Oil-Well Monitoring System

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Abstract — **The objective of this project was to work in collaboration with a buoy team, a turbine team, and a sensor team, converting wave energy input into stable DC output in order to power the sensors. The motivation for this project came from the more than 27,000 abandoned oil wells in the Gulf of Mexico alone. The solution was expected to efficiently provide reliable, DC energy to the oil sensors despite the unsteady energy input from wave motion. The team chose this project, sponsored by the Harris Corporation, in order to utilize engineering skills in an eco-friendly endeavor.**

Index Terms — **AC-DC power converters, DC-DC power converters, hydro-electric power generation, oil pollution, sea floor.**

I. INTRODUCTION

Hydrocarbons and their derivatives are a vital energy source for the world. This energy source must be managed effectively. Failure to do so often results in severe economic and environmental damage. Oil spills and leaks remain an area of hydrocarbon management that needs improvement. The Gulf of Mexico alone is home to 27,000 abandoned oil well heads. Currently, there is no monitoring system in place to detect oil leakage from these abandoned wells [1]. A system with the ability to actively prevent, monitor and respond to oil spills is desperately needed.

A small contingent of engineers was assembled to develop such a system. A plethora of oil detection senor packages can be developed to detect underwater oil leaks. However, all of these packages require power. Obtaining useful electrical energy in the middle of the ocean is not an easy task. Nature provides three main sources of convertible energy. These include solar, wind, and waves. A mechanical energy team decided to design and build a hydro turbine to power a generator. Deep water ocean waves will move water over the turbine, causing it to rotate. The wave generator will be placed on a large buoy that is tethered to the underwater apparatus. Several factors influence the magnitude, direction, and frequency of waves. Thus, ocean waves fluctuate at random which directly impacts the output of the generator. The output of the generator was a signal of variable voltage, current and frequency. Such a signal could not be used by any electronic components. Additionally, the generator was only efficient if it operated above a particular RPM [2]. Thus, the electrical energy from this generator needed to be efficiently managed, converted and stored for use by the remaining components of the system.

The team analyzed, designed, built, and tested a low cost power management circuit. The AC signal was first converted to high voltage DC. A step down DC-to-DC converter brought the DC voltage down to a useable level. Also, the circuit utilized effective control mechanisms to automatically adjust the load based on input voltage. Excess power was stored in a battery. A charging circuit was integrated into the design to allow the charging of a 12V battery. Lastly, it was designed to withstand harsh weather conditions in the gulf coast.

II. OIL WELL MONITORING SYSTEM PROFILE

This project is a four part project that consists of three Mechanical teams: Turbine, Buoy and Sensors, and an Electrical team.

A. Turbine Team Description

The purpose of the Turbine team is to convert wave motion to rotational motion by means of a bi-directional turbine. The turbine will be connected to the generator shaft. After extensive testing, the team expects to produce an RPM range of 0 – 150 RPM based on the performance characteristics of the turbine.

B. Buoy Team Description

The Buoy team is responsible for designing a rigid geometry platform for consistent powerful motion. The buoy design will also provide stabilization, house the generator and drive the turbine. The buoy design includes an outer hollow shaft that will not only prevent horizontal forces to interrupt turbine shaft rotation but also prevent water entering generator housing. This is ideal as the electrical unit will be placed on the buoy next to the generator housing.

C. Sensor Team Description

The Sensor team is responsible to design a system that can detect the presence of oil in water. The data will be transmitted wirelessly to the stations on land.

D. Electrical Team Description

The purpose of the Electrical team is to condition the varying AC signal to a steady DC signal and supply it to the sensor system.

III. PROBLEM FORMULATION

The objective of this senior design project was to research and design a power conversion system that could take an unsteady AC input from the wave-powered generator and produce a steady DC output that could charge a battery and feed into the sensor system. It was critical that the project was able to perform efficiently even when the turbine was not turning and no power was being supplied. Maintaining a minimum rotational inertia of the turbine via load management was also a critical part of the project. In order to achieve this, the system needed to be able to successfully charge and draw power from a 12V battery. To that end, the following goals and requirements were established.

A. System Goals

In order to effectively and efficiently power the sensors using the wave energy output from the generator, the following system goals needed to be met.

- Convert unsteady AC input to steady DC output.
- Maximize the energy supplied to the sensors from the wave generator.
- Operate when the generator output voltage is less than the battery voltage.
- Remove the load when the turbine RPM falls below a minimum value.
- Reengage the load after the RPM has sufficiently exceeded the minimum value.
- Prevent the battery from feeding back into the circuit when the connection to the generator is turned off.
- Minimize the cost of components.
- Protect the entire circuit in a waterproof enclosure.

B. System Requirements

To meet the goals stated above and effectively integrate with the generator and sensor systems, the following system requirements needed to be met.

- Operate with an input range of 0V-60V AC.
- Produce a constant 13.8V to charge a 12V lead-acid battery.
- Sustain a maximum charging current of 2.1A
- Remove the load with an input under 15V.
- Reengage the load upon reaching an input of 30V.
- Meet a budget of $2,000.

IV. DESIGN

To make the system cost-effective and easy to implement, while keeping in mind the objectives and requirements of the system, appropriate components had to be chosen. To convert the turbine's rotational energy, a generator was provided. So, then the basic idea was to extract the AC signal from the generator, convert it to DC and provide a stable DC output to power the sensors. Hence, the project was divided in four main categories: Input Circuit, Buck Converter, Microcontroller, and Battery Charger Controller. The block diagram of the overall system is shown in Fig. 1.
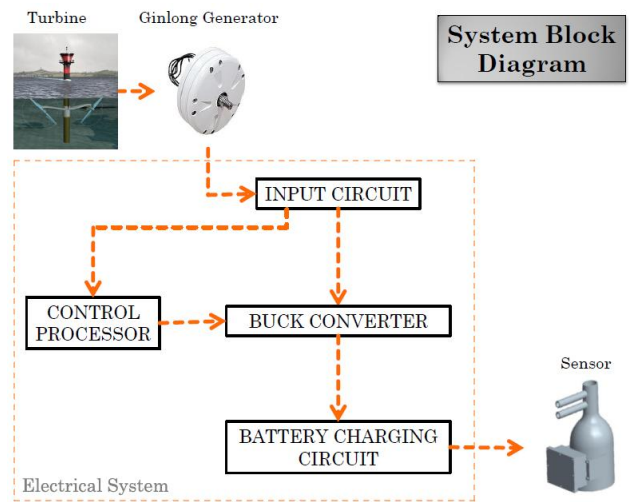

Fig. 1.   System Block Diagram

A. Generator

A Ginlong GL-PMG-500A permanent magnet generator (shown in Fig. 2) was used to convert the wave energy into electrical energy. The generator is capable of producing 500 Watts at 450 RPM. Thus, to compensate for the high output power, the generator was outfitted with a 3-phase star connection. Three phase systems are common in higher power applications because it lowers the electrical stress on components. However, the sensor team only required 15 Watts to power their equipment. Our design is self powered and added to this total power consumption. Because a low power microcontroller was used in the design, the total power consumption was only slightly over 15 Watts.

Rather than designing a more complicated and more expensive three phase system, we opted to implement a single phase design. A three phase to single phase conversion was relatively simple because the generator had three hot terminals and one neutral. Thus, our system was connected to one hot terminal and the neutral terminal. The disconnected terminals have no effect on the generator. These disconnected terminals can't draw any current. Therefore, the two open connections don't add any rotational resistance to the generator shaft.

Fig. 2.   Ginlong GL-PMG-500A

The generator will be turned by wave energy harnessed through a uniquely designed turbine system, it was expected that the rotations per minute of the generator would vary significantly. No load would be placed upon the generator at startup, but the load control circuitry would ultimately be responsible for maintaining the steadiest possible rotation in the generator. Fig. 3 shows the power voltage (V) output for the Ginlong generator as a function of rotation speed (RPM) [2]. The power output is very low and grows very slowly for low rotation speeds, but at higher rotation speeds, the power output begins to climb more rapidly. The voltage output has an approximately linear relationship with rotation speed, where the voltage in volts is equal to one tenth of the rotation speed in RPM.
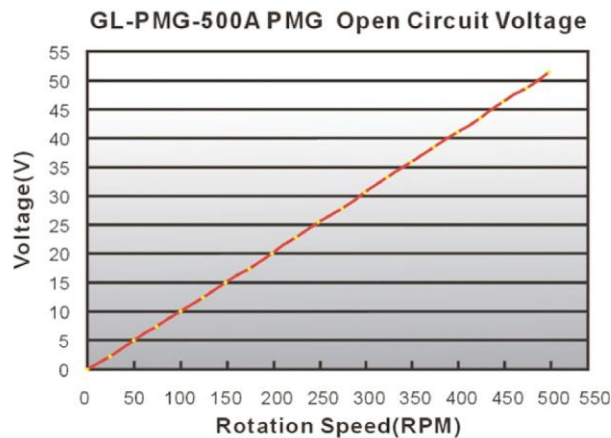

Fig. 3.   GL-PMG-500A PMG Open Circuit Voltage vs. RPM

The desired RPM range was from 150 to 450. This corresponds to an open circuit voltage of 15 to 45 V. The output of the generator was connected to an input circuit. The goal of the input circuit was to provide notification that the generator was supplying voltage and to convert that varying AC to varying DC.

B. Input Circuit

The AC voltage from the generator was first connected to an LED indicator circuit. This circuit was created for safety and convenience only. While the LED is lit, we know the generator is producing an output high enough to charge the battery. The schematic for the LED indicator and its PCB layout are shown in Fig. 4 and Fig. 5 respectively.
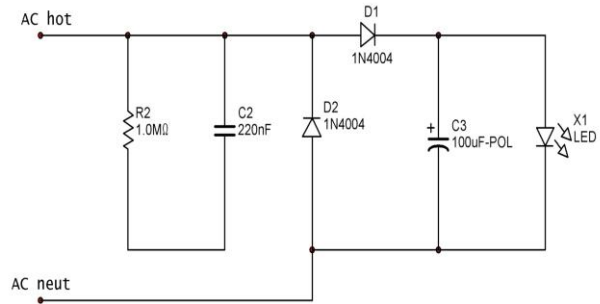

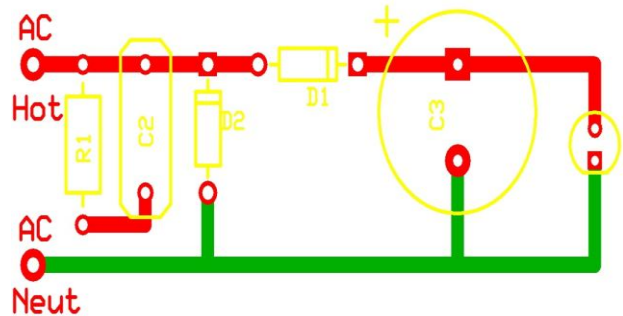Fig. 4.   LED Indicator Schematic

Fig. 5.   LED Indicator PCB layout (top layer).

The AC voltage was then connected to an AC-to-DC converter. The first stage of the converter is a low pass filter. The filter prevents the high frequency switching noise from being driven back onto the AC line. The low pass filter was connected to a full wave bridge rectifier. This simple circuit will output a rectified AC voltage. When the input voltage is positive, two of the diodes are forward biased, while the opposite two are reverse biased, providing a positive output voltage. When the input voltage is negative, the diode biases are switched, and a positive output voltage is still produced. At this point, we are able to deliver a form of DC. However our desire was to produce constant-voltage DC. In order to produce steady DC from a rectified AC supply, we needed to add a smoothing capacitor at the DC output of the rectifier. There will still remain an amount of AC ripple voltage

where the voltage is not completely smoothed. Also, the sizing of the capacitor represents a tradeoff. For a given load, a larger capacitor would reduce ripple but would cost more and would create higher peak currents. For a given tolerable ripple the required capacitor size is proportional to the load current and inversely proportional to the supply frequency and the number of output peaks of the rectifier per input cycle. A 150uF electrolytic capacitor was chosen as the reservoir capacitor. The schematic for the AC-to-DC converter and its PCB layout are shown in Fig. 6 and Fig. 7 respectively.
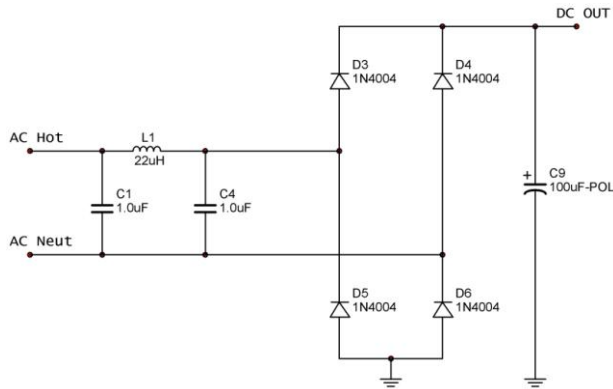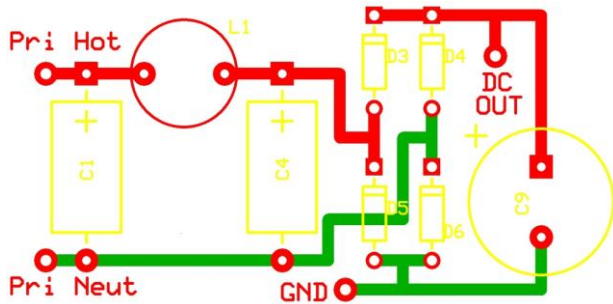

Fig. 6.   AC-DC Converter Schematic

Fig. 7.   AC-DC Converter PCB layout (top layer)

To power the microcontroller, a DC voltage of 3.3 V was needed. So, the 12 V output of the battery was first connected to a LM340AT-5 three terminal positive fixed voltage regulator. This regulator was chosen because it supported a wide input range from 5 – 18 volts. The battery voltage could vary from 10 – 14.5 volts. Also, the TO-220 package (without a heatsink) was selected because the microcontroller only had a current draw of 250 mA. The output of the LM340AT-5 is a constant 5 volts. So, another voltage regulator was needed to bring the voltage down to 3.3 volts. The LM3940 was a perfect component for the latter for several reasons. First, it had excellent load regulation and a guaranteed 1A of output

current. It had built-in protection against excess temperature and was short circuit protected. This regulator also featured low dropout. So, it could hold its 3.3 V output in regulation even with input voltages as low as 4.5 V. The schematic for the voltage regulation circuit and its PCB layout are shown in Fig. 8 and Fig. 9 respectively.
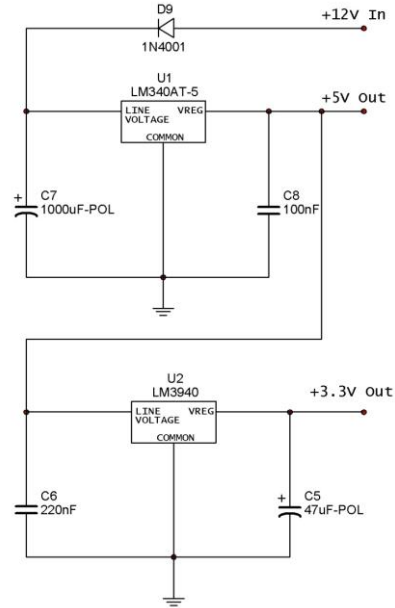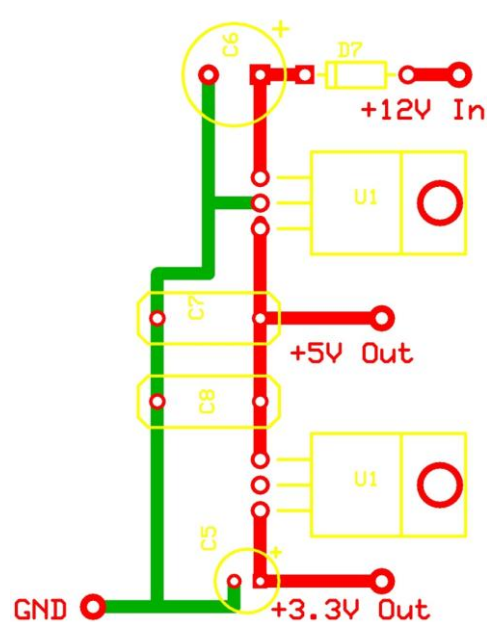

Fig. 8.   Voltage Regulator Schematic

Fig. 9.   Voltage Regulator PCB layout (top layer)

C. DC/DC Converter

For the DC/DC Converter, the TPS54260 Step Down (Buck) Regulator was chosen (shown in Fig. 10). TPS54260 features a wide range of input voltage from 3.5V to 60V [3]. It also features adjustable UVLO voltage and hysteresis. This converter is able to synchronize to external clocks. Additionally, the 200mΩ high side MOSFET is integrated within the regulator. This allows up to 2.5A of continuous load current. As mentioned in Table I, the TPS54260 requires a low shutdown supply voltage and a low supply current. The typical current limit threshold for the circuit is 6.1A and the typical thermal shutdown temperature is 182 °C which is much higher for the system design.
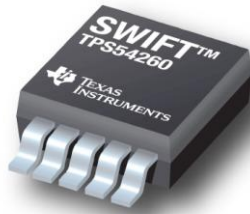

Fig. 10.   TPS54260 Step Down Regulator

TABLE I
TPS54260 ELECTRICAL CHARACTERISTICS

Parameter	Values		
	min	typ	max
Operating Input Voltage	3.5 V		60 V
Shutdown supply current		1.3 µA	4 µA
Output current range	0 A		2.5 A
Operating: nonswitching supply current		138 µA	200 µA
Enable threshold voltage	1.5 V	1.25 V	1.36 V
Current limit threshold	3.5 A	6.1 A	
Thermal shutdown		182 °C	

This step-down regulator features an enable (EN) pin that has an internal pull-up current (I1) source of 0.9 µA. By default, the regulator will shut down if the input voltage falls below 2.5V. However, this input voltage can be adjusted if the application requires a higher

undervoltage lockout (UVLO). This can be done by adjusting the values of two resistors. (1) computes the value for resistor R1 for external hysteresis while (2) computes the value for resistor R2 for the input start voltage.

$$R1 = \frac{V_{START} - V_{STOP}}{I_{HYS}} \quad (1)$$

and

$$. R2 = \frac{V_{ENA}}{\frac{V_{START} - V_{ENA}}{R_1} + I_1} \quad (2)$$

Here, I_{HYS} is the current that controls hysteresis and V_{EN} is the voltage for the enable pin.

The TPS54260 has the switching frequency internally set to 500KHz. Also, to allow higher efficiencies, the low drain-to-source on-resistance MOSFET is used within the controller. The converter also provides adjustable output and slow start conditions.

For this design, the TPS4260EVM-597 was used. This is the Evaluation Module which consists of the TPS54260 regulator. The setup for this evaluation board is maximized for a 10.8V to 13.2V input voltage. However, the EVM was modified to operate from input voltages up to 60V with lesser efficiency. Fig. 11 shows the PCB layout of the TPS54260EVM-590 [4].
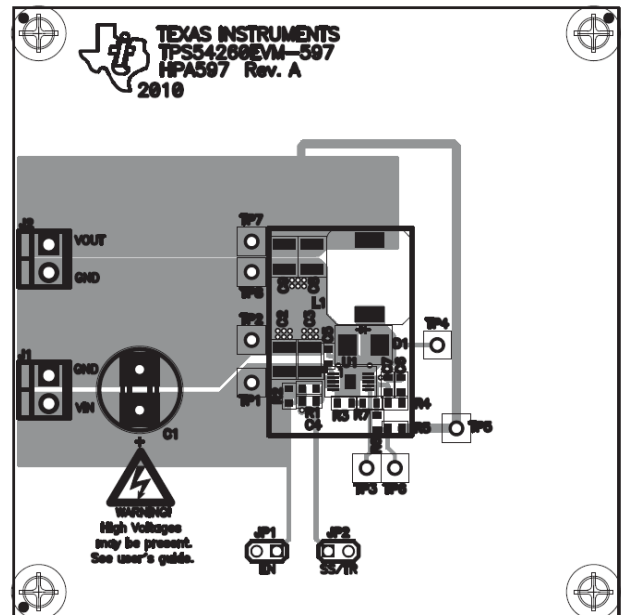

Fig. 11.   Printed Circuit Board layout (top assembly layer) of the TPS54260EVM-590.

The output of the TPS54260EVM-590 will provide necessary input for the battery charge controller.

D. Battery Charge Controller

To provide a constant DC output to power the sensors, a lead-acid battery had to be used. However, it was necessary to control and monitor the battery charge. In order to charge the lead-acid battery, the bq24450 which is an integrated charge controller for lead-acid batteries was chosen. Some of the features of this controller are [5]:

- Voltage and Current Regulation
- Optimization and maximization of battery capacity over temperature
- Ensure battery safety for charging at high temperature

There are two configuration modes for the bq24450 controller: simple constant-voltage float charge controller or a dual-voltage float-cum-boost charge controller. An improved dual-level float-cum-boost charger with pre-charge circuit will be used in this design as this circuit is optimized for deeply discharged batteries. This configuration limits the current level as it depends on the charge level of the battery.

The bq22450 IC provides temperature compensated built-in precision voltage reference which enables the tracking of lead-acid cell characteristics, also providing optimum charging environment, without use of external components, over an extended temperature range.

The bq22450 IC can be configured to drive various types of external pass transistors. The topologies for the external pass transistor circuits include: Common-Emitter PNP, PNP in a Quasi-Darlington with Internal Driver, External Quasi-Darlington, and NPN Emitter-Follower. It was necessary for the design purposes to use a topology with broad range for charging current while having a minimum voltage difference from input to the battery [6]. As shown in Fig. 12, the External Quasi-Darlington topology features a maximum charging current range from 0.6A to 15A and a low voltage difference (ΔV) of 1.2V, which is why this topology was used in the design.
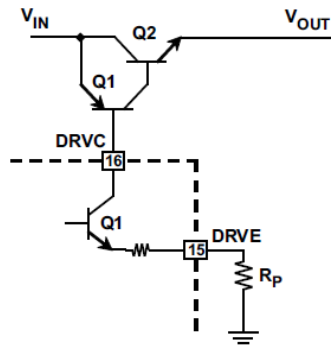

Fig. 12.   External Quasi Darlington Circuit Schematic.

The bq24450 IC monitors the output voltage to the battery. If the output voltage is less than the charge of the battery, the IC will come to a halt and start charging as soon as the charge voltage drops below the IC output voltage.

For this design, the bq24450EVM was used. By default, this evaluation module is optimized for a 3-cell 6V lead acid battery. However, the EVM was altered in order to produce higher voltage for the 12V battery. This was accomplished by changing some resistor values.

The EVM was initially populated with the Common-Emitter PNP topology. But, with a few changes, the Quasi-Darlington topology was established. Fig. 13 shows the PCB layout for the EVM [6].
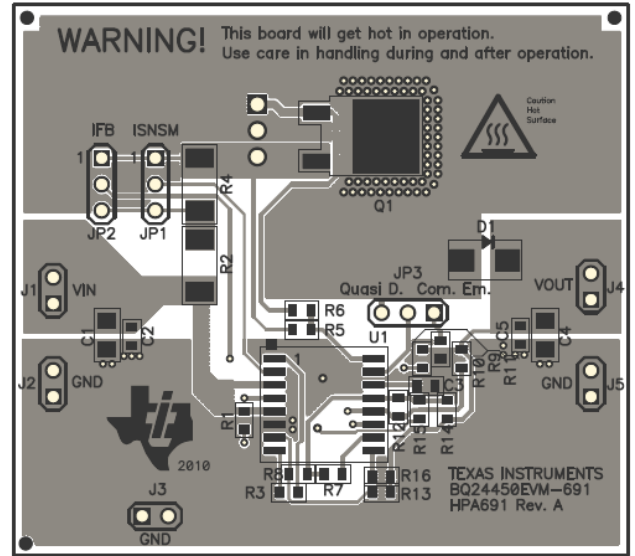

Fig. 13.   Printed Circuit Board layout (top assembly layer) of the bq24450EVM.

E. Microcontroller

The purpose of the microcontroller for this project was to implement load control in order to make the system as efficient as possible, to turn the system off in the event of excessive waves and on again once the waves diminished, and to display to the LCD screen the current voltage input as well at the battery voltage in real time. The microcontroller chosen for this purpose was the PIC24FJ96GA010 [7], shown in Fig. 14.

The PIC24FJ96GA010 was chosen as it runs on low power and is easily programmable in various languages including C. This 16-bit microcontroller was chosen because of its extensive features as shown in Table II. This provides the ability to upgrade the system in the future to include various efficiency based applications such as

Power Factor Correction (PFC), Maximum Power Point Tracking (MPPT), etc.

Fig. 14. PIC24FJ96GA010 mounted on an MCU card.

Load control of the system was accomplished by utilizing the enable pin on the TPS54260EVM-597 DC-DC buck converter [4]. The converter was able to take in a maximum voltage of 60V, and a minimum input of approximately 15V was necessary to successfully charge the 12V lead acid battery. To maintain efficiency of the system, the microcontroller was programmed to disable the converter when the input voltage was measured at below 15V (150 RPM). To prevent the microcontroller from rapidly enabling and disabling the converter around the 150 RPM point, it was determined that after a disable, the generator should be allowed to build an additional 100 RPM before the load was reintroduced. Thus, the generator was then allowed to build momentum without any load until the input reached 25V (250 RPM). The microcontroller would then turn the enable the converter until the input voltage again dropped under 15V. To compensate for DC ripple at the input, the microcontroller sampled the input voltage every millisecond for a duration of 500 milliseconds. The average voltage was computed, and the converter was only enabled or disabled if the input voltage was found to have sustained its value for the duration of the sampling.

Because the buck converter had an absolute maximum input voltage rating of 60V, it was necessary to implement control to prevent damaging the device if the generator output exceeded 60V. Airing on the side of caution, the maximum allowable voltage was chosen to be 55V. In the event that strong waves resulted in an output from the generator of greater than 55V, the microcontroller disabled the converter. The converter was then enabled after the input voltage had fallen under 55V.

Both the load control and the overvoltage compensation relied on the measurement of the input voltage. A simple voltage divider was used to scale down the input voltage to a range acceptable to the microcontroller. The microcontroller then used this value to determine the input

voltage and disable or enable the buck converter as needed. Furthermore, for the purpose of conveniently monitoring the system, the microcontroller was programmed to display both the system input voltage as well as the battery voltage in real time. To accomplish this, the input voltage and the battery voltage were scaled down using voltage dividers and fed into ADC pins on the microcontroller. The ADC reading was then converted to a millivolt scale, and the voltage digits were extracted one at a time, converted to ASCII digits, and printed to the LCD display. The measurement and conversion were kept in an infinite while loop with a 500ms delay, resulting in an updated voltage measurement twice every second.

TABLE II
MICROCRONTROLLER TECHNICAL SPECS

Parameter Name	Value
Architecture	16-bit
CPU Speed (MIPS)	16
Memory Type	Flash
Program Memory (KB)	96
RAM Bytes	8,192
Temperature Range C	-40 to 85
Operating Voltage Range (V)	2 to 3.6
I/O Pins	85
Ping Count	100
System Management Features	BOR
Internal Oscillator	8 MHz, 32 kHz
nanoWatt Features	Fast Wake/Fast Control
Digital Communication Peripherals	2-UART, 2-SPI, 2-I2C
Analog Peripherals	1-A/D 16x10-bit @ 500(ksps)
Comparators	2
CAN (#,type)	0 None
Capture/Compare/PWM Peripherals	5/5
16-bit PWM resolutions	16
Timers	5 x 16-bit
Parallel Port	PMP
Hardware RTCC	Yes

V. LEAD ACID BATTERY

The output of the bq24450EVM was used to charge a lead acid battery. It was necessary to take into account that the battery should be able to sustain several hours of negligible or no wave conditions. Hence, for this project, an Enercell 12V, 7000mAH sealed lead acid battery was chosen that had enough mAH to sustain the necessary

conditions. The technical specs for this battery are provided in Table III [8].

TABLE III
BATTERY TECHNICAL SPECS

Dimensions	
Product Height	3.84 inches
Product Width	5.94 inches
Product Depth	2.56 inches
Battery Features	
Chemistry	Sealed Lead Acid
Capacity	7000 mAH
Voltage	12 V
Rechargeable	Yes
Normal Charge	14.4 V – 15 V
Stand by/Trickle charge	13.5 V – 13.8V
Max initial charging current	2.1 A

VI. CONCLUSION

This year long project provided everyone with vital practical real world experience. It helped combine the teachings of the classroom with professional side of business and industry. Having to research, design, build and test a real product took us far beyond pen and paper. We learned about the value of project management. We had to work together and communicate. Our group planned at least a dozen meetings. We learned to delegate critical tasks and work around various obstacles. We developed timelines and met deadlines. Our writing and presenting skills were improved throughout the two semesters as we continually wrote different types of technical documents and made a plethora of presentations. The wealth of knowledge and experience gained from Senior Design has been invaluable.

ACKNOWLEDGEMENT

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MEMBERS

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Jimit Shah is currently a senior at the University of Central Florida. He will be graduating with a Bachelor's of Science degree in Electrical Engineering in May 2011. He plans to join Texas Instruments starting July 2011 as a Technical Sales Associate. He is a current member of IEEE and plans to get his MSEE and MBA in the future.

Kaleb M Stunkard is a senior at the University of Central Florida. He will be graduating in May 2011 with a Bachelor's degree in Electrical Engineering and a minor in Computer Science. Presently, he works as an I.T. Manager at Lighthouse Central Florida. He plans to pursue a career in I.T. or as an electrical engineering patent reviewer for the U.S. government