Power Converter for an Electric Vehicle

Senior Project Final Report

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Abstract

A Plug-In-Hybrid Electric Vehicle (PHEV) is a hybrid vehicle that utilizes a battery to power a vehicle's electric motor, and can be recharged when it is plugged into a power source from the grid. PHEVs can significantly improve their fuel economy and produce fewer pollutants compared to conventional vehicles by employing this hybrid technology. The primary goal of this project is to design a charging and discharging system for PHEVs by means of Digital Signal Processing (DSP) and power electronics systems. In order to optimally charge a Li-Ion battery, an understanding of various charging methods and charging stages of Li-Ion cells are necessary. A generic Saft battery model can be used for the Matlab simulation and understanding the Li-Ion battery characteristics. Since the battery can be charged from the gird, safety is taken into account during the battery testing. In this report, the progress toward this goal is addressed in terms of charging of the battery, specifically 400W, 51.8V Li-Ion battery using a Texas Instrument 32-bit fixed-point DSP TMS320F2812.

Introduction

Hybrid technology has become a demand of both the regular consumer and the automobile industry. Hybrid vehicles can significantly improve the fuel economy, producing far less pollutants than traditional vehicles. Further integrating this technology, Hybrid Electric Vehicles (HEV) can be re-engineered to feature a plug-in capability that is known as Plug-In Hybrid Electric Vehicle (PHEV). This form of hybrid vehicle uses a plug-in from a grid (120Vrms), with a larger battery and motor. PHEV reduces the amount of space needed for a normal hybrid electric vehicle by eliminating the need for a combustion engine and gas tank.

Project Description

The primary goal of this project is to design a power converter system that will charge and discharge a battery. In order to achieve this goal, the system must use a Digital Signal Processor (DSP) that will drive the power electronics system. Along with this system, a bridge diode rectifier will be used to convert the AC grid power of 120Vrms to the 51.8Vpeak DC value to charge the battery. In order to implement this system, the charging and discharging characteristics of a battery must be understood. Furthermore, a control algorithm must be developed using the TMS320F2812 DSP board.

Theory

Designing the power converter system is not as easy as connecting the battery straight to the grid. The battery must be designed with certain specifications in order to

prevent harm to the battery. If these specifications are not followed, the battery could potentially explode or cause a fire. Even with a suitable system, the battery will still need to be enclosed to prevent any possible harm to the person attending to it or the system itself. In terms of PHEV, the high energy battery pack is to be charged with the Power Factor Correction (PFC) circuit from an AC outlet. The most common structure for the PHEV battery system is a two-stage approach with cascaded AC-DC converters and DC-DC converters. In the PFC system, AC single phase is rectified and boosted with Power Factor Correction. The output from the boost converter is connected to the DC bus along with the bidirectional converter.

Large-Scale System

The large-scale system handles the high voltage and current of the overall system. The system contains subsystems that include: a bridge diode rectifier, boost converter, and a bi-directional converter. The easiest way to design this overall system is by separately building each subsystem, testing to see that they would work, and then adding them to the overall system. In figure 1 below, the overall system is seen.
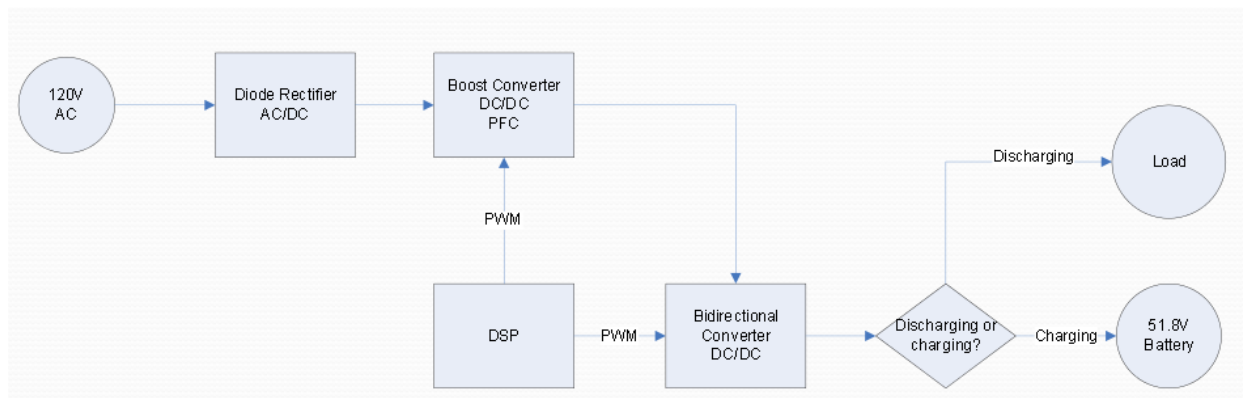

Figure 1: Large Scale System Block Diagram

AC/DC Diode Rectifier

The main purpose of the diode rectifier is to take the RMS AC voltage and convert it to a DC voltage. For the design of the Plug-In Hybrid Electric Vehicle Converter an uncontrolled diode rectifier will be used. The Figure 2 represents the general circuit for an uncontrolled diode rectifier.
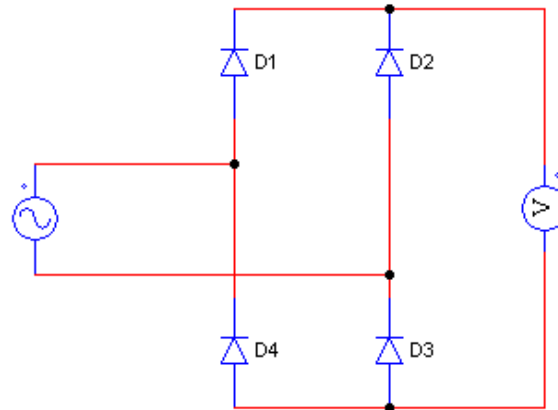

Figure 2: Uncontrolled Diode Rectifier

When the input voltage is positive, D1 and D3 diodes are conducting. These are then forward biased. D2 and D4 are in the "off" states when D1 and D3 are conducting. Furthermore, when the input voltage is negative, D2 and D4 are now conducting while D1 and D3 are then in the "off" states or not conducting. The switching functionality of the diodes converts the sinusoidal wave input into a rectified sine wave.

Power Factor Correction

The power factor correction circuit will be designed and implemented to increase the efficiency of the overall system. Power factor can be defined as the ratio between real power and apparent power. The main difference between real and apparent power is that one is used as the actual amount being dissipated, where the other is a combination of real and reactive power. The PHEV converter system then consumes this wasted power,

which in return lowers the efficiency of the system. The power factor correction system will increase the amount of real power and reduce the reactive power, thus creating unity power factor. By having a unity power factor, this will put the input voltage in phase with the inductor current. This can be shown below in Figure 3.
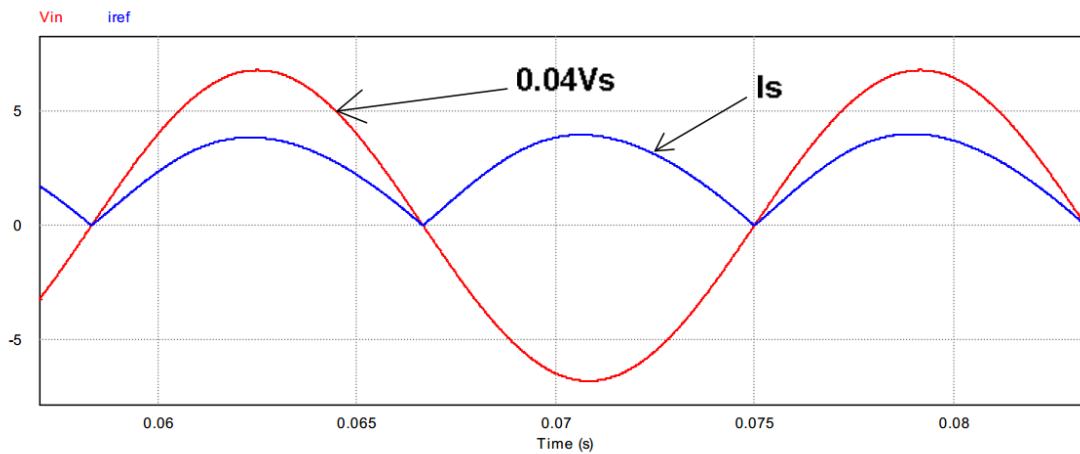

Figure 3: Input Voltage in phase with Inductor Current

Power factor correction can be achieved by adjusting the duty cycle of a boost converter. This type of power factor correction is called active power factor correction.

Bi-Directional Converter

The next step of the project after the Power Factor Correction circuit is the Bi-Directional converter. As shown in Figure 4, a Bi-Directional converter is interfaced with the battery to allow the charging and discharging of the PHEV system. The Bi-Directional Converter consists of two switches which control what mode the Bi-
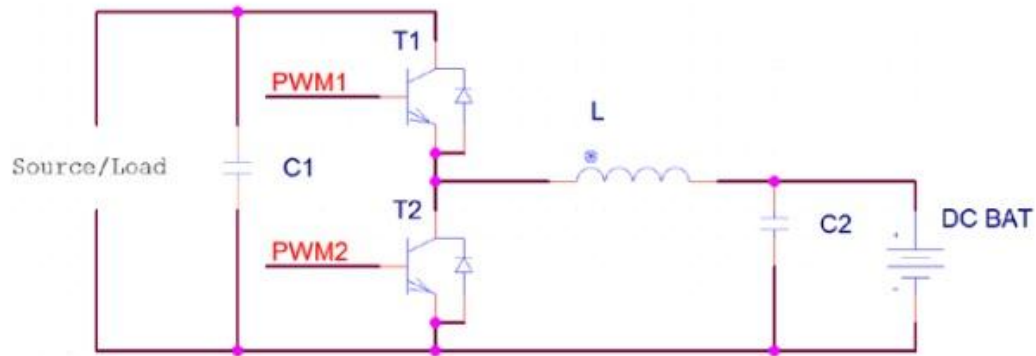

Figure 4: Bi-Directional Converter

Directional Converter is in. The Bi-Directional Converter has two modes, a buck converter or boost converter. When switch T1 is on, the Bi-Directional Converter is in buck mode. Switch 2 can act as a diode when it can also act as a boost converter for the system. In figure 4, the functionality of the circuit is given by the two switching transistors, T1 and T2. The transistors will receive PWM controls signals from the DSP directing the flow of the current. As mentioned earlier each of these modes can be used to charge or discharge the battery. To charge the battery the Bi-Directional Converter will be in buck mode. When the system is in buck mode, the output voltage will be lowered going to the input of the battery. This allows the battery to be safely charged to its full capacity. When the system is not charging, the converter switches to its second mode. In this mode, the battery discharges and boosts the voltage to a level that will drive the load.

Buck Converter

The buck converter, in addition to the boost converter, makes up the part of the bi-directional converter. The buck converter's main purpose is to lower the DC link voltage. By lowering the voltage, the DC Battery can be charged safely. If the buck converter were to not be implemented, high voltage could potentially cause harm to the battery. In Figure 5 below, the buck converter functionality is illustrated.

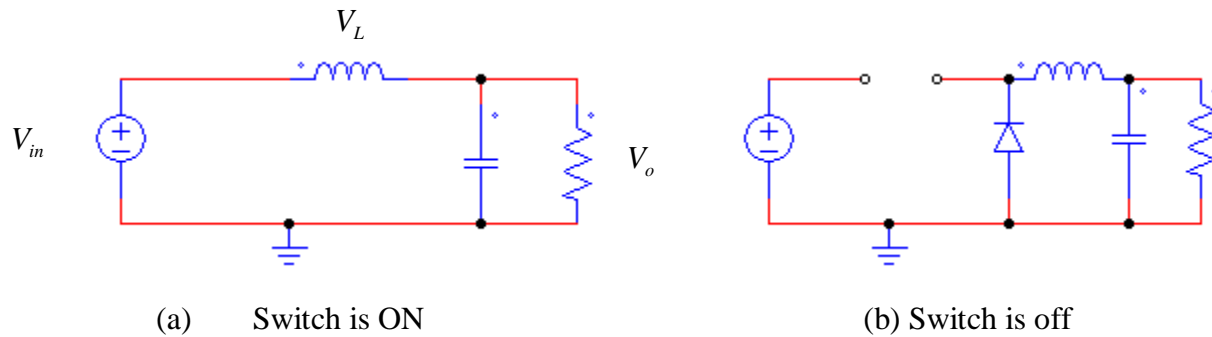(a)   Switch is ON   (b) Switch is off

Figure 5: Two Stages of the Buck Converter

As shown in Figure 5, the left circuit above, the transistor is closed and the voltage across the inductor can be found by $V_L = V_{in} - V_o$. The current through the inductor will then rise from this phenomenon. The diode is also in reverse biased during this stage. When the transistor is switched open, shown in the right circuit above, the diode then becomes forward biased and the voltage across the inductor can be found by $V_L = -V_o$. As a result, the current from the inductor decreases. The equation from calculating the effects of the buck converter are shown below.

$$V_o = \alpha V_{in} \tag{1}$$

The alpha shown in equation 1 is the duty cycle of the Pulse Width Modulated
(PWM) wave going into the transistor or switch.

Boost Converter

The second mode of the bi-directional converter is a boost converter. This will help with
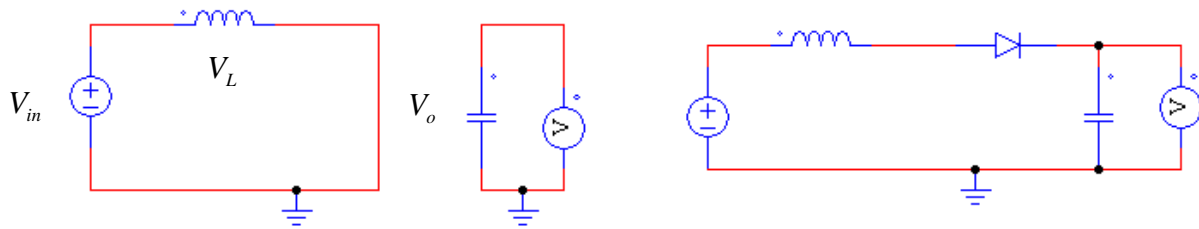the discharging of the battery and boosting the voltage to power the load.

Figure 6: Two Stages of the Boost Converter

The circuit illustrated on the left in Figure 6 shows the transistor, T, is turned on. This
then means that the diode, D, is turned off and the energy is stored in the inductor. In the
illustration on the right, the stored energy in the inductor is transferred to the load. The
output voltage is dependent on the rate of change from its current, thus providing steady
power through the load and into the capacitor. If the system switches back to its previous
stage, the energy stored in the capacitor will continue to provide a steady output. This
capacitor also helps to reduce the amount of ripples that occur in the output signal. The
output voltage, inductor value, and capacitor value can be calculated from the equations
provided below. The values chosen for the bi-directional converter were 1500uF and
1mH inductor. These values were chosen by equations (3) and (4).

(2)

$$V_{out} = \frac{1}{(1-\alpha)} V_{in}$$

$$C = \frac{V_M I_M}{2 \Delta V_{out} w V_{out}} \qquad (3)$$

$$L = \frac{V_{out}}{4 f_{swimax} \Delta I} \qquad (4)$$

Interfacing Circuits

To be able to control the power factor correction circuit and the bi-directional converter, a Digital Signal Processor (DSP) must be used to generate PWM signals. This can be shown in figure 1. In order for the DSP to generate these signals it must be able to receive feedback signals such as current and voltges from the power factor correction circuit and from the bi-directional converter. However, the DSP can only handle voltages that are from 0-3.3V. Therefore interfacing circuits are needed for both voltage control and current control of the power factor correction circuit and the bi-directional converter circuit.

Voltage Interfacing Circuit

For both the power factor correction circuit and the bi-directional converter voltage feedback is needed. However in both of these circuits the output voltage is much higher than 3.3V. Therefore, a voltage interfacing circuit is needed. The first step in this interfacing is a voltage divider. This will decrease the voltage to an acceptable value to be read by the DSP. The next step will be an op-amp in unity configuration which will act as

a buffer. After the voltage passes through the op-amp it will then be pulled up to 3.3V. If the voltage exceeds 3.3V or pulled down to 0V the voltage is than received as 0V. This is achieved by having diodes that will either pull up to 3.3V or pull down to 0V. The last step in the voltage interfacing circuit is important because this will handle any transients that are above 3.3V or below 0V. It will also prevent any voltage spikes due to the MOSFET switching. The figure 7 is how this system is implemented. For small scale we used 1k ohm and an 11k ohm resistor.
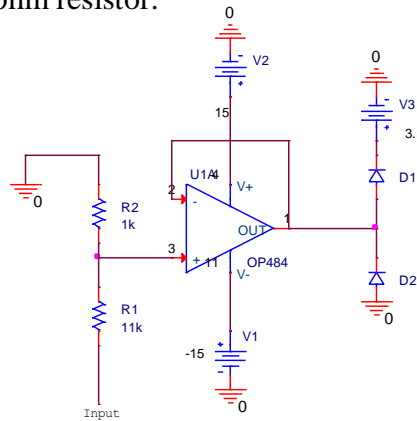

Figure 7: Interfacing Circuit Design (Small Scale)

Current Interfacing Circuit

The DSP can only read voltages and not current. Therefore an interfacing circuit must be used to convert the feedback current into a voltage. In order to achieve this, a L08P050D15 current transducer is used. The transducer will convert the current to a voltage by wrapping the wire in which the current flows around the transducer. In order to get better accuracy more wraps are needed. Two diodes are used in the same fashion as the voltage sensing circuit in order to prevent any voltage from being over 3.3V or below 0V. The figure below shows this.
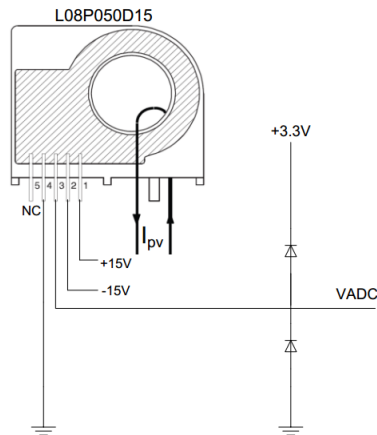
Figure 8: Current Transducer Circuit

Gate Driver Circuit

The main purpose of using the gate drivers for the system is to have a medium between the pulse width modulated signal from the DSP and the switching transistors in the high power circuit. Since the DSP's PWM output does not supply enough voltage to switch the transistor, a gate driver must be used. Using the power supply from the gate driver, the output from the DSP will effectively control the switching characteristics of the transistor at a higher power level. The high power MOSFET (IRFP460A) requires a voltage of 12V to completely turn on. The PWM output from the DSP provides 3.3V at low level current, which would require the gate driver to provide additional power to fully turn on the MOSFETs.

HCPL-3180 Gate Driver

The HCPL-3180 was selected for the system since the gate driver has its own built in optical isolator. The system has a lot of voltage that is constantly changing. Since the DSP board can only handle 3.3V, this makes the DSP board very susceptible to high voltage that could potentially harm or destroy the board. When connecting the gate driver

, a TTL inverter 74HC04 was used to help act as an additional buffer to the DSP. The HCPL-3180 has an optical isolator to protect the DSP board. If a voltage exceeds the 3.3V, the HCPL-3180 gate driver would be destroyed, allowing the DSP board to be protected. The HCPL-3180 has current capacity of 2.5 Amps. The typical layout of the HCPL-3180 gate driver can be seen the Figure 9.
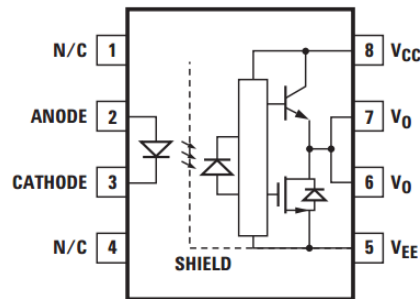

Figure 9: Gate Driver Circuit Layout

Li-Ion Battery

This projects main goal was to charge a 7.4V 3000mWatt and a 51.8V 10Amp Hour battery. However when doing this, characteristics of the battery must be taken into consideration. Lithium ion batteries have their own unique characteristics when compared to other batteries.

Figure 10: 7.4V Li-Ion Battery (Small Scale Testing Battery)

Figure 11: 51.8V Li-Ion Battery (Large Scale Testing Battery)

Internal Impedance

It is important to take into account the internal components of the battery. A lithium ion

battery has an internal resistance and an internal capacitance. A saft battery model shown

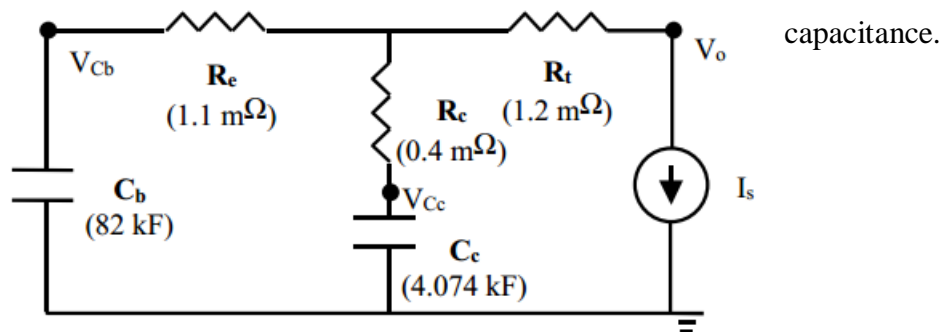in Figure 12 shows how lithium ion batteries contain an internal resistance and

 capacitance.

Figure 12: Saft Battery Model [9]

These values however can be difficult to find because they change when the state of

charge (SOC) changes. Therefore a model is needed to figure out what these values are.

To find these values a discharging method was used from [10]. This method allowed

them to calculate the internal resistance and internal capacitance.

Charging

One important characteristic is how lithium ion batteries charge. Each cell of the 51.8V

battery has a maximum capacity of 4.2V. The first stage of charging a lithium ion battery

is to have the input current be constant as the cell gains voltage. Once each cell has reached its rated voltage the current must then start to decay. The current will continue to decay until it is 3% of the rated current. For the 51.8V battery this will be 300mA. This second stage of charge is known as the saturation stage where the charge on the surfaces of the anodes and cathodes are dispersed throughout the bodies of the cells. Once the current is at 3% of the rated current the charging process terminates. It is possible to over charge lithium ion batteries. It is highly recommended that the batteries do not get overcharged because this will harm the structure of the battery. The figure 13 below illustrates this process.
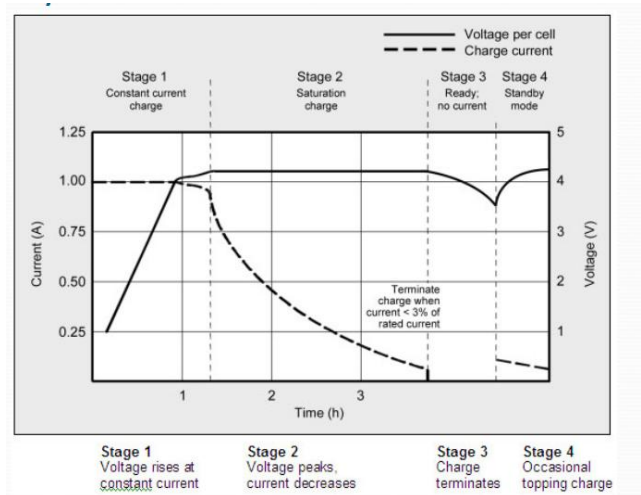

Figure 13: Charging Rate for Li-Ion Battery [11]

Software Control

The main component of the PHEV charger system is the Digital Signal Processor (DSP). A DSP is a fast chip, optimized for detection, processing, and generation of real world signals. This processor is ideal for controlling the overall PHEV system due to its speed and reliability. The DSP is programmed with C code and this code can be generated with

a block diagram model. The block diagram models are designed in MATLAB and Simulink toolboxes. The DSP can generate a PWM signal which is sent to the gate drivers to power the switching transistors. PWM is normally a square wave signal with a constant frequency that then adjusts the duty cycle. This adjustment of the duty cycle is to determine the on time period over the switching period in the switching transistors.

For this stage of the project only the buck converter was considered. This is because the buck converter is responsible for charging the battery and as mentioned earlier there are special considerations to be taken into account when charging a lithium ion battery. Below is a simple flow chart to achieve this.
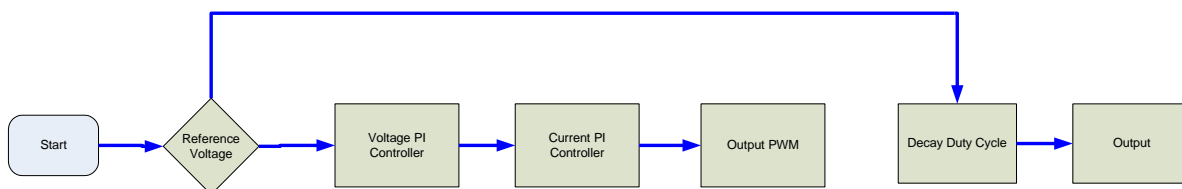

Figure 14: Flowchart of the software control of the system

First, the DSP checks to see if the output voltage of the buck converter is at the reference voltage defined by the user. If it is not at this value, then it will go through a voltage PI controller and then a current PI controller. This value will be the duty cycle, and then will be outputted by the DSP. If the output of the buck converter is at the desired value, then the DSP will begin to gradually decay the duty cycle of the PWM waveform. This will then reduce the current going into the battery. Once it reaches the 3% of the rated current

,it will shut off. The Simulink model in Figure 15 is a further representation of the flow chart.
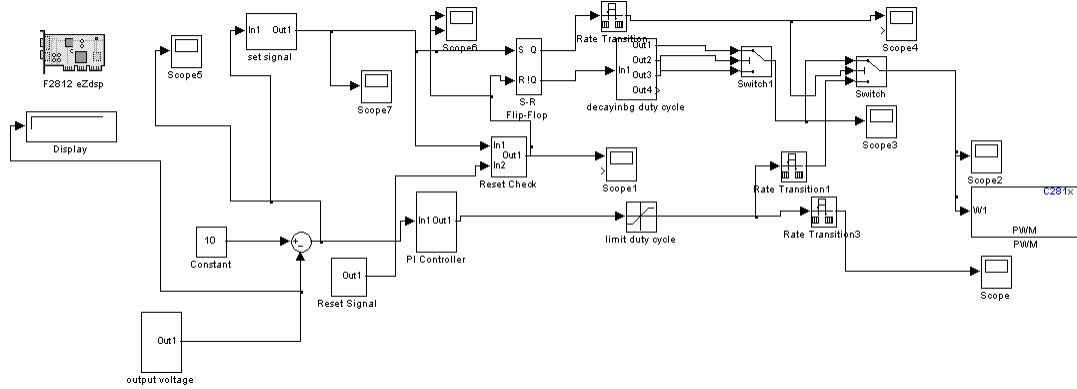

Figure 15: Simulink of the overall software control system

The first block reads the output voltage of the buck converter. The DSP reads this value ,however it does not read the exact value. For example a voltage of 1V going into the DSP gets read as 2549. Therefore a multiplier must be added to correct this. The multiplier used was .00073. This will put the value back to 1V, however while going into the DSP there was a voltage divider. This also has to be taken into account. Therefore after both the ADC multiplier and the voltage divider multiplier are applied the value will now be the correct value. This can be shown in figure 16.

Figure 16: The ADC and voltage divider multiplier block

The value then gets compared to the reference voltage. In the Simulink diagram this is the constant. It gets compared by using a subtractor block. This value now has two different paths. One is the PI controller, and the other is a test to see if the value is within plus or minus .5. This was done using the interval test block in Simulink shown in Figure 17.
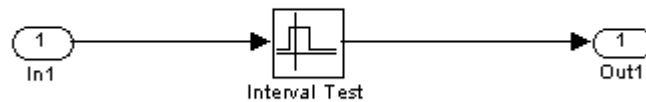

Figure 17: Interval test block

If the value is within plus or minus .5 then the output of this interval test block is 1. This then sets the set-reset flip flop. This will now switch the final switch to the decaying duty cycle instead of using closed loop control. The switch that is mentioned is shown in Figure 18.
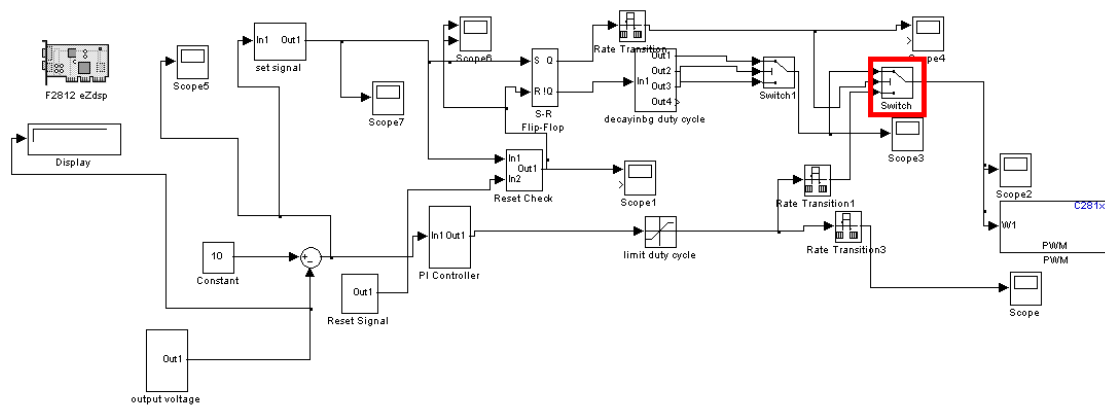

Figure 18: Highlighted region showing switch block

The decaying duty cycle block works by using a repeating sequence block that starts at 50 and then drops incrementally by 10 until it reaches 10. This repeating sequence is fed to as in input to the switch shown above. It is also fed into a relational operator that compares that value to the constant 10. If the repeating equals 10, then the relational operator will set a set-reset flip flop. This flip flop will then turn on a switch that will now only be 10. This 10 now is fed into the switch in figure 18 so the DSP will now only output a PWM of duty cycle 10. The figure below shows the decaying duty cycle.
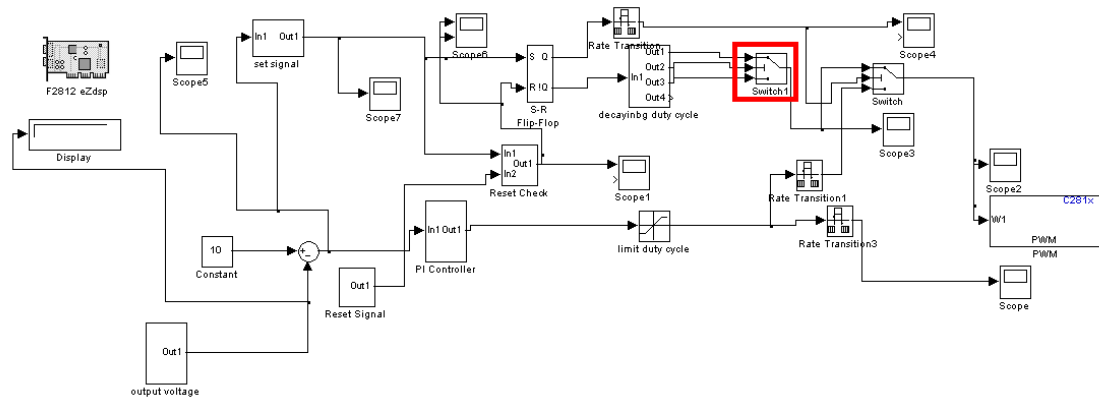

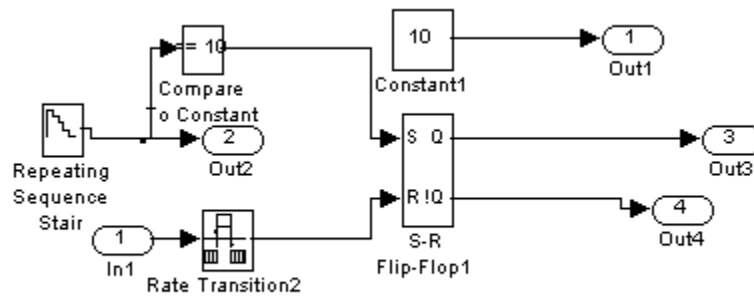Figure 19: Highlighted region showing decaying duty cycle

Figure 20: Sub-blocks for decaying duty cycle block

The decaying duty cycle portion of the Simulink model has been described. The next important feature that must be described is the PI controller block. The figure below is the PI controller.
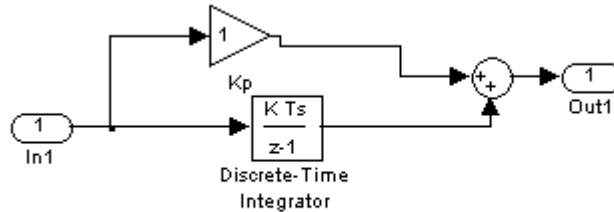

Figure 21: PI controller block

The values shown for Ki and Kp are not correct. Also the Simulink model does not include the second PI controller for the current. Future groups would have to add another input ADC and feed it into another PI controller. As mentioned the values for Kp and Ki were not calculated for the voltage or current controller. However the equations on how to calculate those values are shown below. First the small signal transfer function for the buck converter must be known. Then the magnitude and phase response must be examined. A cut off frequency must be chosen. This cut off frequency must be above the reciprocal of the square root of the value of the inductor multiplied by the value of the capacitor. The magnitude of the response must be examined at the cut off frequency. This value will represent the magnitude of the power system. This will be denoted by $|G_{ps}|$. The angle of the response must also be examined. This will be denoted by the angle of G_{ps}. The following equations show how to find the values of Kp and Ki.

$$G_c(s) = \frac{sk_p + k_i}{s} \qquad (5)$$

$$f_c > \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

$$|G_c(s)|_{fc} = \sqrt{k_p^2 + \left(\frac{k_i}{w}\right)^2} \tag{7}$$

$$\angle G_c(s)_{fc} = \tan^{-1}\left(\frac{-\frac{k_i}{w}}{k_p}\right) \tag{8}$$

$$1 = |G_c(s)|_{f_c} \cdot |G_{pwm}(s)|_{f_c} \cdot |G_{ps}(s)|_{f_c} \cdot k_{fb} \tag{9}$$

$$\phi_{boost} = -90^o + \phi_{pm} - \angle G_{ps}(s)_{fc} \tag{10}$$

The same process is used for finding the Ki and Kp values for the current PI controller.

The only difference is the cutoff frequency is chosen where the phase response levels off.

The following equations are used.

$$|G_c(s)|_f = \sqrt{k_p^2 + \left(\frac{k_i}{w}\right)^2} \tag{11}$$

$$\angle G_c(s)_f = \tan^{-1}\left(\frac{\frac{-k_i}{w}}{k_p}\right) \tag{12}$$

$$\phi_{boost} = -90^o + \phi_{pm} - \angle G_{ps}(s)_f \tag{13}$$

$$|G_C(s)| \; X \; |G_{ps}(s)|_{fc} = 1 \tag{14}$$

After finding these gains the buck converter can be controlled using PI controllers. One of the problems with using this method with the current calculated values is that the system runs at 92 kHz and the DSP can not create many duty cycles at this frequency. However the model will work perfectly at 10 kHz. A way to reduce this is to reduce the capacitor used. This is because the system is running at resonance so by decreasing the capacitance it will reduce the resonance frequency allowing the DSP to be used.
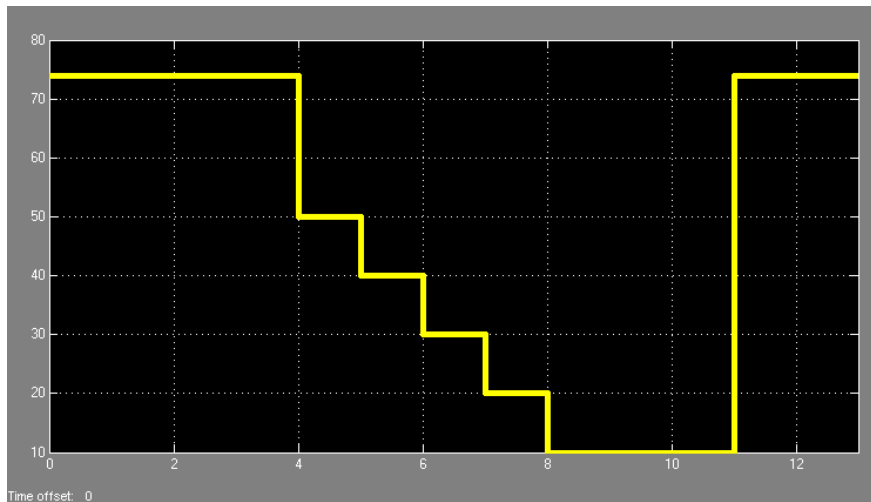
Simulation Results

Figure 22: Simulation Results

As shown the duty cycle starts off at 74 and then when the reference voltage is applied it steps down from 50 to 10. It then waited for the reset signal and then it was put back to 74. The way this was tested was a repeating sequence was put in for the output voltage. This value would change so that initially it would not be at the reference voltage but then would at 4 seconds. The closed loop control was replaced by the constant 74.

Battery Testing

As mentioned above the system runs at 92 kHz and the DSP can not handle this frequency. In order to test the Simulink model a DC power supply was used as the input to the DSP. The input voltage to the DSP would be corresponded to the reference voltage. For example, the voltage divider would be 7.4V and the reference voltage for the model would be 7.4V also. So the voltage provided by the DC power supply would be 1V and this would be feed into the DSP. Now this voltage would then be read as 7.4V by the DSP. This would then enable the decaying duty cycle portion of the Simulink model. In order to make sure that the model would switch back to closed loop control the voltage provided by the DC power supply was changed. This accomplished the task.

Battery Testing Results

As mentioned before finding a battery model to model the different components of the battery is necessary. The model chosen was the Georgia Tech paper [10]. The paper suggested having the battery hooked up to a switch with a load attached to the other end. An IGBT was used as a switch and below is how the testing was done.
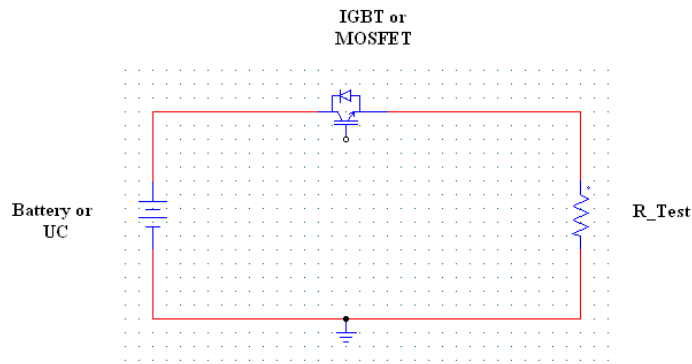
Figure 23: Battery Testing Circuit

The IGBT was controlled using an IR2110. The two different batteries were tested using this method. Each battery had a different R_{test} value. The 7.4V battery had 20 ohms value and the 51.8V battery had a value of 100 ohms. The full system hooked up is showed below.

A protection resistor is needed to protect the IR2110. If this resistor is not here the IR2110 will get damaged. This is especially needed for testing with the 51.8V battery.
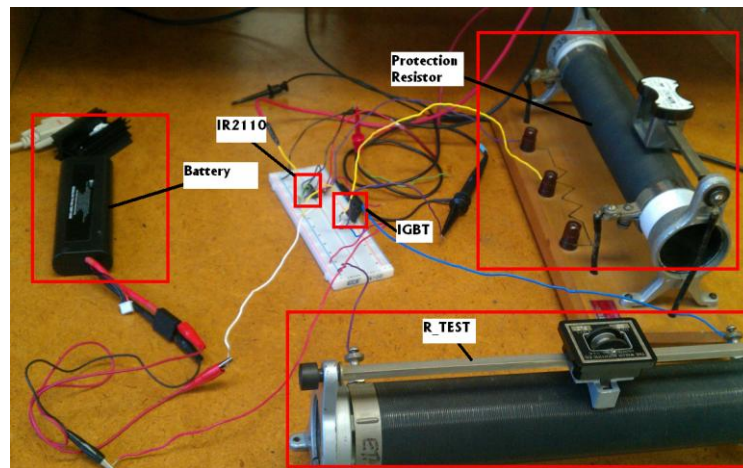

Figure 23: Small Scale Battery Testing circuit

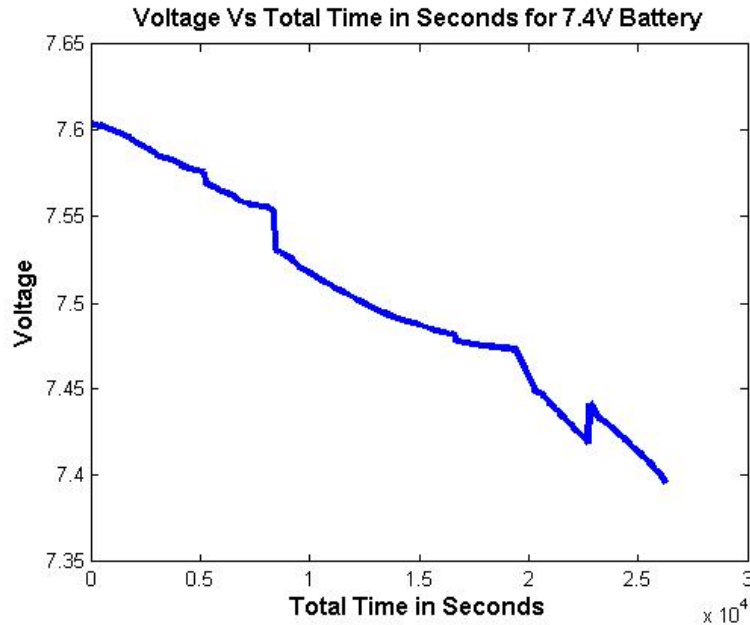When testing was completed these were the following results for the small scale.

Figure 24: Discharging Rate for the 7.4V battery

This graph is a representation of total time spent discharging. This was not a
representation of discharging all at one time this graph is actually discontinuous because
data was taken intermittently. This graph shows all the time spent discharging. Since the
circuit had to be taken apart and r-emade every time testing was taken there was a
mistake made. This mistake is shown when the graph becomes vertical. While setting up
the testing circuit, there was a short circuit and the battery began to rapidly discharge.
When factoring this in however this graph does fit the data curve of the Georgia Tech
paper [10]. This shows that the testing method we were using was accurate and could
now be applied to testing the 51.8V battery. Testing then began on the 51.8V battery. The
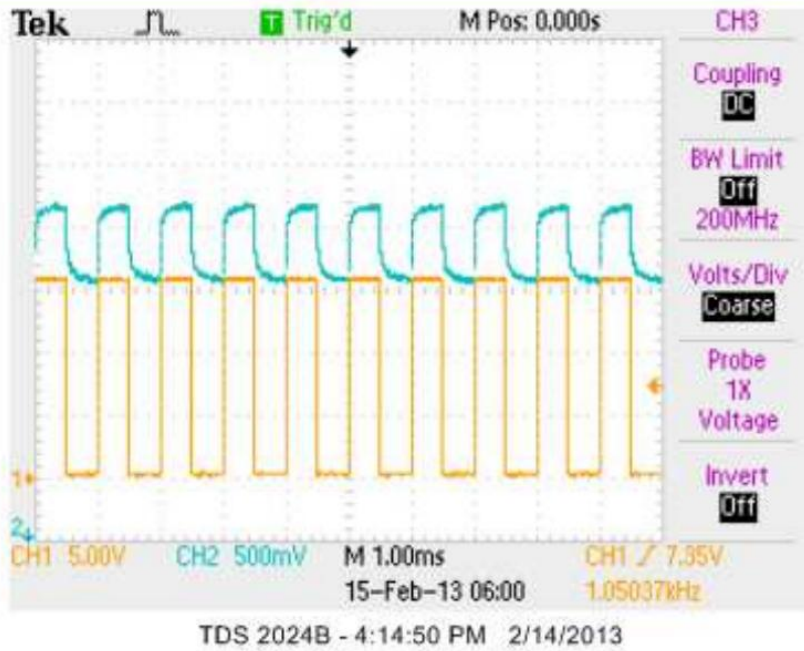results were the following.

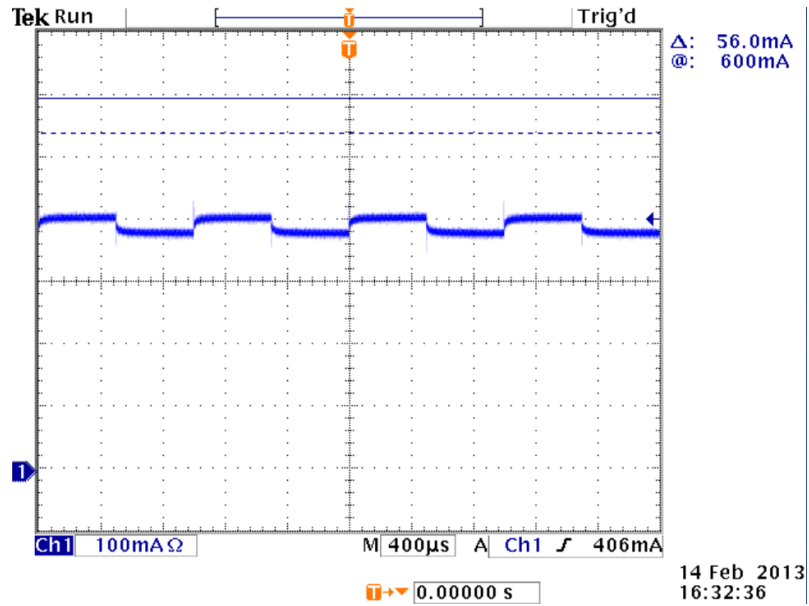Figure 25: Voltage from 51.8V battery

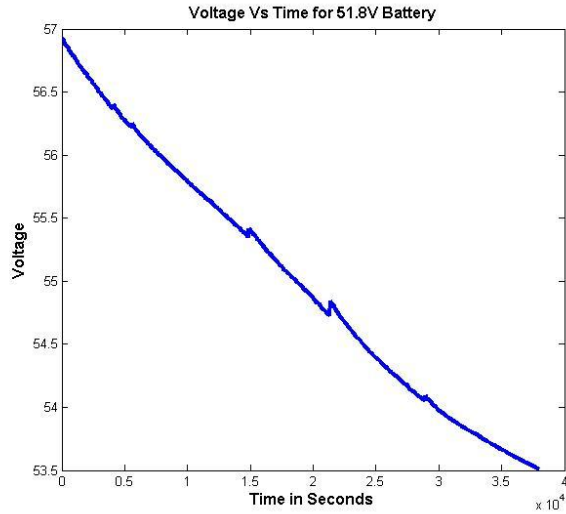Figure 26: Current from 51.8V battery

Figure 27: Discharging rate from the 51.8V battery

Now knowing that the battery follows the Georgia Tech paper [10], the following

equations can be used.

$$V_{oc}(SOC) = -1.031e^{-35*SOC} + 3.685 + 0.2156 * SOC - 0.1178 * SOC^2 + 0.3201 * SOC^3 \quad (15)$$

$$R_{Series}(SOC) = 0.1562 * e^{-24.37*SOC} + 0.07446 \quad (16)$$

$$R_{Transient_s}(SOC) = 0.3208 * e^{-29.14*SOC} + 0.04669 \quad (17)$$

$$C_{Transient_s}(SOC) = -752.9 * e^{-13.51*SOC} + 703.6 \quad (18)$$

$$C_{Transient_L}(SOC) = -6056 * e^{-27.12*SOC} + 4475 \tag{19}$$

$$R_{Transient_L}(SOC) = 6.603 * e^{-155.2*SOC} + 0.04984 \tag{20}$$

Future Work

If a future designing team were to take this project further they could begin by re-designing the system. Rather than having an analog system that is soldered together they could make a printed circuit board (PCB). This printed board circuit would help to reduce the amount of components needed in the system that are big and bulky. It would also make the system way more efficient and would not need as much space. Furthermore, a future group could look into discharging the battery through an inverter to run a variable load. This part of the project could actually be done prior to the PCB designing. Finally, a group could build a protective structure for the battery that would prevent any harm to anyone using it.

Conclusion

By understanding battery characteristics, we were able to get a better idea of how to make the system more efficient and more protective. We also were able to get a better understanding of what gate drivers can help make the system safer and easier to use. These results could help impact efficiency of the plug-in hybrid electric vehicle (PHEV),

which could then greatly impact society. Developing these systems, specifically charging, can make a huge step towards the whole system. As time goes on further research and development will continue to make a greener future.

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