5-2011

Battery Electric Vehicle and Hybrid Fuel-cell/Battery Electric Vehicle for EPA P3 2011 Competition

Yue Cao
University of Tennessee - Knoxville, ycao6@utk.edu

Jonathan M. Coplon
University of Tennessee - Knoxville, jcoplon@utk.edu

Eugene V. Ng
University of Tennessee - Knoxville, eng@utk.edu

Michael C. Pickelsimer
University of Tennessee - Knoxville, mpickels@utk.edu

Recommended Citation

Cao, Yue; Coplon, Jonathan M.; Ng, Eugene V.; and Pickelsimer, Michael C., "Battery Electric Vehicle and Hybrid Fuel-cell/Battery Electric Vehicle for EPA P3 2011 Competition" (2011). *University of Tennessee Honors Thesis Projects.*
http://trace.tennessee.edu/utk_chanhonoproj/1344

ECE 400 Senior Design Report

Battery Electric Vehicle and Hybrid Fuel-cell/Battery Electric Vehicle for EPA P3 2011 Competition

Yue Cao

Jonathan Coplon

Eugene Ng

Michael Pickelsimer

for

ECE 400: Senior Design

Prof. Leon Tolbert

December 10, 2010

INDEX

I. Introduction

A. History and Background

What is EPA P3 competition? EPA's P3 – People, Prosperity, and the Planet – is a unique college competition for designing solutions for a sustainable future. P3 offers students quality hands-on experience that brings their classroom learning to life. The competition has two phases. For the first phase of the competition, teams are awarded a $10,000 grant to develop their idea. They bring the design in April to the National Sustainable Design Expo in Washington D.C. to compete for the P3 Award and an additional grant of $75,000 to take their design to real world application.

The College of Engineering at the University of Tennessee – Knoxville (UTK) has previously entered the EPA P3 competition and won the top award with the project titled "The New Norris House: A Sustainable Home for the 21st Century." Motivated by the huge success from the previous competition, the university decided to participate in the event once more. In Fall 2009, four faculty members, Dr. Paul Frymier and Dr. Chris Cherry of Chemical Engineering (ChemE), Dr. Leon Tolbert of Electrical Engineering (EE), and Dr. David Irick of Mechanical Engineering (ME), formed a new group representing UTK in the EPA P3 2011 competition, which is to be held April 15-17, 2011. Several undergraduate students from a number of engineering specialties were recruited to create a new idea, discuss the preliminary design, and submit the proposal for Phase I grant of the competition. Among these students were Yue Cao and Michael Pickelsimer of EE.

B. Preliminary Design

In spring 2010, the student and faculty group assembled to finalize the topic to be presented. A new idea was quickly created for the project: to build and test a hydrogen fuel cell based vehicle for urban non-highway commuting. Several issues were raised during the discussion of preliminary design. What is the typical commuting distance for the average Knoxville citizen? How fast is the vehicle expected to run? How many people can the vehicle carry? Then many subsequent questions were brought up: What kind of platform is suitable for the vehicle? Does a sole hydrogen fuel cell source provide enough energy to meet the expected distance and power range to meet expected speeds? Lastly, how does one determine that such a hydrogen fuel cell powered vehicle is more applicable than another type of alternative energy based car?

All of the above issues and questions led to a number of solutions. Due to limited funding, time constraints, and limited student knowledge and experience, the vehicle is designed to travel only on secondary roads in an urban setting. This means that one-way commuting distance is within 15 miles, and that the speed is limited to a maximum of 40 mph. Transporting one person would sufficiently meet the project requirement. After in depth research, the most suitable vehicle platform was the BugE, a pre-manufactured platform made by Blue Sky Design (http://www.bugev.net/). Different angles of BugE are shown in Figure 1.1.

Figure 1.1. Different angles of BugE platform.

The BugE can meet or exceed all the requirements depicted above. In addition, the BugE, as a patented product, has been implemented as a platform on many successful electric or hybrid cars. Other advantages of the BugE platform include many compatible parts, such as batteries, motors, controllers, and accessories are available in the market. The potential of the vehicle to being licensed in Tennessee is optimistic, since the vehicle has been approved by the Oregon Department of transportation. Also it simply looks aesthetically pleasing.

After an estimation from the ME students, it was determined that the maximum power required for the BugE to run at 40 mph while traveling up an incline is approximately 5 kW. The available fuel cells in the market suitable for the BugE's size cannot provide such an extensive amount of power. Thus, a fuel cell/battery hybrid design was required. There are many potential batteries in the market to meet the specifications. The most suitable batteries for transportation applications are Li-ion type. These batteries come in the form of $LiFePO_4$ or as $LiFeMnPO_4$, and are sold by multiple vendors around the world.

Since the goal is to determine whether a fuel cell powered vehicle is more efficient, more ecologically friendly, and more economical to residents living in mid-size cities such as

Knoxville, one fuel cell vehicle alone cannot judge the level of satisfaction. To compare, a pure electric vehicle powered solely by batteries also needs to be designed and constructed.

C. Proposals and Results

After the preliminary design (late spring 2010), the ChemE, EE, and ME students were ready to submit the proposal for EPA P3 competition. The most serious issue the group was confronted with was the amount of funding granted. Since two cars were proposed to be built, the mere $10,000 from EPA would not be enough, even for a single car. Therefore, in addition to submitting a proposal to EPA P3, the group also submitted a similar proposal to UT Environmental Design Competition. The proposal was named *"H2 v. BE": A Case Study of the Reliability, Cost, and Environmental Sustainability of Hydrogen Fuel Cell Hybrids vs. Battery Electrics for Near Urban Personal Transportation*. In totality of 46 pages long, the proposal was a combined effort of both the student group and the faculty group. This proposition consisted of the basic project idea, contact information, preliminary design, timeline, goal, budget, and potential support information. In addition to the EPA and UT funding opportunities, the group also reached out to several major automobile manufactures, such as GM, Ford, and Toyota.

A few months later, the group heard back from EPA P3. As a result of the proposal, UT was awarded the Phase I grant of $10,000. Soon after, UT Environmental Design Competition awarded the group a top award of $25,000. What made the situation even more optimistic was that the student team was able to have a cost sharing of $12,000 to match the EPA P3 award. Therefore, a total of $47,000 was granted.

The proposal is attached as an appendix to this report. Figure 1.2 shows the proposed timeline that the team needed to follow for the project.

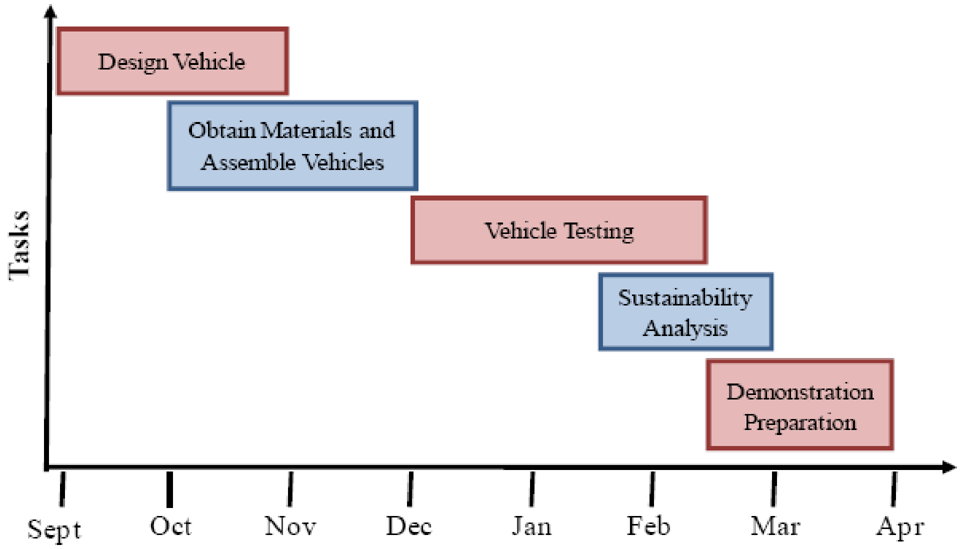


Figure 1.2. Proposed timeline for the project.

In Fall 2010, two more members of EE group were recruited. They are Jonathan Coplon and Eugene Ng.

II. Battery Electric Vehicle Design

A. Outline

A completely battery powered electric vehicle was the first of the two near urban commuter vehicles to be designed and built. A large aspect of the design process of this vehicle for the EE group is the power system that will propel the vehicle down the road. The design process of the frame and mechanical aspects of the vehicle were primarily handled by the ME group. The three main components of the vehicle power system are the battery, the motor controller, and the motor. The overall system block diagram for the power system to be implemented on the vehicle is as follows in Figure 2.1.

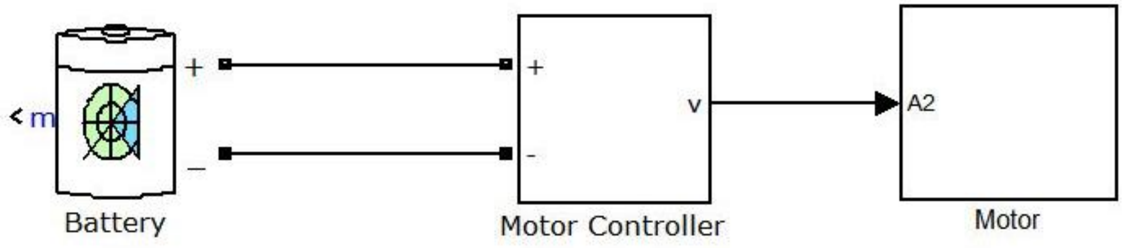


Figure 2.1. Block diagram of the power system in the electric vehicle.

The battery is to be connected to the motor controller that draws the correct amount of energy from the battery to run the DC motor at the correct speed and torque levels. Careful selection of each of these components was paramount to the safety, efficiency, and usability of the vehicle as a viable near urban mode of transportation. In selecting the batteries, consideration had to be given to the operating voltage of the whole system and to the most optimal voltage to power a DC motor driving the vehicle. In addition, calculations had to be performed to determine the capacity of the battery, while keeping dimensions to a reasonable size to fit in the BugE's battery box. In conjunction with choosing a battery, a DC motor and a compatible motor controller had to be selected that operate at the selected voltage for the battery. In the process of selecting these components, many companies and competing technologies were surveyed and analyzed for ease of implementation into the design of the power system. Pricing, reputation, warranty, and customer service of the products the companies offered were also taken into consideration in the selections of the components. In the end, a 36 V 40 Ah $LiFeMnPO_4$ battery from Elite Power Solutions was selected. Chosen to be mated to the Elite Power Solutions battery were an Alltrax motor controller and an Advanced brushed DC motor with a 17 hp peak power.

In addition to the battery, motor controller, and motor, other miscellaneous components, such as wires, terminal connectors, switches, contactor, throttle, fuses, and diodes and resistors, all need to be carefully selected for compatibility and safety purposes. The process of selecting these components is documented and elaborated upon in the following sections.

B. Battery

Battery is the sole power source of the electric vehicle. An appropriate selection of battery packs is essential to the success of the vehicle performance. In the current market, the most suitable battery type for transportation purpose is Li-ion (either $LiFePO_4$ or $LiFeMnPO_4$). Without researching battery companies first, some of the basic requirements of the batteries need to be specified. The entire battery package cannot exceed the dimension of the BugE’s battery box, which is 35” × 25” × 15”. The weight limit of the battery, given by the BugE’s manufacturer, is 150 lb. The battery is compatible with the BugE’s motor, which is rated 24-48 V.

Lastly, the battery can supply up to 6 kW of peak power and at least 20 Ah of energy storage, a requirement calculated by the ME group.

With the same Ah rating, a 48 V battery pack was initially chosen because this battery pack would provide more power than a 24 V or 36 V battery pack. However, the 48 V battery pack idea was eliminated at a later design stage due to several reasons. First, although motor is rated 24-48 V, the optimum operation voltage is 36 V, which is confirmed by direct consultation with the motor vendor. Also mentioned by the vendor is that the motor may run well under 48 V, but under no load or little load, the motor RPM may be so high that it can damage the motor. Second, the battery may be used later in the hybrid vehicle, which is supposed to be hybridized or charged by the fuel cell. The fuel cell, to be discussed more in depth later, is rated for 36-48 V output (adjustable), however, the charging voltage of a 48 V battery is normally 20% higher than the output voltage. This means that the fuel cell would not able to provide sufficient voltage to charge a 48 V battery. Third, in the current market, there are already 36 V batteries made to meet the power and energy requirements described above. Therefore, eventually a 36 V Li-ion battery became the target to research and purchase.

The power rating of a battery is directly related to the Ah rating and C rating of the battery. The formula to calculate the power is the following:

$$P = V \times (\#\ in\ Ah) \times (\#\ in\ C)$$

Since a 6 kW peak power is required and voltage of the battery is determined to be 36 V, then $(\#\ in\ Ah) \times (\#\ in\ C)$ can be calculated to be at least 167. Given a 60 Ah battery pack, the maximum C rating then will be at least 3.

With all the above requirements in mind, the EE group did some intensive research on Li-ion battery companies. Many of the battery options were eliminated due to exceeding the specified dimensions, weight, or lacking the requisite power. In the end, the group came up with the following two battery brands: Ping and Elite Power Solutions. Table 2.2 summarizes the basic specs of these two branded batteries – both are based on 36 V 60 Ah packs. Table 2.3 is a comparison chart that lists the advantage of each battery in certain categories.

	Ping	**Elite Power Solutions**
Battery Type	$LiFePO_4$	$LiFeMnPO_4$
Dimension (in^3)	18 x 17 x 12	20 x 18 x 12
Weight (lb)	50	61
Continuous Power (W)	2,160	2,160
Max Cont. Power (W)	4,320	6,480
Abs. Max Power (W)	7,200	21,600
Cost ($)	1,500	1,600

Table 2.2. Summary of basic specs of Ping and Elite 36 V 60 Ah batteries.

	Ping	**Elite Power Solutions**
Dimension	√	
Weight	√	
Max Cont. Power		√
Abs. Max Power		√
Cost	√	
Company in the U.S.		√
Reputation	√	
Shipping Time		√
1-year Warranty	√	√
Free Charger Included	√	√
Adjustable Cells		√
LCD Display		√

Table 2.3. Comparison of each battery's advantage in different categories.

The decision was difficult to make because each battery brand has its own advantage in different aspects. However, more weight was put on meeting or exceeding the design specifications, i.e. power rating. In addition, it was important that the company is located in the U.S. so that in case there is a problem, communication and return or exchange is convenient. Although Ping is better in dimension, weight, cost, and reputation, but Elite Power Solutions does not fall very far behind Ping in these categories. Therefore, Elite Power Solutions' battery won the group's favor in the end.

C. Motor and Controller

In order to choose the proper motor and controller, the power requirements must first be known. Simulations were conducted from map and driving data to determine the required power and torque for the BugE. These calculations showed that the motor and controller needed to handle an output of a maximum instantaneous power of 5 kW (6.7 hp) and 20 ft-lbs of torque calculated at 90% efficiency. This means the required current would be 139 A for a 36 V motor and 104 A for a 48 V motor. The diameter of the motor must be no larger than 5.58 inches in order to fit into the BugE motor mount. It is also preferable that the motor support reverse functionality and that the controller be programmable.

According to the BugE manual, the stock motor should be run at 48 V. However, the motor rating suggested by the vendor was 36 V. Also mentioned by the vendor is that the motor may run fine under 48 V, but under no load or little load, the motor RPM may be so high that it can damage the motor. In order to avoid the risk of motor burnout, it was decided that a replacement for the motor should be found or the motor's voltage dropped to 36 V.

There are two motors that are suggested by the BugE manual and website. The motor suggested by the BugE website is an Advanced DC series wound 140-01-4005. This is a 24-48 V motor that outputs 2.8 kW (3.8 hp) continuous, 3.8 kW (5.1 hp) for one hour, and a 12.6 kW (17 hp) peak at 1000-3000 rpm. Current ratings include 60 amps continuous, 80 amps for one hour, 350 amps peak. This motor met all design requirements; however, it did not support the ability to run in reverse.

Figure 2.4. The 140-01-4009 Advanced DC series wound motor (left); The Alltrax AXE CT1947 (right).

The motor suggested by the BugE manual and evparts.com, a BugE electrical distributor, is the 140-01-4009 (Figure 2.4). It is of the same family of motors as the 4005 and has the same power and current ratings. The difference between the two motors is that the 4009 supports reverse. The shortcoming of this motor is that it is a brushed motor. Brushes in the motor have friction between the armature and stator which creates heat and causes a loss in efficiency.

The controller suggested by the manual is manufactured by Alltrax and is also available on evparts.com. The suggested controller is the Alltrax AXE CT1937. This controller supports 24 to 48 volt input and 300 amps, however, it is non-programmable. A programmable alternative within the same Alltrax family was found in the AXE CT1947 (Figure 2.4).

A possible solution to the inefficiency of a brushed motor was sought in the form of a brushless DC motor. The best candidate found was the HPM5000B - High Power BLDC Motor from goldenmotor.com (Figure 2.5). This motor is rated from 24-72 V, 3-7 kW (4-9.3 hp) and 2000-6000 rpm. Most importantly, it has an advertised efficiency of 88%.

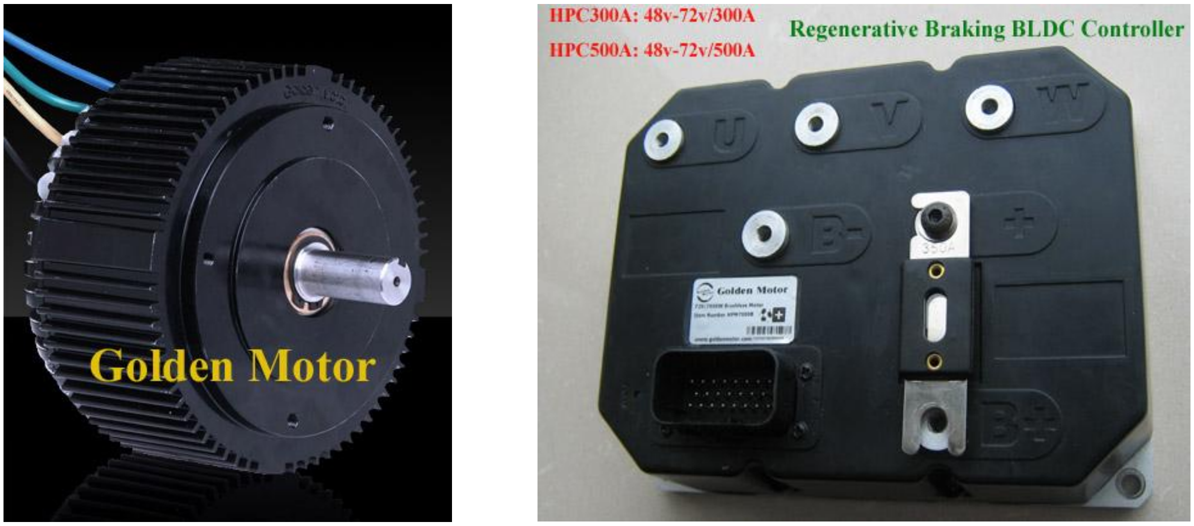


Figure 1.5. The HPM5000B BLDC motor (left); The HPC300A motor controller (right)

The controller available from golden motor is the HPC300A (Figure 2.5). This controller is rated for 24-48 V, 300 A and offers a fuse breaker, regenerative braking, temperature sensoring, and nano-second high current sampling. However, this controller was not programmable. The lethal pitfall of this system was found in its size. This motor has a diameter of 8.1 inches and would not fit into the motor mount in the BugE without major modifications to the chassis.

Both motor and controller systems fell within budget. The cost of the 140-01-4009 ADC series wound motor was priced online from evparts.com at $749.15. The corresponding programmable Alltrax AXE CT1947 controller was priced online at $432.90. The HPM5000B BLDC motor from goldenmotor.com was priced at $346.00. The corresponding controller, the HPC300A, was priced at $385.00.

The initial choice for the motor and controller was the BLDC motor and controller from goldenmotor.com because it was cheaper and more efficient. The size issue of the BLDC motor was discussed at length with the ME group in charge of chassis modification. It was determined that a proper modification of the frame was not feasible for the BLDC motor. Thus, the stock 140-01-4009 ADC motor and programmable Alltrax AXE CT1947 was chosen. A full comparison of the two motor systems can be seen in Table 2.6.

Motor	**Type**	**Voltage**	**Power**	**Current**	**RPM**	**Diameter**	**Reverse?**	**Price**
140-01-4005	ADC	24-36 V	2.8-12 kW	60-350 A	1000-3000	5.5 inches	No	$728.77
140-01-4009	ADC	24-36 V	2.8-12 kW	60-350 A	1000-3000	5.5 inches	Yes	$748.15
HPM5000B	BLDC	24-72 V	3-7 kW	60-145 A	2000-6000	8.1 inches	No	$346.00

Controller	**Type**	**Voltage**	**Current**	**Programmable?**	**Price**
AXE CT1937	ADC	24-48 V	300 A	No	$303.40
AXE CT1947	ADC	24-48 V	300 A	Yes	$432.90
HPC300A	BLDC	24-72 V	300 A	No	$385.00

Table 2.6. Motor and Controller comparison

D. Miscellaneous

Along with the choice made to go to a 36 V power system there is an added complication to the selection of suitable wiring. Since the voltage was reduced by 25%, the current was going to have to be increased by 25%. The 48 V power system required approximately 105 A to result in a 5 kW output, supposing a 100% efficiency. This current requirement is increased to 135 A when a 36 V power system is used. Due to the increased current requirement, a much larger wire is required. To allow for the larger current and a lower loss, a 1/0 wire (rated at 150A) was chosen.

The wire bought to cope with the high current required much larger connectors. Initially, the idea was to use open-ended connectors and simply crimp them to the wire. However, upon further inspection, the connectors were judged inadequate for the current load. As such, connectors with a much larger capacities were required. Accompanying this necessity were difficulties in finding a supplier of the connectors and wire itself.

Minor electrical systems are another topic of specific interest. The lighting provided by the supplier is not certified by the Department of Transportation. Instead, it is necessary to switch to an automotive LED system. This should increase the chance of getting the vehicle licensed to operate on the road system. Another added benefit of the replacement will be a decrease in power usage from the minor electrical system.

E. Summary

The design and selection of the power system for the solely battery powered electric vehicle was the primary concern for the EE group of the collaborative project proposal for a near urban commuter vehicle during the Fall 2010 semester. It is also important to note that it was not a trivial matter. This is especially because the power system plays a great role in the safety, efficiency, and usability of the vehicle as a mode of near urban transportation. The components that had to be selected after careful deliberation include a battery, a motor controller, and a DC motor. These three are connected in a power system as specified in Figure 2.1. As the diagram shows, the battery is to be initially connected to the motor controller. The motor controller is designed to pull the correct amount of current and, therefore, energy from the battery and push the correct voltage and power into the DC motor. During the selection process of the battery, great consideration had to be given to the voltage output of a battery. In addition, due to the energy requirements for the vehicle to be viable, careful calculations were needed to determine the capacity of energy the battery needed in amp hours. The battery was also required to fit size specifications of the BugE's battery box. A compatible motor controller and a DC motor also had to be selected that would work in conjunction with the specified output of the battery.

In the midst of this decision process, pricing, reputation, and warranty were important factors in deciding upon the components. Multiple companies and competing technologies were surveyed and analyzed before reaching a final decision. In the end, the components selected for use were a 36 V, 60 Ah Li-ion $LiFeMnPO_4$ battery from Elite Power Solutions, an Alltrax AXE DC motor controller, and a brushed DC motor made by Advanced DC Motors with 80% efficiency and a peak instantaneous power of 17 hp. Miscellaneous parts of the power system were also considered into the design process.

III. Hybrid Fuel-cell/Electric Vehicle Design

A. Outline

The second of the two near urban commuter vehicles to be designed and built is the hybridized hydrogen fuel cell battery electric powered vehicle. This vehicle is similar to the purely battery electric vehicle in all aspects except the power system. The power system differs with respect to the primary source of energy. In this case, the energy provider includes a hydrogen fuel cell system, and the system will require a fuel cell voltage stabilizer and controller. The fuel cell will be hybridized with a battery in the sense that the fuel cell will power the vehicle under normal conditions, but when the motor requires more power than the fuel cell can supply, the battery will provide the extra energy needed to propel the vehicle down the asphalt. The system block diagram for the new system will be as shown in Figure 3.1.

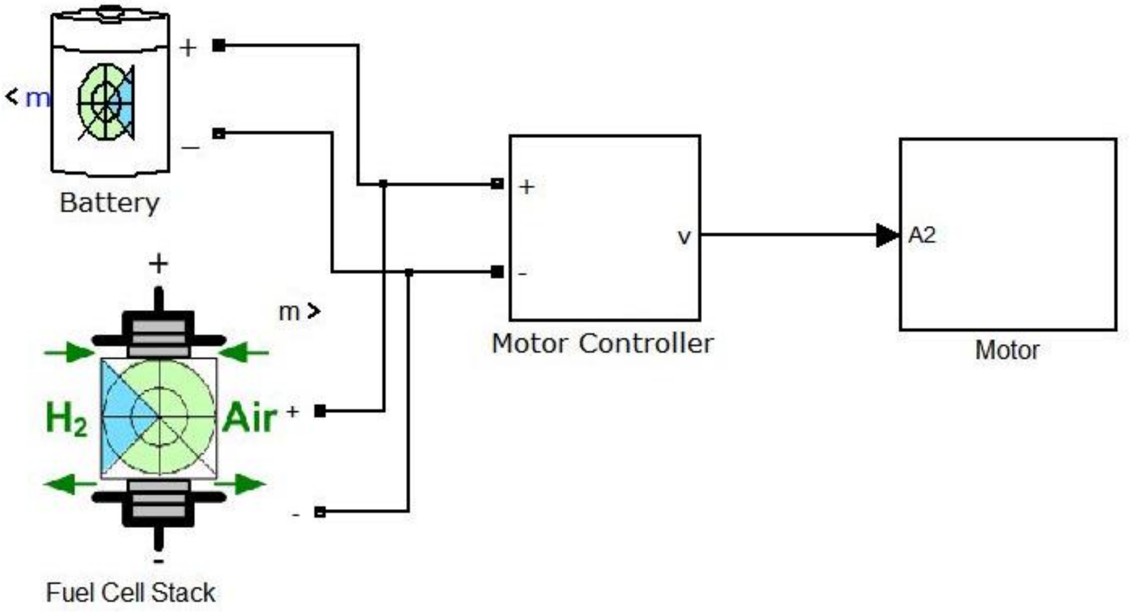


Figure 3.1. Block diagram of the power system in the hybrid vehicle.

As the diagram depicts, the DC/DC converter will tie the hydrogen fuel cell and the battery together. The DC/DC converter will also help to stabilize the voltage going to the motor controller. The careful selection of the five components, fuel cell, DC/DC controller, battery, motor controller, and DC motor is even more important than on the first vehicle because of the volatility of fuel cells. Making them work together in a safe manner was a primary concern.

In selecting of the fuel cell, voltage and power output will be large considerations. The fuel cell must have dimensions that fit the BugE’s battery box as well. Then a battery must be selected that will have enough power to generate the extra power the motor requires. In addition, the battery must have a large enough capacity to be able to provide that energy more than once. The motor controller and DC motor selection has to be compatible with the voltage and current output that the fuel cell and battery provide.

The end of the selections resulted in a Heliocentris Nexa 1200 fuel cell and a matching fuel cell DC/DC converter in the form of the Heliocentris Nexa 1200 24-48 V DC. The battery selection has not been finalized yet due to some unknown functioning of the fuel cell system. However, once the fuel cell comes in, the decision on batteries will be made quickly, which can be normally purchased and shipped in within two weeks. The motor controller and DC motor from the pure battery electric vehicle were deemed appropriate for the task of driving the wheels for this vehicle. The following sections document the process of selecting the components and the reasons they were chosen.

B. Fuel Cell

Ideally, the fuel cell should be capable of delivering the average power requirements of the vehicle and use a battery assistant system to meet peak power needs. While the vehicle is stopped, or the fuel cell's power output is greater than the power requirement of the vehicle, this extra power should recharge the battery. Despite that the average instantaneous power over the entire ride is approximately 2 kW, a significantly smaller fuel cell could be used. A 1 kW fuel cell would be able to provide the power for about 80% of the total ride. As such, the minimum output power for the fuel cell is 1 kW, though a larger output would be preferred.

Several large power fuel cells were found that met the output needs of the project. However, there are several other factors that must be taken into consideration. The voltage output for the fuel cell must be regulated. Most manufacturers provide voltage versus current curves (a common chart associated with fuel cell statistics) that reveal a much higher voltage when the current level is low. To prevent damage to the motor and controller, the voltage must remain relatively constant, at most wavering only a few volts along the entire current output range. Initially this voltage was mandated at 48 V; however, more recent developments have dictated an output between 36 V and 44 V, depending on hybridization techniques.

Two other constraints on the fuel cell were size and weight. The entire cell must be able to fit within the battery box of the BugE and have a maximum weight of 75 lb. Weight constraints were made to fit the 150 lb battery weight estimate of the BugE manufacturer. This 150 lb estimate was to be the maximum weight of the combination of fuel cell, fuel cell controller, possible converters, hydrogen tanks, and hybridization batteries. Another constraint that can be derived from the weight limitation is the maximum hydrogen consumption rate that varies with the size of the fuel cell and batteries. All constraints are listed in Table 3.2.

Fuel Cell Selection Constraints and Preferences	
Constraints	
Minimum Power Output:	1 kW
Maximum Dimensions:	cm x cm x cm (w x h x d)
Maximum Cost:	~ $15,000
Preferences	
Voltage regulation:	Either by controller or external device
Maximum Weight:	~ 75 lb
Maximum Hydrogen Consumption Rate:	Dependent on previously listed constraints
Hybridization Components:	Internal or external
Customizable:	Programming set by user

Table 3.2. Size and weight restrictions placed upon fuel cell choices.

The most strenuous constraint on fuel cell selection was power output. A few models fit this most important statistic. Produced by Heliocentris, the Nexa 1200 proved to fit the minimum requirements and preferences with the help of additional components. Another choice that presented itself as a viable selection is the Horizon H-3000. Lastly, the MES 1.0 Fuel Cell System presented itself as a high powered contender. Table 3.6 displays how the different cells match the constraints and preferences.

i) Nexa 1200

Figure 3.3. The picture of the Nexa 1200 (Left) and Nexa DC1200 (Right).

Manufactured by Heliocentris to deliver 1.2 kW of power at peak performance, the Nexa 1200 presented itself as the best fuel cell for the project. Fitting all constraints and preferences, this fuel cell is the highest ranking fuel cell in the lineup. Initially rated at 1.2 kW at 24 V, the fuel cell requires a DC/DC converter to boost the voltage to a useable level. However, the DC/DC converter supplied by Heliocentris contains a voltage regulator and supports hybridization.

ii) Horizon H-3000

Figure 3.4. The H-3000.

Distributed by the Horizon Corporation, the H-3000 met all constraints and several of the preferences. The main reason the H-3000 was considered is that it has a rated output power of 3 kW, over twice the output power of the Nexa system. However, this fuel cell system does not contain a voltage regulation device, does not internally support hybridization, and is not customizable via user controlled programming. Despite these shortcomings, the H-3000 nearly makes up for them with overall output power.

iii) MES 1.0 Fuel Cell System

Figure 3.5. The MES 1.0 Fuel Cell System.

Despite having a high power output and meeting all constraints, the MES 1.0 Fuel Cell System was the least preferable selection among all fuel cell choices found. While it had the lightest weight of three models, it could not meet the voltage requirements by itself (via either stabilization or a 36 V output setting) and did not have accessories capable of meeting any preferences. Though MES made a larger fuel cell capable of generating up to 3 kW, it was significantly more than $5,000 over the budgeted cost and had a lower voltage bound of 72 V.

Comparing Most Notable Fuel Cells			
	Heliocentris: Nexa 1200	Horizon: H-3000	MES: 1.0 Fuel Cell System
Constraints			
Power Output:	**1.2 kW**	3.0 kW	1.0 kW
Maximum Dimensions:	**40 cm x 55 cm x 22cm**	38 cm x 16 cm x 28 cm	21.3cm x 17.4cm x 8cm
Cost:	**~ $12,500**	$10,500	~ $7,000
Preferences			
Voltage regulation:	**Yes**	No	No
Weight: (Stacks only)	**48.5 lbs**	24.3 lbs	4.9 lbs
Maximum Hydrogen Consumption Rate:	**15 slm**	42 l/min	13 slm
Hybridization Components:	**Yes**	No	No
Customizable:	**Yes**	No	No

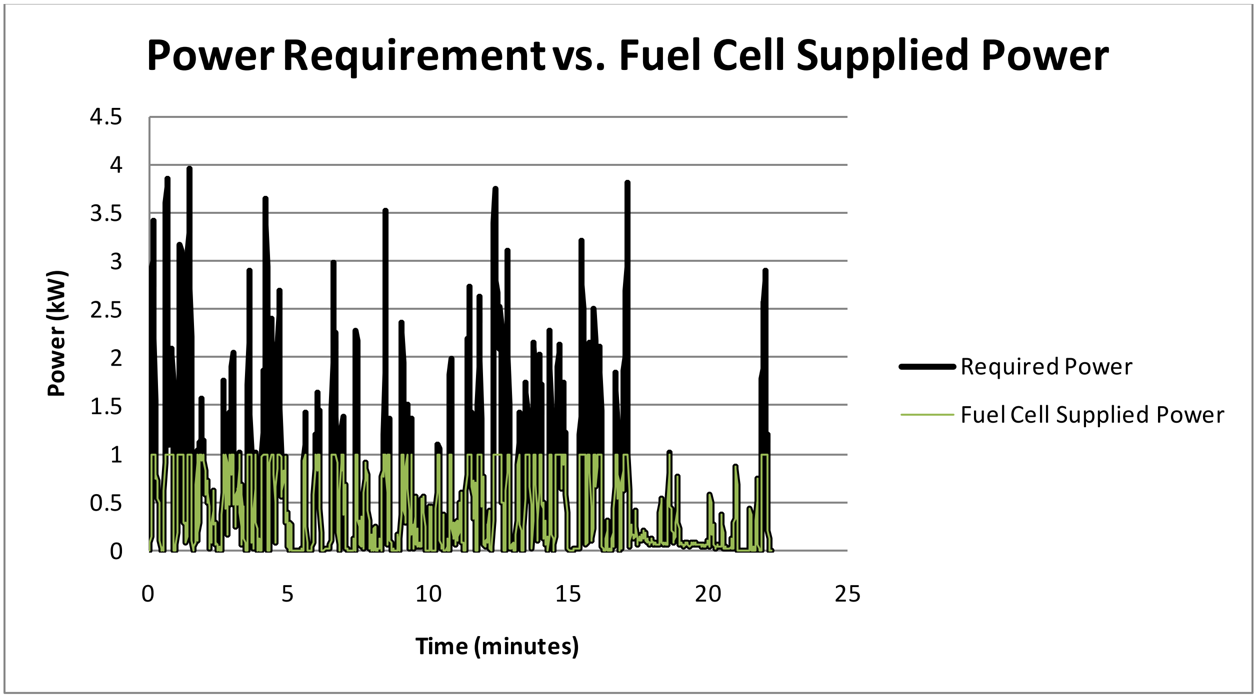
Table 3.6. This table displays how the three most notable fuel cells meet the requirements and preferences. The Nexa fuel cell system is bolded specifically, as it most closely matched all parameters.

Considering all restrictions and preferences, the Nexa 1200 was the fuel cell of choice. This is chosen despite offers from Horizon to custom make a fuel cell for us, which would require too much time and potentially money in the all too limited build schedule and budget.

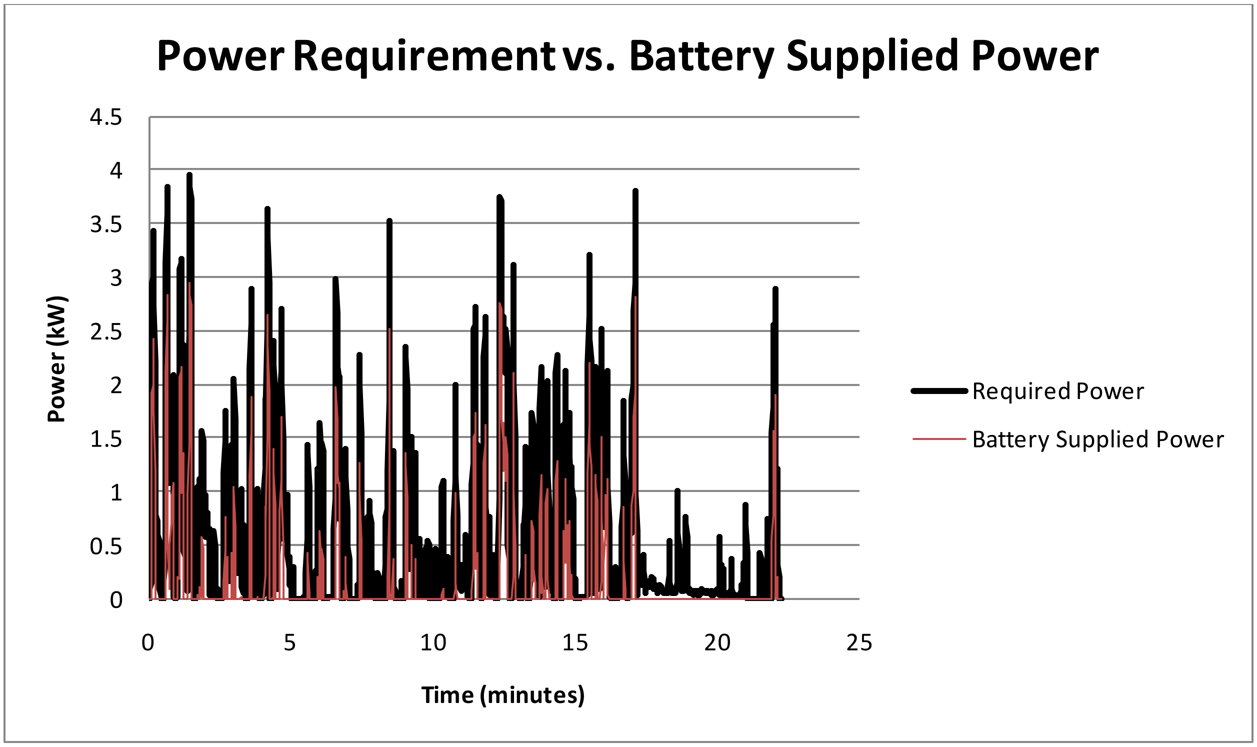
C. Battery

Battery sizing is just as important on the hydrogen vehicle as it is on the battery electric vehicle. However, the selection of battery sizing is much more difficult using the hybridization feature of the Nexa 1200 fuel cell than simply using the battery as the sole source of power. Supposing that the fuel cell charges the battery through this connection, the battery can be smaller. If the fuel cell is incapable of charging the battery, the battery must be nearly the size of the one used for the battery electric vehicle.

The data displayed in Figure 3.7 shows that the battery is only used for approximately 17% of each 15-mile trip. Though this results in a maximum charging percentage of 83% of the trip, there are restrictions on the amount of charge going into the battery from several sources.

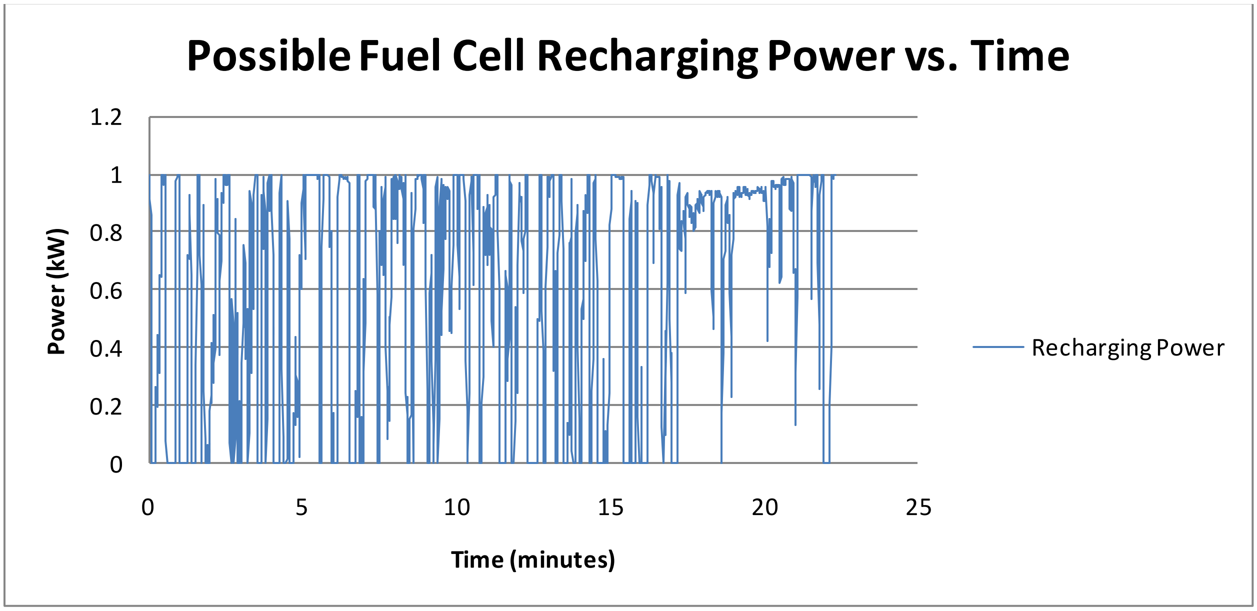


a)

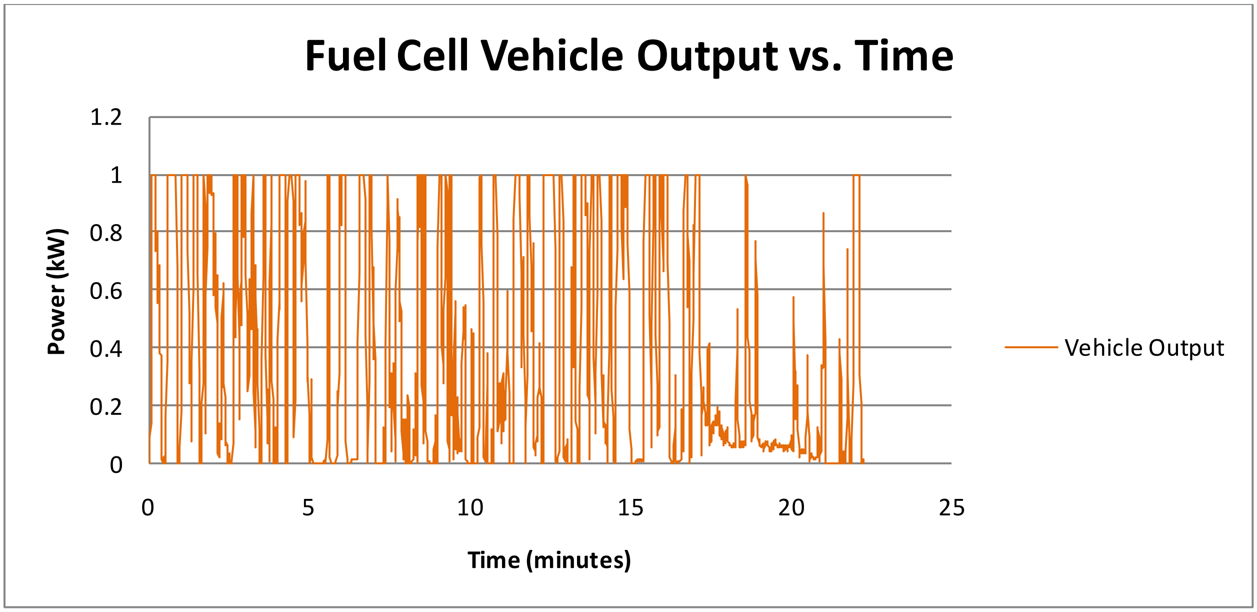


b)

Figure 3.7. a) Route Power Requirements (Black) vs. Fuel Cell Power Contribution (Green). b) Route Power Requirements (Black) vs. Battery Power Contribution (Red). All figures listed are related to time in minutes. This data is taken from most recent data collected.



a)



b)

Figure 3.8. a) Fuel Cell Charging Capability (Blue) b) Fuel Cell's Vehicle Contribution (Orange). All figures listed are related to time in minutes. This data is taken from most recent data collected.

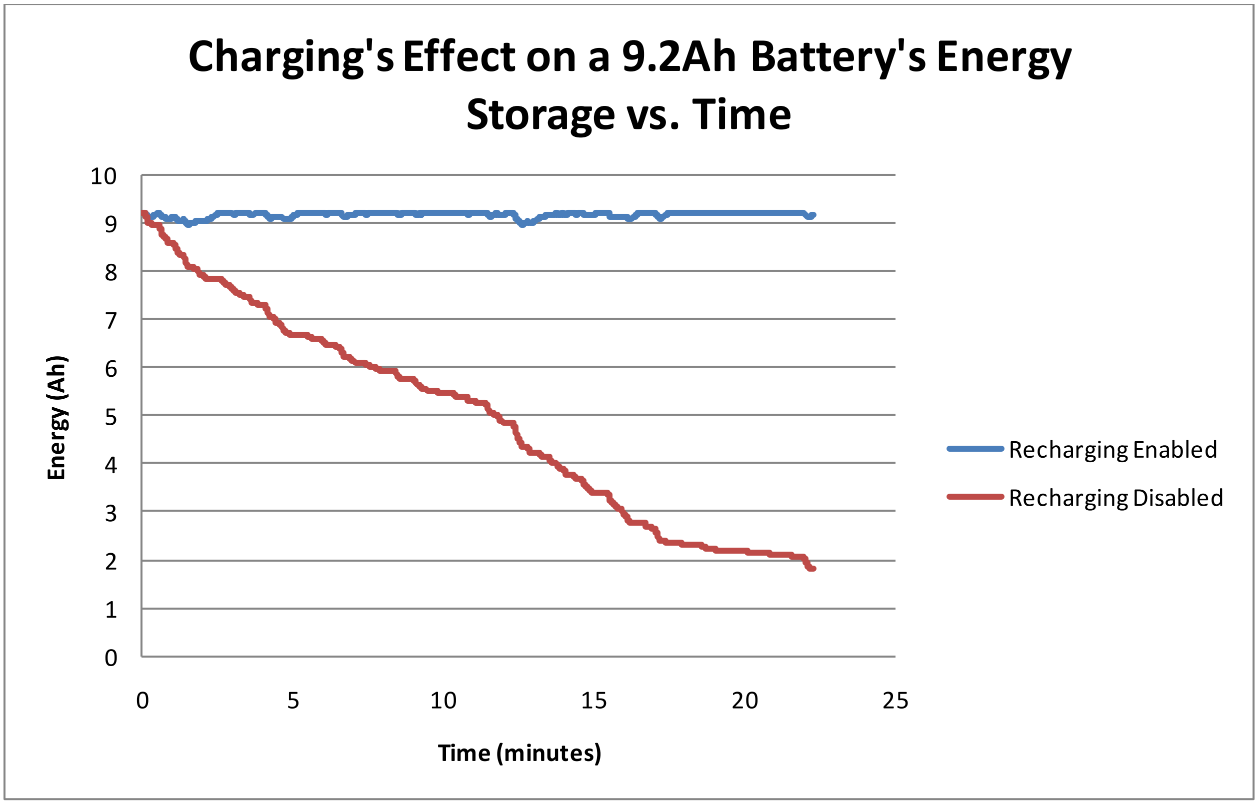


Figure 3.9: Charging's Effects on the amount of energy left in a 9.2 Ah battery. Battery Recharging Enabled (blue) vs. Battery Recharging Disabled (Red) are related to time in minutes. This data is taken from most recent data collected.

One such source is the limitation of the battery system itself. This is because the charging current must be restricted when the charge percentage is highest. Normally, the charger and the battery management system work together to adjust the charging current. With this atypical charging method, problems may arise when the battery is near full capacity.

Another constraint is the fuel cell itself. The fuel cell must still provide its portion of the needed power to the vehicle at all times. When the battery is not required to meet the instantaneous power requirement, the fuel cell is able to satisfy the need of the vehicle and potentially charge the battery with the power remaining after vehicle demands have been met. As such, while the vehicle is in motion, the fuel cell is not likely to supply its full charging capabilities to the battery.

D. Summary

As stated earlier, the second of the two near urban commuter vehicles that were to be designed and built is a hybridized hydrogen fuel cell and battery electric powered vehicle. The primary source of power and energy for this vehicle is the fuel cell as opposed to purely battery power. Outside of the power system, the hydrogen fuel cell battery electric hybrid vehicle and the battery electric vehicle are similar in all aspects. The primary difference in the two is the main power source. The difference in the primary source of power and energy results in a need for a system block diagram of the power system. Figure 3.1 from earlier displays this fact.

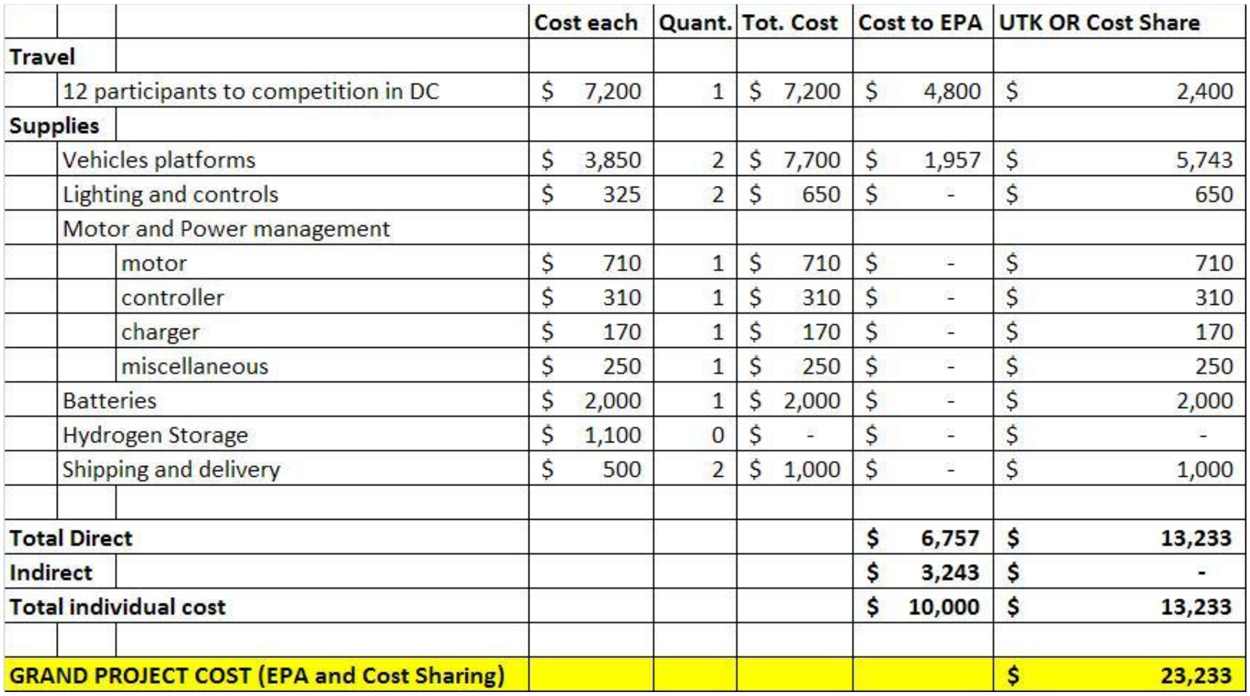
The need for careful selection was paramount because one poorly selected component could have led to disastrous results. Safety was the primary concern in the selection process. The fuel cell had to be selected with the right power and voltage output in order to work with the selected DC motor and motor controller. A fuel cell controller and voltage stabilizer were needed to provide a constant predictable output from the fuel cell. In the midst of this selection, dimensions of the fuel cell and controller had to be kept in mind in order to assure that it would fit on the BugE platform. Budgeting was also a factor in the selection process as the project had limited funds.

Following the selection of a fuel cell and controller, an appropriate battery had to be selected. The key factors in the selection of the battery were the compatibility of the battery with the overall design of the power system, size, and capacity. The battery must be able to provide the extra amount of power that the motor needs when the fuel cell does not provide enough power; for example, when attempting to drive up an incline. The result of all the specifications laid down for the components is the selection of the Heliocentris Nexa 1200 hydrogen fuel cell, the matching fuel cell controller Heliocentris Nexa 1200 24V DC, and the Nexa 1200DC DC/DC converter. The DC motor from Advanced DC Motors and Alltrax Axe motor controller selected for the battery electric vehicle were retained for use in the hybrid hydrogen fuel cell vehicle.

IV. PURCHASING

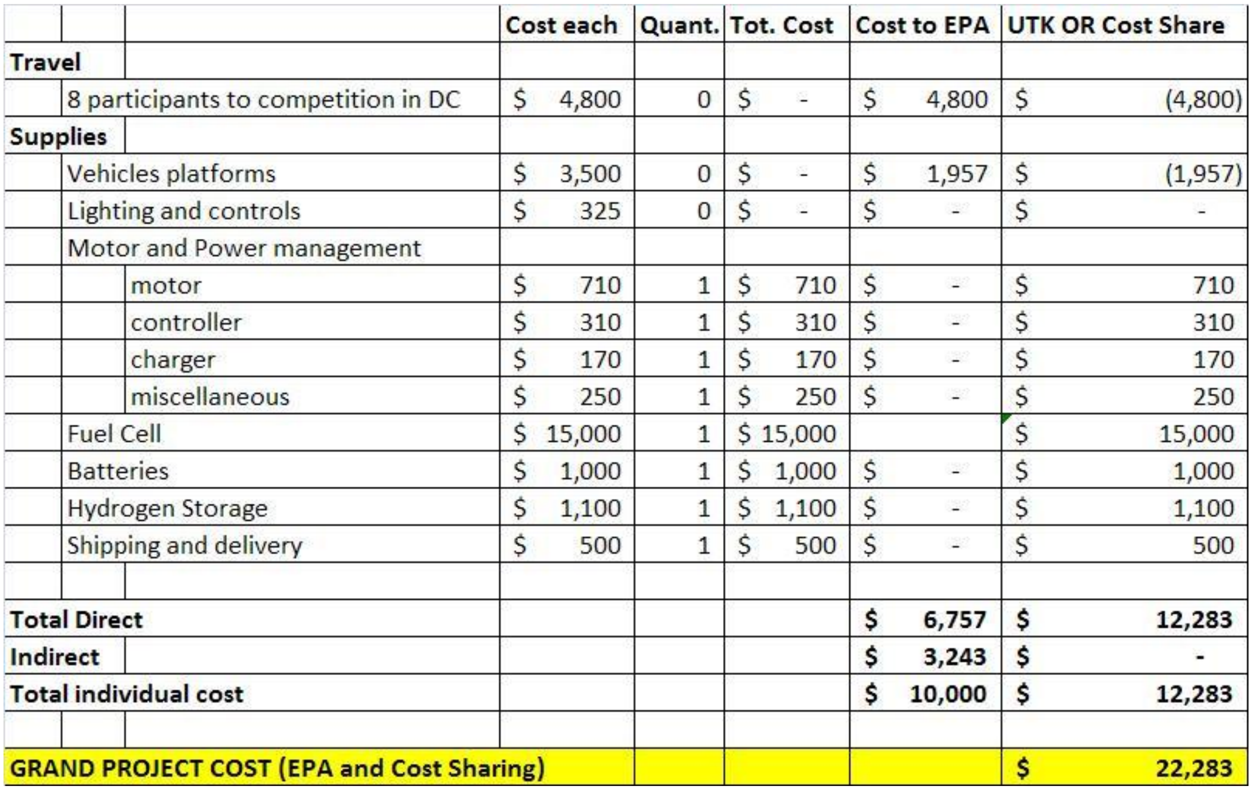
A. Budgeting

A price list needed to be compiled before purchasing the required parts. This was done so that the total cost would not exceed what was budgeted. As a combined effort from mechanical, electrical, and chemical groups, the following two budget lists were generated based on the estimation from each group. These budgets can be seen in Table 4.1 for the electric vehicle and Table 4.2 for the hybrid vehicle.



	Cost each	Quant.	Tot. Cost	Cost to EPA	UTK OR Cost Share
Travel					
12 participants to competition in DC	$ 7,200	1	$ 7,200	$ 4,800	$ 2,400
Supplies					
Vehicles platforms	$ 3,850	2	$ 7,700	$ 1,957	$ 5,743
Lighting and controls	$ 325	2	$ 650	$ -	$ 650
Motor and Power management					
motor	$ 710	1	$ 710	$ -	$ 710
controller	$ 310	1	$ 310	$ -	$ 310
charger	$ 170	1	$ 170	$ -	$ 170
miscellaneous	$ 250	1	$ 250	$ -	$ 250
Batteries	$ 2,000	1	$ 2,000	$ -	$ 2,000
Hydrogen Storage	$ 1,100	0	$ -	$ -	$ -
Shipping and delivery	$ 500	2	$ 1,000	$ -	$ 1,000
Total Direct				**$ 6,757**	**$ 13,233**
Indirect				**$ 3,243**	**$ -**
Total individual cost				**$ 10,000**	**$ 13,233**
GRAND PROJECT COST (EPA and Cost Sharing)					**$ 23,233**

Table 4.1. Budget for electric vehicle.



			Cost each	Quant.	Tot. Cost	Cost to EPA	UTK OR Cost Share
Travel							
	8 participants to competition in DC		$ 4,800	0	$ -	$ 4,800	$ (4,800)
Supplies							
	Vehicles platforms		$ 3,500	0	$ -	$ 1,957	$ (1,957)
	Lighting and controls		$ 325	0	$ -	$ -	$ -
	Motor and Power management						
		motor	$ 710	1	$ 710	$ -	$ 710
		controller	$ 310	1	$ 310	$ -	$ 310
		charger	$ 170	1	$ 170	$ -	$ 170
		miscellaneous	$ 250	1	$ 250	$ -	$ 250
	Fuel Cell		$ 15,000	1	$ 15,000		$ 15,000
	Batteries		$ 1,000	1	$ 1,000	$ -	$ 1,000
	Hydrogen Storage		$ 1,100	1	$ 1,100	$ -	$ 1,100
	Shipping and delivery		$ 500	1	$ 500	$ -	$ 500
Total Direct						**$ 6,757**	**$ 12,283**
Indirect						**$ 3,243**	**$ -**
Total individual cost						**$ 10,000**	**$ 12,283**
GRAND PROJECT COST (EPA and Cost Sharing)							**$ 22,283**

Table 4.2. Budget for hybrid hydrogen fuel cell vehicle.

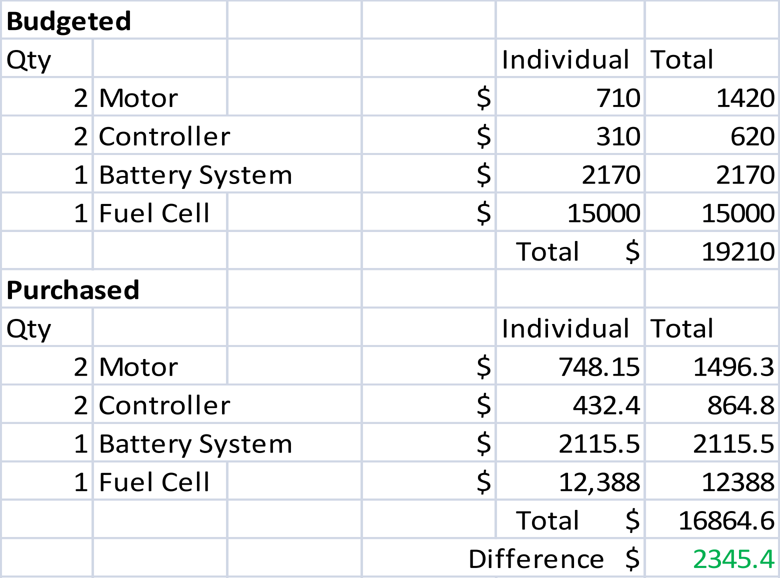
After parts were selected and vendors were chosen, all parts with concrete quoted prices were compared to the budget. The motor and controller were budgeted for $710 and $310 respectively. The chosen system from evparts.com was priced at $748.15 for the motor and $432.40 for the controller. These parts came in over budget; however, the extra cost would be made up later in the purchase the fuel cell system (detailed later).

The battery system was budgeted for $2,000. The chosen system from Elite Power Solutions included a 60 Ah battery pack, a replacement battery stack, and a charger. The total price came to $2,115.50. The price breakdown can be seen in Table 4.3. This may seem over budget; however, the budget included the price of the charger in the motor and power management section for $170.00. In actuality the batteries came in under budget by $54.50.

BEV	Item name	Model number (hyperlinked)	
	60 Ah Battery Pack B. EPS BMS System C. 3 x 12 V Stacks D. 15 A Charger E. LCD Display F. 60.9 lbs G. 38.4 V H. 12 Cells	EG-60-12	$1,595.00
	60 Ah Replacement Battery Stack • 12 V Stack • 4 Cells	GBS-LFMP60AH	$372.00
	Single Cell Battery Charger • Protection for: ○ Overload ○ Over Heating ○ Over Voltage ○ Short Circuiting ○ Incorrect Polarity • 29.4 V • 15 A	TSL24-15	$148.50
		Unit Total:	$2115.50

Table 4.3. Elite Power Solutions battery purchasing quote

The fuel cell was originally budgeted for $15,000. The chosen fuel cell from Heliocentris included a fully integrated system, system monitoring and control software, and a DC/DC convertor for hybridization. The final quotation from Heliocentris came to $12,388. This quotation can be found in the Appendix. This single part came in $2,612 under budget, leaving much desired room for other parts in the budget. Table 4.4 shows a full analysis of parts purchased.



Budgeted					
Qty				Individual	Total
2	Motor		$	710	1420
2	Controller		$	310	620
1	Battery System		$	2170	2170
1	Fuel Cell		$	15000	15000
				Total $	19210
Purchased					
Qty				Individual	Total
2	Motor		$	748.15	1496.3
2	Controller		$	432.4	864.8
1	Battery System		$	2115.5	2115.5
1	Fuel Cell		$	12,388	12388
				Total $	16864.6
			Difference	$	2345.4

Table 4.4. Budget to Price analysis.

B. Purchasing Process

All major purchases for this project had to be made through the chemical engineering department. Any part that was priced over $5,000 had to be approved by the university purchasing department which could take up to 4 weeks to complete. Thus, it was of the upmost importance to keep all possible parts under $5,000. The motor, controller and battery systems came in under $5,000 and were simply purchased online from evparts.com and Elite Power Solutions. All the motor, controller and battery systems were shipped and arrived at UT within two weeks.

The purchasing process for the Heliocentris fuel cell proved to be a much more arduous task. At first simply contacting Heliocentris to express interest in the fuel cell system was difficult. Several attempts were made to contact a university relations sales associate. After several weeks of calling and leaving messages, a sales representative was finally reached, and important questions were answered. An official quotation was then received. As expected, the quotation was larger than $5,000, and a sole source request for purchase was made to expedite the process. The EE group soon wrote a purchasing proposal for the sole source request, attached in Appendix. Fortunately, the request was approved within two weeks. The order of the fuel cell has been sent to Heliocentris. However, as stated in the quote, the company claims that it can take about 4-8 weeks for the fuel cell system to arrive, which means that it will come around mid or late January.

V. TESTING

A. Parts Arrival

The orders of two motors, two controllers, and one set of batteries were submitted at the beginning of November. Approximately two weeks later, both motors arrived at UT. Although there was not much to do with the motors at that time, it was still promising to see that the dimension, weight, and power rating of the motors met what was expected. However, there was very few accessories accompanying the motors, which meant that there would be added challenges when testing the motor. Such challenges included a proper way to mount the motor onto a stack for stability, an appropriate method to couple the two motors together, and secure connections between the motor terminals and the large 1/0 gauge wires.

Approximately another week later, the controllers came in. Along with the controllers, there were also accessories such as hand throttles, solenoids/contactors, forward/reverse switches, and several diodes, resistors, and fuses. Again there were no terminal connectors, so an appropriate way to wire the system together required some additional work.

Lastly, the batteries and their charger came in about the same time as the controllers. There was trouble with the packaging and shipping. The battery box was damaged during the UPS transit. Although UPS replaced the box, the stacks of two battery packs were misshapen. Several battery terminals were missing, and two battery cell covers were also missing. Immediate contact with the manufacturer was initiated by Dr. Frymier and the EE group. Elite Power Solutions agreed to send the missing battery terminals and covers and advised the UT proposal team to file a claim with UPS about the misshapen battery stacks. Eventually, the EE group was able to fix the battery stacks by rearranging the cells. Once the cells had been reassembled, the EE students were able to test the batteries and in doing so verified the healthy condition of the batteries by installing the battery management system (BMS), measuring the output voltage of each cell, and charging and discharging the batteries. Therefore, no claim of damage was filed with UPS.

All the components for the electric vehicle had arrived. However, a few components for the hybrid vehicle are still in the process of purchasing or delivery. These components include: 1) fuel cell system, which was approved for sole source and has been ordered; 2) batteries, whose selection is still under discussion due to unknown functionality of the fuel cell system and also several weight and dimension concerns. The approximate arrival of the fuel cell system is mid-January, 2011. The final decision on the batteries will be made once the fuel cell's DC/DC converter has been analyzed. The order and shipping process of the batteries will be much faster than other components had been, usually within two weeks. All parts will eventually arrive with a significant amount of time for vehicle construction and testing.

B. Battery Testing

Based on the manufacturer’s note, the Elite Power Solutions’ $LiFeMnPO_4$ batteries came in with a 50% charge. Upon arrival, the terminal voltage across each battery cell was measured as 3.2 V, and the voltage across the three battery packs (12 cells) was 38.4 V.

Before charging and discharging the battery, the battery management system (BMS) needed to be properly installed so that the voltage level between individual cells could be balanced and also the battery status could be monitored through an LCD display. The first step was to install the cell status circuit blocks. There were 12 of them connected in series. After the cell status circuit blocks were mounted, each board's LED briefly lit 5 times to verify a proper connection. This can be seen in Figure 5.1.

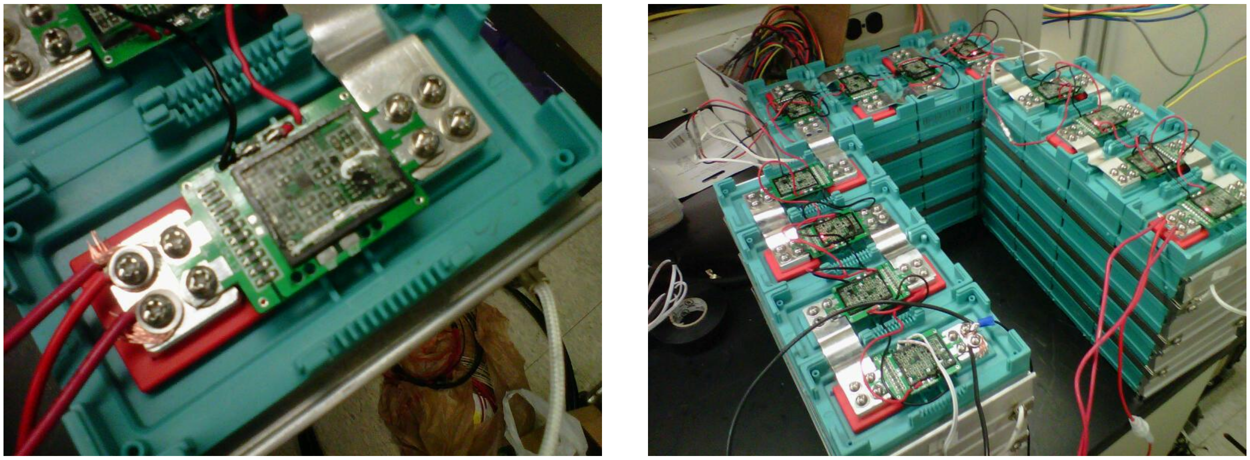


Figure 5.1. The cell status circuit blocks mounted to their individual cells. An overview of all cell blocks with cell status circuits (Left). A close up view of one of the circuits (Right).

The next step was to correctly wire the BMS according to the diagram shown in Figure 5.2. Notice that 1) the LIN Hub is the "heart" of the system that communicates between each component of the BMS, 2) Control Unit is another important part that measures the current flowing through the system and communicates with the Hub and the LCD, and 3) the charger also communicates with the BMS so that the charger stops charging when the battery capacity reaches full.

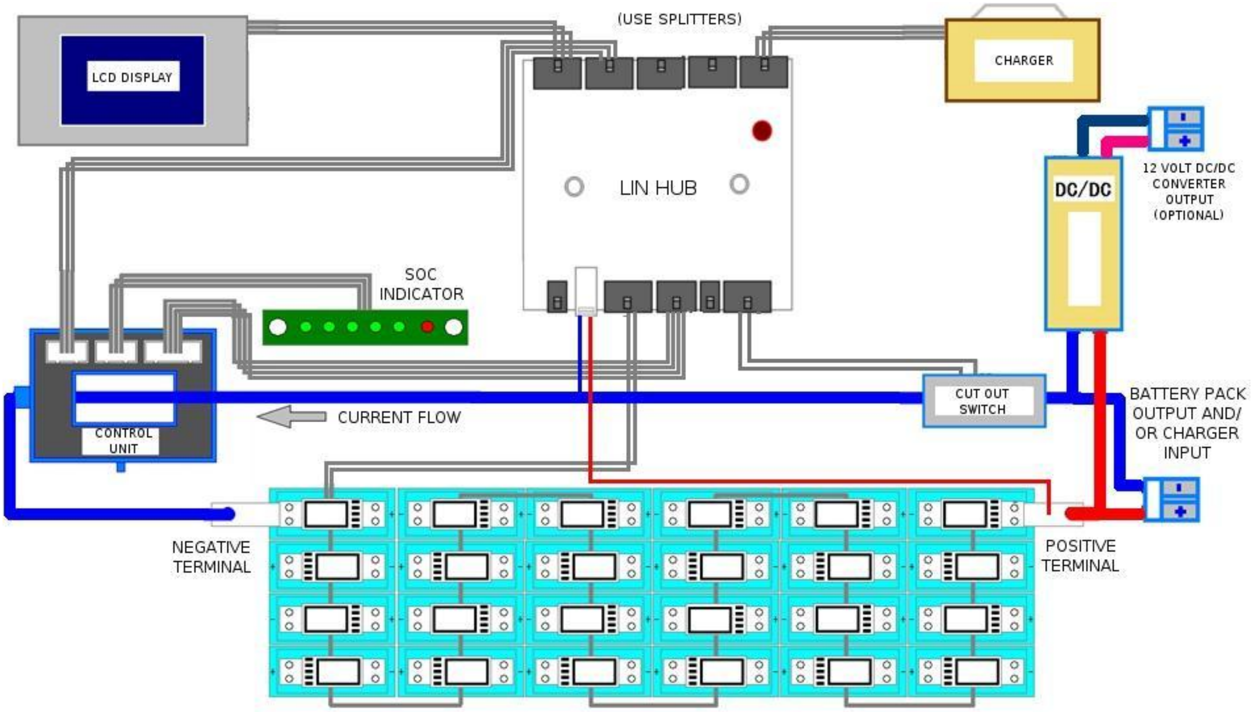


Figure 5.2. Complete wiring diagram of the battery system.

The LCD is versatile in displaying real-time battery status and setting necessary system parameters. Among the attributes to be adjusted within the battery management system primary control unit were total battery capacity, number of cells, pre-applied charge level, minimum and maximum cell voltage for critical voltage alerts, minimum cell voltage for cutoff protection, and maximum cell temperature for alert and cutoff. These settings are listed in Table 5.3. Some attributes were indisputable and were set to their proper values. Given the manufacturer's suggestion, the initial assumption was made that the batteries were shipped at half of their maximum charge. The remaining values were agreed upon by the four members of the team.

Battery Management System Attributes	
Known Values	
Number of Cells:	12
Stack Amp-Hour Capacity:	60 Ah
Manufacturer Supplied Shipping Specifications:	
Pre-applied Shipping Charge Capacity:	30 Ah
Decided Values:	
Minimum/Maximum Warning Cell Voltage	2.8 V/3.5 V
Minimum Cutoff Voltage	2.5 V
Maximum Cutoff Temperature	70 ℃

Table 5.3. BMS settings and entered values.

Once the BMS had been set to the proper values, the charger was tested. The connecting plug for the charger port had to be assembled using four lengths of 14 AWG wire and the provided contacts. Two wires were used for each contact to ensure a proper connection to the batteries and to reduce the load on each individual wire. These wires were run through the magnetic current detector before being run to the battery terminals to allow the BMS to properly read the current flowing into the system from the charger. A final connection was run between the charger and BMS to allow for communication of the two systems. As the batteries near a full charge, the BMS must be able to tell the charger to reduce current output to avoid overcharging the cells.

With the wiring between the battery and the charger completed, the test charge could begin. The BMS control box was linked to the battery connector assembly and allowed to run its initial programming. Once the BMS was successfully booted, the charger was wired to the battery connector assembly. As the charger came online, the BMS began to open communication. Initial charge current was applied at 14.4 A. Also it could be noted that the charging voltage was 42-43 V, about 20% higher than the rated battery voltage. This remained the steady charging current until the battery neared 92% capacity 3 hours later. Upon reaching this point, the BMS directed the charger to begin its first current limitation setting. Current was limited to 5.6 A for another 4% charge before dropping to 2.2 A. This continued until the system reached 98% charge capacity. Shortly after reaching 98% charge, the BMS instructed the charger to cease operation. Figure 5.4 displays several of the pictures taken during the charging process, and Figure 5.5 contains pictures taken after the charging process had completed.

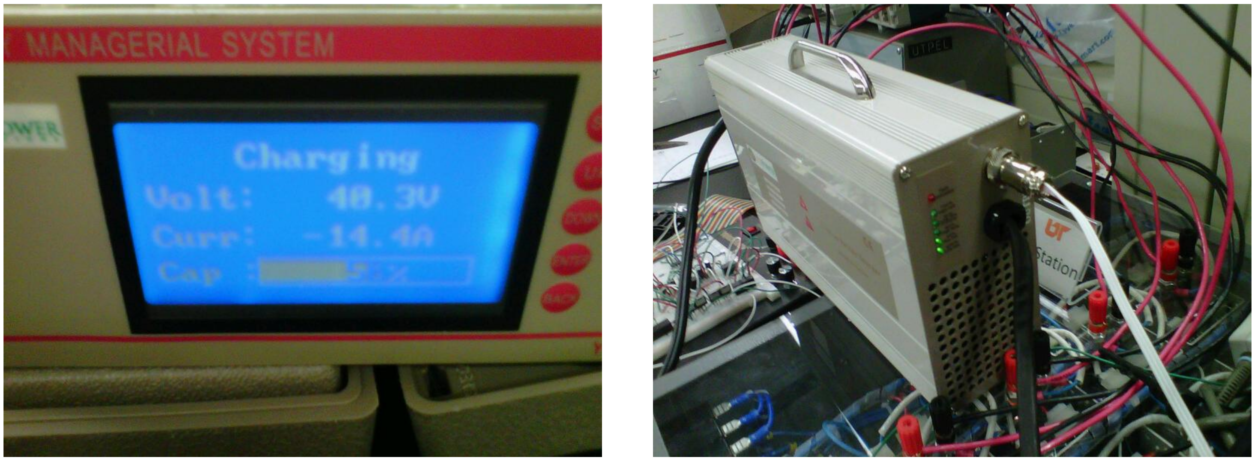


Figure 5.4. Charging report as displayed by the BMS (Left). Charging status report as displayed by the charger (Right).

Figure 5.5. Charging complete as displayed by the BMS (Left) and charger (Right).

Once the motor testing was complete, the battery packs were subject to be tested for their discharging mode. The battery was connected to a resistor bank, which consists of 30 10 Ω resistors rated at 1 kW. To achieve the fastest discharging rate and at the same time to maintain a safe discharging current, 5 of these 10 Ω resistors were connected in parallel to result in approximately 1.8 Ω resistance. Figure 5.6 shows the discharging status on the LCD screen at two points during the discharge process: 50% discharge and 18% discharge, where the low voltage alarm sounded. The average current drawn from the battery was about 22-23 A. It took about 1 hour 30 minutes for the battery capacity to go down from 98% to 50% and another hour to decrease from 50% to 18%.

Figure 5.6. BMS displays at 50% charge (Left) and 18% charge (Right).

Once the battery capacity dropped to 18% and the voltage level dropped to 35.8 V the alarm sounded from the BMS warning that the voltage level was low. The cutoff voltage stage was not tested due to the concern of damaging the battery. An interesting phenomenon later arose when the batteries regained a small amount of their lost voltage. This brought the total voltage of the stack to 36.0 V after approximately 30 seconds disconnecting them.

Another topic of testing was the total voltage drop across the stack over a range of charge percentages. The total stack voltage ripple was 6.8 V at peak. However, after obtaining a maximum voltage of 42.6 V just after charging, the voltage settled to 40.4 V, resulting in a smaller voltage variation of 4.6 V.

C. Motor and Controller Testing

The first task that had to be completed was the development of a testing rig for the motors. Running a motor free and unloaded can be dangerous and can burn out the motor. To simulate a load the two motors ordered for the two vehicles were coupled. One motor was connected to a resistor bank and used as a generator. The other motor was connected to the BugE's power system. With some assistance from the mechanical engineers, a frame was placed around and clamped to the coupled motors. This was done so that the transient torque on the motor bodies on startup would not cause the motors to jump. This rig is shown in Figure 5.7.

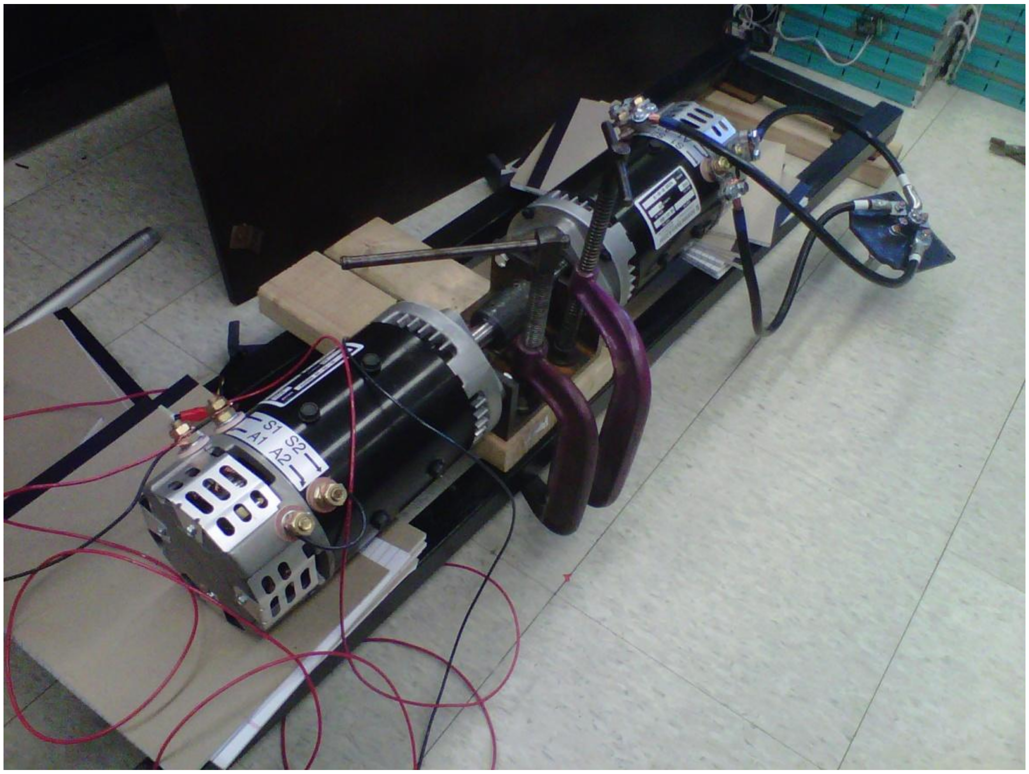


Figure 5.7. Coupled motor testing rig.

Five main parts had to be connected in order to test the motor and controller: the battery, contactor, reversing switch, motor controller, and the motor. The throttle was also attached to the controller so that the motor speed could be controlled. A kill switch was used as the key so that if something were to happen, the system could be disabled quickly and safely. Several fuses were also placed within the system to protect sensitive parts from too much current and to prevent short circuits. These parts were connected using the wiring diagrams and instructions found in the BugE manual. The overall system wiring diagram can be seen in Figure 5.8. The more detailed contactor and controller diagrams can be found later in this section in Figures 5.14 and Figures 5.15. While wiring the test rig, it was found that the 1/0 gauge wire used was very difficult to bend and maneuver.

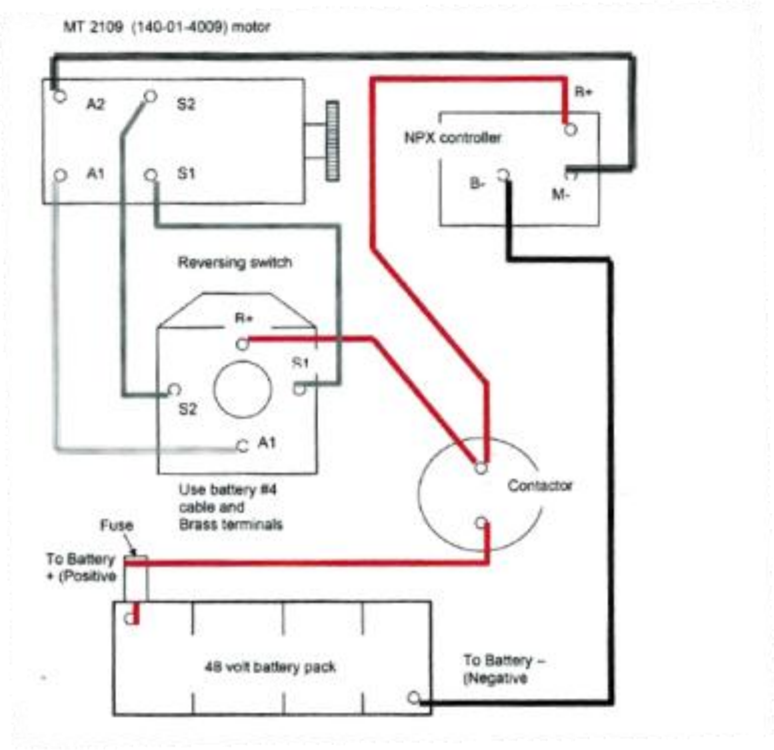


Figure 5.8. Wiring Diagram of high power system.

Testing was done by using the motor controller to log several different variables. These variables included: throttle position, diode temperature, battery voltage, battery current, and output current. Three different tests were done to look at the system's response. These tests included running the motor to bring the battery current to 10 amps, and 20 amps. Then a final test was done by holding the battery current between 10 and 15 amps for 4 minutes.

i. Temperature Response

Each test observed a rise in the controller's temperature proportional to the amount of current being put into it. The maximum temperature reached in the 10 amp test was found to be 23.2 ℃ with an average temperature of 22.7 ℃. The maximum temperature reached in the 20 amp test was found to be 23.7 ℃ with an average temperature of 22.9 ℃. The maximum temperature reached in the 4 minute test was found to be 26.1 ℃ with an average temperature of 24.9 ℃. The 4 minute test clearly showed that prolonging the amount of time that current is running through the controller, the higher the temperature rises. A graph of the controller's temperature during the four minute test can be seen in Figure 5.9.

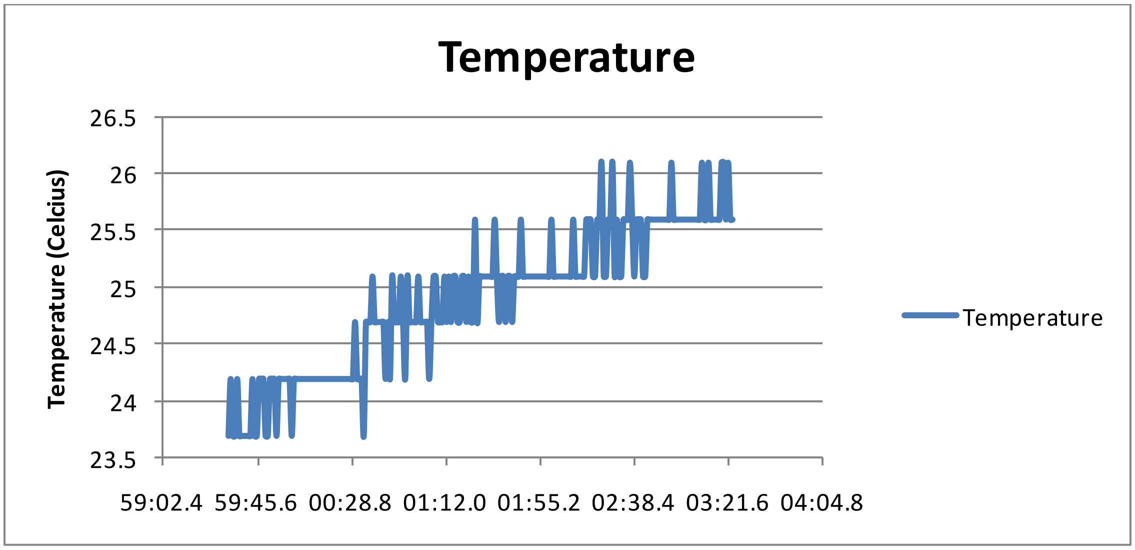


Figure 5.9. Temperature recordings of the controller during the 4-min test.

ii. Current Response

During each test the controller monitored the battery's current (the controller's input current) and the controller's output current. These currents were proportional to the throttle position and thus the amount of acceleration "asked for" by the throttle operator. Graphs showing the throttle position, input and output current over the course of the tests can be seen in Figures 5.10-12.

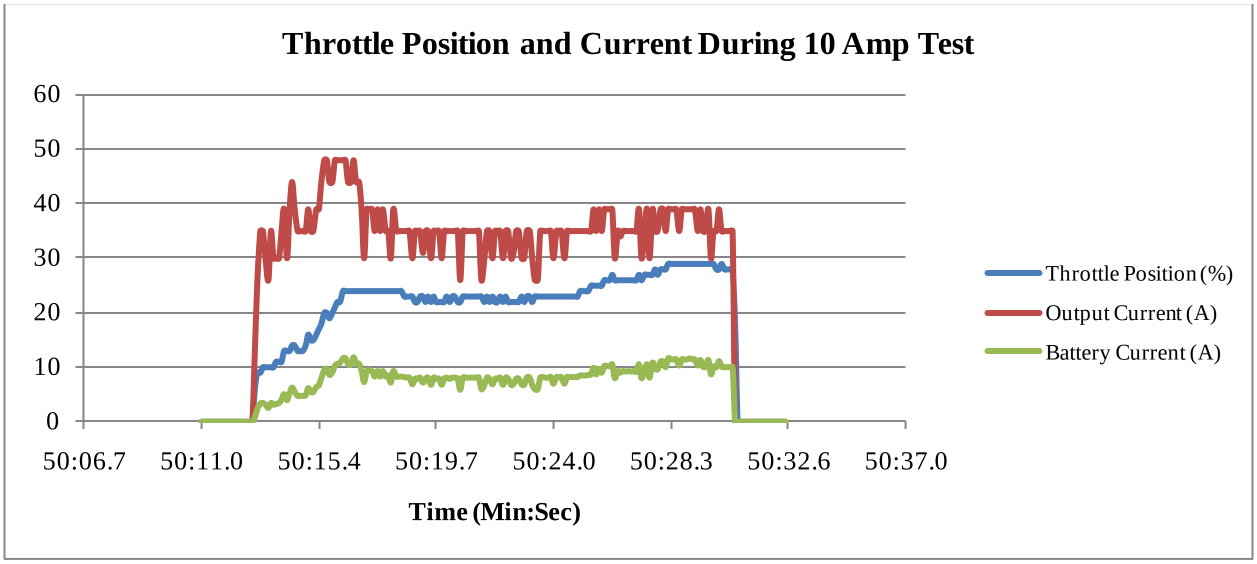


Figure 5.10. Current and Throttle position during 10 amp test.

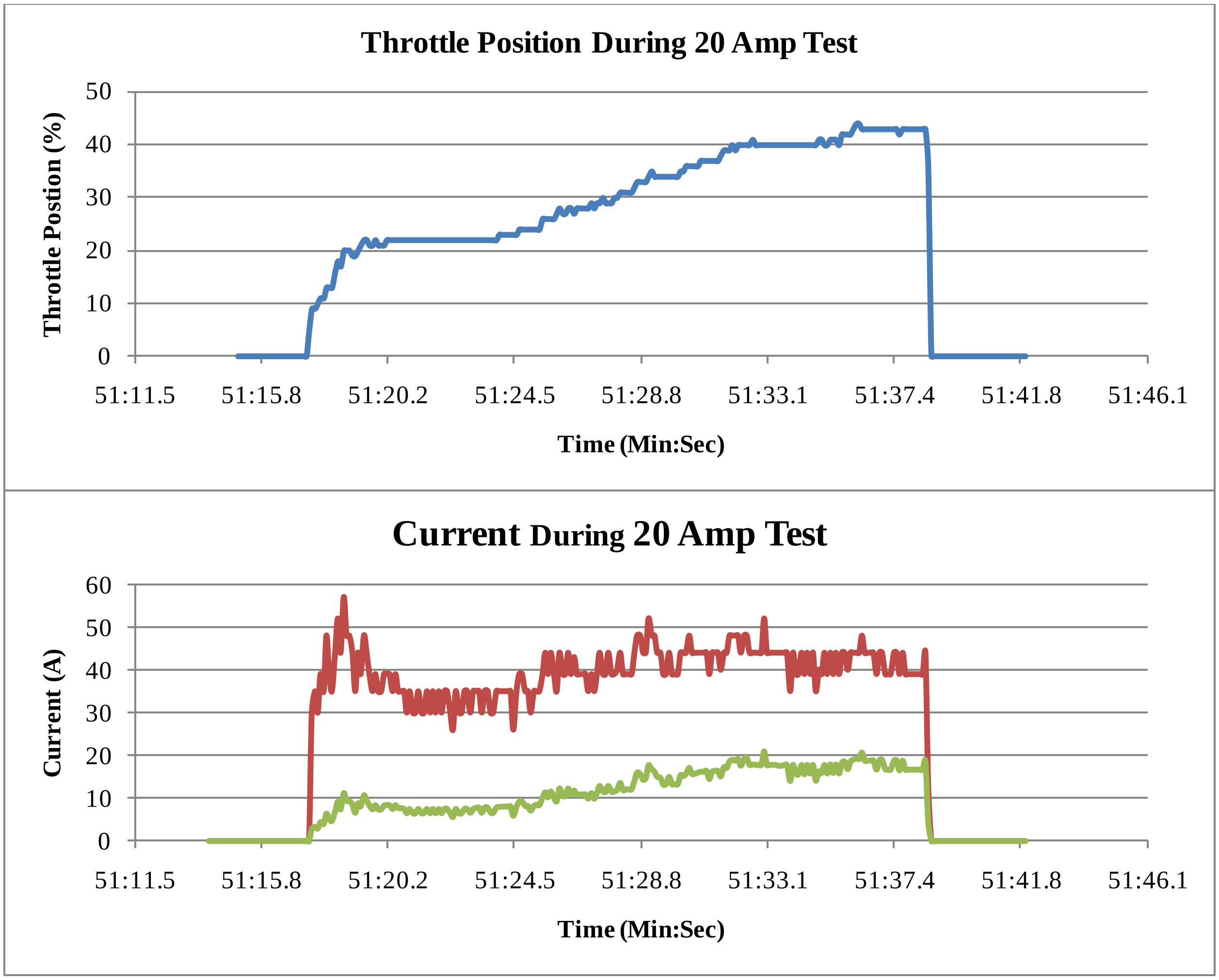


Figure 5.11. *Throttle response and current during 20 Amp test*.

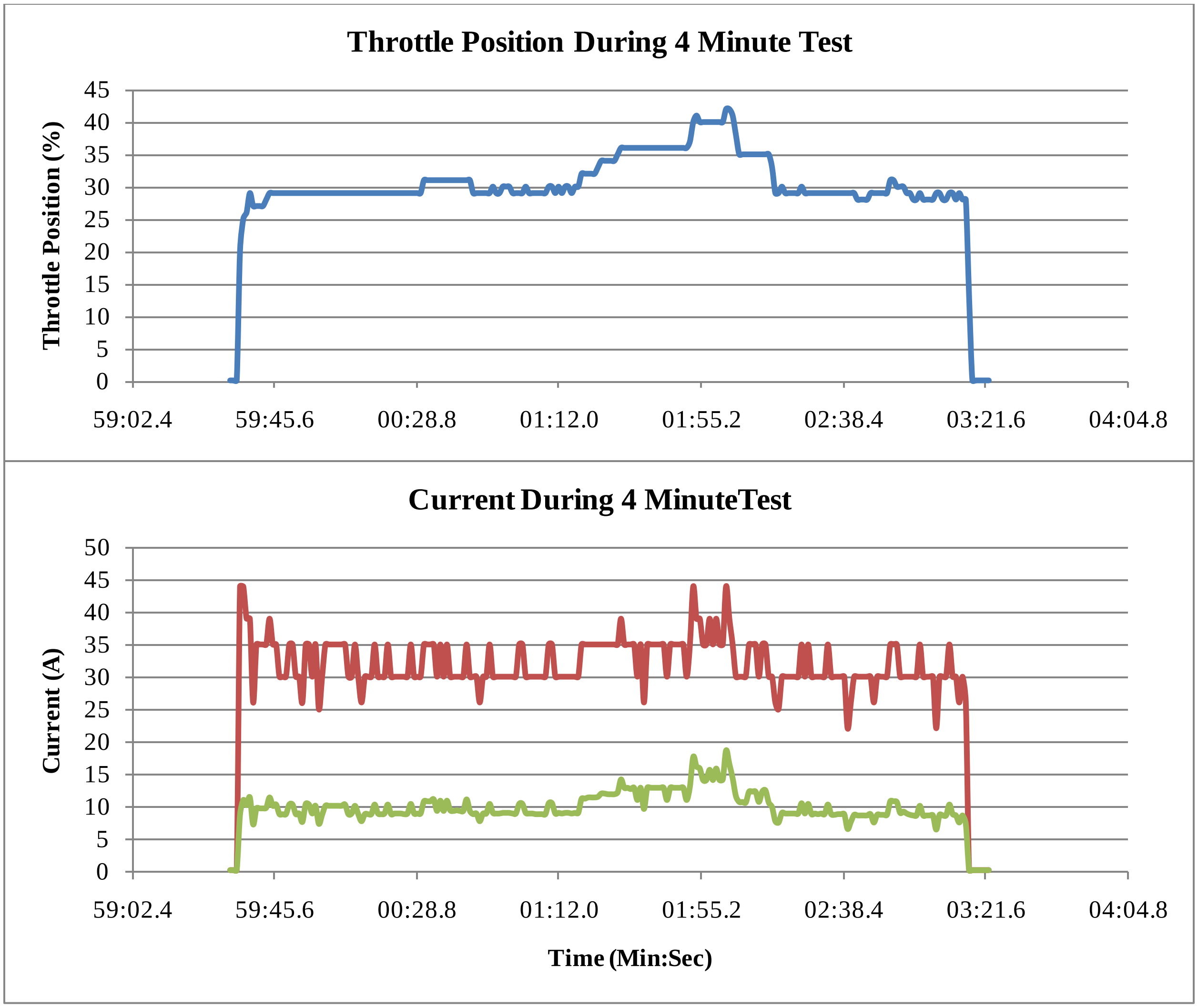
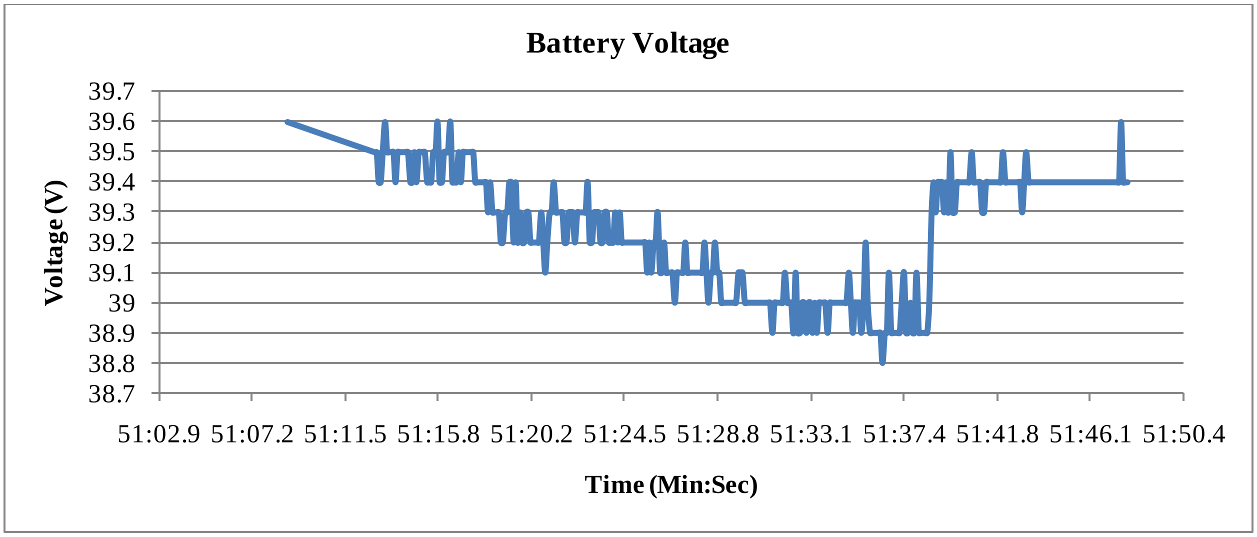


Figure 5.12: Throttle position and current during 4 minute test

It can be seen that as the throttle position increases, “asking” for acceleration, the controller outputs more current to match. This is done until the throttle reaches a steady state, at which the controller then responds by outputting correct current to maintain a constant speed. From this analysis, it can be seen that the controller is stable and seems to be working properly.

iii. Battery Voltage and Power Response

As the controller draws more current, it is important to see how the batteries voltage responds to the output of more power. If the battery’s voltage were to drop too much, it’s overall output power would drop due to the elementary relation of $P = IV$. The 20 amp test showed that as the throttle increased to approximately 40% a peak output power of 819 watts was drawn from the battery. Graphs of the battery's output voltage and power can be seen in Figures 5.13. This shows that with 60% of the throttle remaining to be turned the battery is already nearly supplying the average power required for the system.



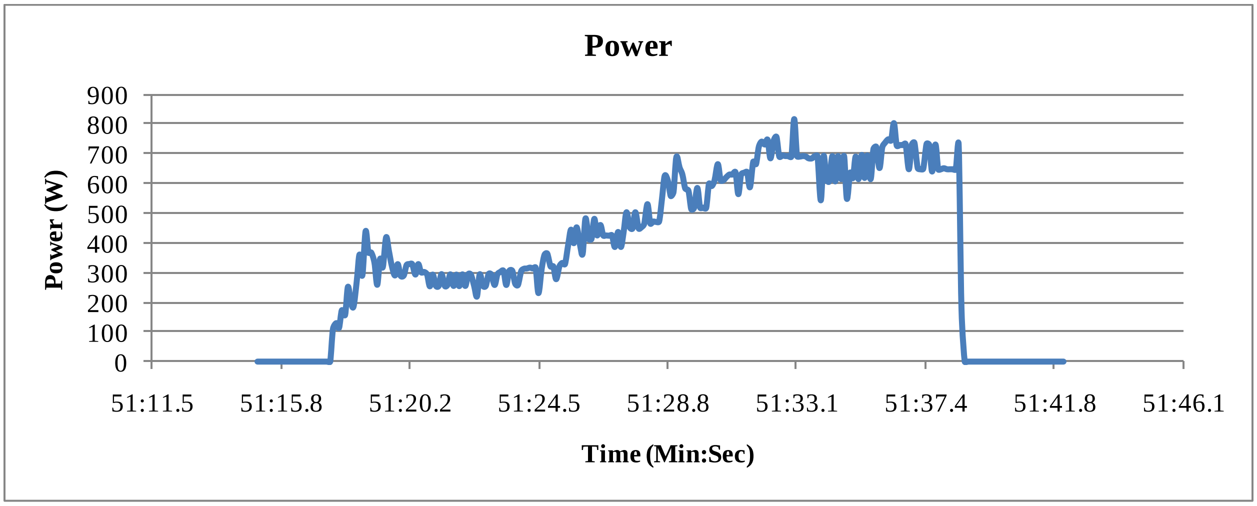


Figure 5.13. *Batter voltage and power during 20 amp test.*

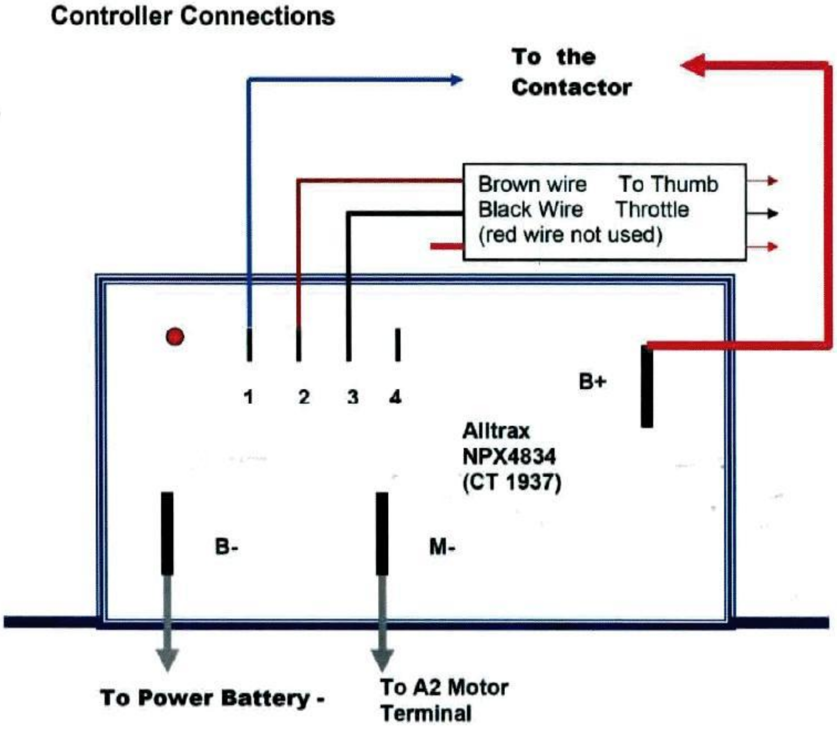


Figure 5.14. Controller wiring diagram

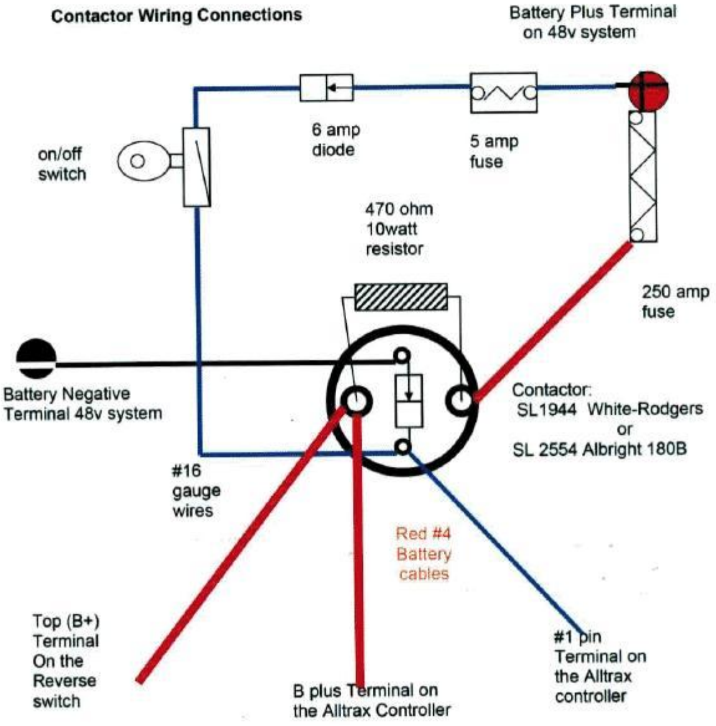


Figure 5.15. Contactor wiring diagram

VI. FUTURE WORK

A. Installation

The future teams working on this project will have to perform the installation of the major components for the two vehicles: the battery electric vehicle and the hybrid fuel cell and battery electric vehicle. The battery electric vehicle is mostly ready for installation. The hybrid fuel cell and battery electric vehicle, on the other hand, is not fully prepped for assembly.

The battery electric vehicle is ready to have its power system installed. Now that the battery testing is completed for the battery electric vehicle, the battery needs to be placed into the BugE battery compartment and bolted down. After properly installing the battery, the DC motor and DC motor controller will have to be mounted with the help of the ME group. Once the motor, battery, and controller are mounted, wiring will have to be completed. Then, the finishing touches will have to be done, such as the minor electrical system and placing the covering on.

In the case of the hybrid fuel cell and battery vehicle, much work will have to done with the ME group in modifying the battery box to fit the fuel cell properly. Once that task is done and the testing is completed on the fuel cell, the fuel cell can be installed in the battery box. Following that, the DC/DC controller will have to be mounted. The motor controller and DC motor will have to be mounted in the appropriate locations. Wiring will also have to be completed again.

B. Fuel Cell Testing

In order to properly test the fuel cell, the system (with DC/DC converter attached) must be connected in such a way as to determine both voltage and current across a load. This is to be done by using the same large resistor bank that was used to discharge the battery as discussed in

Chapter V Section B. Probes can easily be inserted to the resistor bank to measure the voltage across the resistors and the current through them. By using this method, we may easily be able to test the accuracy of the converter under different load conditions. Another possibility of testing this set up is to connect the fuel cell to the motor controller. This may be able to provide information based on what the converter will do with the excess charge generated. This test will also give readings on the current limitations based on different hydrogen flow rates.

C. New Battery

Arguably the most important information needed for the next semester is how the fuel cell and DC/DC converter manage hybridization. According to the resultant information from the fuel cell testing, a battery may then be selected. Supposing that the battery is not recharged by the fuel cell's hybridization feature, a much larger battery pack will be needed. This may be circumvented by a bidirectional DC/DC converter. This would allow the voltage at the battery terminals to be higher when low amounts of current are needed to charge the battery. This would also be capable of allowing the voltage to be stepped back down to proper levels when the battery must output current to supply the load's demand. Using the information found in Chapter IV Section C, it should be relatively simple to find the correct size battery for many different scenarios.

D. Potential Issues

There are many areas in which issues may occur. Most notably, the wire chosen to perform testing is difficult to bend. This is will most likely result in new wire being purchased. A length of welding wire in the same size as the previously purchased wire (1/0 AWG) should be much easier to work with. The minimum recommended length of the wire is 15 feet.

Another potential problem is in the area of hybridization. If the fuel cell does not work as anticipated, it may be difficult to find a bidirectional DC/DC converter capable of bearing the high current. This could result in battery damage or prevent the battery from being charged by the fuel cell at all. If the battery cannot be charged by the fuel cell, then the pack will have to be much larger, rendering the hybrid vehicle the obvious loser in the competition.

VII. CONCLUSION

A. Summary

The result of the proposals was the decision to create two near urban commuter vehicles each with a funding and budget of its own. The first of the two vehicles is a purely battery powered electric vehicle, while the second of the two is a hybridized hydrogen fuel cell and battery powered vehicle. These two vehicles are designed explicitly for near urban commuting, i.e. commuting from within fifteen miles of destination. The two vehicles will be compared and contrasted in their efficiency and reliability in fulfilling their roles as near urban commuter vehicles. The purely electric vehicle being funded by UT will be given to UT at the completion of tests and data gathering. The second vehicle is funded by the EPA P3 project and will be used in the P3 competition. Both vehicles will be built on the BugE platform.

In the designing of the two vehicles, components were properly selected. The purely electric vehicle required a battery, a DC motor controller, and a DC motor. The hybrid fuel cell and battery powered electric vehicle required the components of a fuel cell, a DC/DC controller for the fuel cell, a battery, a DC motor controller, and a DC motor. These components had to be selected with certain specifications in mind. The dimensions of the battery and the DC motor for the battery electric vehicle had to be small enough to fit in the battery box and to give ground clearance. For the hybrid vehicle’s fuel cell selection, dimension was also an important factor, because it had to fit in the battery box. Special attention had to be paid to the voltage output of the batteries and the fuel cell. In deciding the batteries, the capacities of the batteries had to be calculated and accounted. The DC motor controller and DC motor had to be chosen such that they are compatible with the given voltage and current outputs. During the whole process, various companies were researched and consulted prior to a decision being made. Price was also a factor in the decision process.

Following the selection of the components for the power system, the components had to be bought. This required going through the purchasing process. It was not an easy task. There was a significant amount of paperwork involved. The university had specific protocols that must be followed in order for the purchases to be made. For orders that cost over $5,000, it is called a capital purchase and must run through the university’s bid process. For orders less than $5,000, orders could be placed right away and would not be required to go through the university bid process. The fuel cell system purchase turned out to be a capital purchase and had to be put under the bid process. All the other components did not require the capital bid process. Although the bid process could take up to two months, the fuel cell and DC/DC converter passed the bid within two weeks because a sole source purchase was requested and approved. However, the order will take four to eight weeks to complete at Heliocentris.

The other components not requiring a bid process still took a while to be ordered and even longer to receive them from the companies and have them shipped. Upon receiving these components, testing had to be performed. Testing was a rigorous process. It took many days struggling to set it up in order to test due to complications in coupling and mounting the motors onto a stable platform and also obtaining the proper connectors to connect all the components. After setting up the system, many days were needed to test the individual components. Data had to be recorded. The testing result was deemed satisfactory to the expectation.

The future of this project will involve placing the power systems on the BugE platform. A new battery will still have to be ordered that will work with the fuel cell. The fuel cell should be arriving to the university mid to late January 2011. Once the fuel cell arrives, testing has to be done on the fuel cell system before installation onto the vehicle. Wiring the proper components on the vehicle is not a petty task. It will require many hours of intense hands-on work.

B. What We Have Learned

Through this senior design project, we, the EE group, have learned much about the cutting-edge Li-ion battery, motor, controller, and fuel cell technology, especially in the application of vehicle transportation. Not only have we intensively researched online about what is available in the contemporary market, but also we were able to have access to the hardware so that we could gain hands-on experience. In addition, by wiring the components together and testing the system, we have learned how the vehicle's power system works as a whole. There were many challenges during the design and testing process, and sometimes these challenges were unexpected. However, whenever difficulties arose, we usually found resources online, sought advice from professors, or attempted to troubleshoot the problem ourselves. These experiences with dealing with problems were invaluable to the learning process.

We have overcome many obstacles throughout the process. One of the biggest is working as a team. Inside the EE group, we sometimes had different schedules making meetings difficult and we occasionally held different opinions towards approaching a problem or selecting a component. With these challenges in mind, each member of the team acted as a group leader at different times, and the leader usually put in more effort than the other members. This was effective because each member was specialized in different subjects, and also each of the members had different availabilities now and then. We further experienced teamwork with ME and ChemE groups. We have learned how important it was to respect each other's area of specialization and to find a balance point when there is a conflict in the decision making process.

Another important aspect of the senior design project was to interact with people outside of academia. Quite often, we were required to contact companies, request quotes, purchase merchandise, write proposals, and ask for money. It was unavoidable that we needed to deal with sales representatives, managers, secretaries, or workers. We learned that people with different backgrounds have different priorities. We may not always expect everyone to think alike. Furthermore, people outside of academia are busy and are not immediately available to receive our requests or questions and handle them. Thus, we always needed to plan accordingly and leave ample time for people to process our requests.

As part of the senior design requirement, we were also expected to attend a series of ABET lectures to learn certain skills for becoming a successful engineer. Topics covered in these lectures include: presenting your presentation, organizational skills, effective communications, engineering economics, engineering ethics.

At the end of the senior design, we feel that we have improved a lot both as an engineering student and as individuals. Each member of the EE group has become more effective in communication, more efficient in planning and organization, more experienced with "colleagues" and "bosses", more knowledgeable in budgeting and logistics, and most importantly, more devoted to his field of engineering.

C. Acknowledgement

The senior design project could not have been successful without the support from:

- EPA P3 and UTK Office of Research for their generous grants
- Dr. Tolbert, Dr. Frymier, and Dr. Irick for their guidance in technology
- ME and ChemE groups for their areas of specialization
- UTK Power Electronics Lab for its experimentation space and equipment
- Purchasing Department for its prompt quote approval and order placement
- Maintenance stuff for their tools and guidance in construction