Photovoltaic MPPT Charge Controller (PMC^2)

Ersuel Ago, Juan Sebastian Hidalgo, Steven Kobosko, and Amber Scheurer

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

***Abstract* — This paper presents the design and methodology used to create a photovoltaic charge controller that utilizes maximum power point tracking algorithms. In response to the demand for alternative energy sources, solar research is becoming increasingly important. The charge controller presented in this paper is not only designed to maximize the power from the solar panel but also contains added features that make the system beneficial to the researcher. In addition to monitoring the current and voltage from the panel and battery, this system will record the temperature of both as well as the irradiance on the solar panel. Finally, all of this sensor data will be wirelessly transmitted to a computer where it will be recorded for future analysis.**

***Index Terms* — batteries, DC-DC power converters, energy efficiency, photovoltaic systems, power electronics, solar energy**

I. Introduction

In a world of increasing energy demand, it is imperative to come up with innovative solutions to reduce and conserve energy use. There is a significant interest in creating an environmentally friendly system that will save money on electricity and maximize the cost return on investment for solar panels. The photovoltaic industry continues to strive to create efficient and inexpensive systems that can be competitive with other energy sources.

The goal of the project is to create a stand-alone off-the-grid photovoltaic (PV) system that utilizes maximum power point tracking (MPPT) to obtain the most efficiency. Due to the inherent losses that occur in photovoltaic systems, it is essential that the maximum power is extracted. The intent is to create an extremely efficient charge controller that will be able to monitor the power generated by the photovoltaic array and deliver the maximum amount to the battery bank during varying atmospheric conditions. Most estimates report that implementing maximum power point tracking algorithms increase the efficiency approximately 30% when compared to traditional charge controllers [2].

Research institutes such as the Florida Solar Energy Center (FSEC) are instrumental in this pursuit of new energy technologies. They provide the facilities and jobs that enable researchers to make strides towards this common goal. In order to further progress in this area, several additional features have been added to the charge controller to make it more user friendly and beneficial for solar researchers.

II. System Overview

To demonstrate an off-the-grid charge controller, there are four major components needed. First, the solar panel acting as the energy source, then the charge controller, followed by the battery which allows for energy storage and finally the inverter which provides an outlet for the user to access the stored energy. In Fig. 1 the main path of the power through the system is depicted by red arrows. While power is still fed to the individual electronics and sensors, these connections are not illustrated for simplicity.

In order to implement maximum power point tracking, data from several different sensors will be fed into a microcontroller. Here the MPPT algorithms will interpret the incoming current and voltage from the PV panel as well as the battery to calculate what amount of power should be used to charge the battery. The microcontroller can then physically change the voltage by driving the buck and boost DC-DC converters in the circuitry. The charge controller where this conversion takes place is implemented on a custom designed printed circuit board (PCB) depicted as the grey box in Fig. 1.

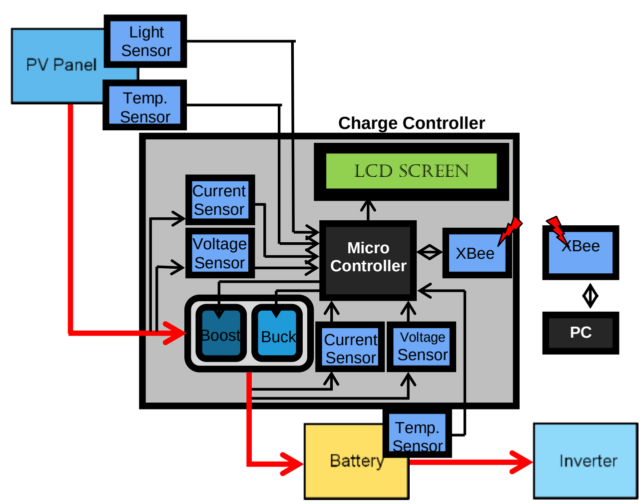

Fig. 1. Overall system block diagram of PMC^2.

In order to quickly view the status of the system, an LCD screen will be attached to the charge controller to display several values such as current, voltage, and temperature. In addition, this information will be transmitted wirelessly to a separate wireless transceiver that is attached to a computer. Along with the previously mentioned sensor quantities, the irradiance on the solar panel will be measured and recorded to give further insight into how the system performs in varying atmospheric conditions. Ultimately, since all of this information can be quickly and easily recorded and stored on a computer, the system will provide a unique and inexpensive solar testing and data collection system.

III. Power Components

In order to generate, store, and distribute the power in this system, three major components are needed. First, the photovoltaic panel is energy source and captures the light. Then a battery is used to store the power that has been captured and regulated by the charge controller and finally the inverter will connect to the battery to allow an end user to charge or power small electronic devices.

The power components of the system require relatively little design on behalf of the team and will be connected as part of the overall system integration. The custom charge controller will be attached in between the solar panel and the battery to allow the DC-DC converter to regulate the power that is supplied to the battery.

A. Solar Panel

The Florida Solar Energy Center, located in Cocoa, Florida, has consulted with the senior design group about the industry relevance and potential applications of the PMC^2 system. This research center conducts state of the art photovoltaic research and has an extensive inventory of solar units. They have provided the solar module for use in this project.

The Siemens Solar SP75 module utilizes 36 single-crystalline solar cells to deliver power to the PMC^2 system. The Voltage-Current characteristics are presented in Fig. 2. This module has an open circuit voltage of 21.7 V and has been factory configured for 12V use. Since the panel has a short circuit current of 4.8 A, much consideration has been given to acquiring parts that are rated for high current. As with most other solar units, efficiency is inversely proportional to the temperature. As the temperature of the panel changes, the maximum power point will also move accordingly. The ability of the MPPT charge controller to dynamically adjust to these changing conditions is what makes it more efficient than other static charge controllers.

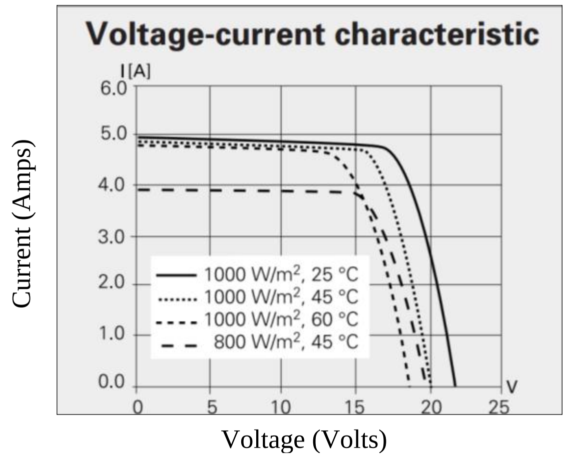

Fig. 2. Voltage-Current (IV) Characteristics of SP75 Solar Module.

This panel was chosen because the power output exceeds that required to charge the battery. Since the optimal output from the panel is greater, the circuitry will operate primarily in buck mode which is more efficient. The two modes of the charge controller, buck and boost mode, will be discussed. This technique for increasing efficiency is considered an indirect method, as opposed to a direct method such as solar tracking which will not be implemented in this project because it would not provide a big enough increase in the power yield to compensate for the motors and electronics necessary.

B. Battery

Many different types of batteries were researched for the system including lead-acid, nickel-cadmium, lithium-ion, and nickel-metal-hydride. Of all these types of batteries, the deep-cycle lead acid was deemed most cost effective and favorable for photovoltaic applications. Out of the three types of lead-acid chemistries, the AGM battery was selected due to long lifetime, resistance to damage, and requiring no maintenance. The specific battery chosen for the system is the Sun Xtender PVX-420T AGM lead-acid battery. This 12V battery has a nominal capacity of 42 Ah, which will provide ample power for effective demonstration of the system.

The charging algorithm used for this battery, as specified in the Sun Xtender datasheet [1], will be very close to the standard lead-acid charging algorithm. A bulk charging stage will be used from 50% (or lower) to 80% battery capacity. In this constant current stage, the MPPT algorithm will function to find the maximum power point and set the voltage accordingly. Next comes the absorption stage of charging, in which the voltage is set between 14.2 to 14.4V, depending on battery temperature as described by the equation

$$V(\text{Absorption}) = 0.00004T^2 - 0.006T + 2.510 \quad (1)$$

where T is the temperature in °C. When the current into the battery has dropped to 0.5% of capacity (0.42A in this case), the battery is considered fully charged. When this current is reached, the battery then goes into the floating charge stage in which the voltage is dropped to between 13.2 and 13.4 volts. Based on the temperature, the exact voltage can be obtained using

$$V(\text{Float}) = 0.00004T^2 - 0.006T + 2.340. \quad (2)$$

This floating stage is used to offset the loss due to self-discharge, even though the self-discharge value is small in the Sun Xtender PVX-420T.

C. Inverter

In order for the end user to access the power stored in the battery, the Cobra CPI 880- 800-Watt Power Inverter was selected. This specific inverter is designed to receive 12 V input and provide 800 Watts to the user via the standard 115 V AC. In addition to the standard 3-prong AC outlets there is also a USB port that enables the use of low power devices such as cell phones and iPods. The inverter will be connected to the battery using 12-gauge wire attached to the positive and negative terminals with clips.

IV. Charge Controller

The charge controller will be designed and manufactured on a custom printed circuit board. This PCB will house the microcontroller and DC-DC buck boost circuitry in addition to the sensors, wireless transceiver, and display peripherals. The charge controller will measure the voltage, current, and temperatures of both the solar panel and battery bank. Using this sensor information, a regulated output will be delivered to the battery bank. The goal is to have efficient charging of the battery bank using the MPPT algorithms implemented in software by the microcontroller.

To make the overall system more user friendly, an LCD screen will be included do display various sensor data. The specific display chosen is the serial enabled LCD-09568 from SparkFun Electronics. The fact that this device uses TTL serial allows easy integration with the ATmega328P. This LCD is a 20x4 character display in order that many values can be displayed simultaneously. The LCD also features an adjustable backlight, and is monochrome (black on green). This style of LCD will provide enough detail for the system while consuming as little power as possible to maintain the best efficiency, drawing only 60 mA during normal operation.

A. Microcontroller

The microcontroller chosen was the ATmega328P with Arduino bootloader. This microcontroller provides all hardware functionality required in the charge controller; all the analog and digital pins required by the sensors and other peripherals are satisfied by this microcontroller. In addition, the 16 MHz clock speed, TTL serial, I^2C communications, and robust programming language were also deciding factors in this decision.

The Atmega328P is connected to the peripheral devices as shown in Fig. 3. The XBee wireless transceiver is attached to the hardware UART ports of the microcontroller. The LCD screen uses one general-purpose digital I/O pin to connect to the microcontroller. In software, a serial port can be established on pin D2 interface with the LCD. The irradiance sensor uses one digital input pin to deliver the light intensity. The current and voltage sensors utilize four of the analog input pins, where an analog voltage between 0 and 5V is read in. The temperature sensor uses I^2C to communicate with the microcontroller using analog pins 4 and 5, which can (and will) be configured as an I^2C data link. Finally, the microcontroller will be tasked with controlling the buck-boost regulator to deliver the appropriate charging voltage to the battery bank. Two pulse width modulation (PWM) lines are required and two additional digital outputs are required to control switches that turn on or off the buck or boost part of the MPPT circuit.

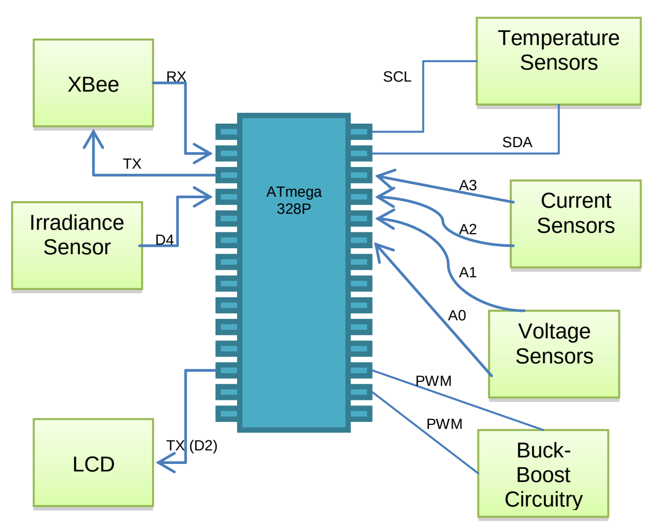

Fig. 3. Microcontroller pin layout for interfacing with peripherals.

B. Sensors

Standard voltage divider techniques will be implemented in order to sense the voltage on both sides of the charge controller as shown in Fig. 4. The voltage on the battery needs to be known in order to determine the charging state. The resistor values are chosen so that the designated pin is fed an analog voltage between 0 and 5 V that the microcontroller can interpret and extrapolate the actual voltage value.

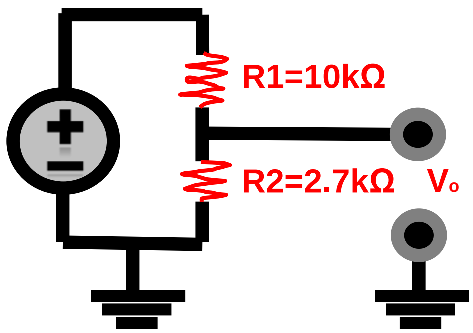

Fig. 4. Voltage divider circuit used to sense voltage.

Similarly, the current sensors send an analog voltage value to the microcontroller, which will determine the nominal value of the current. The current sensors will function alongside the voltage sensors to sense current coming into and out of the charge controller. The ACS711ELCTR-12AB-T current sensor was chosen because it is rated up to 12 A. This specific model is a very accurate and low power circuit, which is advantageous when designing for efficiency.

The DS1624 temperature sensor was selected to monitor the temperature of the solar panel, the battery and charge controller. These values will not affect the operation of the project but provide additional insight into the performance of the system under varying conditions. The temperature on the panel will be recorded and can be correlated against the output power of the panel to examine its performance. The temperature on the battery will be useful for safety considerations to make sure it does not overheat. Each DS1624 will need to be in direct contact with the PV panel, battery, and charge controller in order to provide accurate readings of the temperature on the units themselves and not the environment.

The DS1624 is a low power, precise digital temperature sensor that supports a wide range of temperatures from -55°C to +125°C without limiting its performance. This sensor has the capacity to be assigned a digital address, which allows up to eight temperature sensors to be use in the design and they can all be accessed from the microcontroller through the same I^2C bus line.

The implementation of an irradiance sensor is similar to the temperature sensors in that they create meaningful data for a researcher studying the performance of the solar panel in use. As suggested by a current solar research engineer, an irradiance sensor located at the panel would allow the user to easily understand how the panel was performing in relation to the amount of incident light. A typical photovoltaic panel will perform optimally under bright yet cool conditions, making the irradiance and temperature of interest.

The TSL235R-LF irradiance sensor will convert the light received by a silicon photodiode into a frequency and will output a square waveform. This output signal is fed into the microcontroller where it is translated to lumens, which the user can interpret. The sensor will be powered with a DC voltage of 5 V. 100 nF capacitors will be used to filter each of the analog sensor readings that are fed into the microcontroller; including the irradiance sensor, current sensors, and voltage sensors.

C. Wireless

The implementation of wireless capability is another one of the additional components that makes the PMC^2 system unique. This feature will allow the user to remotely view and record the sensor data collected at the charge controller. This provides a convenient and inexpensive method for testing photovoltaic performance, since the researcher can view and record the efficiency of the panel throughout varying atmospheric conditions.

The range, power, throughput, communication protocol, cost, and form factor were all considered when designing the wireless system. The XBee DigiMesh 2.4 GHz RF modules with wire whip antenna are the wireless modules chosen for PMCC. This module uses the 802.15.4 protocol and can transmit 90 m outdoors and 30 m indoors, which was deemed sufficient for testing purposes. These transceivers have an RF data rate of 250 kbps, more than is needed to transfer the sensor data that will be collected. The chip communicates at 3.3V TTL UART serial, which can plug in directly to TX and RX pins on the ATmega328P microcontroller.

The small form factor of the XBee modules is another advantageous trait. The goal is to make the charge controller as compact as possible and some wireless transceivers (especially their associated antennas) are large in size. The small size of 1.087” x 0.96” allows this module to be designed onto the PCB without taking up too much space.

In order to record the data that is being generated, there will be one Xbee module on the charge controller PCB that will transmit the information using the serial communication protocol. On the receiving end the XBee module will be placed on an Explorer Board that allows the user to connect to any computer via Universal Serial Bus (USB). Since the wireless link is composed of only two wireless modules, point-to-point communication will be used. This scheme is much easier to work with than a mesh protocol such as DigiMesh or ZigBee Mesh.

B. DC-to-DC Regulator

Typically used in an off-grid scenario, charge controllers are used to monitor and regulate the solar array output voltage to the batteries, which store the energy generated. Output voltage regulation is very important in battery charging because batteries require a specific charging method with various voltage and current levels for each specific stage. These charging methods are needed to prolong battery life and performance.

The DC voltage from the panel will vary depending on irradiance and solar panel temperature. On the battery side of the system, the battery voltage will vary depending on the load connected to it. In order to maintain optimal battery charging, it is extremely important that the panel voltage and current matches the required battery charging stage at that particular moment.

A DC-to-DC regulator is needed to increase or decrease the input panel voltage, in order to match the required battery charging level. These regulators are also known as switching regulators where power switches, capacitors, diodes and most importantly an inductor are used to transfer power from input, or PV panel, to output or in this case the battery. These components can be arranged in various ways to form different types of DC-to-DC regulators.

The most common DC-to-DC regulators are: Buck or Step-Down, Boost or Step-Up and Buck-Boost. Capable of operating in either mode Buck-Boost converters are becoming more and more popular in implementing Photovoltaic Charge Controllers. This is one of the main reasons why this architecture will be implemented for this specific project. These regulators can increase “boost up” the input voltage to match a required output voltage or decrease “buck down” the input voltage to a lower output voltage. They do not generate power; therefore the adjusted voltage level affects the current level, ideally maintaining the same power level from input to output. Since current and voltage are both directly proportional to power, it is intuitive that in buck mode the voltage is lowered as the current increases. While in boost mode the voltage is increased as the current decreases.

The single inductor H-Bridge topology in Fig. 5 is a non-inverting circuit that allows the use of a Buck and Boost converter separately or simultaneously. Using synchronous 4-Switch Operation for higher efficiency the regulator will be designed to accept an input range between 10 - 24 V and an output range of 12 - 15.

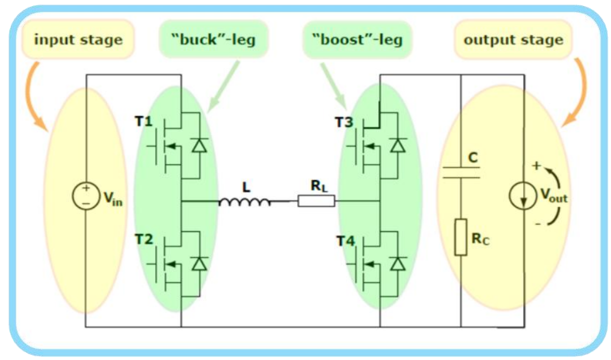

Fig. 5. Voltage divider circuit used to sense voltage.

While operating in Boost Mode a higher regulated output voltage ensures that there is current flowing from input to output even though, at that instance, the solar panel voltage is less than that of the battery. A lower output current will take longer to charge the battery, but in a situation where the panel potential is not high enough to match that of the battery, little current is better than no current at all.

In Buck Mode this regulator steps down the panel voltage to match the required battery voltage. By doing so, the difference in potential is converted to create a higher output current. The increase in charging current reduces battery charge time. In both scenarios the input power is preserved as much as possible with very little circuit power loss. Efficiency is very important in designing a DC-to-DC converter. Efficient circuit components are used, in order to build an efficient converter.

MOSFET transistors are an efficient and reliable way to implement the power stitches mentioned earlier in the Buck-Boost architecture. IRF3205 power N-Channel MOSFET’s will be used in pairs in each “leg” of the H-Bridge circuit. These MOSFET’s are equipped with intrinsic diodes. Pulse width modulation (PWM) will be used to control the duty cycle of the ON and OFF time of the MOSFET’s. Two separate PWM signals from the ATmega328P microcontroller are fed into two IRS2104 MOSFET driving IC’s respectively. Each IRS2104 synchronously controls the MOSFET pairs of the Buck leg and the Boost leg. These drivers are also equipped with shut down pins, which will be controlled by a digital pin from the ATmega328P microcontroller.

In Buck operation MOSFET’s T1 and T2 are switched complimentarily by the Buck-Leg driver at D1 duty cycle, while T3 stays ON to form a short and T4 is turned OFF to form an open circuit. In order to achieve the ON/OFF operation modes of T3 and T4 the PWM duty cycle D2 fed to the Boost-Leg driver is set to 97%. Similarly in Boost Mode MOSFET's T3 and T4 are switched complimentarily by the Boost-Leg driver at D2 duty cycle, as T1 stays ON and T2 is turned OFF. The Buck leg driver is fed a PWM signal with a duty cycle D1 equal to 97%.

In an ideal case equation (3) relates the input voltage Vin, output voltage Vout, the Buck-Leg and Boost-Leg duty cycles D1 and D2.

$$Vout = \frac{D1}{D2} \times Vin \tag{3}$$

Theoretically T2 and T3, the synchronous rectifiers, can be replaced with rectifier diodes without affecting the functionality of the circuit. This will simplify the circuit, but in terms of efficiency the diode will cause more conduction losses than the MOSFET, making the use of a diode inefficient in the grand scheme of things.

Input and output filter capacitors will be used to smooth out the current pulses from the panel and the inductor respectively. A fifth MOSFET T5 will be placed at the input before T1, which will block the battery power from flowing back to the solar panels at night. Normally this is done by a diode in the power path, but since all diodes have a voltage drop, a MOSFET is again much more efficient. T5 will be turned around so the intrinsic diode of the power MOSFET will not conduct. T5 will be driven of the same gate signal path as T1. Another safety feature included in the DC-to-DC regulator design is the input and output fuses that provide over current protection.

V. SOFTWARE

The main loop of the program will consist of the following four functions:

```
read_sensor_data();
charge_controller();
print_data_LCD();
transmit_data_xbee();
```

These functions will read in all of the sensor values, determine the charging state of the battery and perform MPPT algorithms, print the relevant data to the LCD screen, and transmit all of the data to the computer, respectively. This project is addressing the efficiency that can be achieved through the optimal use of the charge controller, specifically by implementing MPPT algorithms.

There are several common methods that are used to implement maximum power point tracking. These iterative approaches imply varying levels of complexity based on the type of tracking that they utilize. The most common methods of MPPT are the Perturb and Observe Method, Incremental Conductance Method, and the Fixed Voltage Method. This software implemented in the PMC^2 charge controller will utilize the perturb and observe method.

This method of power point tracking follows the procedure of constantly checking the voltage (or current in some systems) and continuing to increase the voltage as long as the power continues to increase. After passing over the maximum power point the power will begin to decrease which the algorithm will interpret as having gone too far and will start decreasing the voltage to compensate. This process continues to iterate until the maximum power point has been reached.

Once the microcontroller reads in the sensor values, it can also take into account other relevant information before adjusting the current and voltage sent to the battery. As shown in Fig. 7. the ATmega328P microcontroller will not only be reading in the current and voltage from the PV system but also needs to consider the current, voltage, and temperature from the battery bank. The MPPT algorithms are in place to make sure the maximum power is delivered to the battery, but the value to be supplied can change based on what state the battery is in. The microcontroller will have 3 numerical voltage thresholds in place to designate when to switch between these battery-charging stages, using a `switch/case` statement.

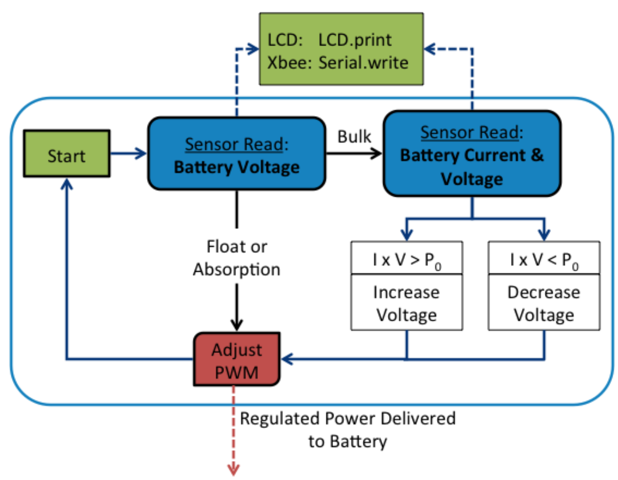

Fig. 7. The perturb and observe method for maximum power point tracking.

In order to physically adjust the voltage, the microcontroller will be able to control toggle switches using two of its digital output pins. This in turn will be able to control the buck and boost converters, which receive the solar input in parallel. The microcontroller is able to designate what voltage this should be using the PWM output.

VI. User Interface

At the receiving end of the wireless configuration the Xbee module will be connected to the Xbee Explorer board, allowing it to communicate with any computer via USB. At this interface, the serial data that has been transmitted wirelessly will be loaded on to the PC. The baud rate will be set at 9600 bits per second but may be increased if necessary.

Once it has been obtained, the data will need to be presented in a way that is informative and useful for the user. The serial data that is received will be continuously stored in an Excel file that is specified by the user in the software on the microcontroller. This will be facilitated by the free software GoBetwino. Since the system will be obtaining data from several sensors, the first line of the .csv file will contain headings for each sensor along with the units they are presented in. Each entry will be time stamped and then the numerical values will continue to fill in the columns until they reach the end of the row, signifying the end of that specific entry.

Since Excel is very widely used in both academia and industry and provides ample graphical and analytical tools, this method of data storage will allow the end user to quickly and easily evaluate the data that has been collected. For example, the user can quickly make a plot of the power versus temperature or irradiance and understand how the panel had been performing.

VII. Printed Circuit Board Design

This custom printed circuit board shown in Fig. 8 has been designed using CadSoft's Eagle PCB Design software. The final design will be 7.5 x 5.5 in and was manufactured by Advanced Circuits. The largest trace widths are 0.07 in. allowing them to handle a maximum of 5 A at a rise temperature of 15°C. The bottom layer of the two-layer board will be a ground plain which will help reduce external noise to the electronics and help keep all grounds well connected. In the power electronics circuitry, top copper plains where added in place of traces to assure high current capacities could be handled without over heating. A similar technique was used for the 5 V and 3.3 V switching regulator, where plains of copper served as traces to keep the circuit as tight as possible for best efficiency.

VIII. Testing

A testing plan was developed to ensure that all of the features of the PMC^2 system work as expected. First, during initial prototyping, each part was tested at the component level to confirm that it works individually before integrating it into the system. Each of the current sensors, irradiance sensor, voltage divider circuits,

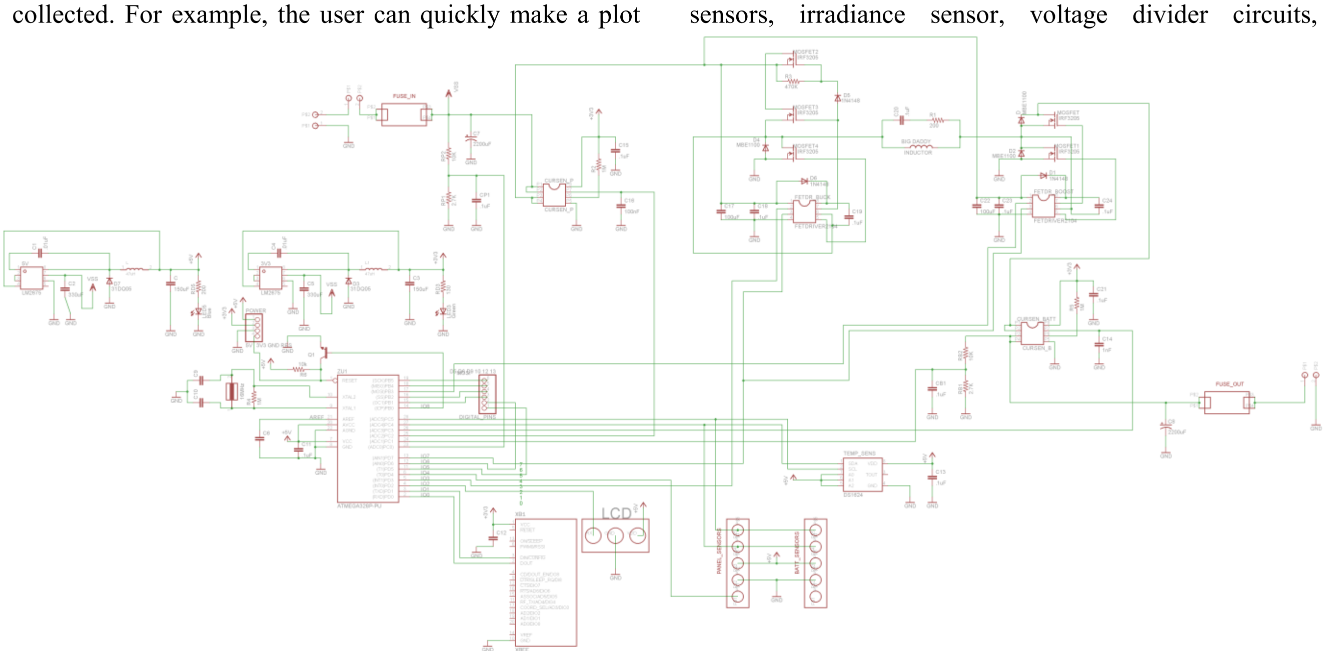

Fig. 8. Final schematic of charge controller printed circuit board.

temperature sensors and LCD screen were connected to the Arduino development board and checked for accuracy. The DC-to-DC regulator circuitry was also replicated on a solderless breadboard to demonstrate its functionality before its layout was designed into the PCB.

The power components were also tested individualy. The PV module was monitored outdoors while attached to a voltmeter. The battery was also connected to a voltmeter and allowed to discharge when a load was attached. Finally the inverter was connected to the battery and was able to power several electronic devices as intended.

System level testing will be performed when the four major components are connected together. The system will have a short list of features to check that will verify correct operation including the solar panel producing power, LCD and wireless are operational, battery is being charged/discharged, and inverter supplying power. All sensor data will be transmitted to the Excel file, streamlining the analysis of the system.

IX. Conclusion

Ultimately the solar panel will be mounted onto a custom designed aluminum frame with caster wheels on the bottom for ease of transport. This cart will hold the charge controller, battery, and inverter as well. The system can be easily moved to different outdoor locations and the system status and sensor data will be remotely monitored. These design features were included to help make the PMC^2 module appealing to solar researchers. Overall, the efficiency of the system is the most important, and is addressed through the use of efficient components, a low power charge controller, and the implementation of maximum power point tracking. These algorithms allow the system to be as efficient as possible through constantly changing atmospheric conditions.

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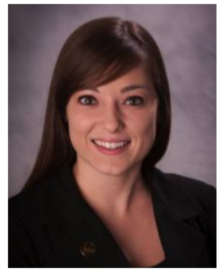
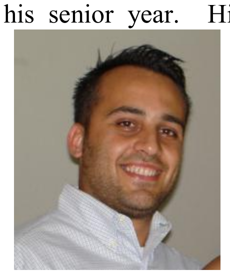
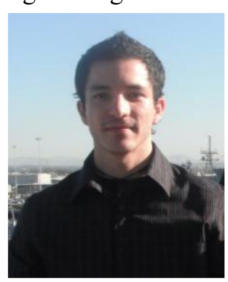
Biographies



Amber Scheurer is a senior in electrical engineering with an interest in semiconductor fabrication. She completed an Honors in the Major Thesis after working in the College of Optics and Photonics (CREOL) for two years. Amber will be working as a process engineer for Texas Instruments in Dallas, TX upon graduation.



Ersuel (Eric) Ago is an electrical engineering student in his senior year. His interests include electrical power systems and power electronics. Upon his graduation in May 2012, he is interested in working for a utility company in the power industry. He plans to continue his education and pursue a master's degree in electrical engineering in the near future.



Juan Sebastian Hidalgo is majoring in electrical engineering and he has obtained an International Engineering minor by completing a semester abroad in Rio de Janeiro, Brazil. He plans on spending the summer studying and backpacking in Italy before graduation. He has been an active member of the Society of Hispanic Professional Engineers (SHPE) and is interested in pursuing a job in the fields of robotics, RF communications, electric machinery, or renewable energy systems.

Steven Kobosko is a graduating senior in electrical engineering. His hobbies include traveling, playing piano, learning foreign languages, and backpacking. He plans to attend graduate school in the area of Materials Science and Engineering researching methods to improve solar cell efficiency.

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