Electric Bicycle System

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Acknowledgments

First, and foremost, our group as a whole would like to thank Dr. Taufik for all his knowledge and guidance he has given us throughout our Cal Poly career as our instructor, as our advisor, and as our friend. After taking some of his courses, we were convinced to select our concentration as Power Systems/ Power Electronics. He has provided us the skills and wisdom needed to use in our careers as Electrical Engineers. We would also like to thank our parents for all their love and support. Without them we would not be able to experience and take part in this project. They have helped us realize how important our education is, as well as how essential it is to the rest of our lives. Also, thanks to all of our family and friends who helped us with the designing process, the testing the bike, and for encouraging us throughout our college careers.

Abstract

The Electric Bicycle System is a systems project that incorporates three different ways of charging a lithium-ion battery: the $120V_{AC}$ wall outlet, regenerative braking, and solar power; which is used to power an electric hub motor running a bicycle. The purpose of the project is to show that it is possible and relatively simple, to build an electric bicycle by oneself. This project can be broken down into five separate categories: the lithium-ion battery, the DC-DC boost converter, the solar panel, the motor, and the motor controller. Each of these will be built upon and improved further by future students, one category at a time. The hope is that this design can become very efficient, cost-effective, and one day mass-produced, especially in developing countries where automotive transportation is an impossibility.

I. Introduction

When thinking of possible senior projects, we all decided that we wanted to do something that would somehow be beneficial to the planet. After discussing with Dr. Taufik, we decided that the electric bicycle would be the best fit. The electric bicycle offers a cleaner alternative to travel short-to-moderate distances rather than driving a gasoline-powered car. In recent years, the United States has increasingly encouraged a cleaner environment and less dependence on foreign oil. The price of crude oil has increased significantly over the past few years and there seems to be no turning back. The environment has also been more of a focus throughout the world in the past few years, and it seems that cleaner alternatives have been steadily on the rise with no end in sight. The electric bicycle is a project that can promote both cleaner technology as well as a lesser dependence on oil. It will run on clean electric power with the ability to recharge the battery 3 separate ways: through the 120 V_{AC} wall source, by generating power through the pedals of the bicycle, and by solar-cell generative power. An extra benefit to building the electric bicycle is that it can also show the general public how much cheaper it would be to convert their regular bicycle into an electric bicycle rather than driving solely in their gas-powered vehicles. The greater importance of the environment in the world leads to an opportunity for students in our position. With the economy trying to get out of one of the worst depressions of the century, there are numerous opportunities for us to help out. This is our opportunity to contribute a greener and more efficient planet.

II. Background

The idea of a motorized bicycle, let alone the electric powered bike, is not a recent concept and has been around for more than a century. In 1867, the first known motor bike was invented by Sylvester Howard Roper of Boston, MA [22]. His innovative approach to the bicycle would be commercially known as the Roper steam velocipede, which was basically a bike powered by a steam engine. Although the use was around for a while during those times, it wasn't until 1895 that the electric bicycle made its place in history. That year, Ogden Bolten was granted U.S. Patent 552,271 for a battery-powered bicycle with a six-pole brush-and-commutator DC hub motor mounted in the rear wheel. His bike itself had no gears and the motor could draw up to 100A with a 10V battery. From there, the concept of the electric bike became feasible and practical. As the years progress, more and more electric bikes were produced with varying driving mechanisms. Some had a motor connected to the wheel with a belt or chain. Other designs had a motor sitting on top of the front wheel and propelled the bike by friction. It wasn't until the mid 1950's in which the motorized bike industry would take a concept patented in 1890, and use it to make a more efficient and environmentally friendly motorized bike. This concept, the first practical wheel motor, was a fully incorporated wheel hub and was called the "Electro-Motor Traction Wheel". It was the patent of Albert Parcelle of Boston, MA. By the year 1992, there were still hardly any commercial electric bicycles available. It wasn't until 1998 when there were at least 49 different bikes manufactured by various companies. Production grew from 1993 to 2004 by an estimated 35%.

Today, we are planning to continue on with the concept of the electric bike and look for new ways of making a more efficient and practical electric bike. By interfacing the power source with additional power charges while in use, it can influence and increase the duration of use and the distance traveled. Ultimately, this system will result as the first Cal Poly "Electric Bike Model". It is desired that for the future, all components will be designed and mass produced in house by different project groups and later interfaced together to reproduce our original system model. By reverse engineering our components, through modern innovations, and more revolutionary techniques it will result in a much more efficient electric bike system.

III. Design Requirements

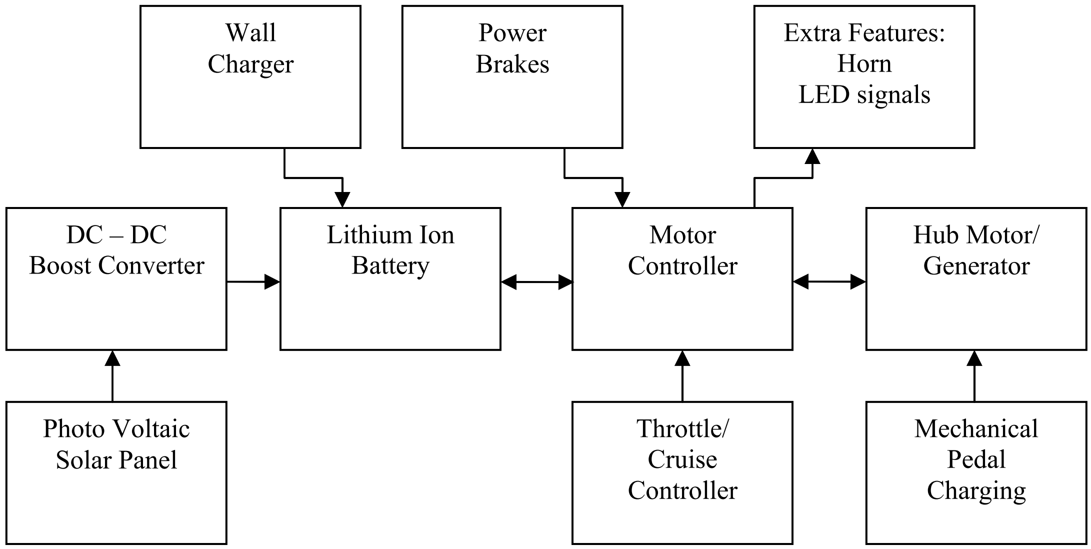

Figure 3.1 System Block Diagram for Entire Project

The basis of this project is to construct a system for an electric bike. There are many key components within the block diagram for this system as shown in Figure 3.1. They consist of a lithium-ion battery, a motor controller, a DC-DC converter, a photo-voltaic solar panel, and a brushless DC motor. The power brakes and throttle/cruise controller are simple button systems that are used to trigger the functions for increasing speed, keeping the speed constant, and turning off the motor. The majority of the components were purchased from Golden Motor Technology Co Ltd. This maximized the interfacing capabilities for the separate block diagrams.

The power source for the system was a DC battery source chosen to output 48V, which was the maximum output voltage on the Golden Motor website. The battery was primarily chosen due to the lithium ion cells used to configure it. A lithium ion battery was the most efficient choice for an electric bike because it offers high energy density while remaining relatively light-weight and compact in size. Lithium ion batteries can be very dangerous; therefore it is essential to research the quality of the lithium ion cells and the protective implementations used. The Golden Motor battery has a high voltage rating diode at the output, and uses it as a current protector. This is essential to the project requirement for interfacing multiple forms of charging such as solar energy, mechanical energy, and high AC voltage through an outlet.

The battery block is interfaced with the motor controller block. The motor controller controls all the functional capabilities and is the central component of the system. The basic requirement for the control is to regulate the amount of power applied to the motor, especially for DC motors. The motor controller can be adjusted to synchronize with other brushless motors. There are also many built-in functions for this controller that vary from detecting any malfunctions with the motor hall sensors, the throttle, and the brake levers to protect functions against excessive current and under-voltage, which are ideal for protecting the lithium ion battery. These functions are beneficial to the success of this project and also provide a solution to any troubleshooting and damages that may occur.

One key feature that is integrated with the interface of the controller and the motor was the regenerative braking. A regenerative brake is an energy recovery mechanism that reduces the bicycle’s speed by converting some of its kinetic energy into a useful form of energy instead of dissipating it as heat from conventional brake friction. The energy is then supplied back to the power source. The control allows the battery to interface with the motor to be bidirectional which can supply and receive power. Software is provided with the controller so that it can adjust the setting and operations for several of the controller's functions. By creating a switch that purposely is "fooling" the controller to use the motor as a generator without completely braking the wheel, it is possible to generate mechanical energy through pedaling.

Another source of battery charging comes from the photovoltaic solar panel. Initially a light-weight and flexible solar panel was desired. For an output power of 20 watts or higher the prices ranged from \$200 - \$400. Due to the project's limited budget and its investment in an expensive lithium ion battery, the budget for a solar panel was approximately \$50. The solar panel with the same requirements of output 12V and 20 watts was found on Ebay. Once a voltage and current is generated through the solar panel a DC – DC boost converter block is needed to step the output voltage from the solar panel to match the battery's voltage of 48V. The power must be conserved in a converter therefore, as the voltage in increased, the current is decreased. It is more efficient to have a higher current input to the boost converter but for the current budget and resources, it is not practical. Due to the inefficient charging power supplied to the battery, it is not realistic for the solar panel to fully charge the battery. Its primary purpose is to provide a longer life cycle for the battery and to provide some charge when access to an outlet is not available.

IV. Design

DC-DC Boost Converter

Including the solar panel into the electric bicycle not only presents an extra source for charging the battery, but also an extra problem. The problem is that the output of the solar panel will not always be stable due to fluctuations in intensity of sunlight, angular changes with respect to the direction of sunlight, as well as other environmental factors. This is where the Boost Converter comes into our project. The output of the solar panel will be the input of the boost converter, which then outputs into the battery for charging. Because the output of the solar panel will be varying constantly, we need a boost converter that will take an input from a wide range of voltages and output a specific, constant voltage value.

A boost converter is a step-up power converter that will take in a DC voltage and output a higher value DC voltage. Our boost converter will require us to take in the output of the solar panel, which can range from 0V to 17.2V, and output 54.6V for optimal charging of the battery [1]. After researching websites, we came upon two different evaluation module boards: the TPS40210EVM from Texas Instruments and the DC1286A-A from Linear Technology.

We were initially attracted to the Texas Instruments Evaluation Module TPS40210EVM because it has the characteristics of taking in an input range of 9.6V to 13.2V and outputting 24V at a maximum of 2 amps [8]. This EVM has an area of 2.5 square inches so it is also very small in size, which makes it very feasible to be placed anywhere on the bike. We originally thought that since the battery is rated at

48V, we would need to supply exactly 48V in order to charge it. This could be done by using a simple voltage doubler added to the output of the EVM and we should theoretically have the appropriate 48V needed for charging. After more research and finding out that we need to provide 54.6V for the battery, we began searching for another converter which would require less modification to obtain 48V. Seeing that this board was already in our possession, we decided to run OrCad PSpice simulations to find out exactly how much modification was needed in order to get the desired output. This can be seen in the Testing Procedures section.

The Linear Technology Evaluation Module DC1286A-A seemed very nice for our application. This EVM operates at an input range of 5V to 36V. It outputs a constant 48V with an output current of 2A-5A [6]. Initially, this evaluation module is the perfect fit for charging our battery because it takes an input in the range of our solar panel, but it also outputs the exact amount of voltage needed to charge the battery. After discovering that we would require a 54.6V output, changes to the voltage divider must be made to account for this. The details can be seen in the Testing Procedures section.

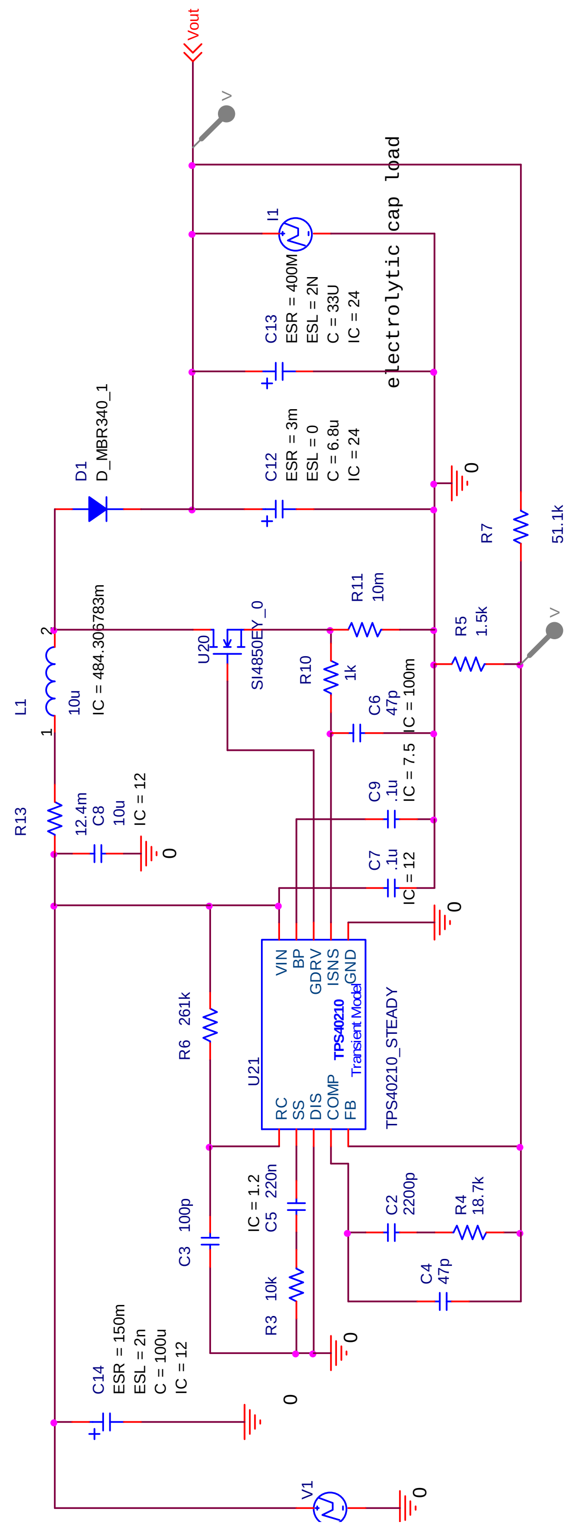

Figure 4.1: Texas Instruments EVM Circuit

Solar Cells

One way we thought of charging the battery is through the use of a solar cell. Solar cells are devices that convert the energy of sunlight directly into electricity through the use of the photovoltaic effect. The photovoltaic effect involves the creation of a voltage in a material upon exposure to electro-magnetic radiation [9]. The photoelectric and photovoltaic effects are related through sunlight, but are different in that electrons are ejected from a material's surface upon exposure to radiation of sufficient energy in photoelectric, and generated electrons are transferred to different bands of valence to conduction within the material, resulting in the buildup of voltage between two electrodes in photovoltaic [9].

Solar cells are often electrically connected and encapsulated as a module with a sheet of glass on top to allow light to pass and protect the semiconductor from the weather. To obtain a desired peak DC voltage with solar cells, you add them in series, and to obtain a desired peak current, you add the solar cells in parallel. In order to calculate the standard energy of an application, kilowatt-hours per day is used. The general rule of thumb is that average power is equal to twenty percent of peak power, so that each peak kilowatt of solar array output power corresponds to energy production of 4.8 kilowatt-hours per day [9].

High efficiency solar cells are a class of solar cell that generates more electricity per incident solar power unit. Most of the industry is focused on making the most cost efficient solar cell in terms of cost per generated power. There are many different types of high efficiency solar cells. The three main types of the high efficiency solar cells are multi-junction solar cells, thin-film solar cells, and crystalline/bulk silicon.

Out of all these choices of solar cells, we selected a polycrystalline solar cell, which is the bulk type silicon. We chose this cell over the other cells based on cost and the amount of efficiency we needed. The multi-junction solar cell is much too expensive for our budget, and the thin-film solar cell is not that reliable. The crystalline type solar cells were the most reliable and commercially available type. Monocrystalline may be more efficient, but with the application we're using, it would not matter if we used either crystalline solar cell. Polycrystalline was cheaper and provided a sufficient amount of output voltage and wattage for the boost converter.

The solar cell was bought on Ebay for about $50 by the company Asunpower, Inc. It provides an output voltage of about 12V and 20 W with a lifespan of about 25 years. This module's efficiency is about 10%, which is sufficient in our application. The dimensions are 22 in. × 14.2 in. × 0.98 in. We decided to mount the solar panel on top of the battery, which is located above the rear tire. This way, the rider is not prevented from riding the bike comfortably and protects the battery from directly being heated by the sun. There will be housing for the solar cell that will keep it in place and provide protection from damage.

Advantages

Solar energy has been one of the most used, cleanest, and sustainable forms of energy obtained through solar cells. They are environmentally friendly with no use of any fuels or release of toxic fumes that may cause global warming. Solar cells are independent from a power source and can charge constantly, which helps lower time to charge through a high AC voltage charger. They also have a long life span of at least twenty years and require little to no maintenance.

Disadvantages

With all its advantages, there are some disadvantages to solar cells as well. Solar cells are not easy to manufacture, so their prices are high and increase with each watt needed. Sunlight is not always provided, especially at night, and may not be evenly distributed where you're located, so it cannot always provide the sufficient amount of power. Therefore, it cannot be used as a primary source of charging, since it is also not highly energy efficient.

Innovations

There are currently more advanced ways solar cells can be mounted on the bike. There are bendable forms of solar cells and can be applied around the frame to conserve space and lower weight on the bike. Solar cell wheels that act like hub caps to the bike are also available (See Figure 4.2). These means may be more intuitive, but they are not cost efficient. They each run for about $300 at least. If we had the means to afford it, we would have used those solar cells instead. They are more energy efficient and have higher output voltage and wattage.

Figure 4.2: Electric bike with solar hub caps

There are also different forms of solar cells being made besides the typical solar panels. Inflatable solar balloons, “hairlike” solar nanowires, and printed solar panels are among the different types that have recently been made. These new forms of solar cells are currently working and are trying to be more efficient than current forms. They can possibly be used on the bike to conserve even more space.

Brushless Direct Current Motor

Choosing a motor was the first step in creating an appropriate system for the electric bike. Initially, the project was to be driven by DC micro motors that were configured to turn a sprocket. The sprocket is used to transmit rotary motion between two shafts. To change gears and speeds of the bicycle, the diameter of the sprocket needs to be changed. Instead of having multiple sized sprockets in parallel, the initial idea was to place multiple micro motors in parallel to increase the amount of current supplied to the sprocket for more output power. This system seemed to be over complicated and the micro motors would not supply enough power and torque to support a bicycle at high speeds.

It was settled that the best solution in driving the bike is with an electric DC motor; thus, creating an electric bike. In the DC motor, a static field flux is induced using permanent magnets or a stator field winding. Located on the rotor of the DC motor is the armature winding. The armature winding is the series of conducting coils, each connected in segments of a commutator that are wound around the iron core in which voltage is induced. This causes it to rotate within a magnetic field; if the wires are broken or damaged, the armature will not rotate properly [18]. For the DC motor to generate any torque, the coils of the armature must be connected to an external DC circuit with an even number of brush heads. Figure 4.3 shows a circuit model of a DC motor.

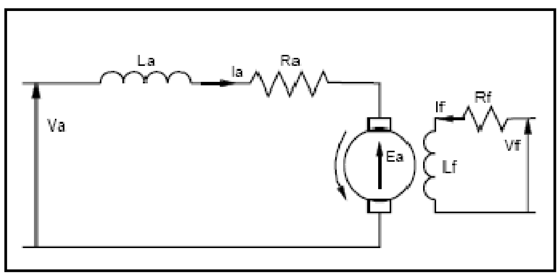

Figure 4.3- Circuit diagram of a brushed DC commutator motor

The application of DC motors has increased dramatically. As technology advances, new and improved designs of the DC motor will be implemented. Brushless DC (BLDC) motors are the primary choice for a wide variety of applications. The BLDC motor system is emerging as one of the most useful drive options for a wide range of applications ranging from small, low power fans and disc drives, through medium size domestic appliance motors and up to larger industrial and aviational robotic and servo drives [19].

When comparing a typical DC motor to an AC motor, the fundamental advantage is the ease with which the motor can be controlled to give varying speeds, direction, and even regenerative breaking. The main drawback to the DC motor is that the carbon brushes of a conventional DC motor wear down and create a great amount of dust. This in-turn requires a great amount of maintenance and lead to the overall replacement of the motor itself. Another major problem that conventional DC motors have is their high level of radio frequency interference (RFI). The RFI generated by the brush gears can be of major concern to communications between certain aspects of a DC motor application and may cause failure. Thus, the brushless DC motor was developed to have the same advantages of a conventional DC motor, without the problems and disadvantages caused by the brushes.

The main advantages and characteristics of a BLDC motor compared to a conventional DC motor include [19]:

- Longer life and higher reliability
- Higher efficiency
- Ability to operate at various speeds, including high speed applications
- Can reach peak torque from stand still
- Construction of motor rigid
- Operational in vacuum or in explosive or hazardous environments
- Eliminates radio frequency interference due to brush commutation

- Heat is generated in the stator: Easier to remove and maintain.
- Rotor has permanent magnets vs. coils thus lighter less inertia: Easier to start and stop
- Linear torque/current relationship smooth acceleration or constant torque
- Higher torque ripple due to lack of information between sectors
- Low Cost to manufacture
- Simple, low-cost design for fixed-speed applications
- Clean, Fast and Efficient
- Speed proportionate to line frequency (50 or 60 Hz)
- Complex control for variable speed and torque

All of this contributed to the decision to use a BLDC motor as the driving source of our electric bike. The benefits of the BLDC motor give the electric bike the reliability and features it needs to make it a practical and reliable alternative source of transportation.

Compared to a typical DC motor, the BLDC motor implements an electric commutator instead of a mechanical commutator which, in effect, increases the reliability. Additionally, the rotor magnets in a BLDC motor generate the rotor's magnetic flux, in turn giving it higher efficiencies than a normal DC motor. The BLDC motor is essentially the opposite of a brushed DC commutator motor, in which the permanent magnets in the motor rotate around the conductors while the conductors are stationary. Current polarity in the DC commutator motor is controlled and varied by the brushes and commutator. With the BLDC, the polarity of the current is driven by power transistors that switch synchronously with respect to the rotor position. In order to monitor the position of the rotor, sensors are typically used, one of which is the Hall Effect sensor which is not needed in conventional DC commutator motors. Figure 4.4 shows a conventional DC motor vs. a BLDC motor for comparison.

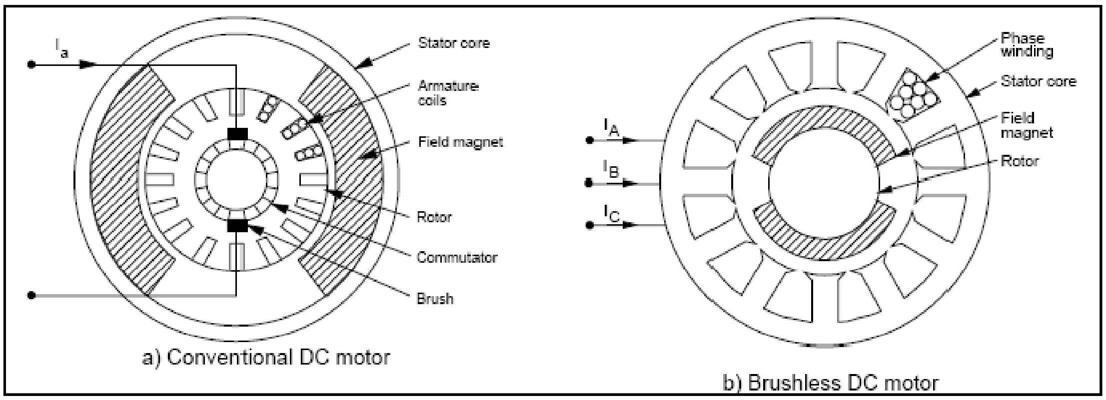

Figure 4.4- Comparison between conventional DC motor and BLDC motor

With the combinations of the hall sensors, the BLDC provides the most efficient way to power and drive a bike. Figure 4.5 below shows the stripped down view of the motor that is being implemented in the overall design.

Figure 4.5 – Inside view of the hub motor implemented in the Electric Bike System

Motor Controller

To drive and control the BLDC motor, the use of a motor controller was implemented. The motor controller is an essential device for any motor driven device. The motor controller is analogous to the human brain, processing information and feeding it back to the end user. Of course, the applications of a motor controller vary based on the task that it will be performing. One of the simplest applications is a basic switch to supply power to the motor, thus making the motor run. As one utilizes more features in the motor, the complexity of the motor controller increases.

To drive the BLDC motor, the motor controller sends rectangular/trapezoidal voltage stokes that are coupled with the position of the rotor. Figure 4.6 shows the timing diagram of the voltage stokes applied with respect to the rotor position dictated by the Hall Effect sensor.

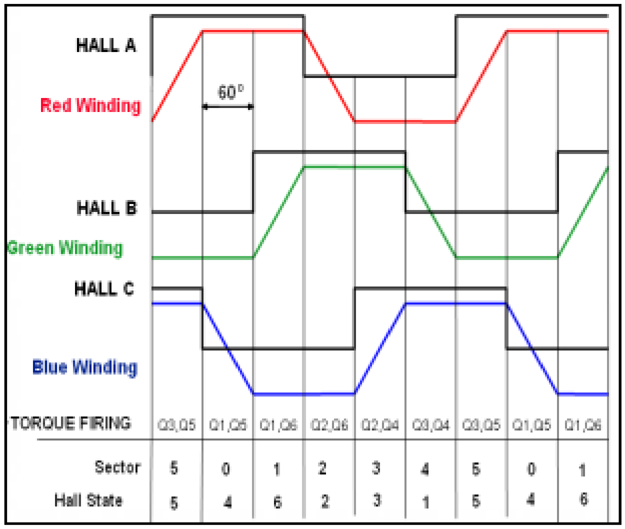

Figure 4.6: Voltage Stokes applied to the 3-phase BLDC motor

The voltage stokes of the BLDC motor need to be applied to the two phases of the 3-phase winding system so that the angle between the stator, flux and the rotor flux is kept close to 90 degrees in order to generate maximum torque from the motor. In order to do that, the motor controller is used to electronically control when the voltage strokes are applied. Figure 4.6 shows the standard power stage for the 3-phase BLDC motor.

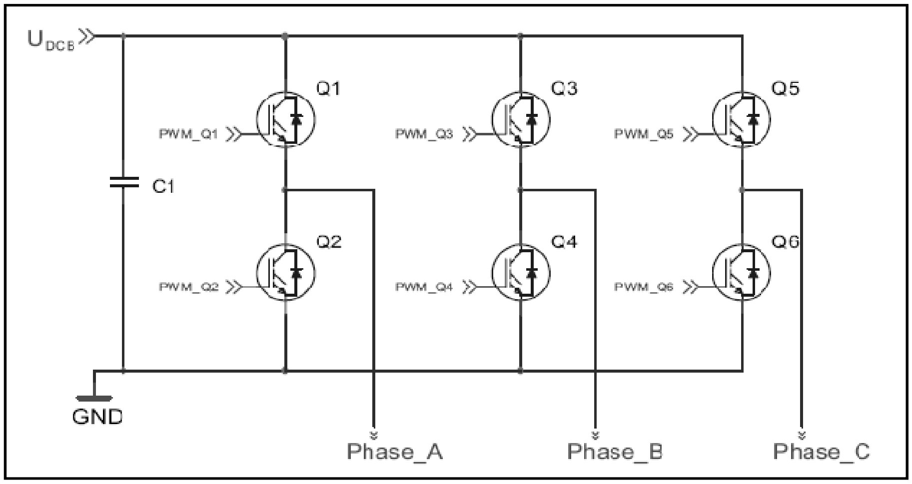

Figure 4.7 - 3-phase power stage of the BLDC motor

The power stage of the BLDC motor uses six transistors in order to switch on and off the signals that are being delivered to each individual phase of the motor. Any timing offset will ruin the timing of the voltage strokes, thus running the motor less than the maximum efficiency. Figure 4.8 below shows the six transistors as well as the other circuitry in the motor controller.

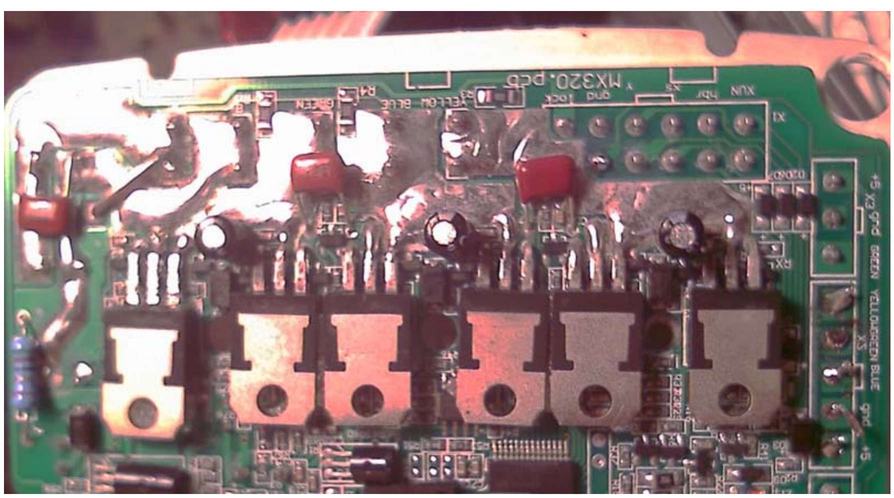

Figure 4.8: Inside view of the motor controller used to control the motor and other features

The overall system of a BLDC with the motor controller is represented in Figure 4.9. The inputs to the controller include the speed and current signals that are supplied by the throttle. The DC power supply feeds power to the motor controller, which then distributes the voltage and current necessary to drive the BLDC motor. The Hall Effect sensors provide the feedback needed for the motor to know the position of the rotor and to tell it when to supply the voltage stoke to the different phases of the BLDC motor.

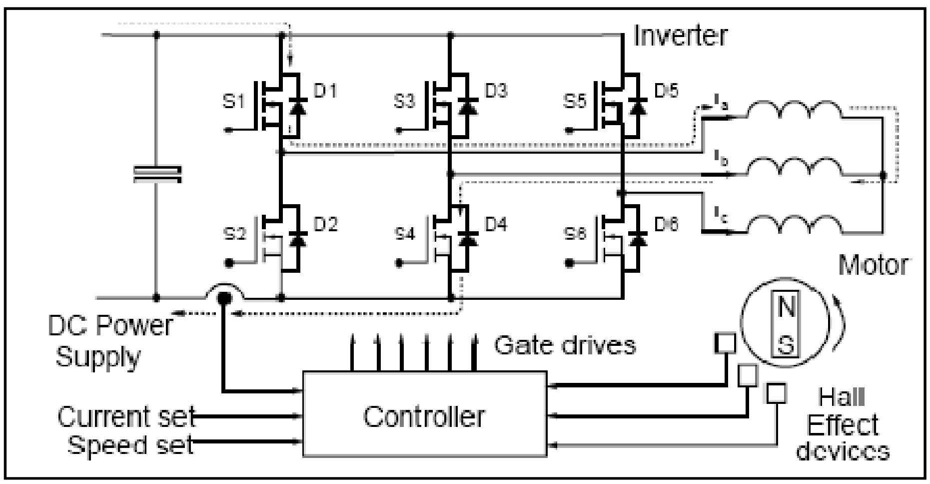

Figure 4.9: Overall System of the BLDC motor and motor controller

Lithium Ion Battery

This project revolves around supplying and utilizing energy within a high voltage battery. It demands for a battery with longer running hours, lighter weight with respect to its high output voltage and higher energy density. Among all the existing rechargeable battery systems, the lithium ion cell technology is the most efficient and practical choice for the desired application. The battery chosen for this project was a high capacity lithium ion battery pack designed specifically for electric bikes by Golden Motor Technology Co Ltd. Aluminum casing is provided to house the internal components of the battery yet remains at a reasonable weight below 12.12 pounds. The battery is rated is at 48V, 12AH. A maximum electrical output results at an approximate constant speed of 50km/h (31mph). The amount of charging cycles of the battery is greater than 800.

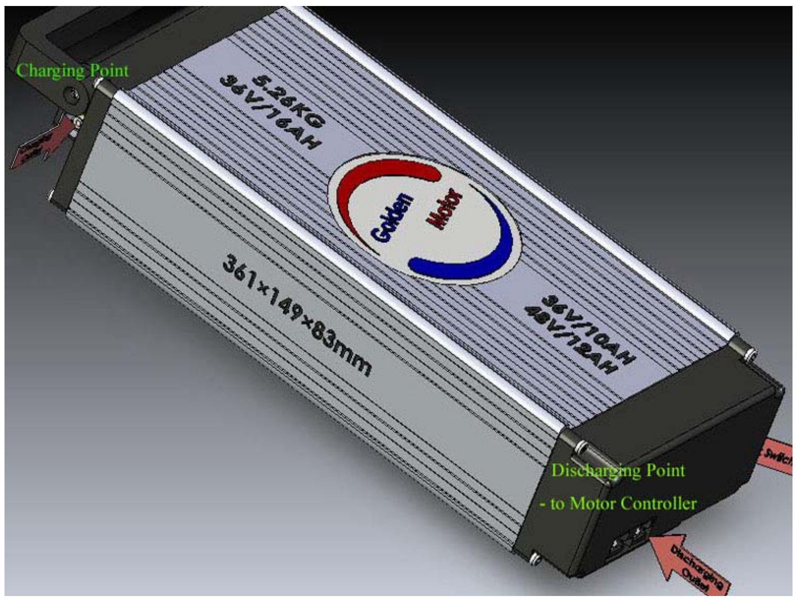

Figure 4.10: Lithium Ion Battery

Lithium ion batteries are one of the most popular types of battery for portable electronics. Although slightly lower in energy density than lithium metal, lithium-ion is safe, provided certain precautions are met when charging and discharging. With its many advantages over other conventional types of batteries, the lithium ion battery was the optimum choice for an electric powered bicycle.

Advantages

Advantages with lithium-ion batteries are that they often are much lighter than other energy equivalent secondary batteries. The electrodes of a lithium ion battery are made of lightweight lithium and carbon. A key advantage of using lithium-ion chemistry is the high open circuit voltage that can be obtained in comparison to aqueous batteries (such as lead acid, nickel-metal hydride and nickel-cadmium). This is beneficial because it increases the amount of power that can be transferred at a lower rate of current. Lithium is also a highly reactive element, meaning that a lot of energy can be stored in its atomic bonds. This translates into a very high energy density for lithium-ion batteries and has the best energy to weight ratio than other battery configurations.

Also, the battery cells are able to hold their charge with minimum losses when not in use. This allows for relatively long storage periods with high residual capacity. A lithium-ion battery pack loses only about 5 percent of its charge per month, compared to a 20 percent loss per month for NiMH batteries [16]. The relatively low self-discharge is less than half that of nickel-based batteries.

Another advantage with lithium ion cells is that they have no memory effect, which means that you do not have to completely discharge them before recharging and no scheduled cycling is required to prolong the battery's life, as with some other battery chemistries. Thus, there is no need to pre-discharge the battery upon fully charging the cells, which provides low maintenance. Lithium-ion batteries can handle hundreds of charge/discharge cycles, and therefore, performance and use are not affected. One regular charge is all that is needed and they cause little harm when disposed.

The protection circuit board for the lithium ion battery from Golden Motor provides for extremely safe usage. It is possible to use under extreme weather temperatures and it is possible to be stored in insulated areas, such as a car. It also was designed to prevent any explosions or fires upon any impacts or collisions. The protection circuit board provides ideal protection features for bicycle applications and conditions.

Figure 4.11: Battery Management System of the Li-Ion Battery

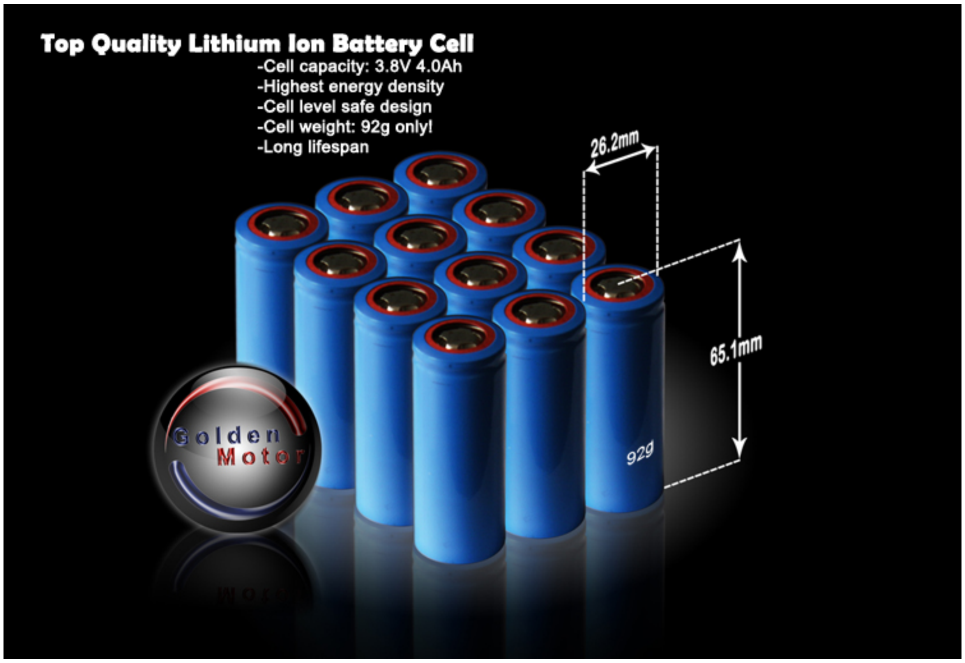

Figure 4.12: Lithium Ion Battery Cells

Disadvantages

Despite its overall advantages, lithium-ion has its drawbacks. The high energy density comes at a price. Manufacturing methods become more critical the denser the cells become. With a separator thickness of only 20-25µm, any small intrusion of metallic dust particles can have devastating consequences. It is fragile and requires a protection circuit to maintain safe operation. Built into each pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the cell temperature is monitored to prevent temperature extremes. The maximum charge and discharge current on most packs are is limited to between 1C and 2C. With these precautions in place, the possibility of metallic lithium plating occurring due to overcharge is virtually eliminated.

Figure 4.13: Actual Lithium-Ion Battery Cell

Aging is a concern with most lithium-ion batteries and many manufacturers remain silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. The battery frequently fails after two or three years. It should be noted that other chemistries also have age-related degenerative effects. This is especially true for nickel-metal-hydride if exposed to high ambient temperatures. At the same time, lithium-ion packs are known to have served for five years in some applications.

Storage in a cool place slows the aging process of lithium-ion cells. Manufacturers recommend storage temperatures of 15°C (59°F). In addition, the battery should be partially charged during storage. The manufacturer recommends a 40% charge.

Innovations

It is also possible to create a battery for this project by using lithium ion polymers batteries rather than lithium ion cells. The primary difference between the two is that the lithium-saltelectrolyte is not held in an organic solvent but in a solid polymer composite. They are also much cheaper and cost efficient due to the type of materials used to manufacture it and also eliminating the need for sophisticated protection circuit boards and advanced battery management system. Connecting several of these cells in series, it can provide desired voltage ratings while connecting additional cells in parallel will provide a higher output current with respect to time.

Lithium ion polymers have faster charging capabilities and safer performance than traditional lithium ion batteries. Currently, the leading choice for lithium ion polymers is lithium iron phosphate ($LiFePO_4$) because of its large capacity and high power applications. It has characteristics that provide safer performance use, similar to lead acid batteries, but still remains as powerful as lithium ion cells. Lithium ion polymer batteries, the "plastic" batteries, are packed by aluminum coated foil, and are much safer than liquid lithium-ion cells with metal cases. Their energy densities are 10 percent to 15 percent higher than the normal liquid lithium ion batteries, and are perfect for portable devices requiring high power and low weight. The C-coated Lithium Iron Phosphate Battery has been proven as the most environmental friendly battery. It is the safest and most suitable for high output usage and the best for storage battery usage.

V. Testing Procedures

DC-DC Boost Converter

In order for the Texas Instruments Evaluation Module to be compatible with our battery, it must be able to output about 48V. This can be done by changing the voltage divider between resistors R5 and R7 on the EVM according to equation (57) on the datasheet [8]

$$R_{BIAS} = \frac{V_{FB} \times R_{FB}}{V_{OUT} - V_{FB}}$$

In the above equation R_{FB} and R_{BIAS} correspond to R7 and R5, respectively. Using an output voltage V_{OUT} = 48V instead of 24V and keeping the error amplifier reference voltage, V_{FB} = 0.7V, the ratio of the resistors now become 68:1, instead of 34:1. This seems like a simple adjustment, but making this change to the resistor ratio also causes other changes. It would also require us to compensate for the various other changes, such as an increase in inductor current as well as higher voltages across the capacitors. An alternative idea was to make use of a basic charge pump voltage doubler. This external circuitry doubles the voltage output without changing anything else on the evaluation module. When attempting to change the voltage divider on the EVM during simulations, the inductor current fluctuated quite largely as the voltage changed; the range became anywhere from 1A to 25A. With the charge pump voltage doubler, the output voltage becomes 41.5V (nearly doubles in output) and gives an output current of 1.36A (See Figure 5.1). The inadvertent change this method creates is that the inductor current at steady state is increased to 8.5A, with minimal peak-to-peak ripple. This presents a problem because the inductor is rated at a maximum of 7.5A [2], so if we used this EVM, we would have to change the inductor to one which yields a higher current rating in addition to building the voltage doubler. We found this to be the best design for the TI EVM that would double the output voltage because of all the other parameters that weren't affected in the process.

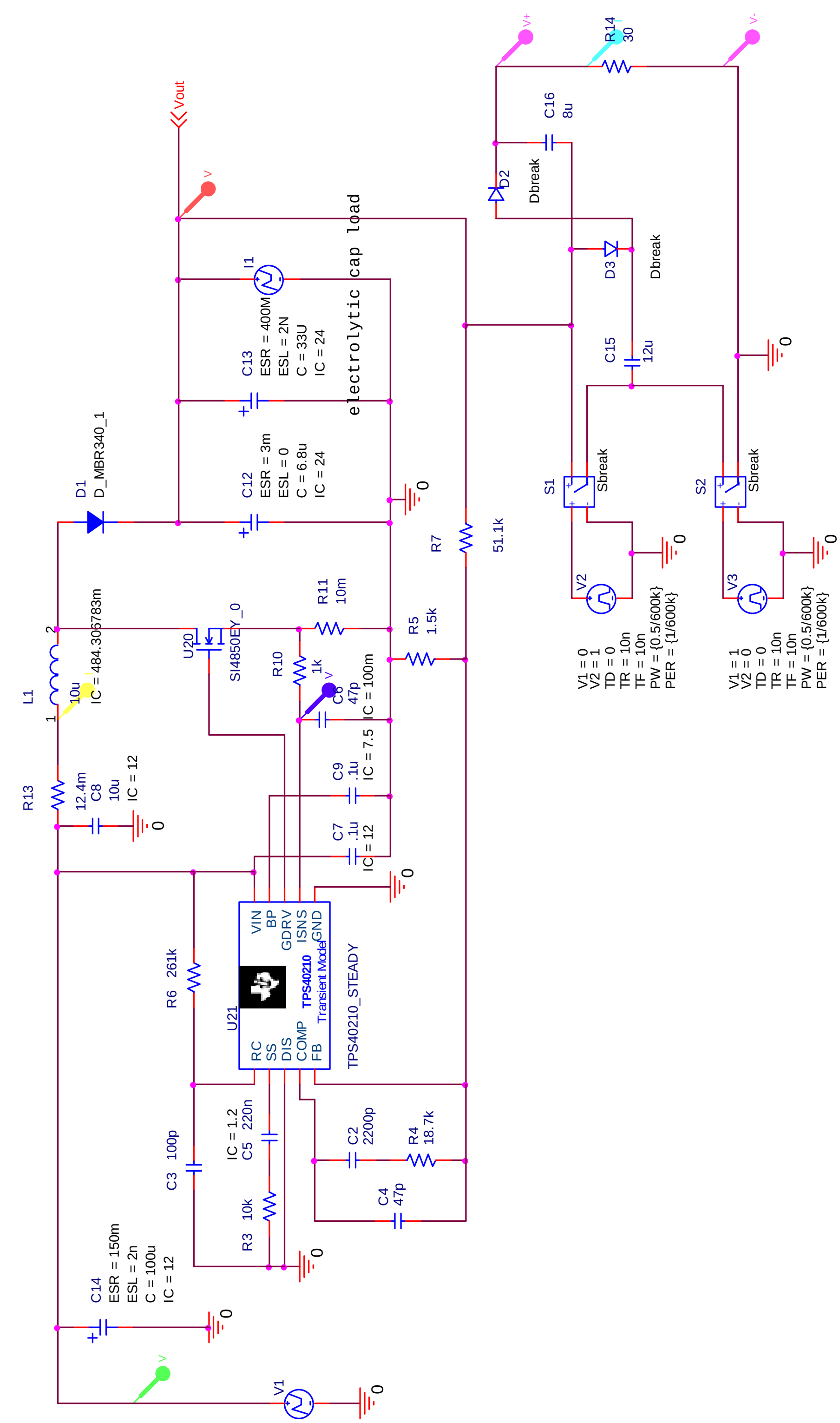

Figure 5.1: Texas Instruments EVM Circuit with Voltage Doubler

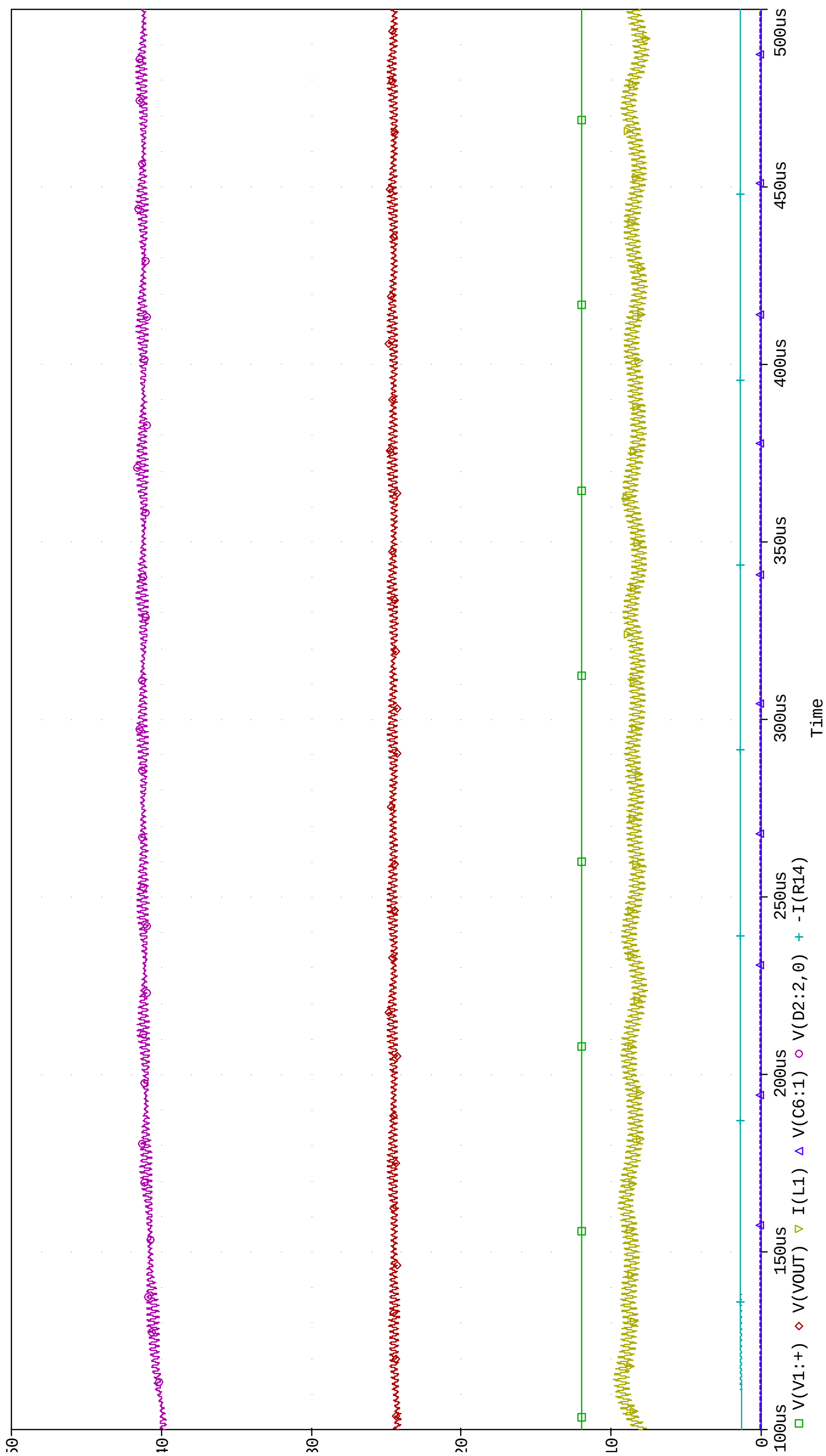

Figure 5.2: OrCad PSpice Simulation Results for TI EVM with Voltage Doubler

The modifications needed for the Linear Technology Evaluation Module DC1286A-A were simple changes to a few components due to the need for higher voltage and current ratings. The feedback resistor R2 had to be changed from 475kΩ to 541kΩ according to the equation in the datasheet [5]

$$V_{OUT} = 1.223V\left(1 + \frac{R2}{R1}\right)$$

where R1 is kept at 12.4kΩ. According to the LTSpice simulations, after changing this resistor, the voltages across the diodes came within 90% of the breakdown voltage, therefore we were required to get similar diodes which would be compatible with the EVM, but have a higher voltage rating. Also, the five 6.8µF output capacitors in parallel, C10-C14, had to be changed because they also needed a higher voltage rating (See Figure 5.3). They have a voltage rating of 50V, but the simulations yield a peak voltage of 54.6V across these capacitors. The FETs also had to be changed because the simulations read a peak current of 16.5A through them, where the maximum current rating is 9.6A [4]. For the inductors, the simulations yielded a current of 7.5A, where the saturation current rating is 11A, therefore the inductors that are currently on the EVM were able to handle the increased current and they need not be changed [3]. The output current of this EVM came out to 2.8A which is relatively close to the 3A current that the wall charger provides to the battery. Also, the output voltage is a very nice 54.58V at steady state, which is the optimal voltage required for our battery. (See Figure 5.4)

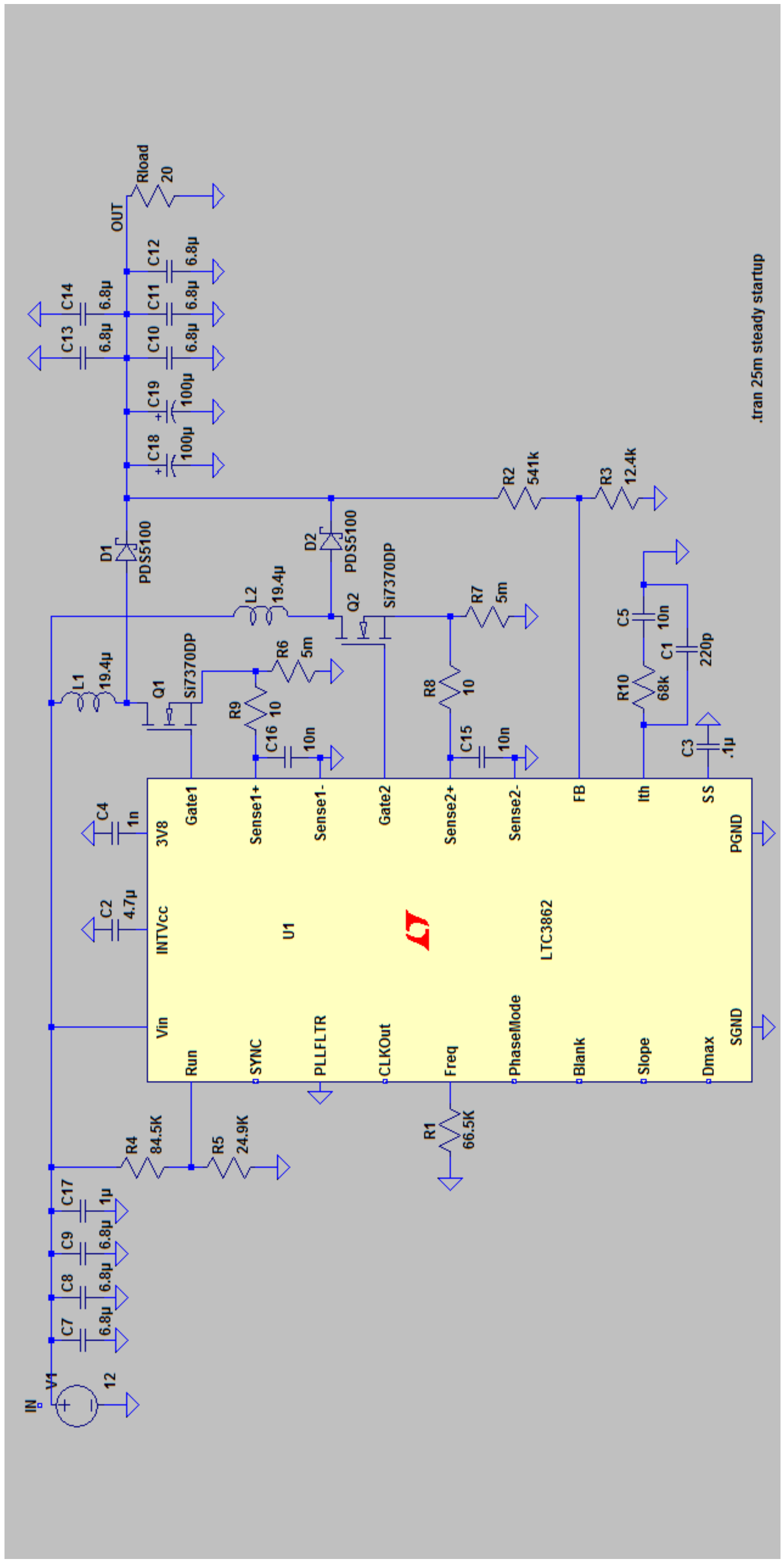

Figure 5.3: LTSpice Circuit for the Linear Technology EVM

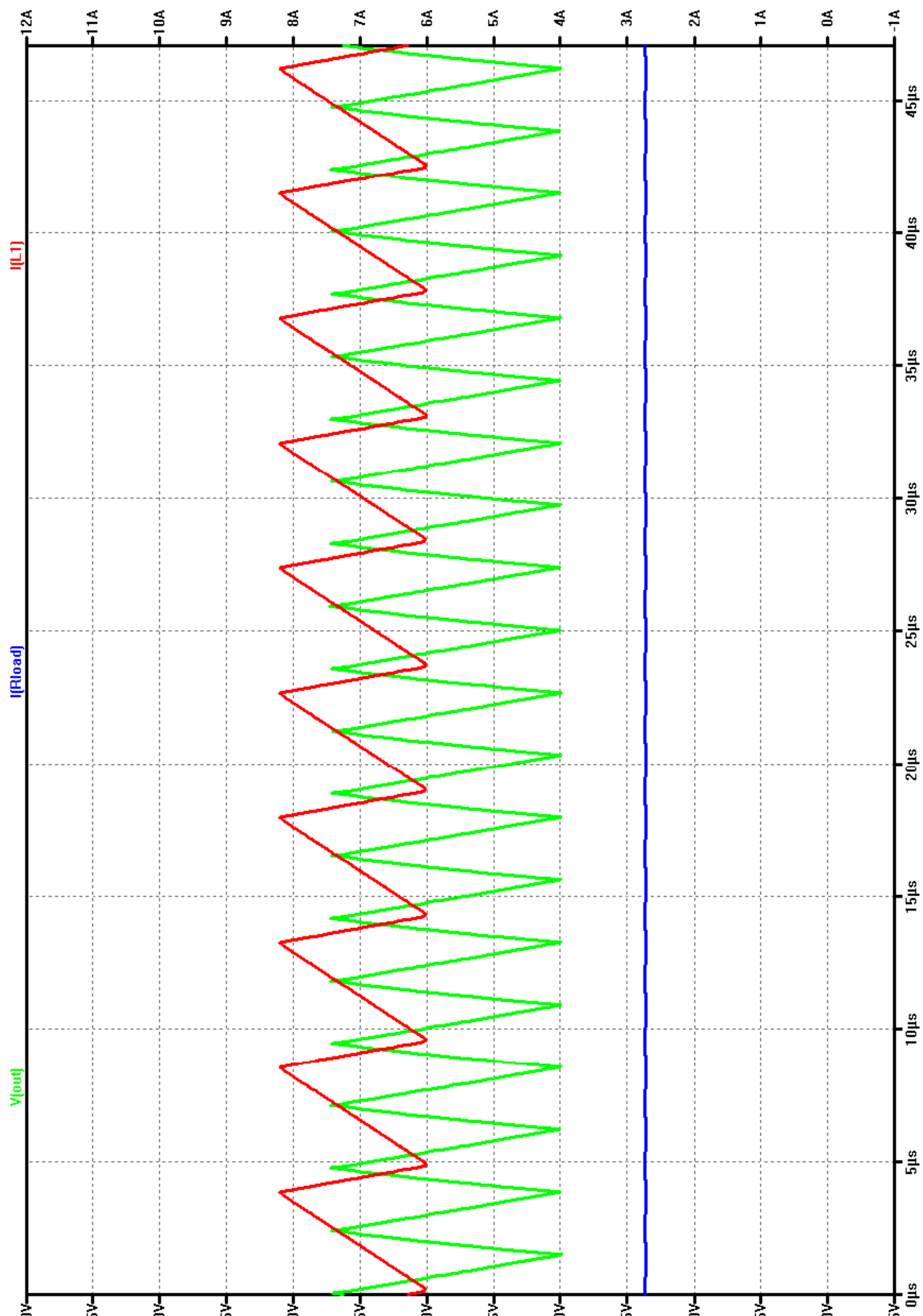

Figure 5.4: LTSpice Simulation Results at Steady State

Lithium Ion Battery

The lithium ion battery is rated to output 48V and 12AH. The testing procedure for this component is essential to see how efficient the system is with and without a weighted load.

It is important to calculate the amount of time that the battery needs to be fully charged with the AC wall charger. That time is then compared to the theoretical time given by the charger. During the process, the open-circuit voltage was recorded after every 30 minutes. It is important to realize that it is not needed to time how long it would take for the battery to be charged by the solar panel and by the pedal system because it would take far too long to fully charge.

Once this was accomplished it was now time to test the battery during discharging. The first process was to test the freewheeling motor with no weighted load applied. This was accomplished by turning the bike upside down and setting the cruise controller set at full throttle or maximum output power to the motor. An inexpensive speedometer was used to record the time, distance, maximum speed, and the average speed once the battery is fully discharged. The voltages of the battery are measured at different times to create a voltage vs. time and a speed vs. time graphs. This shows the correlation of the motor speed decreasing linearly with respect to the voltage output of the battery. The following process is then repeated when a driver, with full load, attempts to discharge the battery.

VI. Development and Construction

Initial Development Stage

The whole premise for this project is to create a functional system for an electric bicycle that uses a DC battery to power a DC motor via a motor controller. The goal of the experiment is to find additional means to recharge the battery to extend its life cycle during use as well as storage. The initial charging feature is supplied with the wall adapter which is a universal high AC voltage charger that has an input range of 110-240VAC. This range is to satisfy both the United States' household outlet voltage of 120VAC and China's household outlet voltage of 220VAC. There is also a battery management system (BMS) built within the charger that ensures there will not be over-current or over-voltage. It also helps regulate the temperature of the charger and battery connection. The second form of charging comes from using the regenerative brake function feature of using the motor as a generator to supply power back to the battery source. By creating a switch that triggers this function but prevents the mechanical brakes from reacting, this can allow the pedals to be used to create mechanical energy and converting it to electrical energy using the motor generator. The last form of charging adopted was the use of solar energy. A polycrystalline photovoltaic panel harnesses the energy from the sun and its voltage is increased to match the battery's rated voltage. It was later discovered that for charging lithium ion cells, it is appropriate to charge at a higher rated voltage than the battery's rated voltage. It was decided to use an output voltage approximately close to the wall charger's rating which was 54V. This was accomplished by changing the output resistor topology to provide an output voltage of 54.6V and changing the output capacitors and diodes to a higher rating. This made it possible to achieve a constant voltage/constant current output application which is desired for lithium ion cells.

In the initial design stage, the three most important components required for the system to be operational is the battery, the motor controller, and the DC motor. The other components are interfaced with the battery to provide additional charging capabilities, interfaced with the controller to create manual button/switch system for the user to control the controller's featured functions, and interfaced with the motor which can be used as a generator to harness the kinetic energy from pedaling.

Equipment List

- Zip ties
- Allen Wrench with diameters 2.5mm, 3.0mm, 6.0mm
- Adjustable wrench
- Philip Screwdriver
- Wire Crimper/Stripper
- Gear Removing Tool (provided with Golden Motor Kit)
- Measuring tape

Mounting Construction

The hub motor replaced the stock rear wheel for the project's bicycle. To transfer the gear settings to the hub motor, the gear removal tool was used as shown in Figure 6.1. The wheel needed a tire to be installed with inner tubing. It was important to choose an inner tube with a longer valve because the rims for Golden Motor are double walled. The rims are double walled to be able to withstand the powerful torque from the motor. To ensure proper installation and alignment, the procedure was professionally achieved through a local bike store called "Foothill Cyclery". Due to the weight of the motor, the tire used had to be stronger to withstand the amount of torque and speed being applied to the wheel. A Kevlar tire was used as a solution to the problem. These tires have Kevlar belt running under the tread area, in addition to the normal bias plies. This is intended as a puncture preventive that may result from debris on the bicycles path or in the project's case, high surface friction and weight. These belts slightly increase in weight and rolling resistance but have any little effect with respect to the amount of torque the motor can apply.

Figure 6.1: Tool used to remove the gear from the stock rear wheel

The twist throttle, cruise controller button, and the lever hand brakes were installed once ensuring that the handlebar’s diameter was 22mm. Once the positions of the parts were placed in a comfortable position, they were tightly secured by using the various sized Allen wrenches. By replacing the original hand brakes with the Golden Motor hand brakes and using the original brake cable connections, it was possible to have the hand brake lever control both the mechanical rim brakes and the electrical brake system that stops the motor via the motor controller cutting off the supplied power.

Figure 6.2: Button/Switch for Motor Controller Basic Functions

A battery rack, compatible with the Golden Motor battery, is fastened to the seat post of the bicycle where the lithium ion battery can slide in and lock the battery in place. The key to operate the battery is also used to lock the battery in and allows it to be stationary while in use.

Figure 6.3: Battery Rack to House the Lithium Ion Battery

The controller is properly labeled and color coordinated for the pin configuration. Once all the components are mounted and secured on the bicycle, the connection can be properly connected by matching the color schemes. Shown in Figure 6.4 and labeled in Table 6.1.

Figure 6.4: Motor Controller with Wire Lead Connection

Table 6.1: Abbreviation and Color Scheme for Wire Connections

Full Name	Abbreviation					Color of Wire				
Alarm	A1	A2				Thin Red				
Brake	B					White				
Cruise	C					Orange				
Gate	G					Red				
Hall	H+	H-	Ha	Hb	Hc	Yellow	Green	Blue	Black	Red
Horn	H					Brown				
Reverse	R					Purple				
Spare (free pin out)	S1	S2	S3	S4		N/A	N/A	N/A	N/A	
Throttle (5V)	T1					Red				
Zero (0V)	Z					Black				

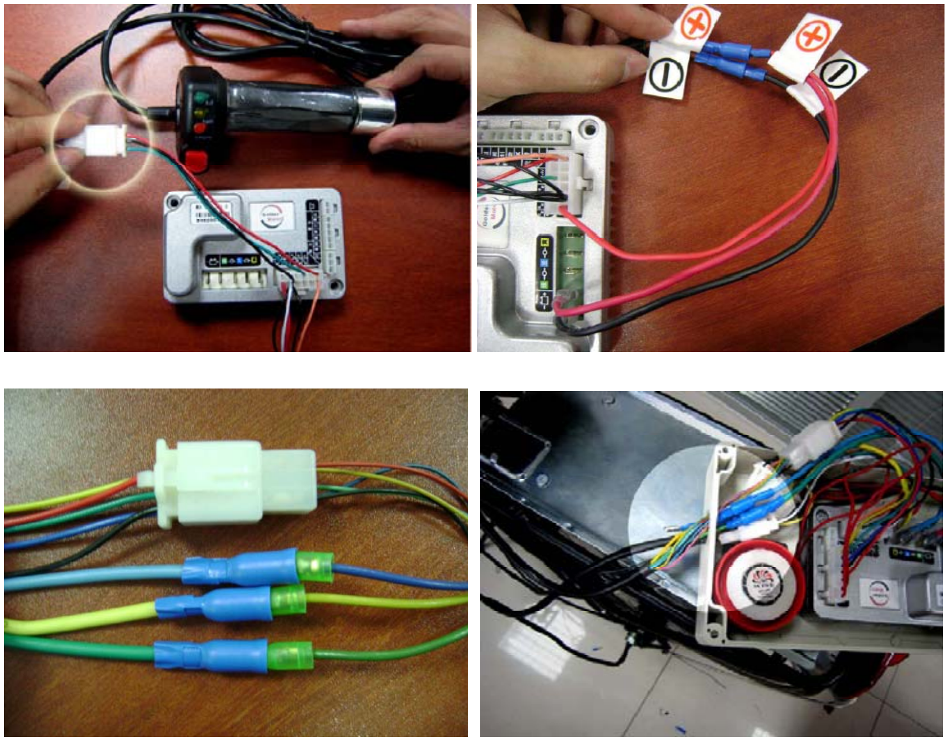

Figure 6.5: Wire Lead Connections Connected with Other Components

VII. Encountered Problems

When we initially touched upon the idea of this project, the motor controller was to be designed by us, but that was later changed when we found that it was also available for purchase on the Golden Motor website. When it came time to order the motor kit, we found the MagicPie motor, which has the motor controller built within the motor. This seemed to be a very size efficient and more proficient motor, so we decided to order the MagicPie motor. After discussing with Dr. Taufik a week later, we found that we should have ordered the 48V, 1000W motor with the external motor controller because Dr. Taufik wanted this project to continue being built upon in future projects. We ordered the 1000W motor, but now we have the MagicPie motor sitting in the garage collecting dust. The two motors have different connections, so this set back our integration process for another week and a half because of the waiting period for the 1000W motor to ship.

Another problem was finding an actual bicycle that would be able to support the weight of the battery, the weight of the solar panel along with the weight of the rider. We planned on getting a bicycle from the annual bicycle auction held by the Cal Poly Police Department. As it would turn out, the bicycle auction wouldn't be held until the fifth week of spring quarter, which was approximately 9 weeks from the date we planned on finding a bicycle and beginning our layout of the design. We then began researching different types of bicycles that would work best with our project on websites such as Ebay and Craigslist. Luckily our friend, Joe Maldonado, had an extra mountain bicycle that he was willing to donate to us. Maintenance was done on the bicycle and now it is in perfect riding condition.

There was also a problem with getting the battery to charge with the boost converter. Upon receiving the battery, no instructions or information was given with the package. There was also very minimal information about the battery on the Golden Motor website, so we had to do our own research as well as some calculations. We found that the battery contained 39 lithium-ion cells, which would take about 54.6V for charging (See Battery for details). We knew 54.6V had to be provided to the battery, but we forgot to take into account how long the voltage would be applied to the battery and exactly how much current would be provided. A charge controller was thought to be needed in order to avoid overcharging the battery, which can be catastrophically devastating, especially to lithium-ion batteries. We decided to open the case to the battery, despite the warnings not to, in order to investigate whether or not there was a controller built into it already. We found that there was a controller circuit built within the battery that would shut the battery down when too much voltage or too much current is being provided. This gave us a big relief as we were worried about how fragile the battery would be and how prone it would be to breaking down.

There was also a last-minute incident with the bicycle in which a friend took the bicycle for a ride and accidently fell causing the brake levers to fracture. The speedometer wire was also torn, along with a few minor scrapes along the frame of the bicycle.

VIII. Conclusion

This project brought together several components and ideas to achieve a common goal: to prove that it is possible to build a bicycle with 3 separate charging sources. We put a lot of time into this bicycle to make sure that it was performing the best it possibly could. Now that the project as a whole is finished, we hand it over to future generations to design and improve each component. Possibly future projects may include:

1) Design of a charge controller for the battery: The battery management system (BMS) built within the battery was very hard to access, so we couldn’t get an idea of how it was designed. Having a BMS with the ability to take in a wider range of voltages and currents will be ideal.

2) Design of the motor controller: The current motor controller is a very nice size and weight, but the connections that it provides are not as stable and protected as it can be. Limiting the amount of wiring and connections may also be desired.

3) Construction of a separate hub motor: There are many levels to the design of the 48V, 1000W hub motor in order to have it so compact in size. The new hub motor can be placed on the front wheel of the bicycle or it can just be used to compare the speeds and efficiencies to the current motor on the bicycle

4) Design of a more effective boost converter: The current boost converter provides only 3mA from the solar panel to charge the battery. That would take about 4000 hours to fully charge the battery from an empty charge. The design of a new boost converter that will output 54.6V but also be able to provide a higher current will

be beneficial to the life of the battery as well as how efficient a single charge will last.

5) Design of the programming system to program the motor controller: The current program allows the user to set a current limit, which causes the motor's speed and torque to be limited as well. It also allows the user to set the amount of desired regenerative braking, which determines how tough it will be to pedal the bicycle and how much charge will be provided to the battery. A new possible program will allow the user to set these changes, but without the need of a traditional computer. Being able to set these changes from the seat of the bicycle will be very convenient. A small on-board LCD screen can be used to do all the programmable functions.

There are multiple opportunities with this project and we hope that within a few years, this bicycle can become very efficient and marketable.

We understand that this bicycle can be intimidating because of its weight and its ability to go 30 mph, but whoever takes it on in the future, we ask that you have an open mind and an open heart. This bicycle has become very special to all of us, and we hope that it will be well taken care of and improved upon. Good luck to the future recipients and remember to have fun.

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X. Appendices

Senior Project Timeline	Winter 2010 quarter							
	Friday 1/15/2010	Friday 1/22/2010	Friday 1/29/2010	Friday 2/5/2010	Friday 2/12/2010	Friday 2/26/2010	Friday 3/5/2010	Friday 3/12/2010
Research charging components	x	x						
Turn in Proposal and Timeline	x							
Weekly Status Report (every Friday)	x	x	x	x	x	x	x	x
Research different batteries	x	x						
Research generators	x	x						
Decide on a configuration for the battery/batteries			x					
Decide on a generator to match			x					
Acquire battery/batteries					x			
Acquire generator					x			
Create set-up for battery and motor						x		
Weld battery/generator housing onto bicycle							x	
First Demonstration of project Due								x
Combine charger together with motor and test								
Troubleshoot problems								
Help with motor designs if necessary								
Combine all components of bicycle and test								
First Draft of Final Report								
Final Report								
	Spring 2010 quarter							
	Friday 4/2/2010	Friday 4/9/2010	Friday 4/30/2010	Friday 5/21/2010	Monday 6/7/2010			
Research charging components								
Turn in Proposal and Timeline								
Weekly Status Report (every Friday)	x	x	x	x				
Research different batteries								
Research generators								
Decide on a configuration for the battery/batteries								
Decide on a generator to match								
Acquire battery/batteries								
Acquire generator								
Create set-up for battery and motor								
Weld battery/generator housing onto bicycle								
First Demonstration of project Due								
Combine charger together with motor and test	x							
Troubleshoot problems		x						
Help with motor designs if necessary		x						
Combine all components of bicycle and test			x					
First Draft of Final Report				x				
Final Report					x			

Figure 11.1: Original Timeline Schedule

Table 11.1- Parts List

Quantity	Description	Cost
1	Rear Magic Pie Conversion kit with 48V Battery	1061
1	48V 1000W 50 Amp Wheel Hub Kit with no Battery	475
1	Solar Panel	55.42
1	Kevlar Rear Tire	39.99
1	Roadster Front Tire	24.99
1	Labor (brake adjustment)	20
1	6 speed shifter	14.99
1	Labor (install shifter)	12
1	Labor (install tube/tire)	9.14
2	Tire Tube	4.99
1	Longer Rim Tip for air	4.99
1	DC1286A-A (Evaluation Board from LT)	Donated
1	TPS40210EVM (Evaluation Board from TI)	Donated
1	Replacement Components for Boost Converter	56.98
	Total Cost	1784.48