Solar Panel Optimization:

Optimizing the power receive is simple. The most ideal system would be perpendicular to the sun, but because of the environment (buildings and other obstacles), curvature of the earth, and seasonal patterns sometimes makes this difficult. Using the meters can help gage the power output. Tilting the panel and moving the sand help improve efficiency and optimization. The solar charger is mobile allowing for increased flexibility and greater range.

Stationary solar chargers would need to account for seasons (Spring, Summer, Fall, and Winter), Hemisphere (North or South), and Regional weather patterns. As you approach closer to the equator, this allows for a 90 degree angle giving the best results and moving away from the equator decreases the angle.

The best optimization is motorizing controls to change the angle and rotation to increase the efficiency and power input. The controls can monitor the change in direction of the sun over time and seasonal changes as well.

Background Information:

When the DC input voltage to a buck converter has a wide range, it becomes important to not only select a suitable switching regulator IC for the application, but to select the power components to handle the worst-case input voltage. For a given component, the worst-case may be the maximum input voltage or the minimum input voltage, but in fact may also be somewhere in between.

Equations and formulas:

The inductor design for a buck converter must be done at the maximum input voltage VIN_MAX. This represents the worst case for all the key inductor parameters: the core loss, the peak/RMS inductor current, the copper loss, the temperature rise, the energy it must handle, and the peak flux density. We define 'D' as the Duty Cycle and 'r' the ripple current ratio ΔI/IO.

$$r = \frac{Et}{L \bullet I_{DC}}$$

Where 'Et' is the applied Voltµsecs, I_{DC} is the maximum rated load in Amps, and L is the inductance in µH. The Duty Cycle is

$$D = \frac{V_O + V_D}{V_{IN} - V_{SW} + V_D}$$

Where V_D is the diode forward voltage drop () 0.5V), and V_{SW} is the drop across the switch when it is ON, plus any parasitic (=1.5V). So at maximum input

$$\frac{7V + 0.5V}{17V - 1.5V + 0.5V} = 0.46875$$

t_{ON} = 0.46875 / 150000 Hz = 3.125 usec

Et = (V_{IN} - Vsw - Vo) x t_{ON} = 17V – 1.5V – 7V x 3.125usec = 26.5625 Vusec

$L = \frac{Et}{r \times I_O}$ L = 26.5625 / (0.3 x 1.2A) = 73.7847222 uH

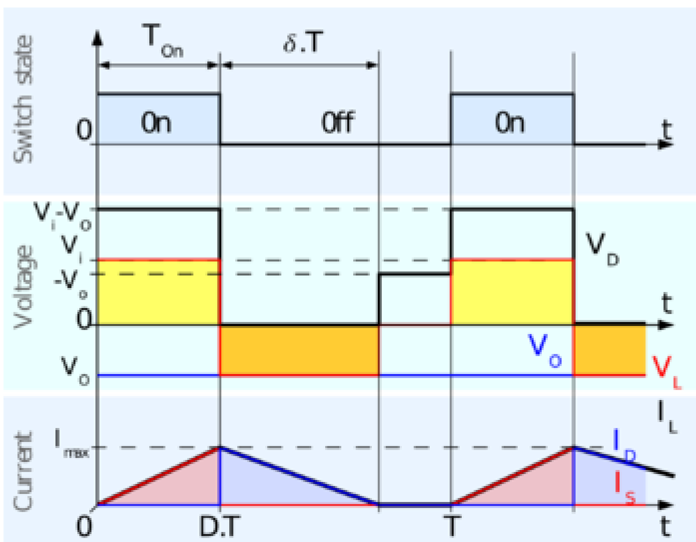


Figure 5. Typical Buck Waveform

The input capacitor of a buck converter sees the maximum ripple current when the duty cycle is 50% (or closest point within range to this). The input voltage corresponding to D=0.5 is $V_{0.5}$ below.

$V_{0.5}$ = (2 x Vo) + Vsw + V_D = (2 x 7V) + 1.5V + 0.5V = 16V

And we would need to calculate the duty cycle at that input voltage for the ripple current calculation below.

$I_{RMS(IN)}$ = Io x √(D x [1 – D]) = 1.2A x √(0.46875 x [1 – 0.46875]) = 0.5988A

For the output capacitor, the worst-case is again the highest input voltage. The basic selection is based on the ripple current and output ripple. The ripple current is

$I_{RMS(OUT)} = Io \times (r / \sqrt{12}) = 1.2 \times (0.3 / \sqrt{12}) = 0.1039A$

The voltage rating of the diode must be higher than the input voltage. The average current in the catch diode is $I_{AVG(D)} = Io \times (1-D)$ The diode conducts during the OFF-time, so minimum duty cycle (or highest input) is again the worst-case here. Therefore $I_{AVG(D)} = 1.2 \times (1-0.46875) = 0.6375A$ We can use a 2A/100V diode from any vendor.

Background on Lead Acid Batteries:

A low self-discharge rate permits storage of fully charged batteries for up to a year at room temperature before charging is required. Lower storage temperatures enhance shelf life characteristics even further. Batteries may be used in series and/or parallel to obtain choice of voltage and capacity. Special separators, advanced plate composition, and a carefully balanced electrolyte system have greatly improved the ability of recovering from excessively deep discharge. The high watt-hour per dollar value is made possible by the materials used in a sealed lead-acid battery: they are readily available and low in cost. No special handling precautions or shipping containers —surface or air — are required due to the leak-proof construction.

The basic electrochemical reaction equation in a lead-acid battery can be written as follows:

Pb	$2H_2SO_4$	PbO_2	Discharging ⇌ Charging	$PbSO_4$	$2H_2O$	$PbSO_4$
(porous lead) active material of negative plate	(sulfuric acid) electrolyte	(porous lead dioxide) active material of positive plate		(lead sulfate) active material of negative plate	(water) electrolyte	(lead sulfate) active material of positive plate

During the discharge portion of the reaction, lead dioxide (positive plate) and lead (negative plate) react with sulfuric acid to create lead sulfate, water and energy.

During the recharge phase of the reaction, the cycle is reversed: the lead sulfate and water are electro-chemically converted to lead, lead oxide and sulfuric acid by an external electrical charging source.

As a result of too high a charge voltage excessive current will flow into the battery after reaching full charge causing decomposition of water in the electrolyte and, hence, premature aging. At high rates of overcharge a battery will progressively heat up. As it gets hotter, it will accept more current, heating up even further. This is called thermal runaway, and can destroy a battery in as little as a few hours.

If too low a charge voltage is applied, the current flow will essentially stop before the battery is fully charged. This allows some of the lead sulfate to remain on the electrodes which will eventually reduce capacity.

During constant voltage or taper charging, the battery’s current acceptance decreases as voltage and state of charge increase. The battery is fully charged once the current stabilizes at a low level for a few hours.

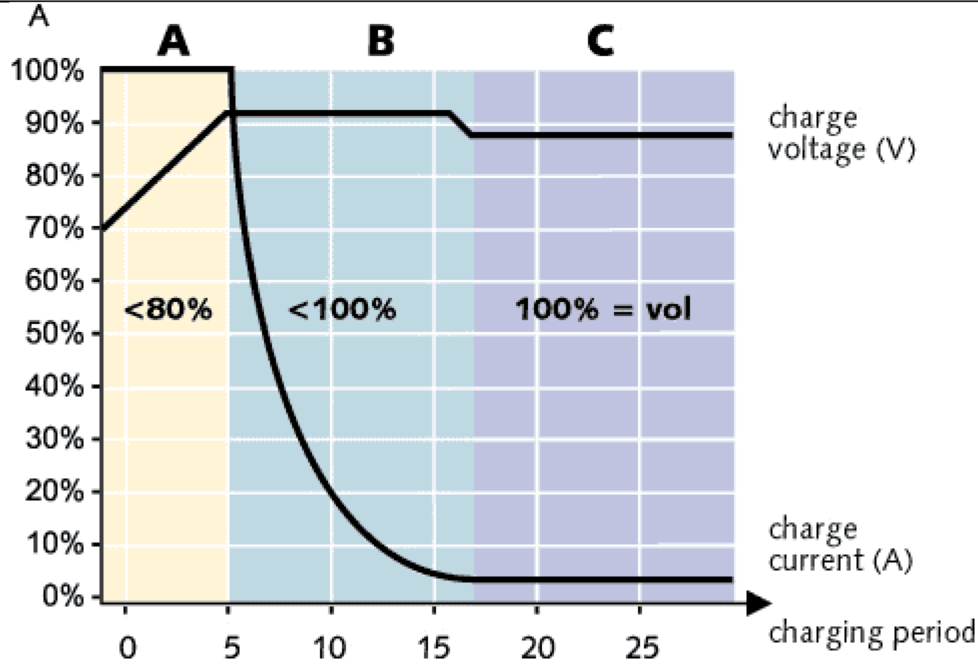


Figure 6. Charge Sates

The first stage is “A” constant current, the second stage is “B” constant voltage, and the third stage is “C” float charge. In the design of the solar charger, we looked at the first stage, giving about an 80% charge. As soon as the second stage hits, the charge is discontinued and the battery stops receiving power from the voltage regulator / MOSFET.

4 Experimental Procedures

Solar Panel Selection:

Research into solar panels revealed rated wattages were biased higher than stated wattage on packaging. A 15W output seemed more than enough to supply power to the battery. Over 8W would go to battery charging, then the fan, comparator circuit, voltage regulator, and inefficiencies in the circuit lead us to 15W. Needing more than double the actual wattage would be a good start to completing the project. Also, optimal conditions are not always available when dealing with weather. We chose a 40W solar panel, going well beyond the double wattage theory.

Testing and experimenting with the 40W solar panel yield the applied voltages and current as specified during peak day light hours. He panel was able to provide constant power even in low day light conditions.

Battery Selection:

Lead acid batteries tend to yield the best results, the biggest problem tend to be weight of the batteries. Choosing a 6V 12Ahr battery to supply a load gave us a good workable storage source. We looked into powering USB load, which is 5V @ 1A. A 12Ahr battery can give 1A for 12 hours, most likely this not the case. We can expand the time by adding batteries in parallel give long hours of operation. Simply tweaking the inductor will product more current out, allowing for more current to charge the batteries. Using four (3) 6V 12Ahr batteries in parallel would make sure a continuous 1A output for 24 hours. This would mean 3.6 of current charge from the voltage regulator. For this experiment we used a 6V 12Ahr battery to lower cost and complexity to the project.

Voltage Regulator:

A simple LM317 voltage regulator could not handle the power dissipation from the solar panels and the device would shut down after heating up from the power received coming from the solar panels. The LM317 was unreliable to use for this application. It is possible that multiple LM317 can be used but this would only add to the deficiencies of the project. A better voltage regulator needed to be found.

Looking under a 2 amp range the LM2599 seemed well suit for the selection of the regulator. The LM2599 can provide a 3A output and worked in a way that heat and power dissipation was not a problem. It was efficient and reliable and worked for long hours.

Other regulators could operate at 3A, but as soon as current reach the maximum output, the regulators would work in discontinuous mode and was therefore unreliable. Other regulators were inefficient as they outputted less current in a buck converter, which should yield higher current in a buck condition.

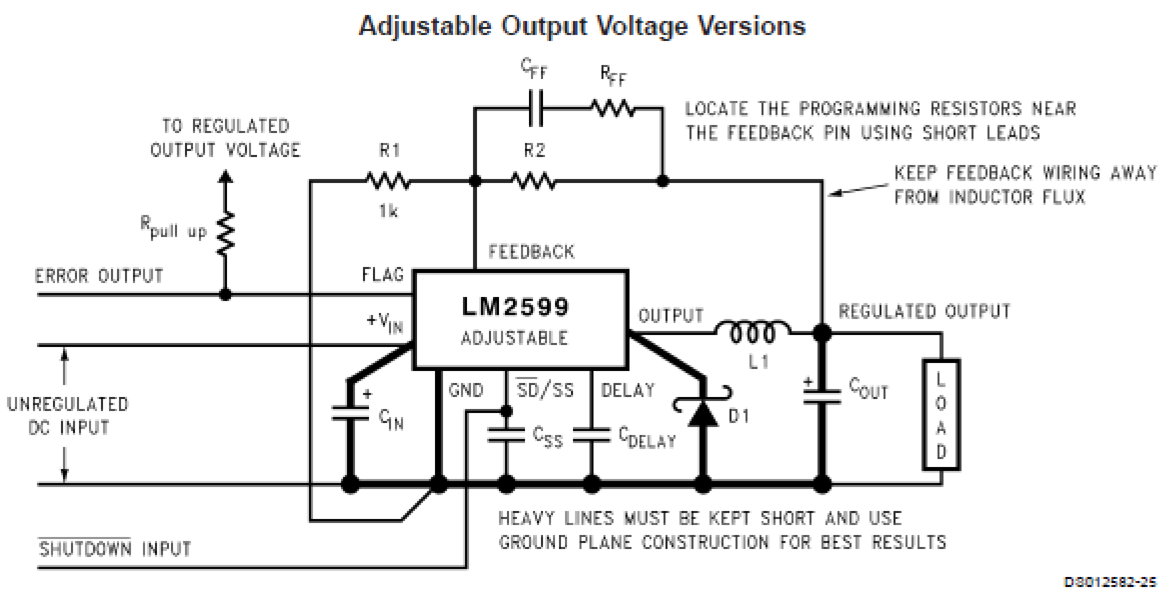


Figure 7. LM2599 in Adjustable Voltage Regulator

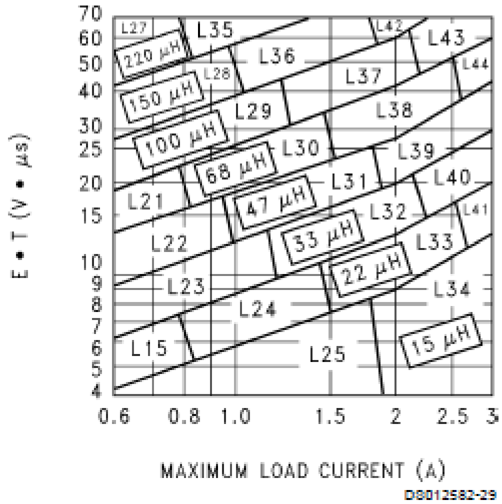


Figure 8. Inductor Value Selection

Vout = Vref (1+ R2/R1) => R2 = R1(Vout/Vref – 1) = 1k(7.4V/1.23 – 1) = 5.02kΩ

$E*T = (V_{IN} – Vout – V_{SAT}) * (Vout + V_D / V_{IN} – V_{SAT} + V_D)$

= (17 – 7.4 – 1.16) * (7.4 + 0.5 / 17 – 1.16 + 0.5) = 27.203(V * usec)

L1 = 68uH

Output Voltage (V)	Through Hole Output Capacitor		
	Panasonic HFQ Series (µF/V)	Nichicon PL Series (µF/V)	Feedforward Capacitor
2	820/35	820/35	33 nF
4	560/35	470/35	10 nF
6	470/25	470/25	3.3 nF
9	330/25	330/25	1.5 nF
1 2	330/25	330/25	1 nF
1 5	220/35	220/35	680 pF
2 4	220/35	150/35	560 pF
2 8	100/50	100/50	390 pF

Figure 9. Output and Feed Forward Capacitor

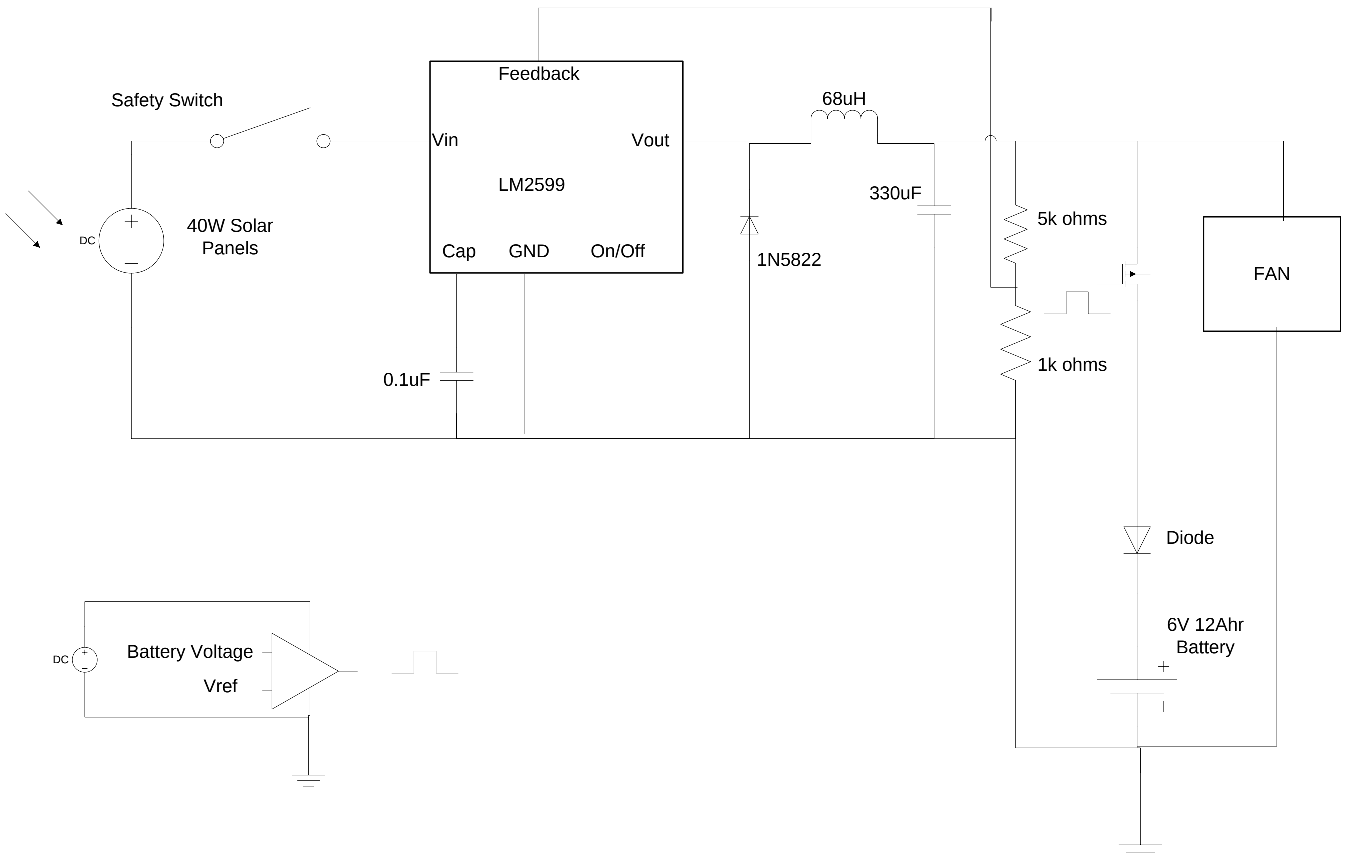
Output Capacitance

Cout = 330uF

Feedforward Capacitance

C_{FF} = 1nF

5 Schematics and Parts



Parts to the Project

1. Buck converter 40V @ 2A
2. Solar Panels (40W)
3. Switches
4. Capacitors (0.1uFand 330uF)
5. Meters (voltage and current)
6. Comparator
7. Inductor (68uH)
8. High wattage diodes
9. Lead-Acid Battery (6V @ 12Ahrs)
10. Resistor (5kohms and 1kohms)
11. Fan

12. Enclosure

13. Stand for the solar panels

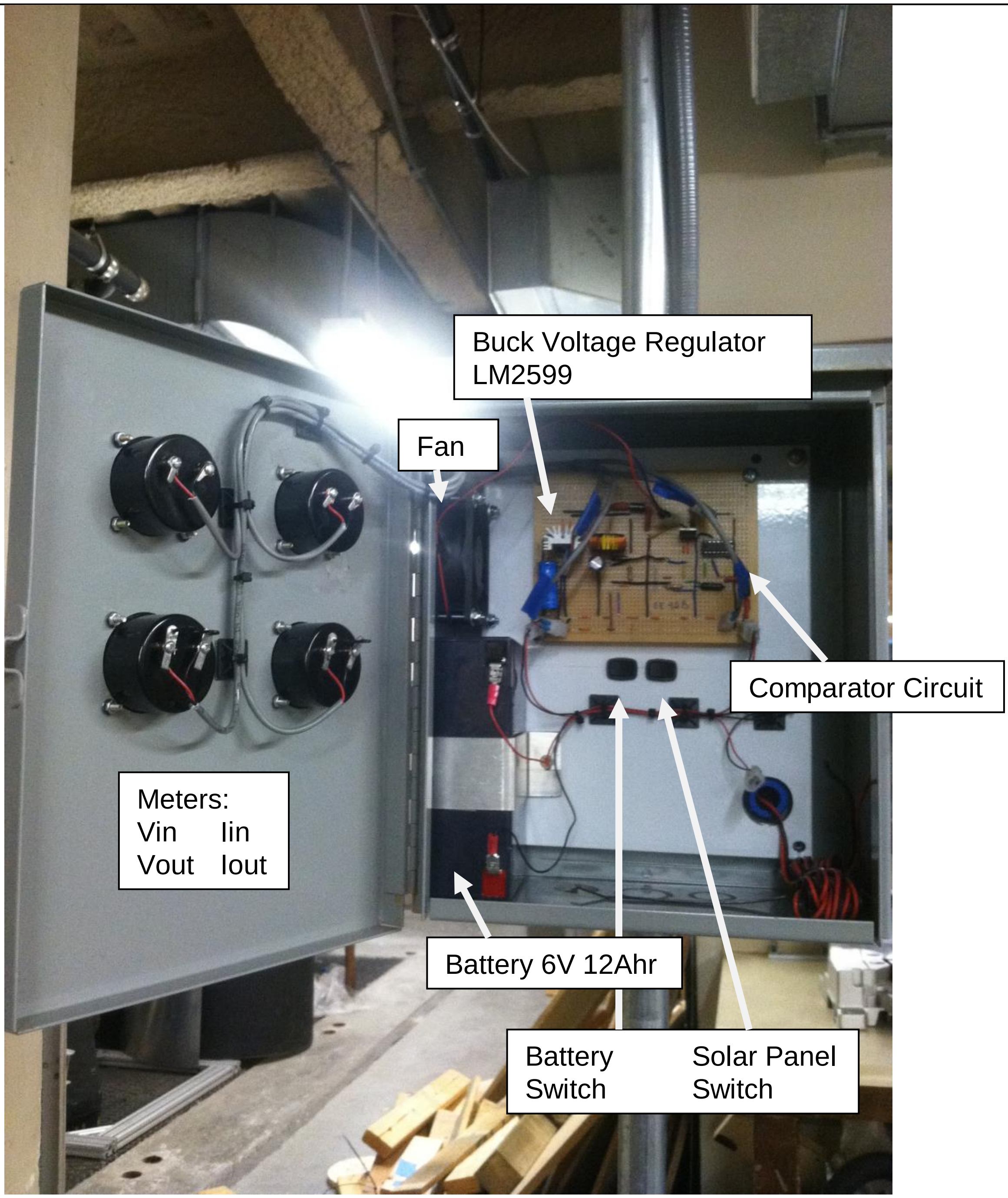
14. DMM (voltage current)

15. Power supply to simulate output from the solar panels

6 Solar Panel Construction

Fully Built Solar Panel Stand

Front view of Solar Panel Stand



Inside Solar Panel Stand

7 Results and Discussion

Simply outputting 5V 1A is not necessarily easy to accomplish. It first starts with the PV panels. Supplying adequate power is very important to maintain the viability of power stored and constant. Learning the rated wattage is under ideal conditions not normal in real world use. Also the power inefficiencies from building a circuit and not minimizing leakage and power consumption added to meet the power requirements to the project.

A 40W panel did very well in supplying enough power to charge the battery and give a consistent amount of power throughout the day light hours. The 40W panel gave 17V and 2A of supply, more than enough for the voltage regulator and battery charging.

The battery used was a 6V 12Ahr battery for the use of a USB 5V 1A load. Assuming good conditions a 12Ahr battery could charge a USB device for a minimum 4 hours to a possible 10 hours. Future expansions can lead to adding batteries in parallel to increase capacity.

An over charge protection circuit was implemented. It used a simple comparator circuit. Using a Zener diode as reference at 8.2V, the comparator would disengage the gate to the MOSFET at 7.2V. The MOSFET acts as a driver to shut off the power to the battery.

In this project we explored different regulators, batteries, solar panels, and comparator circuits. We came up with a very well built solar panel charging station that is mobile, flexible, and has wide ranges with the possibility of expansion for more storage of electricity.

8 Project Resources and References

J.H.R. Enslin, D.B. Snyman, “Combined Low-Cost , High-Efficient Inverter, Peak Power Tracker and Regulator for PV Applications” IEEE Trans. PowerElectronics,.vol. 6, pp. 73-82, Jan. 1991

S. Jain, V. Agarval, “A Single-Stage Grid Connected Inverter Topology for Solar PV Systems With Maximum Power Point Tracking’’ , IEEE Trans. Power Electronics, vol.22, pp. 1928-1940, Sept. 2007

Q. Li, P. Wolfs, “A Review of the Single Phase Photovoltaic Module Integrated Converter Topologies With Three Different DC Link Configurations’’ IEEE Trans. Power Electronics, vol.23, pp. 1320-1333, May2008

K.K. Tse, M.T. Ho, H.S. Chung, and S.Y. Hui, “A Novel Maximum Power Point Tracker for PV Panels Using Switching Frequency Modulation’’

9 Team members

The solar panel was constructed by me, Michael Altamirano. I purchased the solar panel, piping, the enclosure, and materials to build the stand. The stand is mad of rebar, cement, and a small dolly that allows it to move around but has a low center of gravity. The newest stand was manufactured by Luis Hernandez. The stand is much cleaner and higher quality.

I put together the initial solar panel stand and enclosure. The enclosure was modified by Luis making it user friendly and adding protection to wires that can be pinched off and cut. Luis installed the meters, back plating, fan, and battery strap. He also labels the meters.

I came up with the initial design for the buck regulator. Luis came up with using a comparator and MOSFET to control the overcharging protection circuit. From the initial design we modified the buck regulator to output the current needed and limited the voltage. Luis initial design for the comparator used a battery reference. This added to the complexity and cost to the circuit. I devised a plan to use a zener diode as a reference directly from the source of the solar panels. Also the comparator was tied to the Lead acid battery, making this inefficient, so I changed the source voltage to the output of the buck regulator. This way the battery is not drained while it’s not charging.

Throughout the build process we constantly tested the circuits to see if we obtain the desired results. First we started the Buck regulator. After a couple of tries we able to work the regulator and take results from the circuit. The biggest challenge was correctly mounting the regulator to the bread board. The regulator has multiple pins and the inductor made it difficult to work around the circuit. We were successful in the output and input for the regulator. We then looked to the solar panels to see if it could deliver the power needed by the regulator. We positioned different angles and tried to receive the lowest amount of power and the highest amount of power. The boundaries were acceptable and we agreed that the solar panels provide adequate supply.

We then tested the comparator and figured that it had a 1.2V bias. This is why we used a 8.2V zener diode so the desired cutoff is 7.2V. A couple of tried and the comparator worked successfully. Luis continually refined his regulator to give consistent results. Luis upgraded the MOSFET to handle more current because of heat issues and possible failure. Another problem was the gate voltage on the MOSFET. Limiting the gate voltage limited the current to the battery. The comparator used a pull up resistor to activate the MOSFET. Luis and I changed resistor values to allow for the highest voltage while still limiting it to 20V on the gate. This allows for maximum transfer.

Luis made major modification to the enclosure and improved on the design. We worked together to see the best position for each component. Luis finished up on transferring the design from the breadboard to a prototype board to mount in the enclosure. Luis added wiring for the meters, the fan, and drilled the holes for the meters. Luis put all the finishing touches to the project. Luis gave it a “sellable” quality.

I organized the report, research, and initial setup. We advised each other on the progress we made and had continuous updates on the current state of the project.

Through a series of phone calls, emails, and in lab results we have a final project that works well and is design for use and possible expansion.