Design of a Bicycle- and Solar-Powered Lighting System for Rural Vietnamese Students

April 26, 2018

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Abstract

In many developing countries, electric lighting is still inaccessible and many students do not have a sustainable light source for nighttime studying, leading to poorer academic performance. Due to this, the Southeast Asian Coalition (SEAC) of Worcester, MA, requested that we design, construct, and test a sustainable LED lighting system powered by a bicycle- and solar-powered battery pack. The generator and battery cases were designed to be waterproof and dustproof to endure usage in the operating environment of Southeast Asia.

Acknowledgements

We would like to extend our gratitude to the following people for their assistance and guidance during the course of this project. We would like to thank our advisor, Professor Fred J Looft, for guiding us through every step of this project and continuously motivating us throughout the year. Thanks to Boa Newgate and the Southeast Asian Coalition for giving us a meaningful yet challenging project. Also, thank you to Leah Morales and Michael Padberg for helping us with soldering and aiding us on circuit design and constructing the generator prototype components, and thank you to Sam Bickham for helping us with our SolidWorks models.

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1. Introduction

Worldwide, nearly 1.3 billion people in developing nations do not have access to electricity, and another one billion only have access to intermittent electricity (Gale Group). Of the world's population with no access to electricity, 83% live in the mostly rural areas of Sub-Saharan Africa and South Asia (Access Gap). Access to electricity provides people with services such as lighting, heating, and cooking and thus reduces poverty and improves health and education.

Many governments of developing nations have created targets for improving energy access in their countries, and the plans focus on using renewable energy such as wind and solar to extend the electricity access (Gale Group). However, reliable electrification is a slow process, as there are several barriers to electrification, including a lack of incentives to invest in the electrification due to the poverty of the populations there and an inability to pay for electricity (Access Gap).

Access to reliable electric lighting is critical since electricity removes a barrier to education, as lighting leads to more time available for studying and doing homework assignments (United Nations Department of Economic and Social Affairs, 2014). However, many students around the world, especially those in developing nations, do not have access to electricity at home and as a result struggle to keep up with their education due to a lack of lighting in the early morning or evening hours. One report has found that a household connection to the electrical grid increases the chances of children staying in school, likely due to their access to lighting at night to study at will (United Nations Department of Economic and Social Affairs, 2014). In some parts of the world, students must venture to public spaces to study under street lights, or risk causing fires and endangering themselves while trying to study using candlelight or kerosene lanterns (United Nations Department of Economic and Social Affairs, 2014).

Vietnam is one country where poorer families have limited access to electricity. It is ranked 113 out of 144 countries in terms of power reliability; power delivery in rural areas is poorly maintained and of poor quality (Energypedia, n.d.; World Bank, 2015). Around 1 million people in rural Vietnam do not have access to affordable, reliable electricity. As a result, families in these areas have no lighting or other electric household appliances (World Bank, 2014; Hays, 2014). For the school-aged children of these households, this lack of lighting could have negative educational effects. In Vietnam, only 62.5 percent of students attend school past 5th grade (Hays, 2014).

One man who hopes to improve access to electricity is Boa Newgate, Cultural Broker for the Southeast Asian Coalition and Family Continuity. Since early 2016, Boa has travelled to towns and villages all over southeast Asia to deliver school supplies purchased using a combination of donations and personal money. The main country he is focused on is Vietnam, as it is a rapidly developing country whose citizens are requiring more education to match the country's development. Ngoc Bien A Elementary School in Tra Vinh, Vietnam is a school in need of retaining students and Boa is looking to empower the students who attend this school with access to light after nightfall.

The purpose of this project was to design and implement a multipurpose, low cost, battery charging system that conveniently provides a family with access to electricity and as a byproduct, hopefully reduces the barrier to education resulting from the lack of electricity for lighting for the students of Ngoc Bien A Elementary School.. For this charging system, we designed a battery system that was partially charged by a 10W solar panel and also had the capability to adapt to different mechanical generators such as a bicycle generator for another partial charging source. We designed the system to cost less than $50 so that organizations such as Youth Effect International will be able to donate it to communities in need of electricity access.

2. Background

2.1 Introduction

This section highlights background research on topics relating to our project goal and design. To be able to create our system, we conducted research on energy accessibility problems in developing countries, lighting and waterproofing standards, generators, solar cells, and batteries. For our research, we focused on rural Vietnam as a representation of a developing area that could benefit from our system.

2.2 Vietnam

Vietnam, illustrated in the map in Figure 2.1, is located on the lower southeast tip of Asia and shares borders with China, Laos, Cambodia, and the South China Sea.

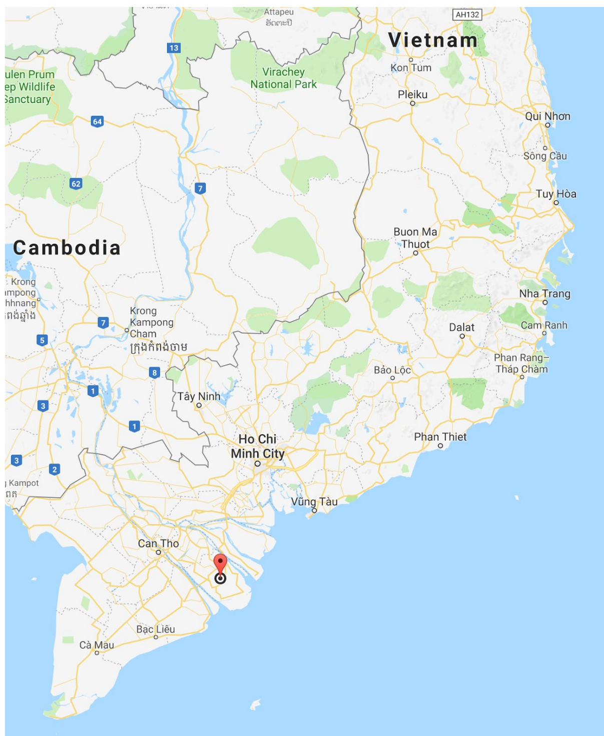

Figure 2.1: Location of Tra Vinh, Vietnam at Red Pin
(Google Images, n.d.)

It is approximately 14 degrees above the equator so the majority of the country has a tropical climate, while other areas are more temperate. Vietnam is a generally humid country which experiences many monsoons coupled with year-round rain and sun. Our town of focus, Tra Vinh, Vietnam, is located near the southern tip of the country where there is tropical weather throughout the year (WeatherOnline).

The annual average temperature of southern Vietnam is generally from 22 to 27 degrees Celsius (72-80 °F) and there are two distinct seasons in Vietnam: winter and summer. Winter temperatures range from 18 to 21 degrees Celsius (64-70 °F) with a dry period, and summer can be over 38 degrees Celsius (100 °F) (WeatherOnline, n.d.).

Figure 2.2 Bicycle in Vietnam,
(Google Images, n.d.)

The small villages and the large cities in Vietnam have different road conditions. In the cities nearly all roads are paved, whereas the small villages have little to no paved roads. The unpaved roads are dangerous for travelling, especially with frequent rainfall creating muddy conditions. In Tra Vinh, the majority of the roads are paved and vehicles traveling these roads include gas and electric scooters, vans, taxis, cars, trucks, and buses with the most common method of travel as the bicycle, as seen in Figure 2.2. Bicycles are a popular method of travel due their low cost and ease of use; about 70 percent of all people in Vietnam own and use bicycles. Students make up a large proportion of this bicycle riding statistic, as they typically do not have the funds for a motor vehicle (Boa Newgate, personal communication, September 2017).

2.3 Education and Electricity

Access to electric lighting has a positive correlation with a student’s success in school. For example, Benjamin Sovacool for the United Nations Department of Economic and Social Affairs describes how lighting helps schools function better (Sovacool, 2014). With artificial lighting, teachers can provide extra help to students in need before or after school hours when natural lighting is diminished and generally inadequate for reading or studying. According to Sovacool, youth literacy rates are directly related to a country's electrification rate; if a country has a lower electrification rate, it also tends to have a lower youth literacy rate (Ibid.). Access to electricity in schools also increases test scores and primary school graduation rates. Similar, lighting at home can also extend the time students can study at home, which can lead to higher academic achievement and higher future incomes (Khandker, S. R., Barnes, D. F., & Samad, H. A., 2013).

2.4 Lighting and Lights

2.4.1 Light Spectrum and Colors

The light and colors that we see are a limited range of wavelengths representing radiation over the full electromagnetic spectrum from radio waves to microwaves, the infrared region, the visible light wavelengths, and then ultraviolet, x-ray and gamma rays (NASA). The types of radiation are described by energy (measured in electron volts), wavelength, and frequency. Low frequencies correspond to long wavelengths and low energy, where higher frequencies relate to short wavelengths and a higher energy. Radio waves and gamma rays are on the opposing ends of the spectrum with the lowest and highest frequencies, respectively, which can be seen in Figure 2.3.

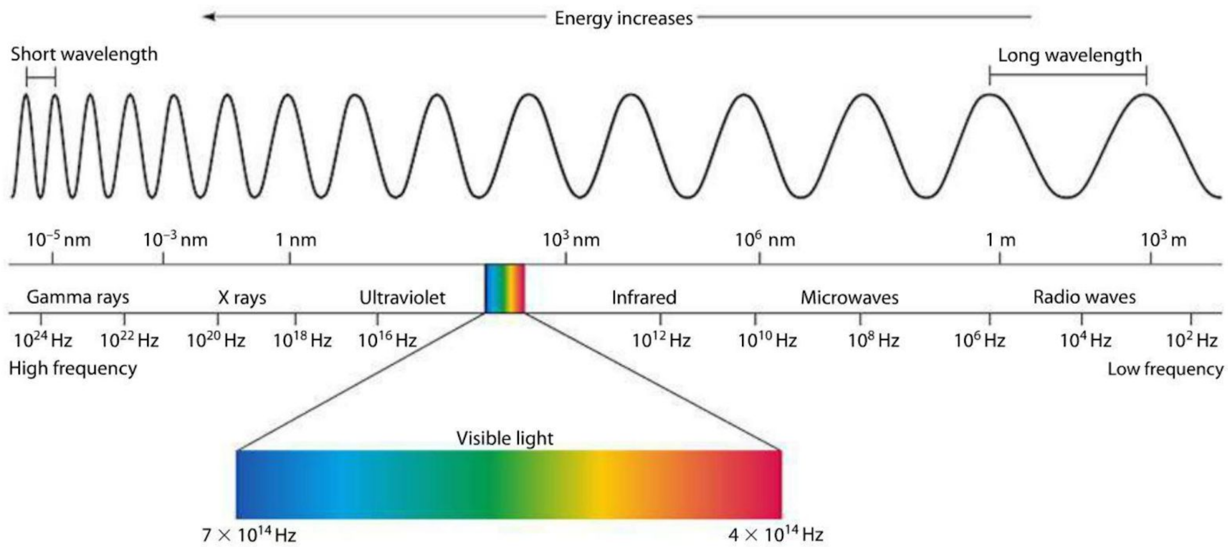

Figure 2.3: Wavelength and Frequency of the Electromagnetic Spectrum
(Mini Physics, n.d.)

The visible portion of the spectrum with the relation between the color and wavelength is shown in Figure 2.4. The visible light section of the electromagnetic spectrum is a small portion from $4x10^{14}$ to $7x10^{14}$ Hz which is the portion that humans are able to visibly perceive. (Mini Physics, n.d.)

Figure 2.4: Visible Light Spectrum
(NASA, n.d.)

The “white” light humans perceive isn’t truly white; it contains all of the different wavelengths of all of the visible colors. When this light travels through a prism, the different wavelength of light will bend varying amounts. This is called dispersion and is what separates each color using a prism (Physics Classroom, n.d.). Violet has the shortest wavelength, at around 380 nanometers, and red has the longest wavelength, at around 700 nanometers (NASA, n.d.). The color of light is dependent on the temperature of the object. At shorter wavelengths, the light appearance will seem cooler, i.e., more blue in visible color, which correlates to a higher color temperature in Kelvin. Using that scale of comparison, the color for electric lighting can be described as a numeric value in Kelvin, as shown below.

Color Temperature (KELVIN)	2000K - 3000K	3100K - 4500K	4600K - 6500K
Light Appearance	Warm White	Cool White	Daylight

Table 2.1: Color Temperature
(NASA, n.d.)

All three light color temperature ranges are useful, as they are suited to different lighting needs and situations, including, for example, to generally matching the natural rhythm and color/temperature of the sun because matching artificial light to the sun is proven to have positive health benefits. Also, living rooms and bedrooms are recommended to be around 2700K, or have warm light, because the light is reminiscent of a sunset or flame fit for a personal, cozy area. Schools and offices are recommended to have 3500K light, or cool white light, because this light is balanced between friendly and alert, and also because people in schools and offices are inside buildings during the middle of the day when the sun is high and bright in the sky. This keeps with the natural cycle of daylight that humans usually witness (ShineRetrofits.)

2.4.2 Lighting Types and Categories

In addition to the color temperature of lighting, there are three additional categories used to describe lighting applications: ambient, task, and accent. Ambient lighting is designed to light up a whole room for overall illumination, while accent lighting is used to bring a focus to one area (such as a piece of artwork). Task lighting is designed for humans to perform tasks, such as reading, and should be of high enough lux to prevent eye strain. (American Lighting Association, n.d.)

In terms of types of bulbs, the most common types are incandescent, fluorescent, and LED as seen in Figure 2.5. Incandescent light is produced when current flows through a resistive material called a filament. This current flow through a resistance creates heat, which causes the filament to glow (Whelan, n.d.). Fluorescent light is produced when a gas is ionized by a high electrical voltage in a glass tube. The ionized gas is then converted to visible light by a phosphorous coating that reacts to the ionized gas (American Lighting Association). A Light

Emitting Diode, otherwise simply known as an LED, is basically a solid state P-N junction diode where an applied voltage causes the carriers to flow across a forward-biased junction to emit light.

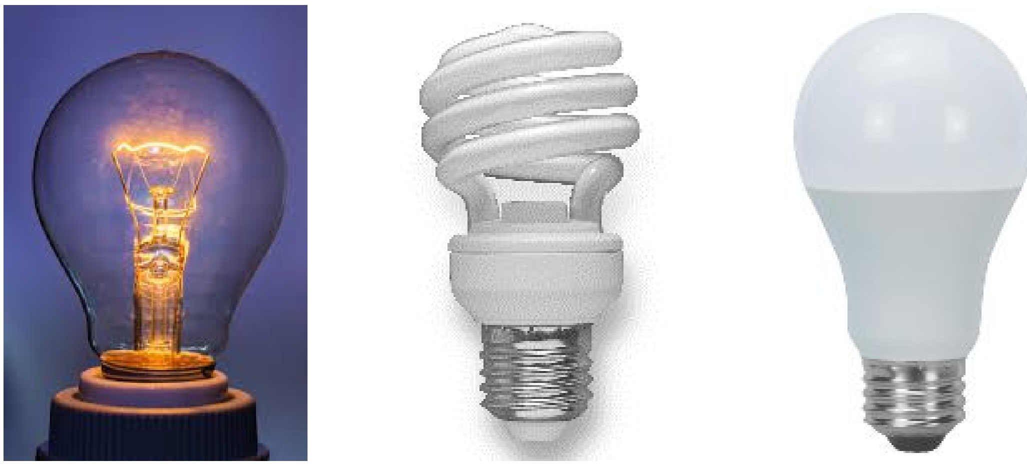

Figure 2.5 Incandescent, Fluorescent, and LED Lights
(Google Images, n.d.)

LEDs are directional light sources, meaning they emit light in a specific direction. This differs from incandescent and fluorescent lights which emit light in all directions. LEDs produce very little heat compared to other bulbs, which correlates to a higher efficiency converting electrical power to light intensity. In comparison, LEDs are approximately 90% more efficient (in terms of converting energy into light) than incandescent bulbs. (U.S. Department of Energy, n.d.).

2.5 Lighting Costs

In locations without access to electricity, residents can use other modes of lighting such as candles and kerosene lanterns. In rural Vietnam, some families cannot afford these forms of lighting on a sustainable basis because the light from a candle or a kerosene lamp comes from a non-renewable source which must be continually replenished (by purchasing new candles or more kerosene). One study found that, after 50,000 hours of use, kerosene lanterns cost $1,251 to operate, while incandescent lamps, CFLs, and white LEDs cost $175, $75, and $20, respectively, for the same hours of usage. These prices reflect the costs of fuel for the kerosene, which is typically expensive in rural areas, and of electricity for the CFLs and LEDs. This study does not include the electrical components needed to run the electric lighting, battery costs, or any acquisition costs associated with electric lighting. Kerosene lanterns are also dangerous, as they pose a fire and carbon monoxide hazard (Pode 2010).

2.6 Light Intensity Measurement and Units

To quantify light intensity, there are standard units which represent how much light a source is emitting. The total perceived intensity that a light source emits is called luminous flux and total luminous flux incident on a surface per unit area is called illuminance. Illuminance is a measure of how much incident light illuminates a surface. From illuminance, the SI derived unit is lux. Lux is used as a measurement of light intensity as perceived by the human eye. A lux meter such as the one in Figure 2.6, can be used to measure the light intensity. To give an example to visualize the amount of lux, a full moon on a clear night is about 0.36 lux, office lighting is between 320-500 lux, and full daylight is between 10,000 and 25,000 lux. (Wikipedia, n.d., Omega, n.d.)

Figure 2.6: Lux Meter
(Google Images, n.d.)

2.7 Design Standards

2.7.1 Lighting Recommendations

Lighting in the workplace is so essential for completing tasks that some countries have lighting standards. The US Occupational Safety and Health Administration (OSHA) recommends that lighting for a workstation where computer work is conducted should be 200 to 730 lux, depending on the type of work that is performed (OSHA, n.d.). Some individual states also have their own regulations for different types of activities. In Florida, educational facilities are required to maintain an average of 430 lux at each desktop so students can properly see the materials they are working with (Florida Department of Education Office of Educational Facilities, 2014).

Lighting recommendations can vary from 20 to 20,000 lux, depending on the type of activities performed in that area. Offices, homes, and schools may have lighting recommendations of 150 to 500 lux, as the only visually-intense activities in these areas are most likely reading and writing. However, machine and electrical shops that constantly require assembly of very small parts may need more lighting, from 500 to 20,000 lux, so that eye strain can be avoided when working for prolonged periods of time (National Optical Astronomy Observatory, n.d.).

2.7.2 Waterproofing Standards

Ingress Protection (IP) Codes are international standards that classify degrees of protection of enclosures against water, solid objects, dust, and accidental contact. Knowing these standards is helpful in determining which materials and methods to use when designing enclosures to be water- or dust-tight. There are two digits in an IP rating; the first digit denotes the level of protection against user access to hazardous or moving parts in the enclosure and denotes the enclosure's protection against foreign solid objects. A zero as a first digit would represent no protection, while a 6 indicates complete protection of user access to moving parts and indicates that the enclosure is dust tight. The second digit indicates the level of protection of the enclosure from water ingression; a zero would represent no protection from water while an eight represents prolonged protection from water immersion deeper than 1 meter. These two digits are combined to give an enclosure's total IP rating. An IP rating chart can be seen below in Figure 2.7. For example, if an enclosure has an IP rating of IP66, it is protected from dust ingress and protected from strong water sprays (IP rating chart, 2017, Standard, 2017).

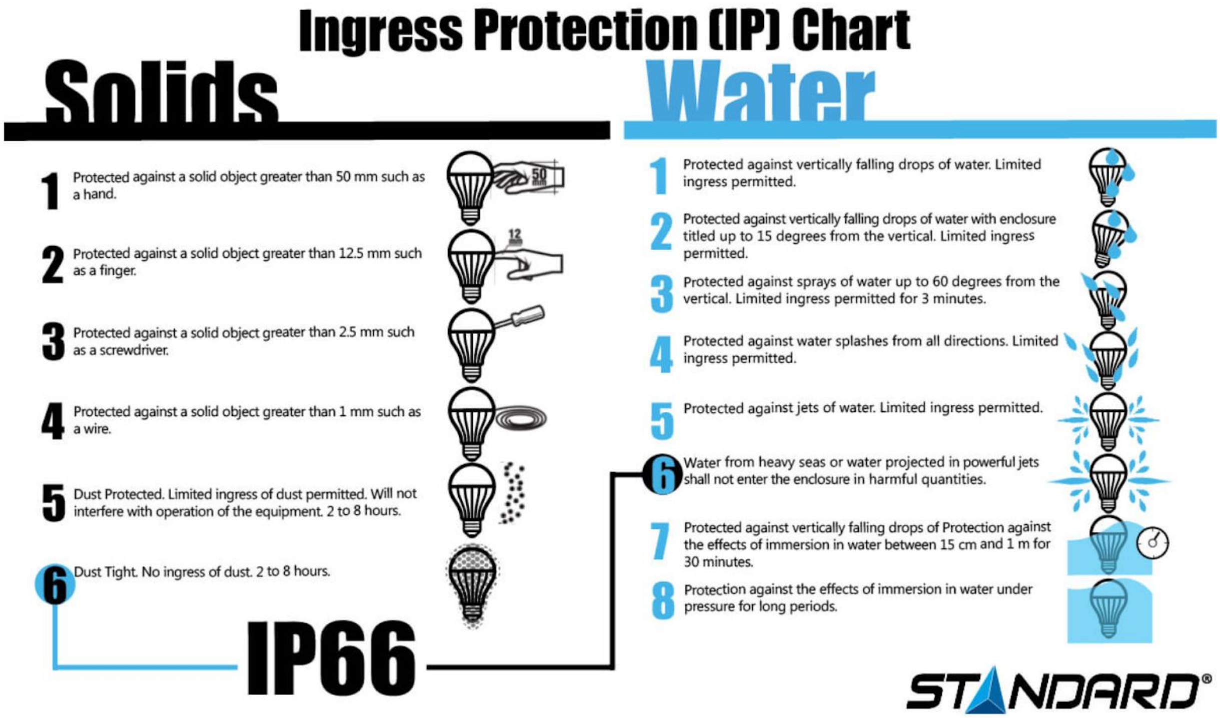

Figure 2.7: IP Rating Chart
(Standard, 2017)

2.8 Mechanical Power Generation

When a magnet is in close proximity to a conductive object (such as an iron nail), it attracts the object because the electrons in the object have intrinsic magnetic fields around them. The magnet causes the electrons in the object to realign themselves and move towards the magnet, thus pulling the two together (Magnetism, 2013). If the conductive object is a wire that is moved in the magnetic field, the electrons in the wire will begin to flow. This motion through a magnetic field is the basic principle used in generators. The flow of electric charge is called current, measured in amperes (amps), and the "pressure" causing the electrons to move is called the voltage, measured in volts (Brain, Harris, & Lamb, 2004).

Generators convert mechanical energy into electrical energy that can be used in a circuit to power electronics. The term "generator" is typically used in a broad sense to describe many devices that use magnets and coils of wire to produce electricity. All generators consist of either permanent magnets or electromagnets and an armature made up of coils of wire. Depending on the generator, these two components can either be positioned on a generator's rotor (the rotating part of the generator) or its stator (the stationary part) (Generators and Dynamos, 2014).

Physically small and relatively low power generators use permanent magnets while physically larger and higher power generators typically use electromagnets. In a simple generator, such as the one shown in Figure 2.8, the rotor, known as an armature, is a wire coil that rotates in the magnetic field produced by stator magnets. The armature is rotated by an external mechanical power source located outside of the general assembly, and can be spun with mechanical energy from sources such as a wind or water turbine or even a hand crank. In Figure 2.8 the "loop" is the rotating armature rotor and the magnets on either side of the loop are the stators.

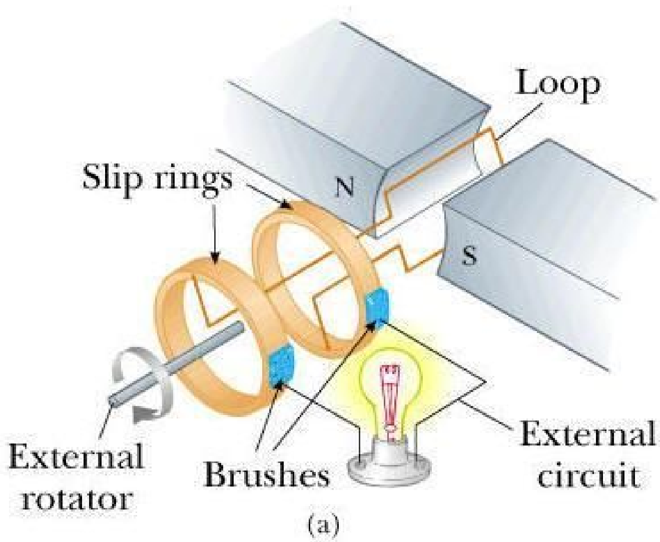

Figure 2.8: Simple Generator
(Schematic Diagram of an AC Generator, n.d)

As the armature in a simple generator rotates in the magnetic field, electrons in the coils of armature wire move, thus producing electricity. To transfer the electricity from the rotating armature to an external circuit, metal slip rings are on the shaft, and in contact with these rings are stationary brushes, typically graphite brushes. The brushes transfer the electrical current to the stationary external circuit, where it can then be used to power external devices such as lights, fans and other household devices (Generators and Dynamos, 2014).

The electricity produced by a generator such as the one shown in Figure 2.9 is alternating current (AC), meaning the current flows in both directions in the wires. The alternating current occurs due to the angle of the armature and the magnetic field; as the these two components continually intersect each other at different angles, the voltage output of the generator varies as can be seen in Figure 2.9.

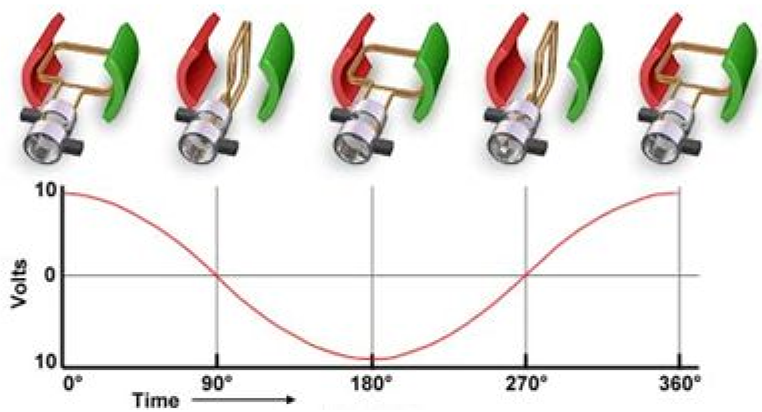

Figure 2.9: Sine Wave Produced by an AC Generator
(McFadyen, 2012)

However, most electrical devices in the late 1800s could only use direct current (DC) power, so early inventors used commutators and brushes instead of slip rings and brushes to mechanically convert the AC into direct current (DC) (Generators and Dynamos, 2014). As shown in Figure 2.10, commutators are similar to slip rings, except there are at least two breaks in the rings. The breaks in the rings act as switches and reverse the connection of the armature windings every half turn to allow the electrical current to flow in only one direction. The voltage waveform of the DC generator is shown in Figure 2.11. A generator that produces DC power with a commutator is known as a dynamo (How the Charging System Works, 2017).

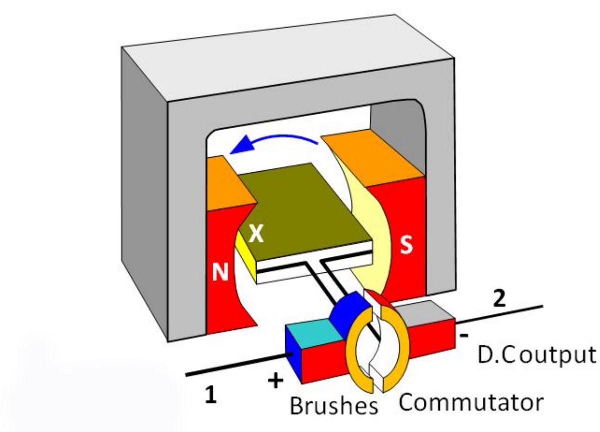

Figure 2.10: DC Generator with Split Ring Commutator
(Generators, n.d.)

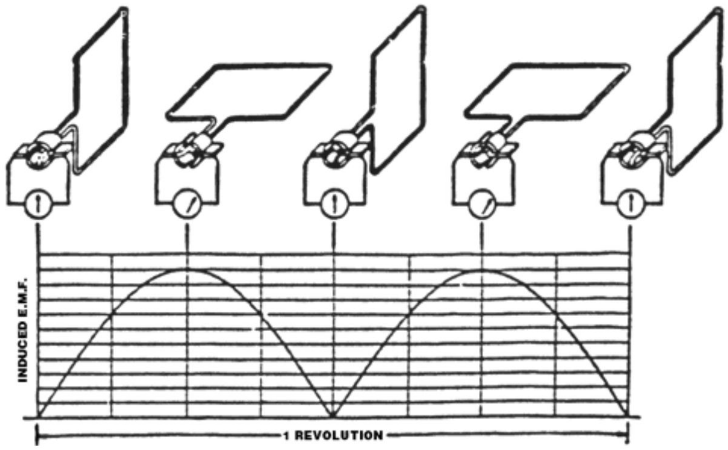

Figure 2.11 Voltage Waveform Produced by a DC Generator
(Electric Motor Theory, n.d.)

A typical household generator that produces power during an electricity outage and generators used in power plants and similar applications do not need to convert the alternating current to direct current since standard wall outlets in the United States provide 120V AC (Brain et al., 2004).

A second type of generator is an alternator, shown in Figure 2.12. In an alternator, a magnetic field rotates inside stationary wire coils, meaning the magnet, typically an electromagnet, is the rotor while the wire coils are the stators, which is the opposite design of simple generators and dynamos. For this type of generator, the output voltage is created in the stator, not the rotor. Like a generator, alternators have brushes and slip rings, though in an alternator these components serve to transfer electricity *into* the rotor to power the rotor's electromagnets, whereas in a generator the slip rings and brushes transfer electrical energy *out* from the rotor to an external circuit (Hymel, 2017).

Due to their compact size and efficiency, alternators are often used in modern cars, although since vehicle electronics such as the radio and lights require DC power to work, car alternators are equipped with additional circuitry to convert the alternator's AC power to DC power (Lampe, 2016).

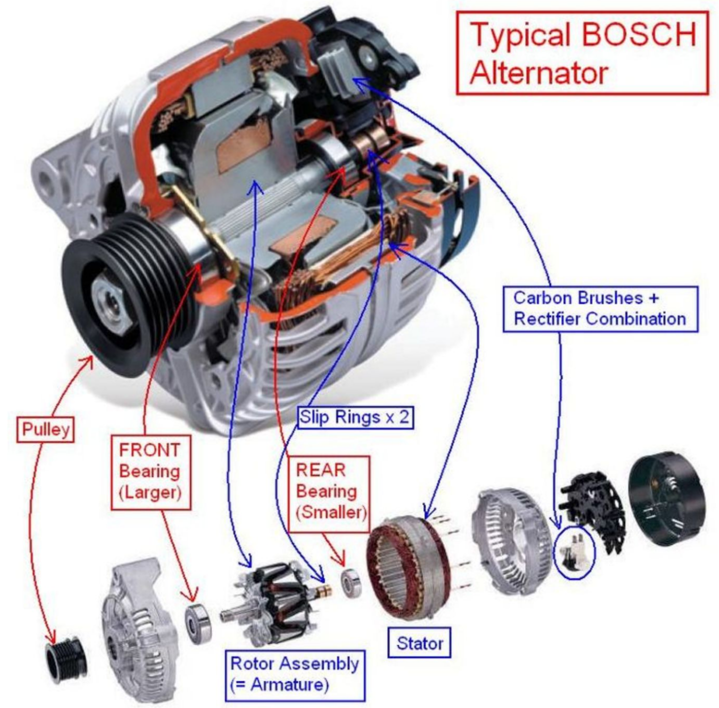

Figure 2.12: Car Alternator
(Car Throttle, n.d.)

2.8.1 Bicycle Dynamos

Bicycles are often outfitted with lights to enhance the rider's safety at night, and the lights on bicycles can either be powered with batteries or with a dynamo. Dynamo powered lights have the advantage of not requiring batteries (Dynamo Powered Lights, 2017). However, bicycle dynamos are not the same as the true dynamos because bicycle dynamos are actually magnetos (a generator containing a permanent magnet); however, when used on a bicycle, magnetos are called dynamos. Magnetos do not have commutators, so they produce pulsing AC power with a wire armature that rotates within the magnetic field of permanent magnets and use slip rings to connect the rotating armature to the external load. All bicycle dynamos create some amount of drag on the bicycle, which adds extra work for the rider (Dynamo, 2017).

There are three main types of bicycle dynamos: bottle or sidewall dynamos, hub dynamos, and bottom-bracket dynamos (Dynamo Powered Lights, 2017). Bottle dynamos, shown in Figure 2.13, are usually mounted to the seat stay or fork on the rear tire of a bicycle and have a small wheel in contact with the tire's sidewall. This wheel rotates as the tire rotates, which rotates the armature in the dynamo and creates enough electrical energy to power the bike's lights. The disadvantages of this system are that the dynamo's wheel can wear down the sidewall of the tire, leading to failure of the tire. The bottle dynamo is also not as reliable in wet conditions because the ribbed wheel in contact with the tire can slip and result in the dynamo not generating any power (Dynamo, 2017).

Figure 2.13: Bottle Dynamo
(Restoring Vintage Bicycles, n.d.)

Hub dynamos, as shown in Figure 2.14, are more efficient than bottle dynamos because they are not affected by wet conditions since they are mounted inside either the bicycle's rear or front wheel hub. These dynamos are directly connected to the bicycle wheels and are a reliable source of electrical energy. However, they are also the least adaptable of the bicycle dynamos, as they are typically built into the bicycle tire hub and cannot be easily removed (Dynamo, 2017).

Figure 2.14: Hub Dynamo
(SP Dynamo Hub PV-8 Review, 2015)

The third type of bicycle dynamo is the bottom bracket dynamo, shown in Figure 2.15. This type of dynamo mounts to the chain stays of the bicycle behind the bottom bracket of the rear wheel. Like a bottle dynamo, the bottom bracket dynamo uses a roller wheel on the bicycle tire to turn its shaft to create electricity. However, the bottom bracket dynamo differs in that its roller wheel makes contact with the outer part of the bicycle tire where the tread is, so it does not wear down the tire's sidewall (Dynamo Powered Lights, 2017).

Figure 2.15: Bottom Bracket Dynamo
(Dynamo Hub on Trike, 2011)

Less common types of bicycle dynamos include chain-driven dynamos and wheel-mounted dynamos. Chain driven dynamos, as seen in Figure 2.16, are attached to the bicycle's frame and have a special gear that gets turned by the bicycle's chain as the rider pedals, which generates electricity that can be used to charge small electronics such as a cell phone. Wheel-mounted dynamos are a newer type of dynamo that can also be used to charge small electronics as well as a battery. These generators have a small gear mounted on the spinning axle of the bicycle's front or rear wheel which rotates the generator rotor to create power as the wheel turns, as seen in Figure 2.17. (Dynamo Chargers Outside of the Hub, n.d.)

Figure 2.16: Chain-Driven Dynamo
(Outdoor Portable Charger Bike Generator-Chain Type, n.d.)

Figure 2.17: Wheel-Mounted Dynamo
(Dynamo Chargers Outside of the Hub, n.d.)

2.8.2 Human Power

Human power, through an action such as pedaling or turning a crank generator, can be the power source used to spin an armature in a generator to create electricity. An average fit person can produce between 50 and 150 Watts during vigorous exercise, and an elite athlete can produce up to 400 Watts for an hour of continuous exercise (Gibson, n.d.). The average energy expenditure of an average human is about 2792 Watt-hours per day (McArdle, n.d.); with this energy release in the forms of heat and motion, it opens opportunities to create a device to capture this energy that can power electrical devices. In fact, there are companies working on ways to convert the energy humans expend while exercising at the gym on gym equipment, such as stationary bicycles and ellipticals, into electricity by hooking the equipment up to generators.

2.9 Solar Power Generation

Solar cells convert energy that is derived from sunlight into electrical energy. Solar cells are generally created with multiple layers: the glass, front contact, n-type semiconductor, p-n junction, p-type semiconductor, and back contact, in that order, as shown in Figure 2.18. According to NASA, a solar cell generates electricity by using the sunlight to attract electrons to travel through the p-type semiconductor to the n-type semiconductor, causing a current flow. This can be demonstrated by connecting the front and back contacts of a solar cell to a circuit with a light bulb (as a visual aid) and directing sunlight onto a solar cell. Once the sun's photons reach the solar cell, the light bulb will turn on. The light will remain on as long as the photons continue to hit the cell. (Energy Informative)

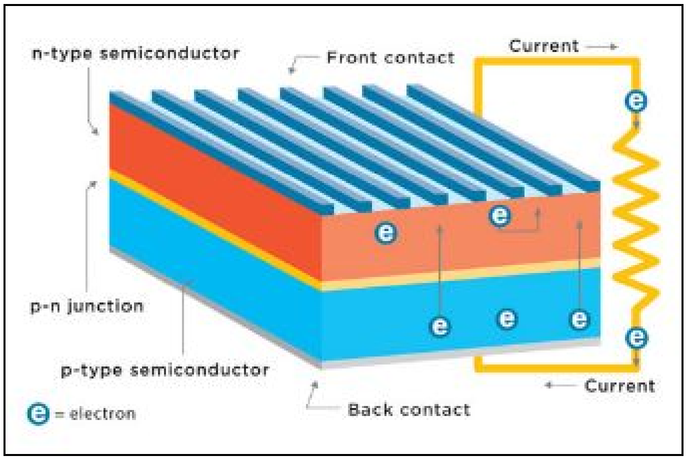

Figure 2.18: Framework of a Solar Cell
(Energy Informative, n.d.)

The three most common solar cells are monocrystalline, polycrystalline, and thin-film. Monocrystalline solar cells are the most efficient at about 17%. Unfortunately, they are also the most expensive which is something to consider in our overall cost of the prototype. Polycrystalline solar cells are similar to monocrystalline, but the purity of the silicon used is lower quality than that used for monocrystalline cells. Polycrystalline cells are slightly less efficient (11-14%) than monocrystalline cells and do not work as well in hot weather, but are less expensive. Thin-film solar cells are the least expensive of the three and has an efficiency of 10-14% and is the easiest to mass produce. (Energy Informative)

2.10 Storing Energy

The power created by a generator or solar panels can be used to directly power electronics and other devices such as lights and household appliances. However, this power can also be stored as energy in batteries when the generator is not in use or there is no sunlight available for the panels, thus the energy can be used at a later time. In this scenario, a generator converts work to electricity that can then be transferred and stored in a battery. The time and energy it takes to fully charge a battery depends on the type and capacity of a battery. The power that is stored in batteries can then be discharged to power a load when no other source is available. (Scientific American, n.d.)

Batteries come in many forms for many different applications. Examples include household (rechargeable and non-rechargeable), industrial, and vehicular varieties. The primary types of rechargeable batteries are composed of lead-acid, nickel-cadmium, nickel-metal hydride, and lithium-ion (li-ion) which can be seen in Figure 2.19 (Rechargeable Battery Association, n.d.).

A battery consists of an anode (negative terminal), a cathode (positive terminal), and an electrolyte (a chemical medium) used as a barrier that prevents the flow of electrons from the anode to cathode when it is in open circuit conditions and is the energy storage medium. Oxidation-reduction reactions, a reaction which a transfer of electrons occurs between two chemical species, happens within the battery which causes electrons to build up on the anode creating different charges on the electrodes. When the circuit is completed, the difference in charge forces the electrons to flow to the cathode. With rechargeable batteries, the reaction can be reversed thus charging the battery (Bates, n.d., Palermo, 2015).

Figure 2.19: Top Row: Lead Acid Battery, Nickel Cadmium Battery, Bottom row: Nickel metal hydride battery, Lithium Ion Battery
(Google Images, n.d.)

Batteries are rated in terms of capacity, or C-rating, which is the amount of charge stored in a battery. The C-ratings describe how much current can be delivered in a certain time period. The C-rating quantifies the current that can be continuously provided over a period of time and is the energy capacity of a battery (Battery University, n.d.). Usually the C specification is followed by a number (e.g. C/100, C/20, C/5) which indicates the current that can be drawn over a period of time. For example, a C/20 5Ah battery can provide 0.25A for 20 hours, but realistically might only be able to supply that current for 12 hours, or 60% of the rating, depending on the age, temperature, and chemistry of the battery.

Batteries have other defining characteristics that separate one type of battery from another. Gravimetric density is an expression of how much energy a battery contains compared to its weight, and volumetric density is a battery's energy in comparison to its volume. Our team would like to minimize weight but maximize energy storage for our design so energy density is important. As seen in Table 2.2, the li-ion battery has a high gravimetric and volumetric density which means that this battery can be a lighter weight while still having a high energy capacity, thus resulting in potentially a longer run time.

Cell Type	Lead Acid	NI-CD	NI-MH	LI-ION
Volumetric Density (W-HR/L)	80	140	180	210
Gravimetric Density (W-HR/KG)	30	50	55	90

Table 2.2: Comparison of Energy Density
(Epec Engineered Technologies, n.d.)

Even when batteries are not in use being purposely discharged, they still will discharge a small percentage based on ambient temperature. Self-discharge rates determines the shelf life of a battery. Li-ion batteries have the lowest self-discharge rate compared to the nickel metal hydride and the nickel cadmium batteries. At 20℃, the li-ion only discharges 5-10% a month while other batteries typically discharge between 15-30% a month (Simpson, n.d.). Unlike nickel cadmium and nickel metal hydride batteries, li-ion batteries also do not have a memory effect. Memory effect is the loss of usable capacity due to a battery being charged repeatedly after being only partially discharged (Sasaki, Ukyo, & Novak, 2013).

In terms of safety, lead acid is a toxic metal that can poison humans as well as the environment, nickel cadmium can be dangerous if incinerated since cadmium is a toxic heavy metal, and lithium-ion batteries have the potential to spontaneously combust if the separating electrolyte breaks down (Battery University, n.d.). The combustion may happen when manufacturers try to reduce costs and pack more capacity in the battery than safely possible (Ravpower, 2017).

2.11 Summary

Vietnam is a mostly rural nation that struggles to provide electricity to its citizens. Education after dusk needs a source of light. For both technical and economic reasons, human power and solar power are the most viable method of generating electricity in remote villages and, while other non-electrical sources of lighting exist, they are dangerous, non-renewable, or expensive.

3. Project Statement

3.1 Introduction

The goal of this project was to design, build, and test a battery charging and lighting system for a bicycle to give young students in rural Vietnam access to light for nighttime studying. To achieve this goal, we developed the following objectives:

1. Understand the needs of the stakeholders.
2. Design, build, and test a rechargeable battery pack that is portable, reliable, and durable.
3. Design, build, and test an inexpensive and compact mechanical power generation system that attaches to a bicycle that is durable and reliable.
4. Evaluate the practicality of our designs for the environment in Vietnam.

3.2 Tasks

In order to meet our objectives, we developed a series of tasks to complete associated with each objective which are as follows:

Objective 1 Stakeholders:

- Research the environment of Vietnam, including the weather, the rural lifestyle, and their lighting needs.
- Talk with first-hand sources to learn more in-depth information about Vietnam and its rural villages.
- Develop requirements for the combined charging, energy storage, and lighting components.

Objective 2 Battery Pack Design:

- Research batteries and choose the best type for the rural Vietnam environment.
- Design a circuit to protect the batteries during charging and discharging.
- Model a concept battery pack.

Objective 3 Charging System:

- Research compact mechanical and solar power generating systems.
- Use CAD to model mechanical bicycle generator options.
- Propose and evaluate multiple system designs.

- Determine which bicycle generator option is best by evaluating the advantages and disadvantages of multiple generator designs.
- Design, build, and test an adjustable attachment system for the generator so it can be used on any type of bicycle and can be easily put on and removed.
- Build a rugged, waterproof case for the bicycle generator.
- Test the solar power charging system by using it to charge the battery pack.

Objective 4 Lighting Module:

- Conduct a survey to determine lighting preferences.
- Select a light that will meet user preferences as well as meet the technical demands of the system.

Objective 5 Testing:

- Test the entire system as it would be used in Vietnam by riding a bicycle with the mechanical generator for an hour and then using the solar charging system for 6 hours and determine whether the battery pack is fully charged.
- Discuss the results of testing the entire system and determine the feasibility of manufacturing and donating the systems to students in Vietnam.

3.3 Summary

With an understanding of the objectives and completion of the associated tasks, the goal of proving a battery charging system for young Vietnamese students will be met.

4. System Considerations

4.1 Introduction

Our goal was to design and build a prototype bicycle generator to charge a battery pack with a 5V output. To design this system, we first had to identify stakeholders and, their needs, as well as the operating environment and user operational scenarios. Finally, based on stakeholder needs, the system requirements could be stated.

4.2 Systems Engineering Approach/Design

4.2.1 Stakeholders

Any individual or group that will be affected by, has influence, or are interested in our project are included in the stakeholder analysis. Table 4.1 shows the stakeholder and role, why they are a stakeholder, and the priority of each. Priority is ranked one to three, with one being the highest priority.

As can be seen in this table, the students of Ngoc Bien Elementary School, their parents, and Boa Newgate all have the highest priority as stakeholders. The students are the main users of this system and are in direct contact with the system which was specifically designed for them to use, and user satisfaction is important. The parents of the students have a direct relationship with the product since their children will be using the system and the safety of their child is held above all else. Boa Newgate is the supporting organization and must find the system worthy to fund. The high priority is given because these stakeholders have the most to gain and to lose depending on the success of the system. Lower priority is given to the manufacturers, designers, and WPI since they are still stakeholders but have less to gain and lose.

Stakeholder - Role	Why	Priority
Students of Ngoc Bien Elementary - Users	These will be the people using the system directly. They must understand how to use it and care for it. They are directly affected if it breaks or causes them harm.	**1**
Parents of the students - Parents of users	Parents manage and care for their children. They must approve of the system for the kids to use it. They must deal with the light from the system. They are directly influenced if their child gets injured.	**1**
Boa Newgate - Supporting organization	Mr. Newgate is the person who in the future will fund and bring the system to the children. He contributes input about the needs of the children.	**1**
Manufacturers	They will make the parts for the system. Could potentially make money.	**3**
Designers/Engineers - this Project Team	They came up with the designs, may improve the device in the future, held accountable for design flaws. Also responsible for safety and signing off on the system.	**2**
WPI	Organization has their name linked to this project and will benefit if it goes well.	**3**

Table 4.1: Stakeholder Analysis

4.2.2 Needs

Our system must satisfy needs based on the end user as well as needs for a good design. Needs are expressed by the stakeholders or by the design team both explicitly and implicitly. The system needs are shown in Table 4.2 below along with a priority rating of each need. Priority is ranked one to three with one being very important, two being important, and three being somewhat important. Priorities such as the system be resistance to dirt, mud, sunlight and water, remaining safe and reliable, and not being a hinderance to the user are ranked highly because if these needs are not met, the system would not function. Priorities such as the system being as lightweight as possible are ranked lower since the system will still function if this need was not met, but it would still deter from the system's purpose.

Need	**Traceability** (Validation, who expressed the need, and why)	**Priority**
System should be durable to withstand drops and falls.	Design team - Do not want the users to have to replace parts, or fall and break any part of the system.	**2**
Generator and battery pack should be resistant to dirt, mud, direct sunlight, and water.	Design team - Do not want particles to interfere with the system or the cases to melt in the sun.	**1**
System should be affordable to the end user or donating organization.	Supporting organization - An affordable system for the supporting organization is desirable because the users of the system have relatively low income levels.	**2**
Battery pack should have sufficient energy storage to enable typical nighttime usage.	Users - It is wanted by the users to be able to study after the sun goes down for an appropriate length of time.	**1**
Light should provide enough lux to allow users to see without strain.	Users - If the lighting is too dim, the users will not be able to study or may strain their eyes.	**2**
System should remain in a reliable safe and functioning condition.	Supporting organization, Users, Design Team - Keep users safe and not endanger users	**1**
Generator should fit on a bicycle without being a hinderance to the rider.	Users - For the users to comfortable use the system, the system should not come into contact with the users when riding the bicycle.	**1**
System should be as lightweight as possible	Design team - It is desirable to have the weight of the system minimized in order to make the system easier to use.	**3**
System should be easily manufactured	SEAC - Funding source - Mass produce the system with easily accessible parts and cost-effective methods will be needed.	**2**

Table 4.2: Needs Analysis

4.2.3 Risk Analysis

For the system to have a successful desired outcome, the risks of a such as breakage, inefficient operation, and repairability had to be evaluated. Risks were evaluated on the likelihood of the event happening and was rated unlikely, possible, or likely. The risks were also rated based on priority. A high priority means the device would be in near-to-completely unusable and a low priority means the device requires a minor fix. Table 4.3 presents the risks along with the associated probabilities and priorities. By analyzing the risks, the system requirements could be formed.

Risk	Probability - Consequence	Priority - Why
Water damage	Likely - The battery pack or generator will short-circuit	High - Unusable conditions
User lets the battery drain over 50% or completely	Possible - The batteries lifespan is shortened and capacity is decreased	Medium - Still usable but if it happens frequently, eventually will have problems with battery capacity/lifespan
Not high enough generator voltage to charge a battery	Possible - The batteries will not get charged	Low - The user should pedal faster or use a higher voltage input to the system
Wires break or fray	Likely - Depending on the wires, the batteries may not charge	Medium - Inconvenient to find new wires and rewire (as long as it is outside of the battery pack container)
Connectors break	Possible - Cannot use the intended output or input to charge or discharge	Medium - If wires are easy to unattach, it is just inconvenient
Input voltage is higher than 36V (highest voltage allowed in the system)	Possible - The system may overheat and parts will break	Medium - Potentially dangerous and the charger and batteries will be unusable, but the internal protection circuit should protect it.
Off the shelf electronics malfunction	Low - The electronics are designed to not malfunction if bought from reputable seller	High - Potentially dangerous if allowed to still charge. Circuit could be rendered useless and batteries won't charge
Charging circuit short-circuits	Possible - If water or wires that shouldn't touch touch, the circuit can short-circuit	High - Can fry entire circuit
Batteries are taken out and damaged	Low - The batteries will be in the module and secured	High - Possible damage can cause the li-ion battery to explode
Batteries overcharge	Low - With the IC control the battery should not overcharge	High - Damages the battery, could overheat and expand
Solar panel breaks	Possible - will need a replacement	High - Solar panel is the main charging source so it will need replacement immediately; requires money
Electronics are damaged by the heat of the sun	Possible - will probably be broken	High - will require maintenance to see if the battery pack is safe or dangerous to use or if it is completely broken
Generator overheats	Low - will need maintenance	Medium - battery can still be charged without the generator, but the generator will need maintenance
Light malfunctions	Low - will need a replacement	High - will need to buy a replacement before it is needed; requires money
Bike falls over and breaks the generator system	Likely - the battery will break	High - Need maintenance to fix if it is broken

Table 4.3: Risk Analysis

With certain risks having a high probability, action must be taken for the risk to be avoided or managed. The team evaluated the probabilities and the priorities to introduce a risk mitigation plan for the likely scenarios with a high priority. Since water damage is at a high probability and is likely to happen, the system will be designed to be waterproof to mitigate the risk. Another likely scenario with a high priority is that the bike falls over and the generator system breaks. The team addresses this risk by designing the generator system to be rugged and withstand falls from a bicycle.

4.2.4 Requirements

After evaluating the risks of the system and the needs of the stakeholders, the system requirements were recognized. The requirements follow the SMART criteria of being specific, measurable, attainable, realistic, and testable (Wikipedia, n.d.). The system shall have the following characteristics:

Water-resistant

Specific: The system shall be designed to meet the IP 5 standard of water: Water projected by a nozzle against the enclosure from any direction shall have no harmful effects.
Measurable: The system shall be rated at a minimum of IP5 standard for water.
Attainable: The system shall use various elements such as nylon gasketing and O-rings to prevent water and dust ingression.
Realistic: IP5 rating is the minimum for outdoor weather protection against rain. IP4 rating only protects the enclosure from splashes of water, and IP6 rating is protection against powerful water jets projected directly onto the enclosure.
Testable: The system shall be tested in water conditions by subjecting the system to the IP5 standards conditions.

Dust-proof

Specific: The system shall be designed to meet the IP5 standard of enclosures against dust: ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment; complete protection against contact.
Measurable: The system shall be rated at a minimum of IP5 standard for dust ingress.
Attainable: The system shall use various elements such as nylon gasketing and O-rings to prevent water and dust ingression.
Realistic: IP5 rating is necessary for our project as the climate in Tra Vinh suggests periods of high dust exposure, but realistically it will be very difficult to guarantee that all

particles of dust will not pass through even with the O-rings and nylon gasketing. This is why we settled for IP5 rating.
Testable: The system shall be tested in dust conditions that subject the system to the IP5 standards conditions.

Durable (Suitable to Outdoor Use)
Specific: The system (generator and circuitry) shall withstand drops of up to 5 feet onto a concrete surface.
Measurable: The durability of the system shall be tested by dropping it at 5 feet onto a concrete surface.
Attainable: Padding shall be added to the generator housing to absorb impact.
Realistic: Rubber or a similar padding material, as is used in cell phone cases, should not be hard to obtain and implement.
Testable: We shall perform various drop tests on the system.

Battery Capacity
Specific: The system shall have a battery capacity of 6Ah.
Measurable: The batteries shall each have a capacity to provide 0.25A for 8 hours.
Attainable: The system shall use batteries in parallel to reach the capacity goal.
Realistic: Batteries are commonly rated at 3000mAh so two in parallel is doable.
Testable: We shall drain the battery by drawing 0.25A for 8 hours to ensure the capacity.

4.3 Summary

After identifying the stakeholders and their explicitly and implicitly expressed needs, the various use cases of the entire system, and the requirements based off of those needs and risks, we were able to progress to the overall design of our system that will meet the design and user requirements formulated in this section

5. High Level Design

5.1 Introduction

This section presents the overall system design which explains the architecture and each individual component of the system. The diagram provides an overview of the whole system while identifying the components and how each interacts with another. Using decision matrices and uses of individual components, we were able to then make an informed choice on what exact device or part to use in our final design.

5.2 System Diagram

The system diagram shows the specifications of the system inputs, the interactions of the circuit components, and the output to a load which will be designed for a 5V light. Each colored block represents a different subset of the overall system as seen in Figure 5.1, The blocks detail the module name and, if applicable, the input and output voltages.

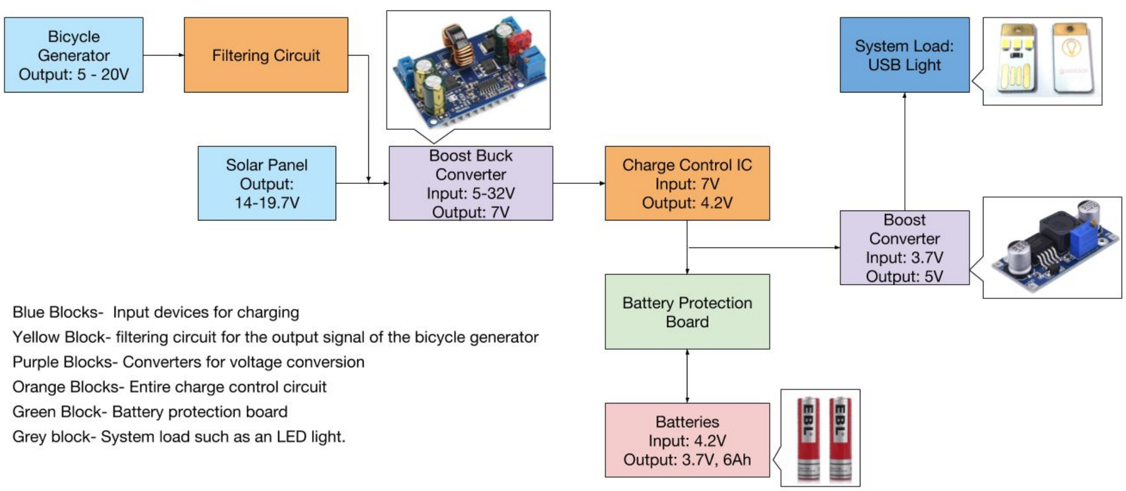

Figure 5.1: Overall System Design

5.3 Concept Architectures Overview

For a top-level block diagram as shown in Figure 5.1, the system can be broken down into three main modules: the inputs for charging the battery pack, the battery charging and discharging circuit, and the output load. This section will go over the detailed descriptions of each module focusing on the functionality and implementation.

5.3.1 Input Devices for Charging

Power generator with a proper voltage and current output are necessary to provide power to charge the battery pack. There will be two methods of charging the battery pack system: solar panels and a generator connected to a bicycle. These sources will allow users the convenience of choosing their desired charging method depending on the situation and environmental conditions. While users are riding bicycles, they can use the generator on their bicycle to charge the battery, and while they are not traveling, they can use the solar panel to charge it depending on weather.

Solar Power Generation

The functionality of the solar panel will be to charge the battery pack in good solar conditions as judged by the user. The solar panel can either permanently attached to the system directly on the battery pack, or be seperate from the system using a wire connection. The first method of charging shall be implemented as a solar panel on the top of the battery pack with an internal connection.

If the solar panel was to attach permanently to the top of the battery pack, then it would be included to follow the IP55 standards of the rest of the system. Putting it on the battery pack would increase the risk for the panel to break if the pack is dropped. The solar panel would need a reinforcement on the edges to reduce impact damage. With the solar panel separate from the system, any drops or falls of the battery pack will not affect the solar panel. Being separate from the system does mean that the user will have to take care of another piece and is at risk for wire damage.

To decide which solar panel was chosen we created a decision matrix, shown in Table 5.1. The final result was polycrystalline, leading only by 2 points. We fully decided to choose the polycrystalline solar panel because of the availability and price point of it compared to the monocrystalline. Polycrystalline is more widely available than monocrystalline with a better price point, yet the differences in efficiency are less than 5 percent of each other.

	Monocrystalline	Polycrystalline	Thin Film
Durability (3)	3 - Very Durable 3 x 3 = 9	3 - Very Durable 3 x 3 = 9	3 - Very Durable 3 x 3 = 9
Price (1)	1 - Expensive 1 x 1 = 1	2 - Moderately Priced 2 x 1 = 2	2 - Moderately Priced 2 x 1 = 2
Efficiency (3)	3 - Highest Efficiency 3 x 3 = 9	2 - Moderate Efficiency 2 x 3 = 6	1 - Low Efficiency 1 x 3 = 3
Life-Span (2)	3 - Long Life Span 3 x 2 = 6	3 - Long Life Span 3 x 2 = 6	1 - Short Life Span 1 x 2 = 2
Size (3)	3 - Little Space Required 3 x 3 = 9	3 - Little Space Required 3 x 3 = 9	1 - Requires a lot of Space 1 x 3 = 3
Availability (2)	1 - Not as Available 1 x 2 = 2	3 - Widely Available 3 x 2 = 6	3 - Widely Available 3 x 2 = 6
Totals	36	38	25

Table 5.1. Solar Panel Decision Matrix

Bicycle Generator

For this project, a motor will be used to produce the electricity to charge the battery pack. After researching the different small motor options available on the market, we obtained different motors to test: two AC motors and two DC motors, as shown in Figure 5.2. The motors look similar with the main difference in appearance being their size. The first step in choosing an appropriate motor to use as the generator in the design was to test the motors to see how they met or did not meet various criteria. We obtained the four motors from various online sources; they were a relatively small and large DC motor and a relatively small and large AC motor. These four motors are pictured in Figure 5.2 below.

Figure 5.2 Four Possible Motors
(Google Images, n.d.)

The first criteria we tested was motor RPM versus output voltage. This test was performed individually on each motor by varying the voltage supplied to the motor and counting the motors shaft revolutions with a laser photo tachometer, as shown in Figure 5.3.

Figure 5.3 Laser Tachometer (Google Images, n.d.)

For the DC motors, a large gear with a piece of reflective tape on its edge was put on the motor shaft to do this, and for the AC motors, the reflective tape was attached directly to the motor's body, as this is the part that spins along with the shaft on the AC motors. In the case of the small AC motor, since the body is reflective, the body was first covered in black electrical tape before attaching the piece of reflective tape, to prevent the tachometer from misreading the revolutions of the motor. In addition to this test, the motors' lengths and diameters were also measured and their k-values were calculated. The k-value of a motor is defined as how fast the motor's shaft turns per volt supplied to the unloaded motor (Learning RC, 2015). We were able to find the k-value of the motors by finding the slope of the RPM vs. supplied voltage for each motor. After calculating the actual k values of each motor with and without a load, we were able to determine the required and recommended speed of travel to efficiently determine how functional each motor would be if used. At the end of our tests we concluded that the large DC motor had the smallest k-value of all four motors, meaning that it would take very little motor shaft speed to produce a high voltage from the motor. The results of these tests and measurements can be seen in Appendix A.

The ease with which each motor could be held in place and encased was also assessed. We determined that the DC motors would be easier to hold in place, as they can simply be put in a clamping motor mount, as shown in Figure 5.4. The AC motors would be more difficult to hold in place due to the fact that the case of the motors rotate; these motors would have to be mounted from the back with screws, which may prove to be more difficult to securely and easily mount. For the need for ventilation, we reasoned that the AC motors, due to their moving bodies and constant air flow, would not need ventilation, while the DC motors might need ventilation to not overheat. However, the AC motors are again at a disadvantage because they require extra circuitry to convert their current output to DC with signal processing and filtering, whereas the DC motors just need filtering and have no need for electronic signal processing.

Figure 5.4: Clamping Motor Mount

To choose our motor, we rated the motors based on the six different criteria: k-value, size, weight, ease of encasement, need for ventilation, and need for electronic signal processing.

In our case, the more desirable aspects of these criteria would be a low k-value, a small size, a low weight, a easy method to encase the motor, no need for ventilation, and no need for electronic signal processing. As such, each motor was rated on a scale of 1 to 3, with 3 being the rating closer to our desired options. The criteria were all given individual weights as well, with a higher weight representing a more important criterion; RPM versus output voltage has a weight of 5 because it is the most important factor, size has a weight of 2, weight has a weight of 3, ease of encasement has a weight of 3, need for ventilation has a weight of 1, and need for electric signal processing has a weight of 2. The results of the decision matrix can be seen below in Table 5.2.

	AC Small Motor	AC Large Motor	DC Small Motor	DC Large Motor
K-Value (5)	1 - High k-value; requires high RPM 1 x 5 = 5	1- High k-value; requires high RPM 1 x 5 = 5	2 - Moderate k-value; requires moderate RPM 2 x 5 = 10	3 - Low k-value; requires low RPM 3 x 5 = 15
Size (2)	3 - Very small size 3 x 2 = 6	2 - Moderate size 2 x 2 = 4	2 - Moderate size 2 x 2 = 4	1 - Large size 1 x 2 = 2
Weight (3)	3 - Low weight 3 x 3 = 9	3 - Low weight 3 x 3 = 9	2 - Moderate weight 2 x 3 = 6	2 - Moderate weight 2 x 3 = 6
Ease of Encasement (3)	2 - Moderately easy 2 x 3 = 6	2 - Moderately easy 2 x 3 =6	3 - Easy 3 x 3 = 9	3 - Easy 3 x 3 = 9
Need for Ventilation (1)	3 - No need for ventilation 3 x 1 = 3	3 - No need for ventilation 3 x 1 = 3	2 - Moderate need for ventilation 2 x 1 = 2	2 - Moderate need for ventilation 2 x 1 = 2
Need for Electronic Signal Processing (2)	1 - Signal processing needed 1 x 2 = 2	1 - Signal processing needed 1 x 2 = 2	3 - No signal processing needed 3 x 2 = 6	3 - No signal processing needed 3 x 2 = 6
Totals	31	29	37	40

Table 5.2: Motor Decision Matrix

As shown in the decision matrix, the large DC motor has the highest score, and so this was the motor we moved forward with. While this motor might be larger and heavier than desired, it had the lowest k-value, which is important for our low-speed application of leisurely riding a bicycle. To this end, the bicycle generator case was designed to fit the large DC motor. Figure 5.5 below demonstrates the expected output voltage of the large DC motor based on the bicycle speed. These values are calculated for a 24-inch bicycle tire and a 18-mm roller, with the roller mounted 0.5 inches below the tire's tread. According to Figure 5.5 below, for even relatively slow speeds, the motor does not require gears to increase the shaft speed.

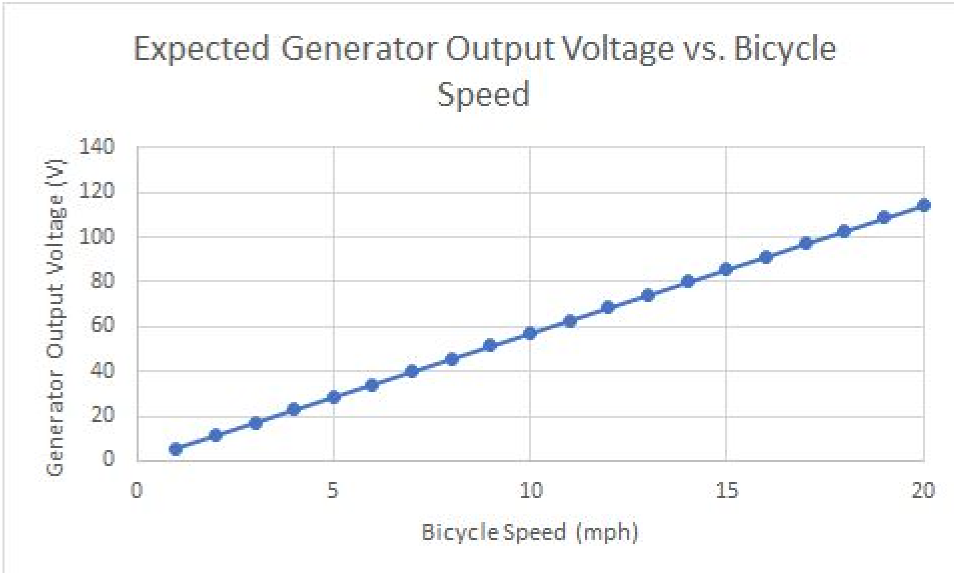

Figure 5.5: Expected Generator Output Voltage vs. Bicycle Speed

Mechanical Design Elements-Generator

As mentioned previously, there are several potential methods to generate electricity from a moving bicycle. The team considered five different methods of using a generator to generate electricity from a bicycle. These five methods include a generator with the roller on the bicycle tire's sidewall, a generator with its roller on the top of the tire, a generator that interfaces with the bicycle's chain, a generator that interfaces with the tire's spokes, and a generator that is in the tire's internal hub. The first two methods mentioned here utilize friction to turn the motor's shaft, and the last three utilize what might be considered more secure methods of interfacing with the tire. The generator with its roller on the tire's sidewall is based off of a standard bicycle bottle dynamo, and the generator with its roller on the top of the tire is based off of a bottom bracket dynamo. Simple figures for the locations of these two generator types on a bicycle are shown below in Figures 5.6 and 5.7, respectively.

Figure 5.6: Tire Sidewall Generator Concept

Figure 5.7: Tire Top Generator Concept

The third option for the generator design is to use a special gear that can interface with the bicycle chain, as shown in Figure 5.8 below. As the chain moves, the gear will serve to rotate the motor's shaft. This design might be difficult to implement on externally geared bikes, as the chain will shift position as the bicycle's gears are shifted. The design of this generator option will require that either the chain does not shift location or that the generator will need to have a sliding mechanism to move the gear and lengthen or shorten the motor shaft as the chain changes location.

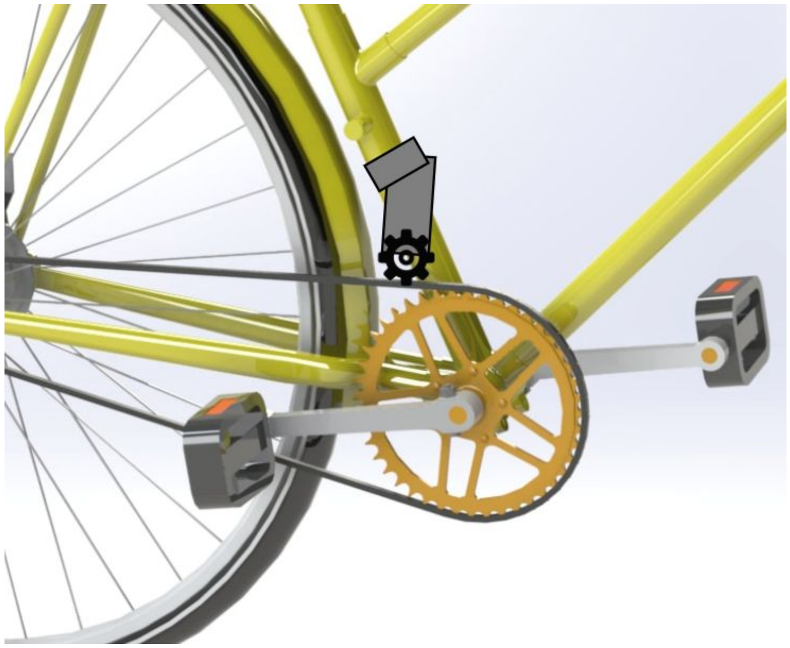

Figure 5.8: Chain Generator Concept

The fourth option for a bicycle generator is to integrate the generator with the spokes of the bicycle wheel. There are several ways this could be potentially done, such as using a plastic piece with tabs that can interlock with the spokes. Designing a part that can interlock with the bicycle's spokes is might prove difficult, as similar bicycle generator products that use this method have been known to slip or not grip the spokes well.

Figure 5.9: Generator that Interfaces with Spokes Concept

The final option is to create an internal hub generator. These types of generators, like the other options, are already products on the market. Internal hub generators require the generator to be inside the bicycle tire's hub. This design would be difficult to recreate as a donatable product because it would require special installation.

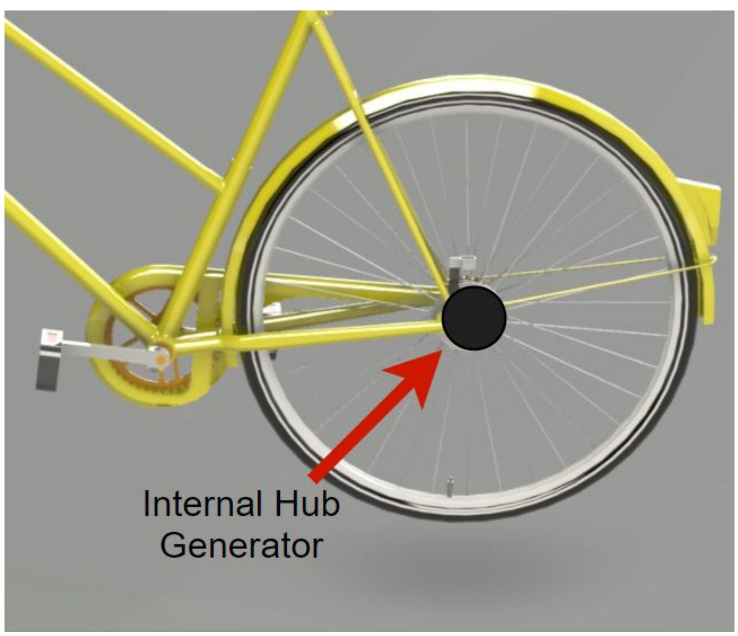

Figure 5.10: Internal Hub Generator Concept

Each of the generator type options have advantages and disadvantages associated with them. A table that summarizes the positive and negative points of each one of these methods can be seen below on Table 5.3.

Generator Type/Positioning	Advantages	Disadvantages
Generator with roller on tire sidewall	● Easy mounting; can be simply attached to rear bicycle stay ● Simpler design, fewer hardware components needed	● Depending on roller type, could cause excessive tire wear ● Tire contact could be more difficult to maintain than on top of tire option due to slippage
Generator with roller on top of tire	● Will not cause tire wear ● Will be easy to maintain roller contact with tire	● Mounting will be more difficult than sidewall option; either the rear bicycle fender will need to be cut away or the generator will need to utilize a 90° shaft assembly to translate motion to generator shaft ● More complicated design
Generator that interfaces with chain	● There would likely be little slippage	● Design might be complicated if bicycle chain changes position
Generator that interfaces with spokes	● If contact can be maintained, it has the potential to generate the consistent electricity	● Design might be difficult to ensure proper interface with spokes
Internal hub generator	● Will likely be the most resistant to water and dust infiltration ● Will create consistent electricity since there will be no slippage	● Will be difficult to design with the resources we have access to ● Will require special installation on a bicycle

Table 5.3: Advantages and Disadvantages of Generator Type/Positioning

From the advantages and disadvantages of the type and positioning of the generator, a decision matrix was created to choose the best method for generating electricity from the moving bicycle, as shown in Table 5.4. As seen from the results of the table, the generator option that involves using a roller on the tire's sidewall garnered the highest score. Since this option is the easiest method to implement, this is the option we decided to pursue.

	Internal Hub	**Integrate with spokes**	**Roller on tire sidewall**	**Roller on top of tire with fender cut**	**Roller on top of tire with 90 degree shaft**	**On chain**
Ability to Interface with tire/wheel/chain (3)	3 - Excellent interface capability 3 x 3 = 9	2 - Moderate 2 x 3 = 6	2 - Moderate 2 x 3 = 6	2 - Moderate 2 x 3 = 6	2 - Moderate 2 x 3 = 6	2 - Moderate 2 x 3 = 6
Ease of Mounting (2)	1 - Very difficult to mount 1 x 2 =2	2 - Moderately easy 2 x 2 = 4	3 - Very easy 3 x 2 = 6	2 - Moderately easy 2 x 2 = 4	3 - Very easy 3 x 2 = 6	1 - Difficult to mount 1 x 2 = 2
Ease of Design (3)	1 - Difficult to design 1 x 3 = 3	2 - Moderately easy 2 x 3 = 6	3 - Easy 3 x 3 = 9	3 - Easy 3 x 3 = 9	2 - Moderately easy 2 x 3 = 6	2 - Moderately easy 2 x 3 = 6
Imperviousness to dirt and water (4)	3 - Very impervious 3 x 4 = 12	3 - Very impervious 3 x 4 = 12	3 - Very impervious 3 x 4 = 12	3 - Very impervious 3 x 4 = 12	3 - Very impervious 3 x 4 = 12	3 - Very impervious 3 x 4 = 12
Impact Resistance/ protection of mounting area (4)	3 - Mount is located in a protected area 3 x 4 = 12	2 - Fairly Protected 2 x 4 = 8	1 - Least protected 1 x 4 = 4	2 - Fairly Protected 2 x 4 = 8	1 - Least protected 1 x 4 = 4	2 - Fairly Protected 2 x 4 = 8
Feasibility (5)	1 - Difficult to build 5 x 1 = 5	2 - Moderately easy to build 2 x 5 = 10	3 - Very feasible 3 x 5 = 15	2 - Moderate 2 x 5 = 10	3 - Very feasible 3 x 5 = 15	2 - Moderately easy to build 2 x 5 = 10
Potential to switch to hand-crank mode (1)	1 - Difficult to use with hand crank 1 x 1 = 1	2 - Moderate 2 x 1 = 2	3 - Good 3 x 1 = 3	3 - Good 3 x 1 = 3	3 - Good 3 x 1 = 3	2 - Moderate 2 x 1 = 2
Totals	44	48	55	52	52	46

Table 5.4: Generator Type Decision Matrix

5.3.2 Battery Pack Components

Batteries

After examining the rechargeable battery characteristics, we decided to use lithium-ion batteries for our system due to their high energy density and capacity, as seen in Table 5.5.

	Lead Acid	Nickel Cadmium	Nickel Metal Hydride	Lithium-ion
Rechargeable (3)	3 - Yes, Rechargeable 3 x 3 = 9	3 - Yes, Rechargeable 3 x 3 = 9	3 - Yes, Rechargeable 3 x 3 = 9	3 - Yes, Rechargeable 3 x 3 = 9
Volumetric Density (2)	1 - Low Density 1 x 2 = 2	2 - Moderate Density 2 x 2 = 4	3 - High Density 3 x 2 = 6	3 - High Density 3 x 3 = 9
Gravimetric Density (2)	1 - Low Density 1 x 2 = 2	2 - Moderate Density 2 x 2 = 4	2 - Moderate Density 2 x 2 = 4	3 - High Density 3 x 2 = 6
Self-discharge Rate (2)	2 - Moderate Discharge Rate 2 x 2 = 4	1 - High Discharge Rate 1 x 2 = 2	1 - High Discharge Rate 1 x 2 = 2	3 - Low Discharge Rate 3 x 2 = 6
Safety (1)	2 - Moderately Safe 2 x 1 = 2	2 - Moderately Safe 2 x 1 = 2	2 - Moderately Safe 2 x 1 = 2	2 - Moderately Safe 2 x 1 = 2
Memory Effect (1)	2 - Moderate Memory Effect 2 x 1 = 2	1 - High Memory Effect 1 x 1 = 1	1 - High Memory Effect 1 x 1 = 1	3 - No Memory Effect 3 x 1 = 3
Totals	22	22	24	35

Table 5.5: Battery Decision Matrix

By having high volumetric and gravimetric densities, it means that the lithium-ion battery is lightweight but is capable of a high capacity when it comes to storing charge. It is also the only battery with no memory effect, so the user will not have to completely drain the battery in order to maintain the capacity throughout the years.

Based on a sunset time between 5:30 and 6:30pm in Tra Vinh, Vietnam, we decided to design a battery pack that would power a light continuously for eight hours. After conducting a basic test on how much current different temperature LEDs draw (Appendix A), we concluded that an LED suitable for evening reading and lighting will draw 0.23A at 5V. We rounded up to a possible 0.25A of current draw for determining the capacity of the batteries. Using the equation P=IV, the power draw calculated is 1.25W. The capacity was determined by using the ampere-hour equation, adding in the restraint of not draining the batteries over 50% due to li-ion characteristics, and a 10% tolerance.

$$8 \text{ hours} * 0.25 \text{ amps} = 2Ah$$
$$2Ah * 2 = 4Ah$$
$$4Ah * 1.1 = 4.4Ah$$

Rounding up the capacity to follow typical li-ion battery capacities, we need a capacity of about 5000-6000 mAh. Since 3000mAh is a common capacity, we can achieve the capacity of 6000mAh by using two batteries in parallel, and then the voltage will be at 3.7V across the batteries.

Battery Protection and Charge Control Circuitry

Charging and discharging lithium ion batteries require circuitry that regulates and protects the batteries against and overcharging. If the battery is subjected to overcharging or depletion, the lifespan of the battery could decrease significantly, or the battery may even potentially combust since lithium-ion batteries have electrolytes within the battery that are highly combustible when exposed to air or when overcharged. Battery Management System (BMS) and Charge Control IC are all designed to protect lithium-ion batteries from combusting and possibly injuring the user.

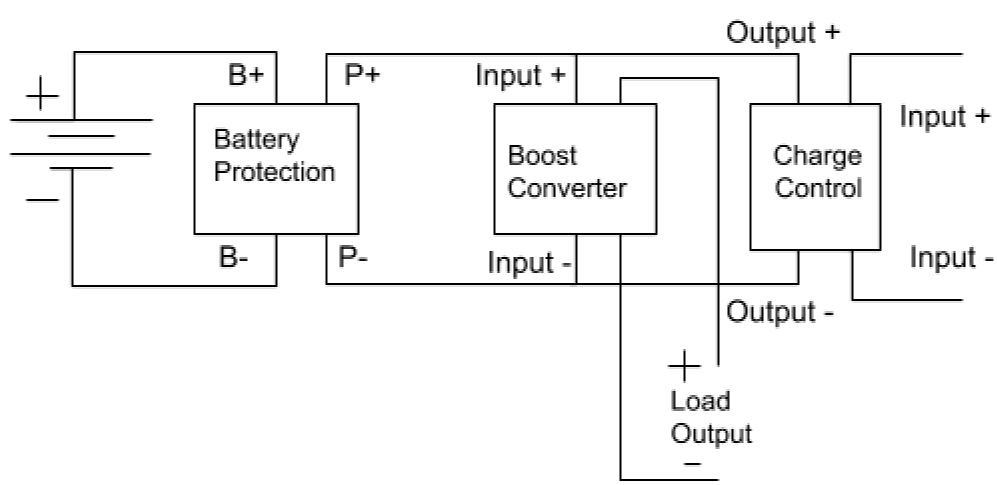

Figure 5.11: Simplified Schematic of Battery Circuit

A charge control IC continuously regulates the voltage and current of an input to a battery. The IC limits the rate in which current is charging or discharging to or from the batteries as well as prevents overcharging and overvoltage. By staying within the safe operating range of the battery, the charge controller mitigates the safety risks and the possible reduction in lifespan due to a current or voltage outside of that range. Due to lithium-ion batteries' chemistry, a charge controller must monitor the charging and discharging of the batteries or else the battery could overheat or even explode as explained in the Section 2.9.1. Specific battery compositions require different charge controllers due to different chemical compositions, so when we selected a charge controller, we were limited to the lithium-ion controllers. When selecting this component, the team had to examine the currents and voltages of the surrounding circuit to ensure that the charge controller would be compatible with the rest of the circuitry in the system.

A battery management system protects a battery by controlling the charge and discharge rate so that the battery stays within its safe operating range. The input and output voltage and current, rate of charge and discharge, and temperature are all factors that keep a battery from combusting. The lithium ion battery protection that we chose is used to control the charging and discharging of the battery by monitoring the charging and discharging process.

Boost-Buck Converter and Boost Converter

Our system design requires a boost-buck and boost converter. A boost-buck converter is a DC-DC converter which takes in a voltage and will either raise or lower the voltage in magnitude. In our system, we will use a boost-buck converter to regulate the voltage coming from the generator and solar panels. The output voltage of the converter can be set to accommodate the voltage restrictions of the rest of the circuit, specifically the charge control IC. It needs to be a boost-buck since the input voltages from the generator and solar panel varies and may either have to be lowered (bucked) or raised (boosted).

The boost converter is needed to boost the output voltage of the batteries, which output 3.7V, to the needed voltage input of the system's load, which is 5V. A boost is needed since the output voltage of the batteries will remain at approximately 3.7V and the voltage will always need to be increased to the 5V load. As for the current, the boost converter will max out at 4A output, although our system will never reach that value. If there is no load connected, the converter will draw 18mA of current.

5.3.3 Output Load

The load of the system is designed for a 5V LED light, but the load can be any 5V load if necessary. The difference in loads will be the current draw which directly affects how fast the batteries will drain.

For the lighting design, we conducted a survey on preferred brightness level and color temperature (Appendix B). From this survey, we decided on using a light that had a 2700K, or warm color temperature at about 200 lux so reading texts would be easy on the eyes and bright enough to read without straining. Trying to remain to a power consumption of around 1.25W, we wanted the current draw of the total LED system to be less than 0.25A.

Since the light will be used for reading texts and studying, we will have the light represent a book light so the angle can be adjusted to the user's preference. This book light will have a USB male connector to plug into the battery pack.

5.4 Summary

By examining the possible design options for each block in our overall system diagram, it allowed the team to make an informed decision on what specific type of component to implement in the project. The large DC motor and the ideal position, lithium-ion batteries, a lithium-ion charge control IC, a BMS with discharge current protection, DC-DC converters with the proper voltage ranges, and an LED lighting module load that draws less than 0.25A and has around 200 lux are all selected after this analysis. Next, the team was able to delve more in depth to the constraints and product specifications of each module.

6. Electrical System Design Details

6.1 Introduction

This section further elaborates the details of the electrical system components explained in the High Level Design section. It describes the parameters of each component and the exact devices implemented in the system.

6.2 Detailed Design

This section describes in detail the specific components that were decided upon in the previous section. It presents the inputs and outputs for the voltages and currents handled by each device as well as explains the functionality of the solar panel, batteries and its protection board and charge control IC, the DC-DC converters, and the LED lighting module load.

6.2.1 Solar Charging

We decided to use a 10W polycrystalline solar panel, as shown in Figure 6.1. After testing the panel, we noticed that it generated about 14-18V, and 0.5A from artificial sunlight. The solar panel output would only require 6 hours of constant, ideal sunlight to fully charge the battery system with only the solar panel.

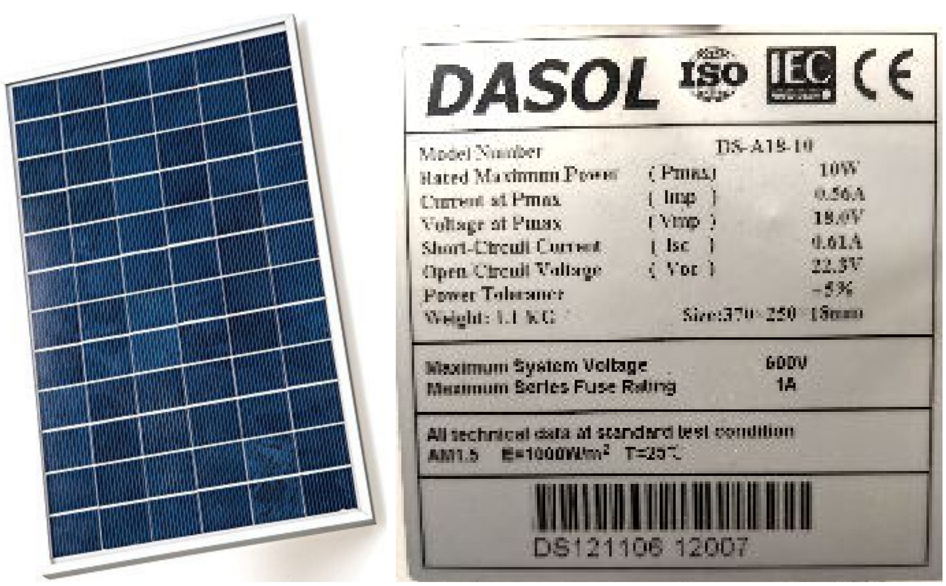

Figure 6.1: 10W Solar Panel Front and Back Panel

6.2.2 Battery Charging and Discharging Circuit

Batteries

Lithium ion batteries were chosen for this project after all the battery types were taken into consideration in decision matrix in Table 5.7. This choice defines the charging circuit since lithium-ion batteries require certain types of charging circuits. The capacity of the battery pack was suggested to be 6000mAh which can be met by putting two 3000mAh batteries in parallel. This will give an output of 3.7V and require a charging voltage of 4.2V.

Using a 18650 battery will satisfy the requirement of a 3000mAh capacity since this size fulfills the need for a larger capacity compared to AA, AAA, and other rechargeable lithium-ion battery types. We chose a 3.7V, 3000mAh EBL battery to use in the system. Table 6.1 displays the specifications for the batteries and Figure 6.2 shows the EBL battery.

	Input	Output
Voltages	4.2V	3.7V
Currents	Safely charge at 1A or less	Load-Dependent

Table 6.1: EBL Battery Inputs and Outputs

Figure 6.2: EBL 18650 3000mAh, 3.7V Batteries

Battery Protection Board

Since the 18650 lithium-ion batteries require extra protection compared to other battery types, the Icstation's 1S Lithium Battery Protection PCB BMS board was selected to add that additional protection. This board below in Figure 6.3 allows the batteries to be safely discharged to the load. The current allows a maximum of 2.5A to be discharged continuously which complies with the maximum discharge current of the batteries themselves.

Figure 6.3: 3.7V 2.7A 1S Lithium Battery Protection PCB BMS Board

This board consists of a DW01-P battery protection integrated circuit detects overcharging and over-discharging of the battery as well as possesses short circuit detector and overcurrent detector (Fortune Semiconductor Corporation, 2006). The protection board also has an 8205A MOSFET chip to protect against overvoltage (Fortune Semiconductor Corporation, 2009).

Charge Control Integrated Circuit (IC)

From a boost-buck converter, a charge control integrated circuit (IC) for lithium ion batteries must be used to protect and monitor the battery when charging and discharging. The IC should accept a 4.2V input and should output 4.2V and a current at approximately 1A to charge the batteries safely. The charge control circuit consists of the Texas Instrument BQ24278 lithium-ion battery charging chip in a QFN-24 package and an external application circuit. This chip is designed to be able to charge a single-cell li-ion battery and also power a source directly, but for this project's application of charging a battery, the power path management is not needed. The BQ24278 protects against overvoltage, has a programmable charge current control to protect against overcurrent, provides thermoregulation protection, and battery short-circuit protection. The chip operates within a range of 4.2-10V and in our application we determined to set the input to 7V. The chip also allows a battery to be charged up to a maximum of 2.5A and in this project we set the current to 1A for safety reasons.

Internally, the BQ24278 contains a DC-DC converter with PWM logic which controls the output voltage to the battery (and source if it were connected). It also operates using multiple voltage comparators to regulate the charge. Each of the 24 pins on the chip have specific functions to ensure proper charging of a li-ion battery. The datasheet for the BQ24278 can be found in Appendix B and was used to make design decisions and calculations to properly charge the batteries that are included in section 5.3.2.

	Input	Output
Voltages	4.2-10V	4.2V
Currents	1-2.5A	0.55-2.5A

Table 6.2: BQ24278 Charge Control IC Inputs and Outputs

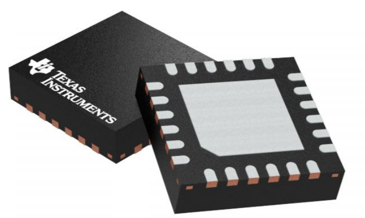

Figure 6.4: BQ24278 Charge Control IC

To implement the IC, we followed the suggested application circuit diagram found in the BQ24278 data sheet and can be seen in Figure 6.5 below:

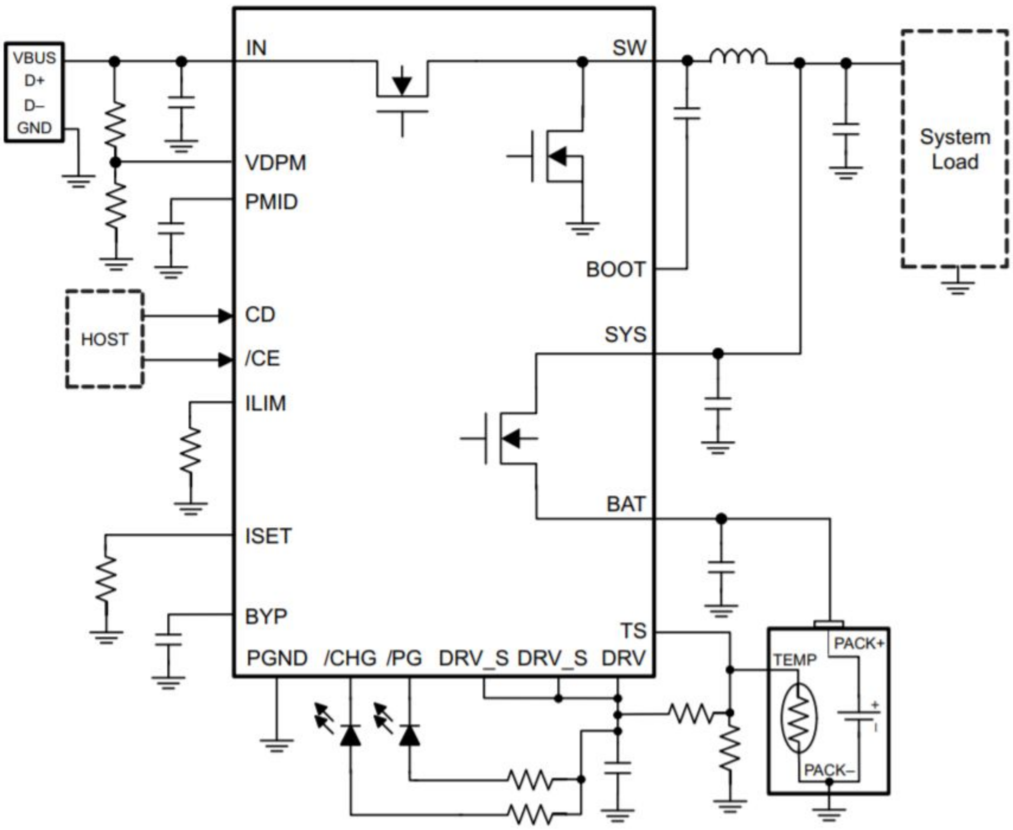

Figure 6.5: BQ24278 Typical Application Circuit

Boost-Buck and Boost Converters

From the input devices, the voltage has a range which needs to be controlled to one output voltage to be compatible with the rest of the charging circuit. The output from the generator ranges from 1.5-36V, depending on bicycle speed, with the average bicycle speed of eight mph, giving an expected output voltage of about 21V. The output voltage from the solar panel ranges from 5-19.7V. To find an applicable boost-buck converter, it needed to cover the range of 5-19.7V. Table 6.3 displays the inputs and outputs of a DROK boost-buck converter. The output voltage needs to be 4.2V for the charge control IC to function properly and can be set to that voltage by using the The design parameters of the input devices fit within the confines of this boost-buck converter. This boost-buck converter can be seen in Figure 6.6.

	Input	Output
Voltages (DC)	5-32V	1.25-20V
Currents	4mA-8A	0.2-5A

Table 6.3: Boost-Buck Converter Inputs and Outputs

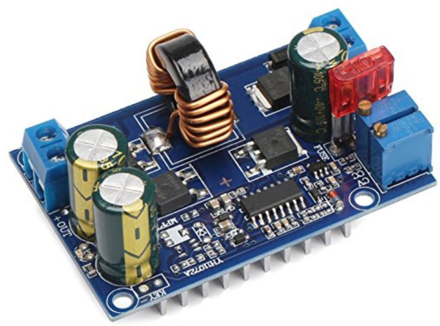

Figure 6.6: DC/DC DROK Automatic Boost Buck Converter

On the output end of the system, a boost converter is necessary to increase the output voltage of the batteries, 3.7V, to the load voltage of 5V. A DC/DC eBoot Module XL6009 boost converter's specifications are shown in Table 6.4. The voltage and current requirements of the system falls within this boost converter's inputs and outputs so it shall function well in the circuit. The boost converter can be seen in Figure 6.7.

	Input	Output
Voltages	3-30V	5-35V
Currents	0.01-4A	0.01-4A

Table 6.4: Boost Converter Inputs and Outputs

Figure 6.7: DC/DC Boost Converter Module XL6009

6.2.3 Output Load

The LED lighting module is the output load of the final system. To maximize the system requirements, the current draw of the LED light should be as small as possible while maintaining the 250 Lux specification from our study. The energy saving LED light below draws 5V, 40mA which allows the user to use the light without recharging the battery for a couple days in case the user forgets to recharge the battery.

Figure 6.8: USB Light
(Amazon, n.d.)

6.3 Electrical Testing

6.3.1 DC-DC Converter Testing

The boost buck and boost converters were bought as a premade device, but we performed testing on each device to ensure that it would work properly in our overall system.

To test the boost buck converter, we used a DC supply and a load on the output side of the boost buck converter to simulate the input and output conditions of the device once implemented in the overall system. Figure 6.9 shows the boost buck converter being tested without a load to set the output voltage to be 5V.

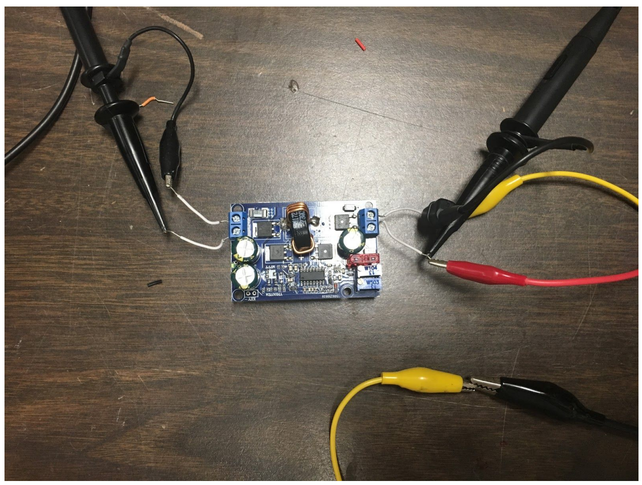

Figure 6.9: Boost Buck Testing

Figure 6.10 shows the input voltage that the boost buck converter will see from the source and the output voltage that the charge control circuit will experience. With an input of 1.6V, the circuit will see approximately 5V. This means that the boost buck converter works properly.

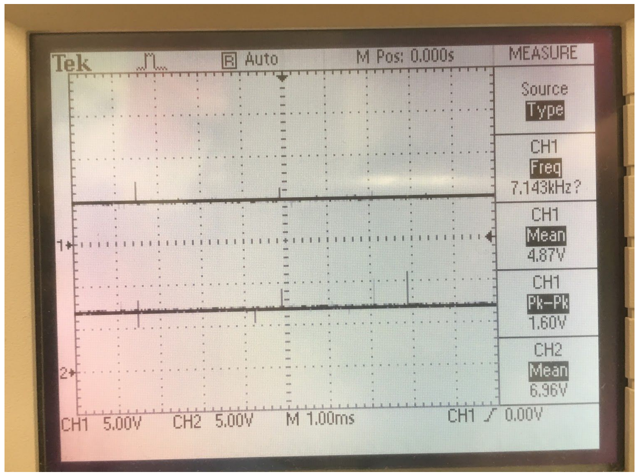

Figure 6.10: Voltages of the Input and Output for the Boost Buck Converter

To test the boost converter, we used a DC supply and a load on the output side of the boost converter to simulate the input and output conditions of the device once implemented in the overall system, just as we tested the boost buck converter. Figure 6.11 shows the boost converter being tested without a load to set the output voltage to be 5V.

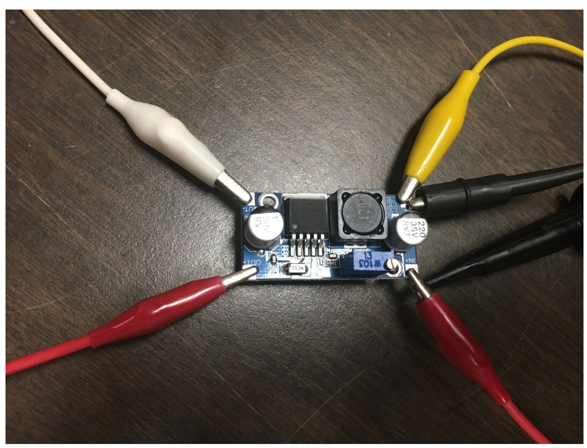

Figure 6.11: Boost Converter Testing

Figure 6.12 shows the input voltage that the boost converter will see from the battery and the output voltage that the load will be subjected to when the 5V load is attached. This means that the boost converter works properly.

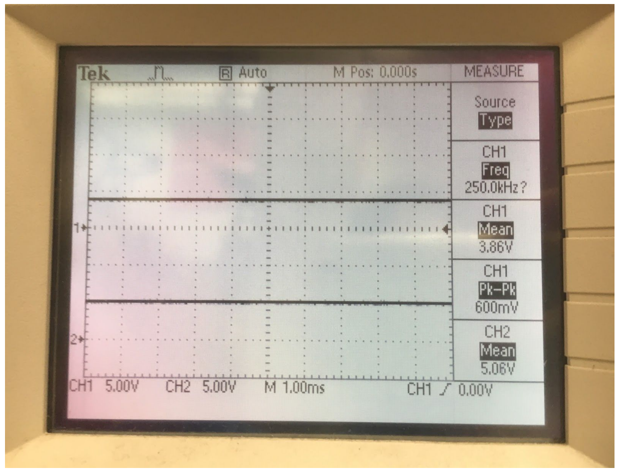

Figure 6.12: Voltages of the Input and Output for the Boost Converter

6.3.2 Filtering Circuit and Filtering Issues

When using a low-impedance source such as the generator used in this project, inductive reactance is taken into account when filtering the signal. The generator produced a low frequency, full wave rectified DC signal that needed to be filtered with a capacitor to smooth the peaks of the wave. The output of the generator can be seen in Figure 6.13 where the yellow line indicates the waveform where the ripples and peaks of the signal are shown.

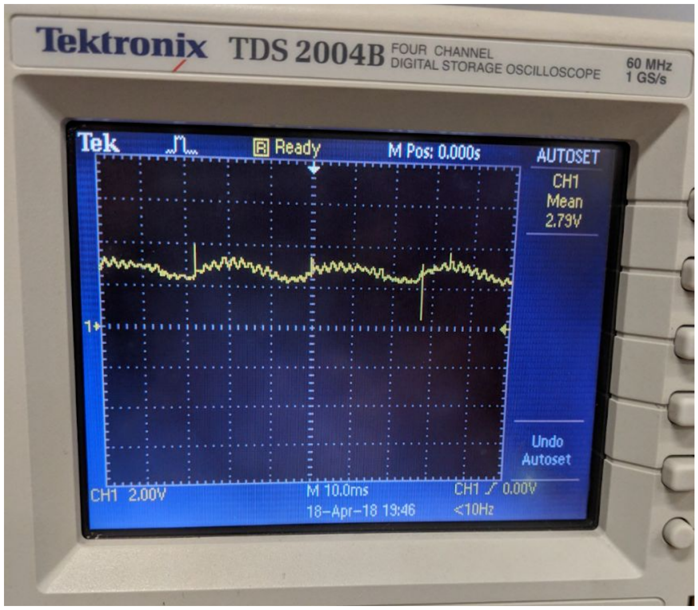

Figure 6.13: Unfiltered Signal of the Generator

In terms of efficiency, the use of an inductor-capacitor filter makes for less power loss due to the inductive reactance of the inductor component XL. Since the inductive reactance is equivalent to $2\pi fL$, when the input is at a low frequency, this makes for a significantly lower DC impedance than a circuit with just a resistor. As far as filtering, inductors in series naturally resist AC components and (ideally) allow DC to pass. When in combination with the capacitor placed across the load, this makes for a greater level of filtering to remove the AC components than a resistor and capacitor would have (All About Circuits, n.d).

Even though using a resistor in series with the diode and capacitor accounts for the I^2R losses which equates to power losses and lower efficiency, we chose this filtering design since an inductor component would be too large to fit into the designed generator case and also needs a large heat sink. The resistor design is sufficient to filter our generator signal as seen in Figure 6.14 which the peaks and ripple smoothed to a filtered DC signal.

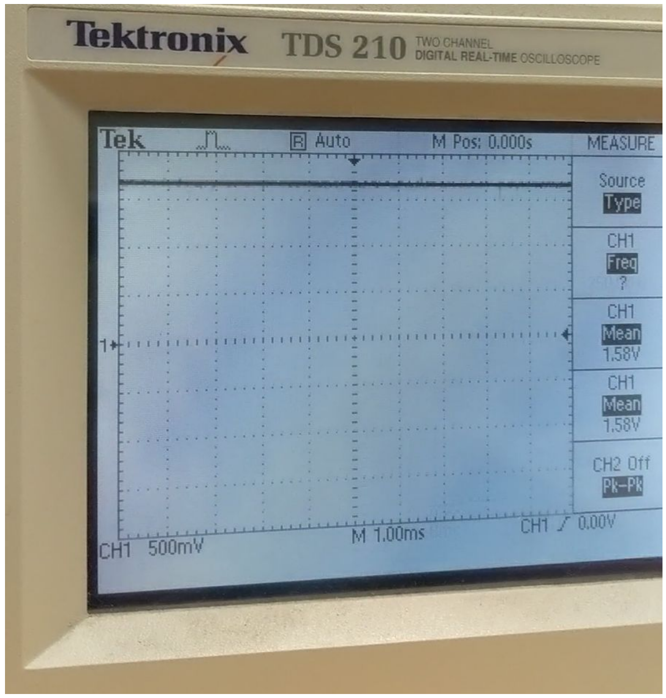

Figure 6.14: Filtered Signal of the Generator

The circuit consisted of a 30V, 5W rated zener diode in order to prevent current flowing back into the source in case the generator were spun counterclockwise instead of the designed clockwise rotation. It also limits the amount of voltage on the circuitry to 30V. The 50V, 100µF capacitor is used to help filter the peaks of the incoming signal and a small resistor is connected in series to create a first order filter. The prototype of this filter can be seen in Figure 6.15 with the green wires leading to the positive and negative output terminals of the generator.

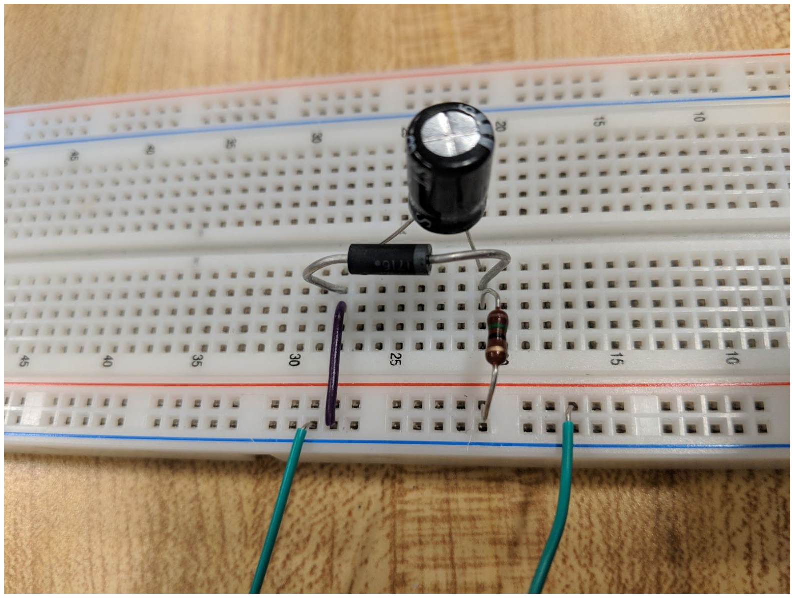

Figure 6.15. Prototype Filtering Circuit

In addition to the prototype on the breadboard, an ExpressPCB design was created to fit in the space behind the generator in the generator's case, as seen in Figure 6.16. This board has the holes for the resistor, capacitor, diode, and the female USB-A output to be soldered onto the board. It also includes a heatsink for the zener diode since it may become hot.

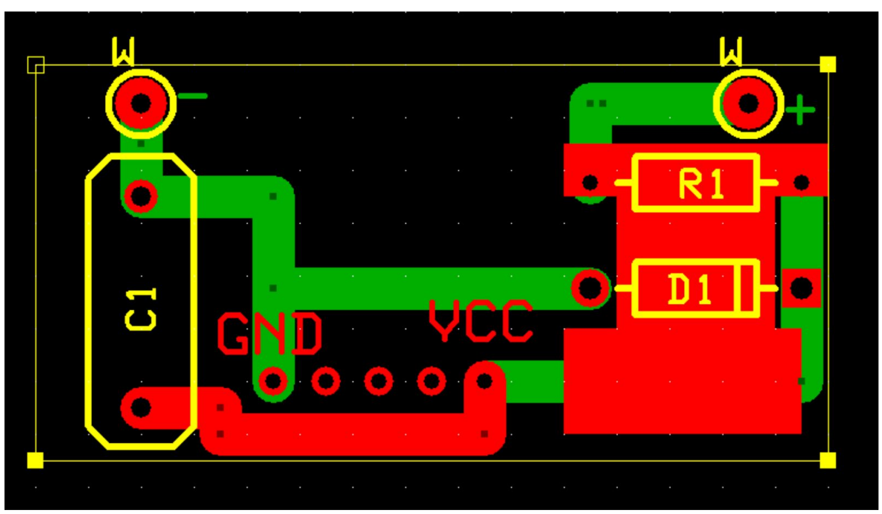

Figure 6.16. ExpressPCB layout of the filtering circuit and pins of USB outputs

6.3.3 Charge Control Circuitry

Calculations

To set the limit of the input current, set the charge current, thermistor thresholds, and select the correct inductor based on thermal analysis. In this section, all the necessary calculations for part selection will be explained.

Setting the input current limits the amount of current allowed into the circuit. The equation for the resistor setting is seen below:

$$R_{ILIM} = \frac{K_{ILIM}}{I_{IN\_LIM}}$$

Since the charge current is specified to be 1A, the limit should be at a slightly higher current. Using the value of K_{ILIM} from the datasheet that on average is 251AΩ and the limiting current of 1.66A, the resistor value implemented in the circuit is 150Ω.

Setting the input charge current requires a specific resistor value that is calculated using the following equation which is similar to the input current equation:

$$R_{ISET} = \frac{K_{ISET}}{I_{CHARGE}}$$

K_{ISET} is on average 490AΩ according to the datasheet, and the desired charging current is 1A which speficies the resistor to be 490Ω.

The system regulates charging also by checking if the source voltage is at a high enough level to charge the batteries. The V_{IN_DPM} is the dynamic power management input voltage. At the selected V_{IN_DPM} level of 4.8V, VDPM pin maintains 1.2V. This pin is checked and when 1.2V is read, the system is aware that the voltage of the source has dropped to a lower voltage that isn't capable of charging the batteries. When the pin voltage is higher than 1.2V, normal charging conditions continue. With the programmable V_{IN_DPM}, a resistor divider is implemented to correspond to the 1.2V on the VDPM pin. The equation to find the corresponding top resistor value is seen below:

$$RTOP = \frac{10k\Omega \times (V_{INDPM} - V_{DPM})}{V_{DPM}}$$

V_{IN_DPM} is the programmable threshold for the input voltage from the source. Since we chose the voltage to be set at 4.8V to allow the source to allow voltages from 4.8-10V. V_{DPM} is pin voltage threshold that averages 1.2V according to the datasheet. Using this information, the value of the top resistor of the voltage divider is calculated to be 30kΩ.

The BQ24278 allows for thermal regulation using a NTC thermistor. A 10kΩ thermistor was selected and based its datasheet values found in Appendix C, highlighted in yellow, the values for the R_{COLD} and the R_{HOT} values were found to be used to calculate the resistors of the NTC voltage divider, R_{LO} and the R_{HI}, whose equations can be found below:

$$RLO = \frac{V_{DRV} \times RCOLD \times RHOT \times \left[\frac{1}{V_{COLD}} - \frac{1}{V_{HOT}}\right]}{RHOT \times \left[\frac{V_{DRV}}{V_{HOT}} - 1\right] - RCOLD \times \left[\frac{V_{DRV}}{V_{COLD}} - 1\right]}$$

$$RHI = \frac{\frac{V_{DRV}}{V_{COLD}} - 1}{\frac{1}{RLO} + \frac{1}{RCOLD}}$$

From the calculations, R_{LO} is 8.6kΩ and the R_{HI} is 4.3Ωk.

The values of V_{COLD} and the V_{HOT} were calculated using the equation below with V_{DRV} is 5.2V in accordance with the datasheet value.

$$V_{COLD} = 0.60 \times V_{DRV}$$
$$V_{HOT} = 0.30 \times V_{DRV}$$

The warm and cool thresholds are not independently programmable and are the thresholds where the monitor whether to reduce the charging voltage is reduced by 140mV with V_{WARM} and the charging current reduced fifty percent with V_{COOL} to protect the batteries. The equations for these resistance thresholds can be seen below and R_{COOL} was calculated to be 18.7kΩ and R_{WARM} is 4.1kΩ.

$$RCOOL = \frac{RLO \times 0.564 \times RHI}{RLO - RLO \times 0.564 - RHI \times 0.564}$$

$$RWARM = \frac{RLO \times 0.383 \times RHI}{RLO - RLO \times 0.383 - RHI \times 0.383}$$

An inductor is needed for the buck power stage and is suggested to be a 1.5µF or 2.2µF inductor. To select the properly rated capacitor, the peak current and the temperature rise must be accounted for to ensure safety by not overheating the capacitor. The equations for this can be seen below:

$$I_{PEAK} = I_{LOAD(MAX)} \times \left(1 + \frac{\%_{RIPPPLE}}{2}\right)$$

$$I_{TEMPRISE} = I_{LOAD} + D \times)I_{PEAK} - I_{LOAD})$$

I_{PEAK} is to find the current rating of the inductor which was determined to be 1.575A when the lad current is at 1.5A and the rippled percentage is 10%. $I_{TEMPRISE}$ evaluates the thermal analysis and was found to be 1.515A based off of a duty cycle of 0.1. The inductor was still rated at these values even though we are not directly connecting a source to the source output on the BQ24278 to account for the buck power mode.

The components with the appropriate values were implemented in the charge control circuit and the completed circuit diagram can be seen in Figure 6.17.

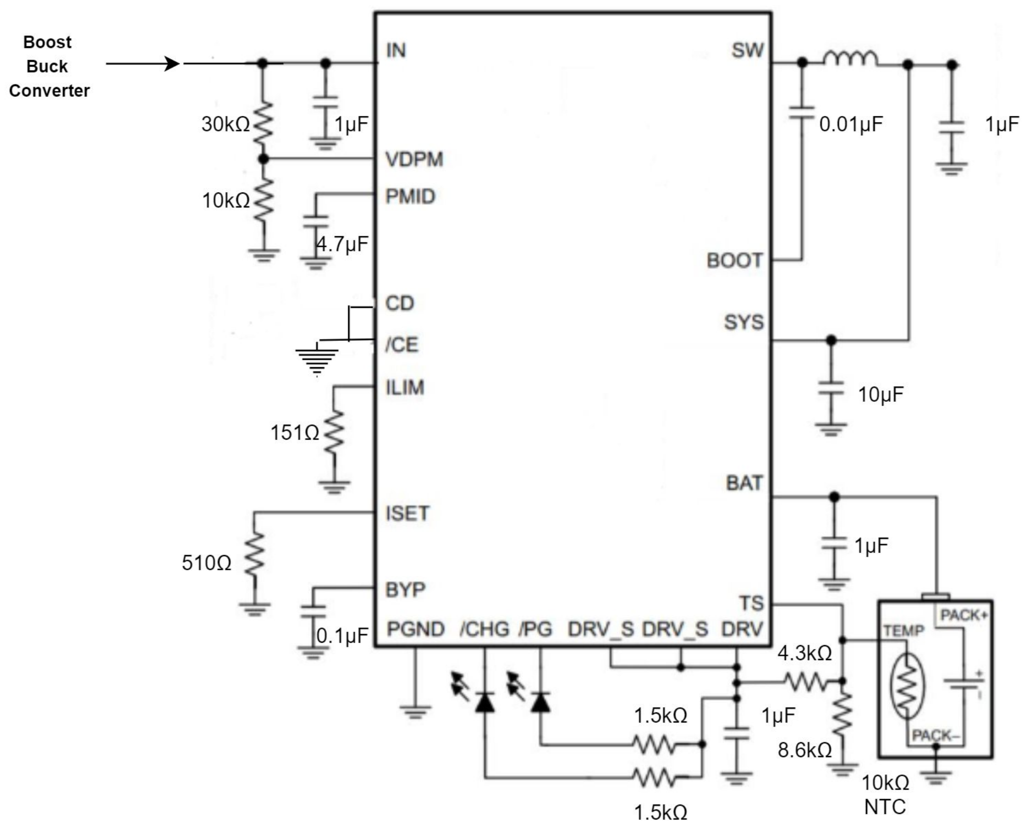

Figure 6.17: Charge Control Implemented Design Circuit

6.3.4 Issues with the Circuit and Debugging

Once the circuit was wired on the breadboard, it was tested using a DC supply and only one 18650 slightly discharged lithium-ion battery at 3.3V. The source was set to 7V DC with 1.5A. When turned on, the source briefly read that the battery was being charged at 0.98A and the voltage across the battery was increasing from the initial 3.3V. Unfortunately, within a few seconds, the source dropped to providing 0.03A and the BQ24278 chip was burning hot.

The assembled external circuit and the BQ24278 is seen in Figure 6.18. This corresponds to the application circuit schematic previously seen in Figure 6.17. The right side view and the left side view give a closer up image of the wiring and can be seen in Figure 6.19 and Figure 6.20.

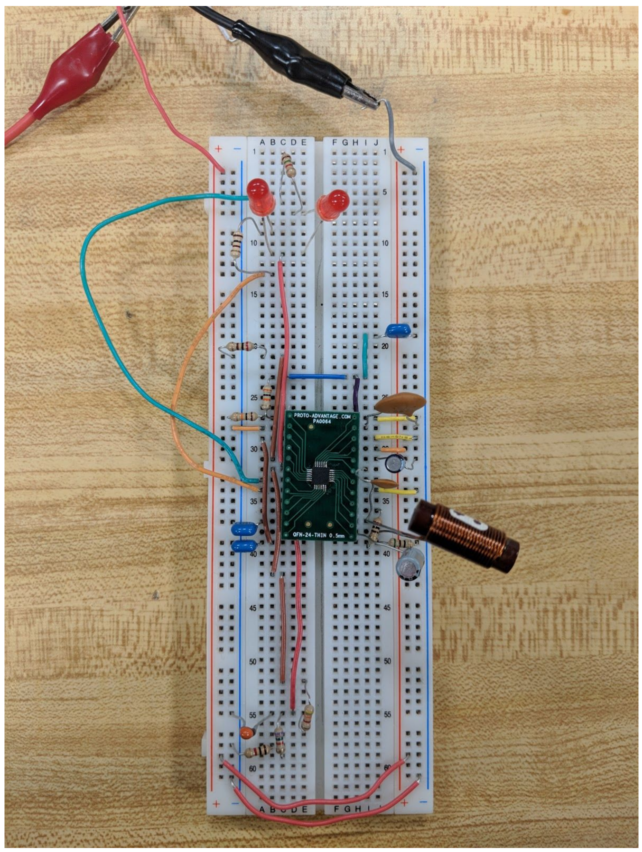

Figure 6.18: Top Down View - Full Integrated Charge Control Circuit

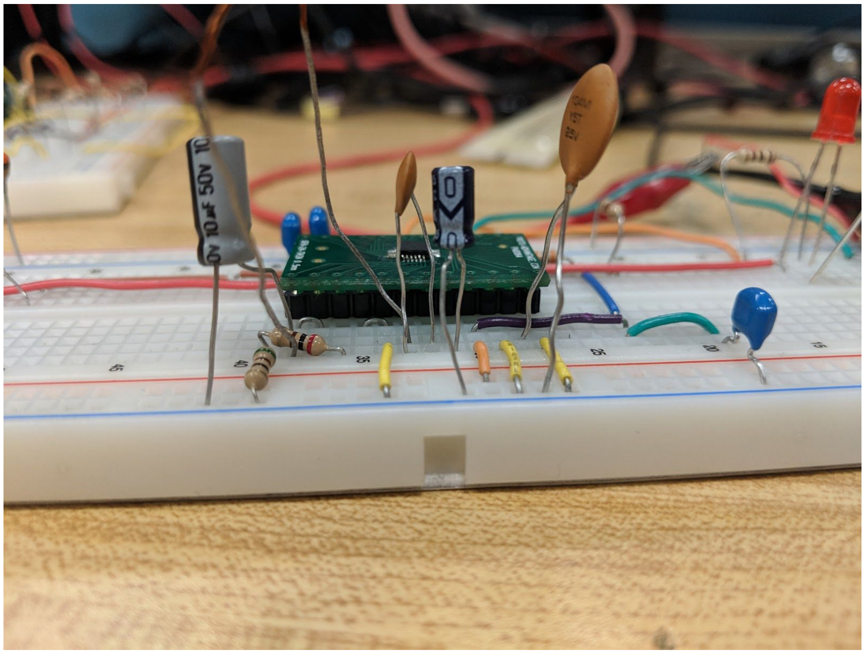

Figure 6.19: Right Side View - Full Integrated Charge Control Circuit: Pins 13-24

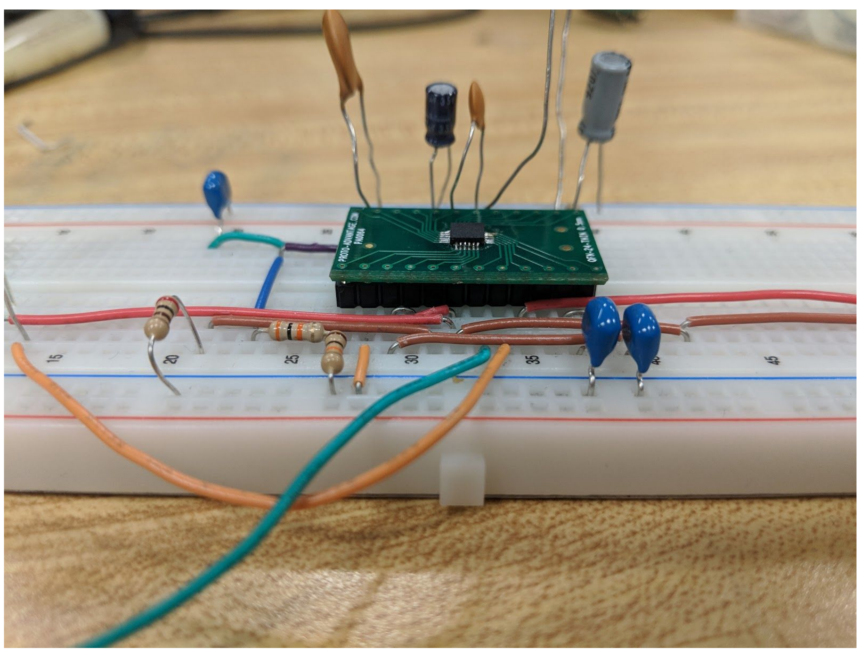

Figure 6.20: Left Side View - Full Integrated Charge Control Circuit: Pins 1-12

The remainder of this section documents the testing of the BQ24278 and its surrounding external circuitry and the status of the circuit. Using the datasheet, BQ24278 TI blog discussions, and previous circuit knowledge, different components of the circuit were replaced, values were re-calculated, and individual pins had their voltage and currents tested. Table 6.5 shows the debugging procedures in order to try to find out what in the circuit was causing the battery to not be properly charged, the rationale for each debugging procedure, and the outcome of procedure.

Debugging Procedure	Rational - Outcome
Checked circuit for proper wiring/grounding	Missed or erroneous connections could cause the circuit to not work properly and the datasheet calls for two grounding planes - The connections were examined and proved to be correct and the grounding was proper.
Re-calculated values of resistors	With incorrect values, the circuit could receive too much or too little current or voltage - Some values were found to be incorrect and were replaced with correct values as seen in the previous calculations. This changed the voltage on a few pins (like V_{DPM}) but the circuit still did not properly charge.
Tested with different resistors for V_{DPM} voltage divider	Different valued resistors could be used for R_{TOP} to set the threshold value of V_{DPM} depending on what voltage was desired to put the chip into slow-charging mode - The best value that produced the desired 1.2V was a 30kΩ resistor at an input voltage of 7V, but the circuit still did not properly charge. This did increase the current from 0.03A to 0.08A during the initial change.
Tested with higher valued capacitor on SYS pin	The datasheet suggested using between a 10-47µF capacitor and initially a 10µF was implemented - The capacitor was changed to 30µF and there was no change in the circuit and it still did not work properly.
Changed I_{LIM} and I_{SET} values	These currents are the maximum current that could come in through the IN pin and one was the current that charged the batteries - Initially, the current for I_{LIM} was at 2.5A and I_{SET} was at 2A. It was changed to 1.66A an 1A, respectively, by changing the resistor values that can be seen in the above calculations. It was ensured that I_{LIM} was a higher current than I_{SET} to allow the battery to charge. The circuit still did not work properly.
Toggled CE and CD pins from low to high	These pins resets the charging cycles of the battery and the circuit - The pins were toggled from low to high, but it did not affect the circuit.
Tested voltage at V_{DRV}	V_{DRV} is expected to be around 5.2V to be able to run the internal and external circuitry such as the LEDs - V_{DRV} ranged from 5.2 to 5.3V so it was at the right voltage.
Tested voltage at V_{DPM}	V_{DPM} is expected to be $0.5V_{DRV}$ according to the datasheet - Depending on the previous changes made to the circuit, this pin was at 2.6V but in some test cases the voltage was as low as 1.7V. Even at the correct expected voltage, the circuit did not work properly.
Tested battery charging currents	The DC source displays the current into the circuit, but it did not mean that the battery was seeing all of the current - The current was tested by using a multimeter, but 0A were recording charging the battery.
Tested battery charging voltages	The voltage across the battery should increase when it is being charged - In different cases, the battery voltage increased (one case, from 1.87V to 2.3V) and in a few cases the battery voltage decreased (3.34V to 3.28V) depending on changing around the circuitry.
Tested different batteries	Differently drained batteries cause the chip to charge in different ways according to the datasheet (ex. deeply discharged batteries charge at 50mA) - To check if the battery affected the charging current, a deeply discharged battery at1.87V and a slightly discharged battery at 3.3V were separately tested. The slightly discharged battery increased the heat of the chip to very hot while the deeply discharged battery did not. Current drawn ranged from 0.03 to, at best, 0.14A.
Tested different BQ24278 chip	After the first case of the battery charging, the chip became really hot, so it was possible that the internal MOSFETs could be damage and affect the rest of the circuit - With a new chip, there was no change in the circuit behavior and it still did not work properly.
Re-constructed circuit	In case wires, components, or the breadboard was damaged in any way, rebuilding the circuit could resolve any damage problems - The board was reconstructed twice after the initial board which create problems that were fixed by the debugging processes, but the circuit still did not work properly.
Read through BQ24278 TI blog discussions	Other users of this chip had issues with the charging process as well and their questions were answered by a TI employee, so all the blogs related to the BQ24278 were read - People had similar problems and properly wired circuit, but they expressed issues such as the chip overheating within a short period of time (10 minutes from one discussion) and not being able to properly charge afterwards. The answers from the TI employees were carefully read, and if any change to our circuit could be made, such as increasing the SYS capacitor, it would be implemented and tested. These are all included in the previous debugging procedures and the circuit still would not work properly.

Table 6.5: Debugging Procedure, Rationale, and Outcomes of the Charge Control Circuit

Figure 6.21 shows the charge control circuit's input voltage and the highest current input that was possible throughout the debugging process.

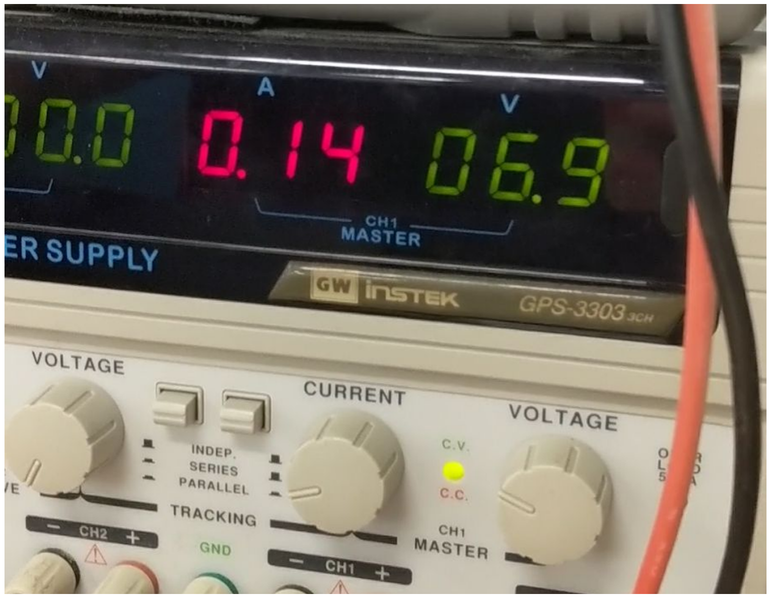

Figure 6.21: Input Test Voltage and Current Drawn at the Highest Current Level

The pins PG and CHG were also visually tested every time since the pins are used with an LED indicator. The PG and CHG pins indicate a valid input source is connected to the circuit and indicates a new charge cycle, respectively. During testing, we tested this by disconnecting the input source which turns of the LED indicator connected to PG. With the source connected between 4.2 and 9.5V, the LED remains on. When the source's voltage is less than 4.2, the LED is off. A summary of the statuses can be seen in Table 6.5.

Input Source Status	**LED State**
On, Voltage = 4.2-9.5V	ON
Off, Voltage = 0	OFF
On, Voltage < 4.2	OFF

Table 6.6: Input Source Status on Pin IN and the Corresponding LED State

The CHG pin was tested by connecting and disconnecting the battery from the system. With the battery connected with the input source on at 7V, the LED is on. When the input source is turned on at 7V with the battery disconnected, the LED is off. These pins properly worked when the circuit was first charged at the 0.96A, but the reliability of the pins changed throughout the debugging procedure depending on what in the circuit was being changed or tested at the time.

The BQ24278 contains a small heatsink on the underside of the device, but we were unable to test increasing the size of the heatsink due to the chip being soldered on an adapter board with the heatsink unreachable.

In addition to the prototype on the breadboard, an ExpressPCB design was created as seen in Figure 6.22. This board has the layout of all of the components needed to complete the charge control circuit, including space for the BMS, the battery in the holder on the reverse side of the circuit, and the USB input and output pins that lead to and from the DC-DC converters.

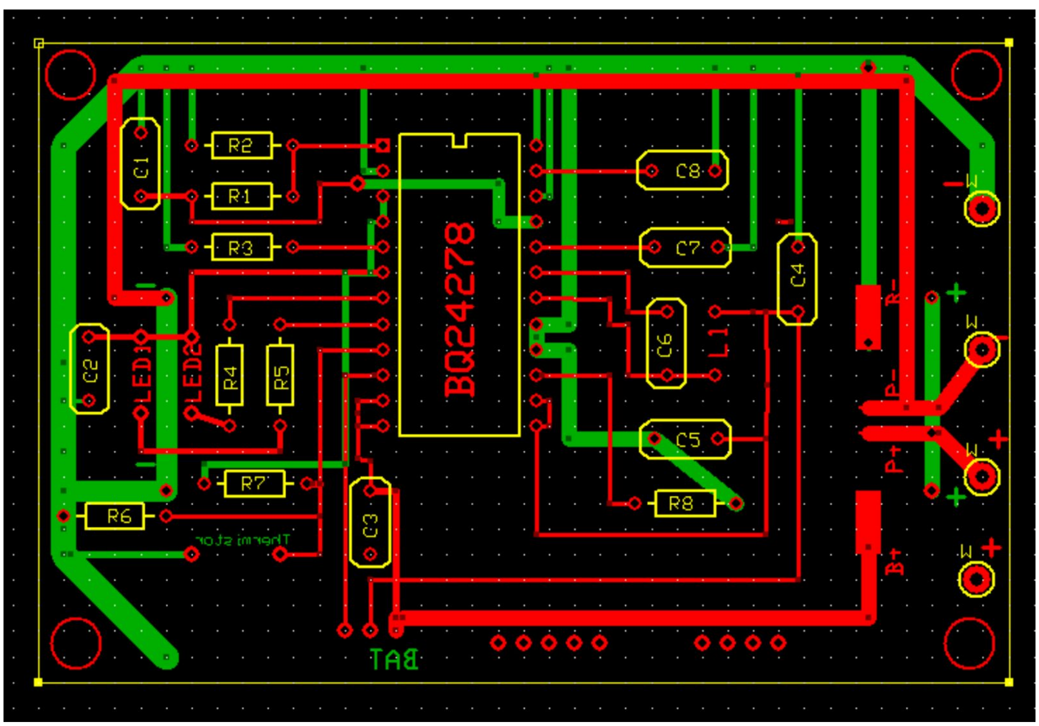

Figure 6.22. ExpressPCB Layout of the Charge Control Circuit, BMS, Batteries, and Pins for the USB Outputs

6.4 Results/Explanations/Interpretations

Both of the DC-DC converters were successfully tested, as well as the filtering circuit. In future iterations, a different circuit using an inductor as a filtering component can be implemented if a thermal analysis is executed and the space for the generator case increases. As for the charging circuit, the charge control circuit using the BQ24278 was not able to successfully charge the 18650 lithium-ion batteries. Even after extensive debugging and analysis of the circuit, the system was only able to charge a battery at a maximum of 0.13A, excluding the initial brief charge of 0.98A. Possibly reasons include the chance that both BQ24278 chips overheated quickly, the chip was stuck in a low charge mode, or a defect in the chip itself. The BQ24278 was not recommended for new designs due to an updated version of the chip with better capabilities such as having a charge current of up to 3A. There is no direct replacement for the BQ24278 and its specifications matched our system specifications, so we tried to use this chip. After further readings from the blog discussions, it appeared that many people who use this chip have issues, such as burning out the chip and the LEDs not functioning correctly.

7. Mechanical System Design Details

7.1 Introduction

This section elaborates the exact details of the mechanical system design from the components explained in the High Level Design section. It describes the parameters of each component and the exact devices implemented in the system. The components discussed in this section include the bicycle generator case, the mount for the generator case, and the battery case. The two main categories in these sections are the prototype product section and the prototype redesign section. The prototype section describes the prototype bicycle generator components, and the redesign section describes how the prototype should be redesigned and incorporated into a manufactured product.

7.2 Prototype Bicycle Generator Design

7.2.1 Bicycle Generator Case Design

As explained in section 5, the type of generator for that will be mounted on the bicycle will be one that works with a roller on the tire's sidewall. However, are still many factors to be considered before implementing a final generator design, such as the overall shape of the case. The shape of the generator may affect its performance and durability. As such, three different bicycle generator case designs were analyzed for their viability as a bicycle generator, as shown below in Figure 7.1. Each of these options were scrutinized for their advantages and disadvantages as shown in Table 7.1, and after review of each option, the best potential generator shape was chosen.

Figure 7.1: (From left to right) Generator Option 1, 2, 3, respectively

Body shape	Advantages	Disadvantages
Option 1	● Simple case construction ● Ease of manufacture ● Ease of prototyping with 3d printer	● Much of the moving shaft is exposed ● The edge of the case top might hit the bicycle's tire if the shaft is not long enough
Option 2	● Shaft is not exposed ● Case will not hit tire due to bottle shape	● More difficult to create prototype
Option 3	● Shaft is not exposed ● Roller will be closer to the tire	● Roller is not inline with motor, meaning gears would be required to transfer power to motor shaft, resulting in a wide case

Table 7.1: Generator Options Advantages and Disadvantages

After review of these factors for each case option, the team decided to go with Option 2, which is modeled off of a typical bicycle dynamo bottle generator. This option seemed to have the best potential for success due to its advantages of having a protected rotating shaft and a shape that will prevent the bicycle tire from rubbing on the case.

The main components of the prototype consist of the outer case body, two end caps, the roller shaft, the roller, the motor mount, the motor, and the shaft coupler, as labeled in the section view of the assembly in Figure 7.2. Some components of the full assembly were designed and manufactured by our team, while others were purchased. The components that we purchased for this assembly are the roller shaft, the bushing, the motor, and the various screws, nuts, and bolts used. The generator case and parts of the motor mount were designed and manufactured for our specific purpose. The completed prototype bicycle generator can be seen mounted on a bicycle in Figure 7.3 below.

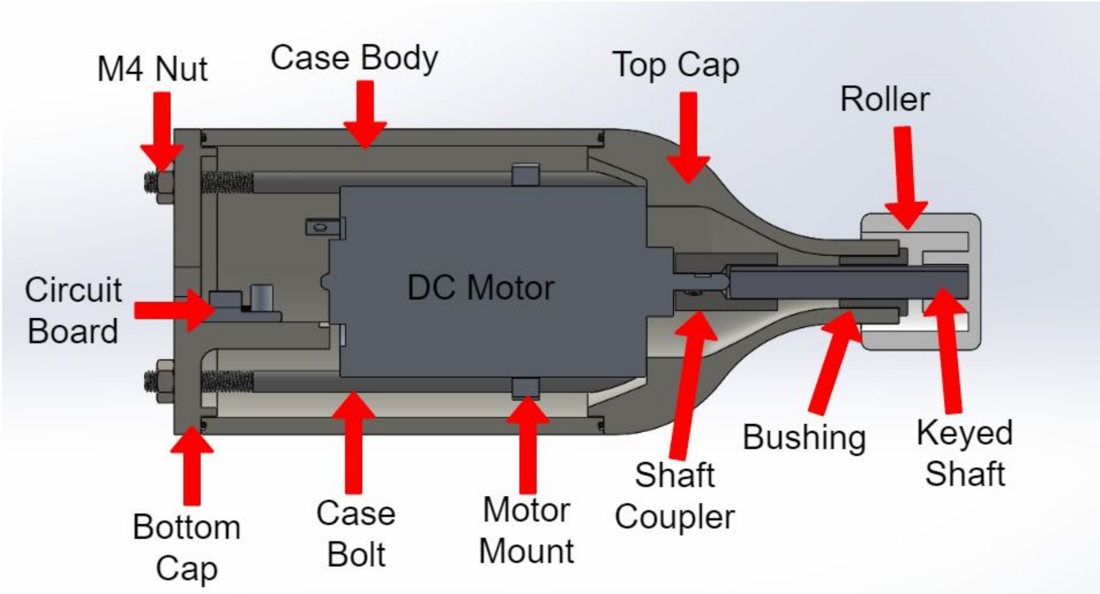

Figure 7.2: Section View of Prototype

Figure 7.3: Prototype Generator Mounted on Bicycle

The generator case was designed to be practical, simple, and modern. Size was taken into considerable consideration, as it was important that the generator fit on one of the rear stays of the bicycle without impeding the bicycle's normal operation, as described in the needs analysis table in Table 4.2. That is, the generator case had to be made large enough to fit the motor, but small enough as not to be hit as a rider pedals the bicycle.

To utilize the least amount of surface area possible to to keep cost down, the generator case body was designed to be cylindrical, as shown in Figure 7.4. The case itself is composed of three main parts: two pieces which act as end caps and the main cylindrical body piece. The two end caps serve different purposes; the top cap, shown in Figures 7.5 and 7.6, has a round opening designed to accommodate the roller shaft, which has the roller on its exterior end which makes contact with the bicycle's tire. Inside the cylindrical protrusion on the inner side of the lid is a bushing which allows the shaft to turn freely. Additionally, this end cap possesses a lip to prevent it from sliding around and has three holes to fit the bolts which hold the assembly together. The bottom end cap, as shown in Figure 7.7, has a rectangular cut out to accommodate the USB-A port that will accept a male USB-A cord that is the connection from the generator to the battery pack. It has a rectangular protrusion to hold the PCB which goes inside the generator case, and like the top cap, the bottom cap also has a lip to prevent sliding and has three holes for the bolts.

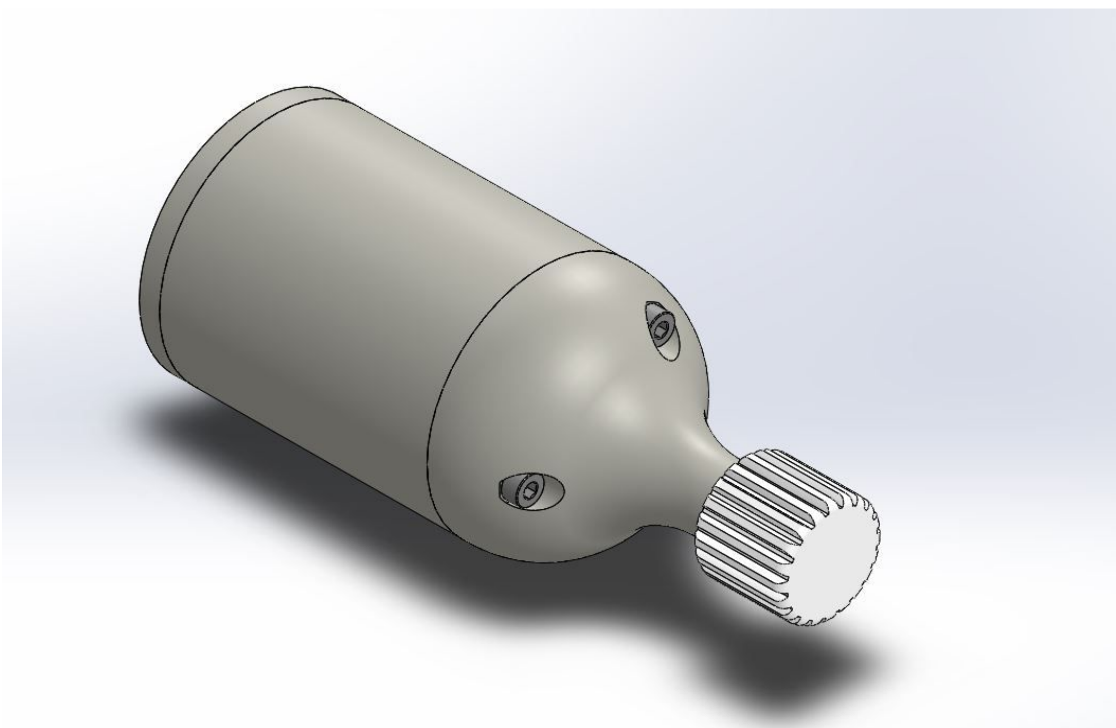

Figure 7.4: Full View of Prototype Generator Case - CAD Design

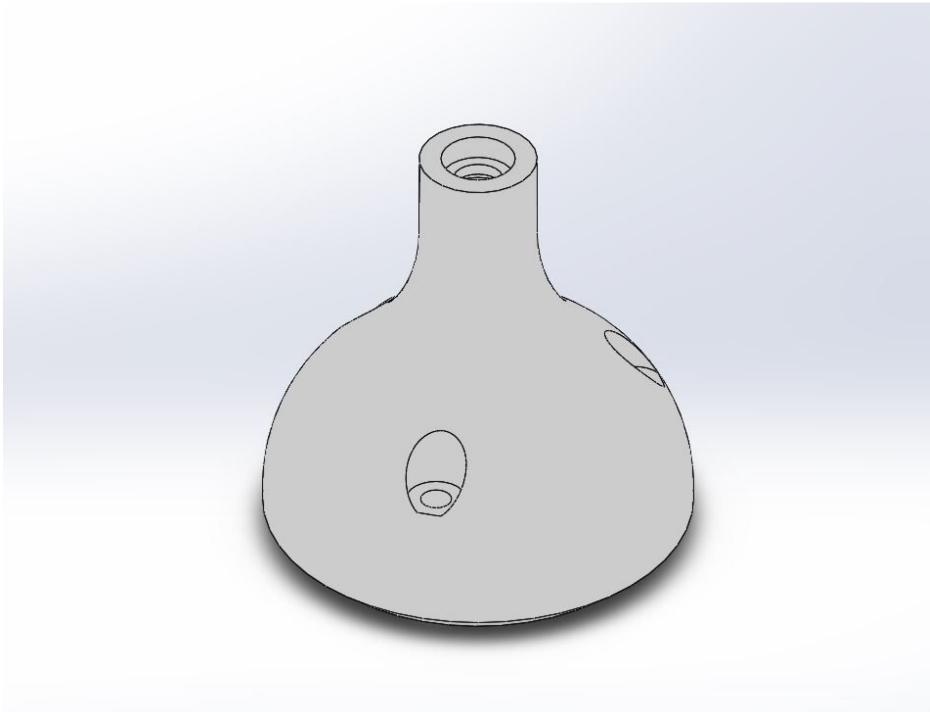

Figure 7.5: Full View of Top Cap - CAD Design

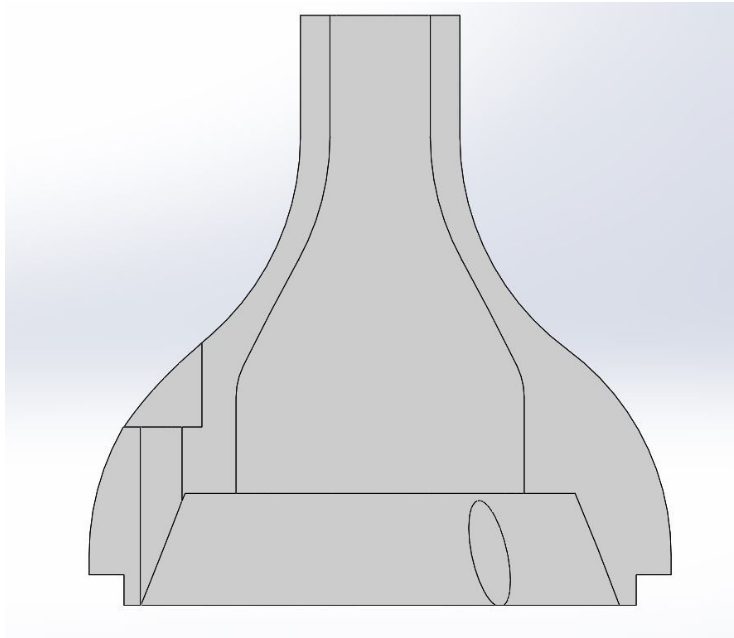

Figure 7.6: Section View of Top Cap - CAD Design

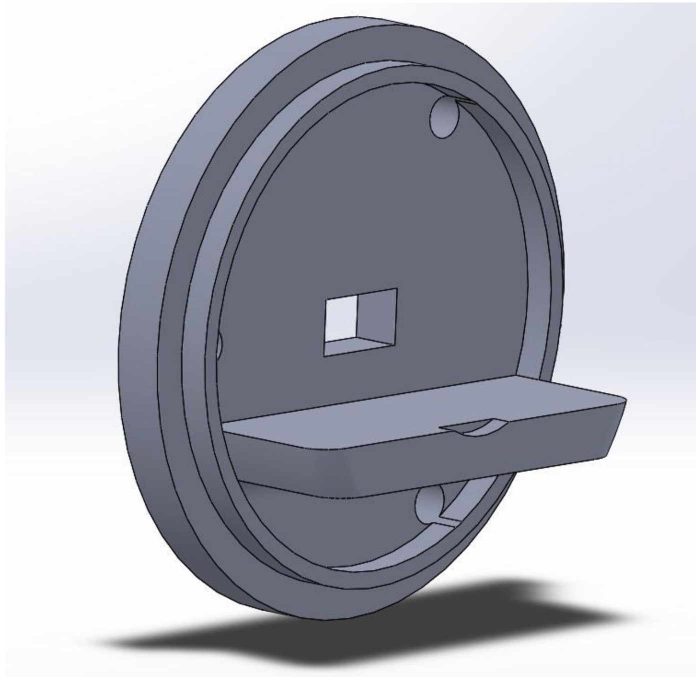

Figure 7.7: Bottom Cap - CAD Design

The motor mount is the final component of the assembly that would be specially manufactured for the generator design. The design is based off a standard clamping motor mount. Figure 7.8 shows our designed motor mount and presents the differences from a standard motor mount. Like a standard mount, our motor mount has a clamp function which becomes engaged upon insertion of a screw into the clamp. The three circular protrusions on the outer side of the clamp are where the three bolts fit to secure the motor mount, and subsequently the motor, in the case.

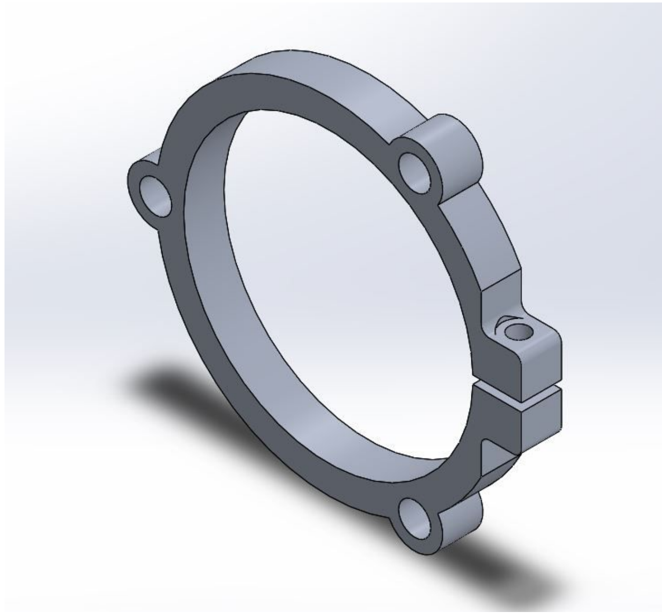

Figure 7.8: Motor Mount - CAD Design

7.2.2 Generator Bicycle Mount

The prototype generator mount, as shown in Figure 7.9 below, consists of two standard dynamo mounting brackets, two specially made 90° angle mounting brackets, one 4-inch bolt, two ¼-inch standard nuts, and one ¼-inch wing nut. The two standard dynamo brackets are mounted and tightened directly to the frame of the bicycle with the ¼-inch bolts they came with, and attached to those are the 90° angle brackets, shown in Figure 7.12. The bolt is inserted through the bottom 90° bracket, then the bottom mounting piece, shown in Figure 7.11, and a nut (not pictured) is placed on top of the bottom 90° bracket. Another nut (not pictured) is placed on the bolt, and the bolt is then inserted through the top 90° bracket, and the top mounting piece, shown in Figure 7.10, for the bicycle generator is placed on top of that. The last piece of the mounting assembly is the wing nut, which holds the top mounting piece in place and tightens the entire assembly to hold it together.

Typical standard bicycle dynamos have a spring-loaded or a swivel-type mount that allows the user to essentially turn the dynamo "on" or "off" by moving the dynamo's roller on or off the bike. In the "on" position, the roller is pressed up against the bicycle's tire to make it turn with the bicycle tire's movement, and the spring-loaded or swivel mount ensures that the roller stays against the tire. The prototype bicycle generator mount the team made was based on the swivel-type mount. The bolt acts as the pivot point for the bicycle generator so that the user can turn the generator "on" or "off" as desired. The wind nut tightened the generator so that it could not pivot out of place.

Upon testing the prototype generator mount, it was determined that while the bolt did allow the generator to properly pivot on and off of the bicycle tire, the roller was not properly held against the tire. The prototype mount design did not provide enough pressure on the generator to ensure that the roller made solid contact with the tire, and thus the roller did not turn properly when the bicycle tire turned. This meant that during testing, the generator had to be pressed against the bicycle tire to get the roller to turn to obtain data. The future design of the bicycle mount must be improved so that it provides more pressure on the generator, and therefore the roller, to hold it in place against the bicycle tire to get good contact between the two.

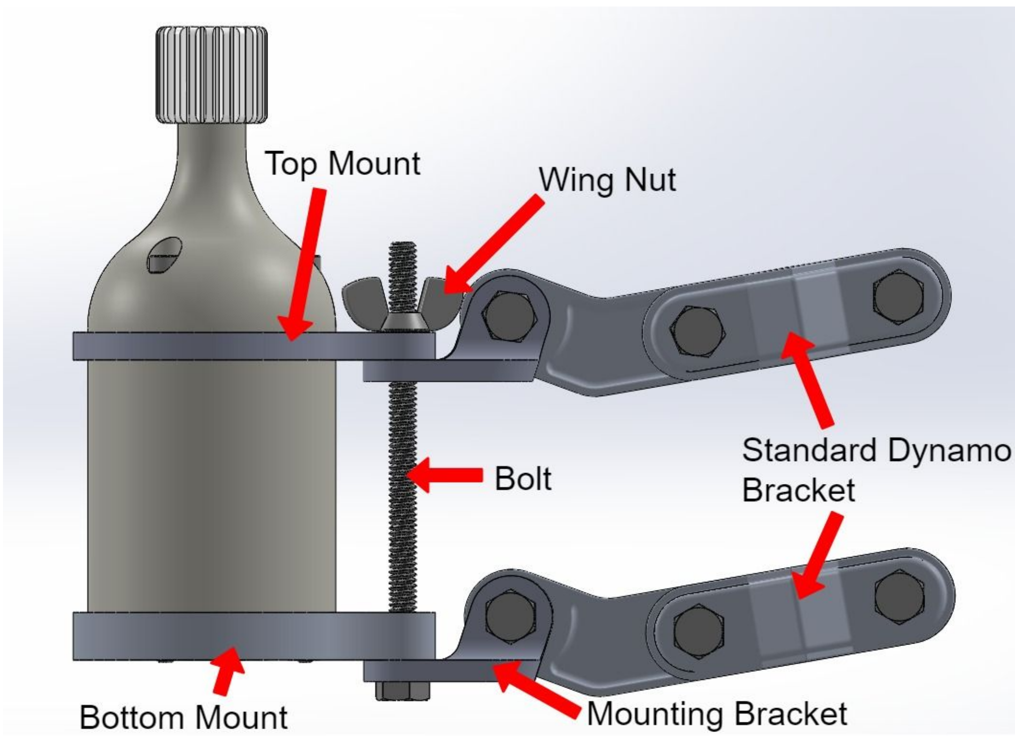

Figure 7.9: Mounting Assembly - CAD Design

Figure 7.10: Top Mount - CAD Design

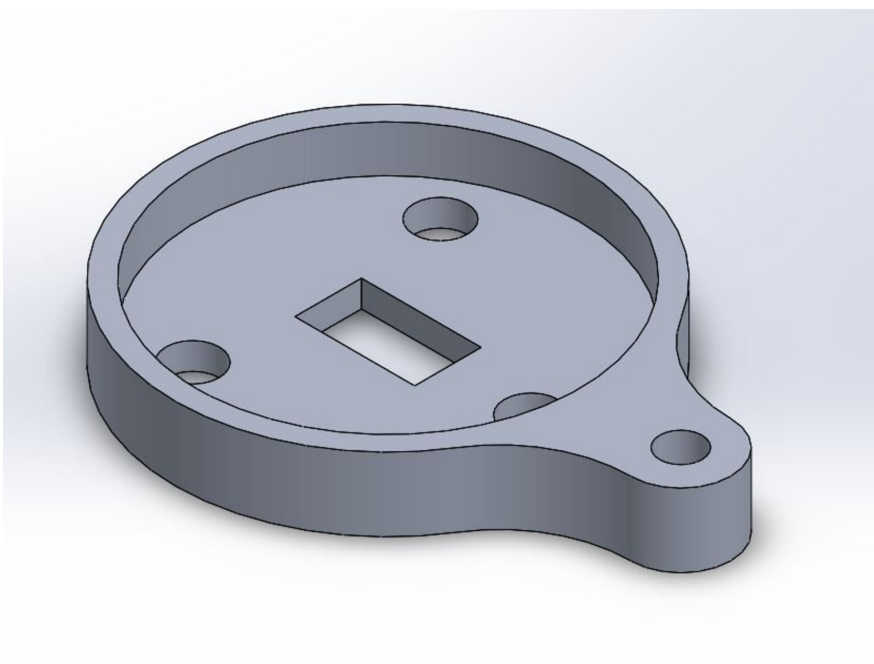

Figure 7.11: Bottom mount - CAD Design

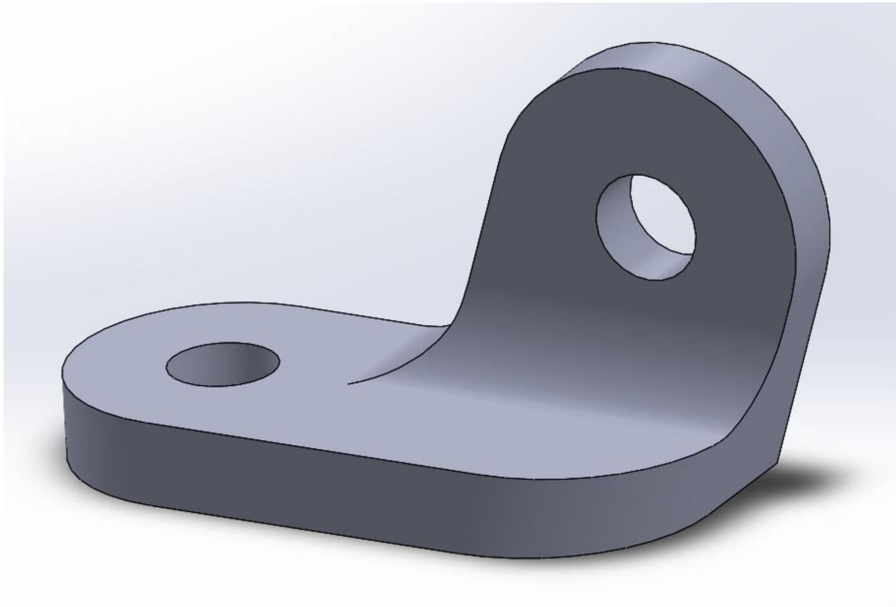

Figure 7.12: 90° Angle Mounting Bracket - CAD Design

7.2.3 Prototype Testing Results

The prototype bicycle generator was mounted onto the bicycle in order to test the actual output voltage that the motor was capable of. This test was performed by mounting the generator to the bicycle with the mounting brackets and putting pressure on the generator to ensure the roller made contact with the tire, as the prototype bicycle mount was insufficient to hold the roller to the tire properly. A piece of reflective tape was adhered to the tire in order to measure the tire's speed as the bicycle was pedalled while on the bicycle stand, and an oscilloscope was used to monitor the generator's output voltage. It was found that the generator did not produce the expected voltage; this was likely due to the slippage of the roller on the bicycle tire and the difficulties experienced during testing, which included difficulties in pedalling the bicycle at a steady speed and in getting a constant reading for the output voltage.

As seen in Figure 7.13 below, even though the actual output voltage from the generator was lower than expected, the generator still managed to produce about 30 volts while the bicycle was being pedalled at the leisurely pace of 8 miles per hour, which is more than enough to charge a battery pack. This means that the generator may actually produce too much voltage while bicycling at higher speeds, but the circuitry described previously in section 6 should ensure that the maximum voltage going into the circuit does not exceed 30 volts in order to protect the circuit components. The results of this test reveal that a motor with a slightly larger k-value could potentially be used in this application if lower voltages at higher speeds were desired.

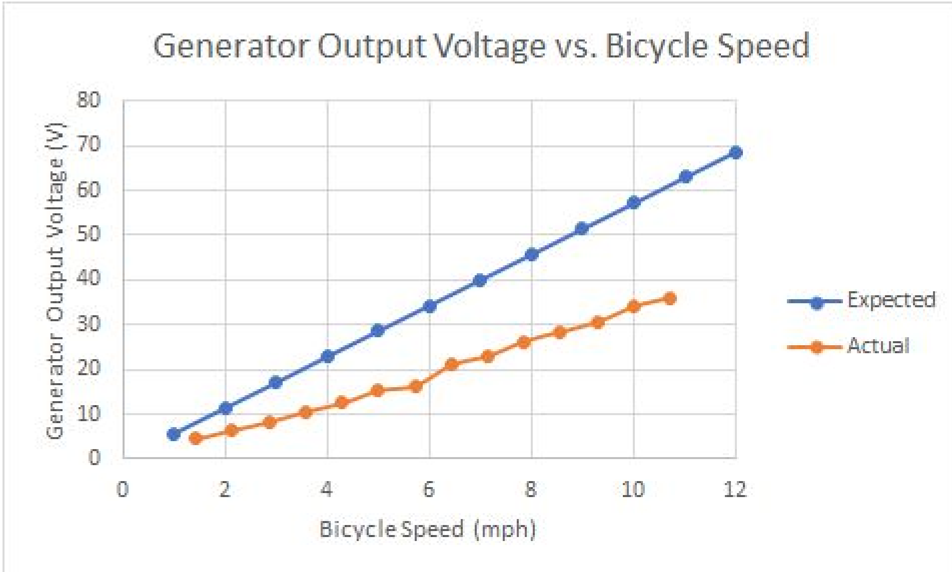

Figure 7.13: Expected and Actual Generator Output Voltages

7.3 Prototype Redesign Methods

7.3.1 Quality Function Deployment Analysis

The prototype was a means to start the redesign process and assess whether or not the prototype meets the consumer needs and whether or not it needs to be improved before being labelled as the final product. The redesign process began with a modified quality function deployment (QFD) analysis of the prototype bicycle generator. This type of analysis is carried out by engineers to assess how well a product meets customer needs, and to determine what can be done to a product to better meet those needs. A typical QFD analysis includes competitor products to determine how well a product might perform in the market, but since our team's product will not be going to market, we used a modified QFD analysis and left out competitor products.

The first step in conducting a QFD analysis is to assess the customer needs and to rank the needs according to their importance. The customer needs which relate directly to the bicycle generator, which in our case would be the user needs, are summarized and ranked below. The needs are ranked from 1 to 5, with a ranking of 5 meaning the need is of more importance to the user.

Customer Needs:

- **Safety.** We determined that safety should have a ranking of 5 due to the imperativeness of this factor. It is important that the generator be contained and operate in a safe manner and have a minimal exposure of moving parts to prevent injury. If the generator is unsafe to use, the customers will not want to use it.
- **Ease of Use.** We determined that ease of use should have a ranking of 5 based on our target users. It is important that the bicycle generator is easy to use in every manner, from mounting it on the bike, to adjusting its position on the tire, and to using it to charge the battery pack. It should also be a simple product to manufacture and assemble, as this will save money on production costs.
- **Waterproof.** We gave the waterproof factor a ranking of 4 for importance. It would be beneficial to have a device that is completely waterproof, but with the resources available to us it may not be possible to make a generator case that is 100% waterproof. Even if the device is not completely waterproof, it can still be used on days with good weather.
- **Dustproof.** Like the waterproof factor, we gave the dustproof factor a ranking of 4, because while a dustproof device would be beneficial, it is not completely necessary to the generator's function.
- **Durability.** The durability factor gets a ranking of 5 for importance. In the environment of rural Vietnam, there will not be a way to easily replace a bicycle generator that becomes broken, and needing to replace any parts or a whole unit will incur additional expense and might be difficult to do given the environment, so it is important to make a durable device from the start.
- **Aesthetics.** Aesthetics deals with the generator's appearance, and we determined that this factor should have an importance rating of 1. This device is set to be donated to its users, so its appearance will not be a large selling point. Trying to make the generator look more appealing might also add to its production cost.
- **Compact Size.** We determined that compact size should have an importance rating of 3. While it is important that the device be small enough to not interfere with the normal operation of the bicycle, the size of the generator is ultimately determined by the size of the motor used. Since we have limited access to small motors that produce enough voltage at low speeds, we are limited in the size of generator we can create.
- **Low Cost.** Low cost was given an importance rating of 5. Since this bicycle generator system will be donated to its users, it is important that it be of a low enough cost for the benefactor to purchase enough devices to then donate them to its users in Vietnam.

- **Long Life.** We determined that long life should have an importance ranking of 5, since it will be difficult to redistribute the bicycle generators due to travel costs. Long life is heavily related to other factors such as durability, and it is important that the bicycle generators be made to last, since there will be no maintenance options once they are donated to users.
- **High Power Generation.** We determined that power generation should have a ranking of 4 for importance. It is necessary to use a motor with enough voltage output to charge the battery pack, but the motor does not necessarily need to be powerful enough to charge the entire battery pack in one bicycle ride.

The second step in the QFD analysis is to review the customer requirements as explained above and to determine the corresponding quality characteristics that we as the design team can control to meet the customer requirements. The quality characteristics are ranked with either a 1, 3, or a 9 depending on how much a particular quality characteristic relates to a customer requirement. A rank of 1 corresponds with little to no correlation, a 3 is moderate correlation, and 9 is strong correlation. The controllable quality characteristics are shown summarized below.

Quality Characteristics:

- **Weight.** We can control the final weight of the product by controlling various factors during construction. The factors that contribute to the final weight are the power and the type of materials used to construct the case; the power contributes to the weight because of the motor size, and the material's density could lead to either a lighter or heavier case.
- **Volume.** The volume of the case is mainly controlled by the size of the motor, so this factor is related to the power we need to generate. A larger motor will generally generate more power, but it will also lead to a larger case volume.
- **Price.** The final price of the bicycle generator system can be determined by all the other quality characteristics of the design. For instance, using different materials will affect the price, as will choosing a different motor, because different motors have different costs, and the size of the motor will affect the size of the outer case, which will determine how much material will be needed to build the case.
- **Materials.** The material of the generator case greatly affects the case's durability, and it would also affect the final cost of the product. The material needs to be durable enough to withstand being dropped, but it also needs to be lightweight enough to not add an excessive amount of weight to the generator case.

- **Number of Parts.** The number of parts that the final bicycle generator has directly correlates with the ease of use for the product. Generally, the more parts a product has, the more complicated it is to use and maintain. More parts also contributes to a higher production and assembly cost. For these reasons, in the final product design, the team will aim to use as few parts as possible.
- **Case Shape.** The shape of the case relates to the aesthetics. Since the aesthetics of the generator case is not the most important factor to consider, the team will simply ensure that the case is functional and will not prioritize a pleasing shape in the design.
- **Power.** The power of the bicycle generator is controlled by choosing the motor size. Typically larger motor will generate more power at slower speeds, but using a larger motor will also make the generator case larger as well, which is undesirable.

The customer requirements and how the quality characteristics correspond with the requirements are shown below in Table 7.2. Table 7.3, below, explains how the prototype is rated compared to the customer requirements. Additionally, our goals for redesigning the prototype to better meet the customer requirements are shown in the table as well.

		Quality Characteristics						
		Weight	Volume	Price	Materials	Number of Parts	Case Shape	Power
Customer Requirements	Safety	1	1	3	9	3	3	9
	Ease of Use	1	1	3	3	9	3	3
	Waterproof	1	1	3	9	9	1	1
	Dustproof	1	1	3	9	9	1	1
	Durability	3	3	9	9	1	3	1
	Aesthetics	1	3	9	3	3	9	1
	Compact Size	9	9	3	3	3	3	1
	Low Cost	3	3	9	9	9	1	9
	Long Life	1	1	1	9	9	1	1
	High Power Generation	1	1	1	1	1	1	9

Table 7.2: Modified Quality Function Deployment Chart

Customer Requirement	Current	Plan
Safety	4	5
Ease of Use	3	5
Waterproof	2	4
Dustproof	2	4
Durability	3	4
Aesthetics	3	3
Compact Size	3	3
Low Cost	3	4
Long Life	3	4
High Power Generation	5	4

Table 7.3: Current Prototype Ratings and Future Plans

7.3.2 Boothroyd-Dewhurst Method for Design for Manufacturability

The Boothroyd-Dewhurst Method (BDM) is a tool used in design engineering that aims to improve a product and reduce its costs of manufacture within the constraints of the product's design features. Typically, reducing the cost of a product in its manufacturing phase is done by reducing the number of components the product contains. This can be done by redesigning parts by either combining two components which don't move relative to each other or by getting rid of nonessential components. The first step in the BDM process is to assess the required assembly time, whether it be manual assembly or automated assembly, by classifying each component of a product by its shape and then using a table to determine the estimated average assembly time for handling and insertion based on the component's shape. Then, by answering specific questions about each component, the designer can assess whether or not a component can be eliminated from the design. The three questions to ask of component are as follows, as taken from the textbook *Product Design for Engineers* (Shetty, 2016):

1) During operation of the product, does the part move relative to all other parts already assembled? Only gross motion should be considered.
2) Must the part be of a different material or be physically isolated from all other parts already assembled?
3) Must the part be separate from all other parts already assembled? If no, necessary assembly or disassembly would be impossible.

Generally, if the answer to any of the above questions is yes, the component is very likely essential to the product's design and cannot be eliminated. The design of the prototype bicycle generator was assessed using the BDM process to help improve its design. Each component of a product is given a number, and the highest numbered component is typically the piece of the product that gets assembled. This is the component that is first secured to the work space and onto or into which all other components are placed. A table of components for the prototype bicycle generator can be seen below in Table 7.4.

Number	Part Description	Dimensions (mm)	Quantity
1	Hex Nuts	7 diameter, 3 thickness	3
2	Bottom Cap	57 diameter, 5 thickness	1
3	Circuit Board	44 length, 24 width	1
4	Adhesive	-	1
5	Case Center	75 length, 57 diameter	1
6	Roller	22 length, 22 diameter	1
7	Motor Mount Screw	10 length, 2 diameter	1
8	Shaft Coupler Set Screw	5 length, 4 diameter	1
9	Outer Shaft	44 length, 6 diameter	1
10	Shaft Coupler Set Screw	5 length, 4 diameter	1
11	Shaft Coupler	19 length, 11 diameter	1
12	DC Motor	57 length, 36 diameter	1
13	Motor Mount	43 diameter, 5 thickness	1
14	Case Bolts	100 length, 4 diameter	3
15	Bearing	13 length, 10 diameter	1
16	Top Cap	57 diameter	1

Table 7.4: Prototype Generator Components List

To estimate the manual assembly time of the prototype bicycle generator, tables from the textbook *Product Design for Engineers* by D. Shetty were used, copies of which can be found in Appendix D. Each component, as labelled above, was examined and its alpha and beta shape values were determined, and these were then used to find the correct time estimate for the handling and insertion of each component in the assembly. As shown above in Table 7.4, the generator's Top Cap has the highest identification number, and so it is the first piece in the assembly. The assembly process for the prototype bicycle generator is as follows:

1) The Top Cap is fixed to the work surface.
2) The bearing is inserted into the appropriate end of the Top Cap.
3) The three case bolts are inserted into the appropriate holes in the the Top Cap.
4) The motor mount is slid onto the three case bolts.
5) In a separate space, the DC motor is held and the appropriate shaft coupler end is inserted on the motor's shaft.
6) A set screw is used to secure the shaft coupler to the motor's shaft.
7) The outer shaft is inserted into the second end of the shaft coupler.
8) The second set screw is used to secure the outer shaft in the shaft coupler.
9) The motor is slid into the motor mount until the outer shaft protrudes out of the Top Cap and the motor makes contact with the Top Cap wall protrusions.
10) The motor mount screw is used to secure the motor in place.
11) The roller is inserted on the protruding end of the outer shaft.
12) The case body is inserted over the inner components and held against the Top Cap.
13) The adhesive is inserted onto the back of the circuit board.
14) The circuit board is glued to the Bottom Cap's protrusion, ensuring the USB port is lined up with the corresponding cutout in the Bottom Cap.
15) The Bottom Cap is placed over the end of the Case Body, ensuring that the three bolts pass through the corresponding holes in the Bottom Cap.
16) The three nuts are screwed onto the ends of the three bolts, holding the entire assembly together.

With the current prototype bicycle generator, there are 16 manual assembly steps. Table 7.5 below summarizes the estimated assembly time for the prototype based on the predicted handling and insertion steps for each component. The table also includes the theoretical minimum number of parts for each component and for the full assembly.

Number	Part Description	Number of Identical Operations	Symmetry (alpha/beta)	Manual Handling Code	Manual Handling Time (s)	Manual Insertion Code	Manual Insertion Time (s)	Total Assembly Time (s)	Theoretical Minimum Number of Parts
1	Hex Nuts	3	180/0	0-1	1.43	3-0	2	10.29	0
2	Bottom Cap	1	360/360	3-0	1.95	0-9	7.5	9.45	1
3	Circuit Board	1	360/360	3-0	1.95	3-0	2	3.95	1
4	Adhesive	1	0/0	0-0	1.13	3-0	2	3.13	1
5	Case Body	1	180/0	0-0	1.13	0-6	5.5	6.63	0
6	Roller	1	360/360	3-0	1.95	3-4	6	7.95	1
7	Motor Mount Screw	1	360/0	1-1	1.8	3-9	8	9.8	0
8	Shaft Coupler Set Screw	1	360/0	5-0	4	3-8	6	10	0
9	Outer Shaft	1	180/90	0-0	1.13	0-1	2.5	3.63	0
10	Shaft Coupler Set Screw	1	360/0	5-0	4	3-8	6	10	0
11	Shaft Coupler	1	360/90	1-0	1.5	0-1	2.5	4	0
12	DC Motor	1	360/0	1-0	1.5	9-8	9	10.5	1
13	Motor Mount	1	180/360	2-0	1.8	3-4	6	7.8	0
14	Case Bolts	3	360/0	1-0	1.5	0-9	7.5	27	0
15	Bearing	1	360/0	1-0	1.5	3-1	5	6.5	1
16	Top Cap	1	360/0	1-0	1.5	3-0	2	3.5	1
Total Product Assembly Time (s)								134.13	-
Total Theoretical Minimum Number of Parts									7

Table 7.5: Prototype Bicycle Generator Estimated Manual Assembly Time

The total estimated assembly time for the prototype bicycle generator is 134.13 seconds, or 2 minutes and 14.4 seconds. Handling and inserting the case bolts takes up the longest time of any other component, as is expected, since often in assemblies, fasteners make up only a small amount of the product cost, but can take up to 70% of the assembly time. In the bicycle generator prototype assembly, the case bolts take up about 20% of the total assembly time, but this is due to the shear number of other components. The next highest component assembly time, the hex nuts, which are also fasteners, take up about 7.67% of the total assembly time, which is less than half of the time it takes to handle and insert the case bolts. All the fasteners combined (which includes the hex nuts, motor mount screw, shaft coupler set screws, and case bolts) take up 67.09 seconds of the assembly time, which is equal to 50% of the total assembly time. If the fasteners could be eliminated from the final design, the total assembly time could be cut in half.

As seen in the table above, many of the components of the prototype have a zero listed in the column for the theoretical minimum number of parts. This is because that the components with a zero have been determined to not be essential to the design of the final bicycle generator. When answering the questions mentioned above for each of the components in the assembly, many of them were deemed unimportant to the generator's function if the generator were to be modified for its final design. The theoretical minimum number of parts is explained below for each component of the assembly.

- **Hex Nuts.** The hex nuts do not move relative to the other assembly components, so therefore, if the generator were to be redesigned to incorporate self-fastening parts, the hex nuts could be eliminated.
- **Case Body.** The Case Body does not move relative to the rest of the assembly, so it too can be eliminated with an appropriate redesign. For instance, merging the Case Body and the Top Cap would eliminate the need for a separate Case Body piece.
- **Motor Mount Screw.** Using a different type of motor might eliminate the need for a motor mount screw if the motor mount was incorporated into the design of the merged Case Body and Top Cap. Since the motor mount screw does not move relative to the rest of the assembly, it can be labelled as nonessential.
- **Shaft Coupler Set Screws.** Ideally, there would be no need for a shaft coupler, and therefore no shaft coupler set screws, in the final bicycle generator design. Using a shaft coupler with set screws, while it does work, leaves more room for slippage if either of the two set screws in the prototype design were to come loose. Since the set screws only move with the shaft coupler and not the entire assembly, they can be eliminated in the final design.
- **Outer Shaft.** The outer shaft, while necessary to the prototype bicycle generator, could be eliminated from the final generator design by using a different type of motor. Using a shaft separate from the motor to place the roller on is inefficient in both the assembly and the cost areas of the design. The outer shaft does move in the assembly, but it does not need to be physically isolated from the motor, as it is in the prototype design.
- **Shaft Coupler.** The shaft coupler, as mentioned in some of the previous component explanations, is not an essential part of the final bicycle generator design. The only reason the team chose to use one was due to the limitations of motors available to us that were suitable to the bicycle generator application. The shaft coupler could be eliminated

from the design if the motor was different and had a larger, longer shaft that could connect directly to the roller.

- **Motor Mount.** The motor mount does not move relative to the other assembly components, so it could be eliminated if other components, such as the DC motor and the Case Body, were modified to incorporate a design in which no extra support is needed to keep the motor in place while in the generator case.
- **Case Bolts.** The case bolts that hold the assembly together are important for the prototype bicycle generator, but since they do not move relative to the other assembly components, they are not necessary in the final bicycle generator design. If redesigned appropriately, the bicycle generator could employ self-fastening components or components that would be joined with adhesive to eliminate the need for the case bolts, which take up the most time during the manual assembly since they are difficult to align correctly.

Using the total manual assembly time and the theoretical minimum number of parts, it is possible to calculate the manual design efficiency using the equation below, where E_m is the manual design efficiency, N_m is the theoretical minimum number of parts, and T_m is the total assembly time (Shetty, 2016).

$$E_m = \frac{3N_m}{T_m}$$

$$E_m = \frac{3*7}{134.13} = 0.157$$

The current manual design efficiency of the bicycle generator prototype is 0.157, or 15.7% efficient. This is a very low efficiency. It is unlikely that any design of any product would ever achieve an efficiency of 100%, but most product designs can be improved in order to increase the design efficiency, as is the case with the prototype bicycle generator. The redesign process for the bicycle generator is discussed in the next section.

7.4 Approach to Redesign

7.4.1 Redesigned Bicycle Generator

To redesign the bicycle generator prototype into a more efficient and marketable product, both the above procedures from the Boothroyd-Dewhurst and the quality function deployment analysis were taken into account. The BDM analysis was considered first, as this process is the one that enabled the design to become more efficient by eliminating unnecessary components of the assembly, and the QFD analysis was completed second, as this analysis simply involved ensuring the product design would meet the needs of consumers.

Considering the low manual design efficiency as calculated above, there is much that could be improved for the final design of the bicycle generator. The modification of each component of the prototype generator assembly is discussed below.

- **Hex Nuts**. The hex nuts were used in the prototype generator to hold the entire assembly together, along with the case bolts. The nuts took up 10.29 seconds of the assembly time. By redesigning other components in the generator assembly, we were able to entirely eliminate the hex nuts from the design.
- **Bottom Cap.** The Bottom Cap of the generator was determined to be essential to the design. It does not move relative to the other parts of the assembly, but it must be separate from the other parts of the assembly in order to give the assembler access to the inside of the generator to allow for proper assembly. The design of the Bottom Cap was changed, however. The changes include the elimination of the protrusion that the circuit board originally was placed on. Instead, in the new design, the circuit board will be adhered directly on the Bottom Cap so it is parallel to it. In addition, the holes for the case bolts were removed, and instead the Bottom Cap will be fused to the rest of the assembly with adhesive.
- **Circuit Board.** The circuit board was not changed from the prototype design as it is an essential part of the prototype.
- **Adhesive.** The adhesive that holds the circuit board to the Bottom Cap was not changed.
- **Case Body.** The Case Body was eliminated as a separate component in the assembly. It was merged with the Top Cap so that these two pieces became one.
- **Roller.** The Roller is essential to the functioning of the bicycle generator. In the prototype, the Roller was inserted on the Outer Shaft with only a press fit, but in the final

design, it was inserted on the outer shaft with both a press fit and adhesive to ensure it stays in place.

- **Motor Mount Screw.** The motor mount screw was deemed nonessential in the prototype generator. With modifications to the Case Body and the DC Motor, there was no longer a need for a motor mount screw in the final design.
- **Shaft Coupler Set Screws.** The shaft coupler set screws were eliminated from the final design, as was the shaft coupler, due to modification of the DC motor.
- **Outer Shaft.** The outer shaft was eliminated from the final design due to the modification of the DC motor.
- **Shaft Coupler.** Like the shaft coupler set screws, the shaft coupler was eliminated from the final design due to modification of the DC motor. In the prototype generator, the shaft coupler was essential because the DC motor only had a short shaft which the roller could not be attached to. Thus, a shaft coupler and outer shaft were needed to extend the motor shaft's reach to the bicycle tire.
- **DC Motor.** The DC motor in the prototype bicycle generator was able to generate enough voltage to supply a steady charge to the batteries. However, the type of motor used in the prototype was not the most efficient for a bicycle generator design. The motor only had a short shaft, which a roller could not be attached to. This meant that a shaft coupler and larger shaft were needed to extend the motor's shaft. In the final bicycle generator design, the team decided that it would be best to use a different type of motor, one that is typically found in standard bicycle dynamos. The motor that would be best suited to the bicycle generator application would be one that has a long shaft attached to rotating magnets inside the wire coils. If this were the case, the coils could be directly attached to the Case Body via adhesive or special protrusions from the case to hold them in place. The magnet rotor with the long shaft would then protrude from the Top Cap and the roller would directly attach to the motor shaft. This design eliminates the need for the outer shaft, shaft coupler, shaft coupler set screws, motor mount, and motor mount screw. A custom motor would need to be found or made to incorporate these motor design changes, as the team was unable to find a motor suitable to this application that could produce enough voltage to charge the battery pack.
- **Motor Mount.** The motor mount was eliminated from the final design by modifying the type of motor used and by modifying the Case Body to hold the motor without the need for a separate mount.

- **Case Bolts.** The case bolts took the longest assembly time of all the other assembly components. They were eliminated from the final design due to the modifications to the Case Body, Top Cap, and Bottom cap, which meant they were no longer required to hold the assembly together.
- **Bearing.** The bearing is essential to the function of the generator, as it holds the roller's shaft in place and allows it to turn freely. The bearing was not eliminated from the final design, but it was upgraded from a simple bushing-type bearing to a waterproof radial ball bearing to further aid in shaft rotation and to ensure the case is waterproof as per the customer's needs.
- **Top Cap.** The Top Cap was merged with the Case Body, as explained above. Additionally, the spout of the Top Cap was modified with new protrusions that can hold the ball bearing and an O-ring for waterproofing.

Upon redesigning the prototype, the QFD analysis was taken into consideration as well. Each factor for the QFD analysis is discussed below.

- **Safety.** Due to the large number of small components in the prototype bicycle generator, the prototype generator was only given a safety factor of 4. This is because the small parts could pose a choking risk, and the fact that the generator case could be opened by anyone meant that it could be easily damaged or the electronic components could pose a shock risk. In the redesign, the new safety rating is a 5 because the case would be unopenable and there would be no small parts.
- **Ease of Use.** The ease of use rating for the prototype generator was 3 due to its many components and the difficulties experienced during assembly. The new ease of use rating would be a 5 after the redesign due to the elimination of several components.
- **Waterproof and Dustproof.** The prototype generator was not very water or dustproof, so it only got a 2 for both of these factors. The redesigned bicycle generator will employ an O-ring, a waterproof ball bearing, waterproof RTV silicone around the USB port hole in the Bottom Cap, and waterproof adhesive.
- **Durability.** The prototype generator was not tested for durability, but it was estimated that the durability rating of the prototype was 3 due to the use of polycarbonate tubing. The goal for the final generator design is a rating of 4 for durability in order to keep the cost of materials down. The durability of the generator case depends greatly on the case's

design and involves factors such as shape and wall thickness. The durability simulation testing of the redesigned generator is discussed in section 7.4.2 below.

- **Aesthetics.** The aesthetics of the generator were not improved in the final design, as this factor was deemed the least important. Both ratings will remain a 3.
- **Compact Size.** The size of the generator will not be changed diameter-wise in the final design, as the diameter of the case depends on the size of the motor. To get enough voltage from the motor, the even the modified motor in the final design will likely still have to be a large size similar to that of the prototype. Both ratings will remain a 3.
- **Long Life.** There was not a way for our team to measure the prototype's lifespan with the resources at our disposal, and the same goes for the final design. The prototype was given a rating of 3 for this factor based on the materials used to construct it. By using fewer components, the generator is likely to last longer, as fewer components means fewer things that could go wrong. We estimated that the final generator design would have long life rating of 4.
- **High Power Generation.** The prototype generator actually generates too much voltage, even at moderate speeds. To improve efficiency, this will need to be modified so that the generator will still provide sufficient, but not too high, voltage even while going at higher bicycle speeds. This can be achieved by switching the motor used in the final design.
- **Low Cost.** The low cost rating of the prototype generator was given a 3 due to the high costs of prototypes. We estimate that the cost rating can be brought up to a 4 if the generators were to be produced in volume due to the associated cost reduction of mass production.

After taking the design modifications into consideration, new models were created for the new bicycle generator components, as shown below in Figures 7.14 and 7.15.

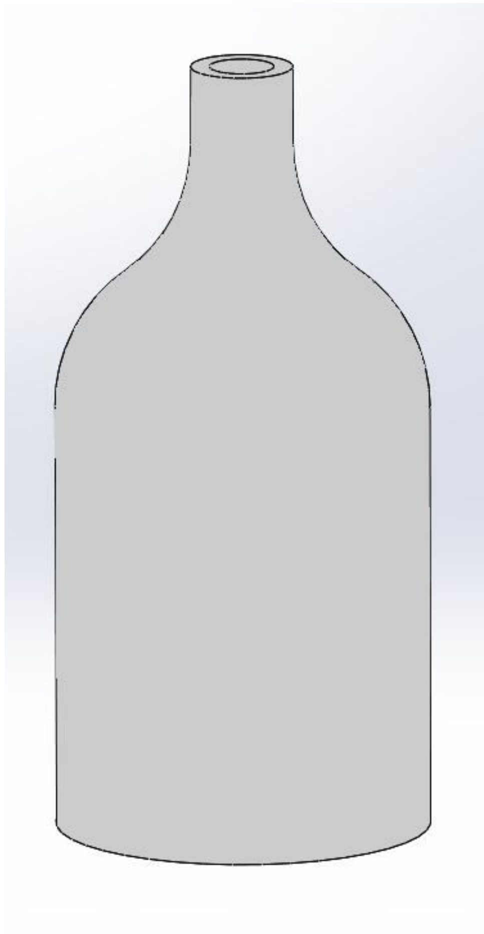

Figure 7.14: Redesigned Generator Case Top

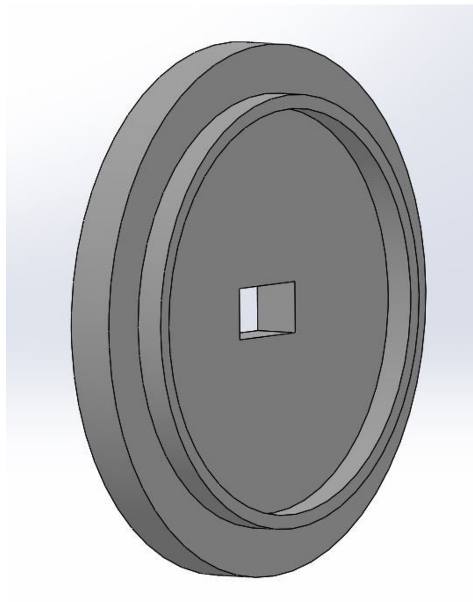

Figure 7.15: Redesigned Generator Bottom Cap

The motor used in the redesigned bicycle generator is different than the motor used in the prototype; the redesigned generator features a motor with exposed coils, inside which the magnets rotate. The magnets are directly attached to the motor's shaft, which is large and long enough to accomodate the roller. This type of motor eliminated the need for a shaft coupler, which was one of the major weak points in the prototype design. The new section view of the assembly can be seen below in Figure 7.16. With the circuit board set to be adhered vertically to the Bottom Cap, and with a shorter motor, the total size of the bicycle generator was reduced.

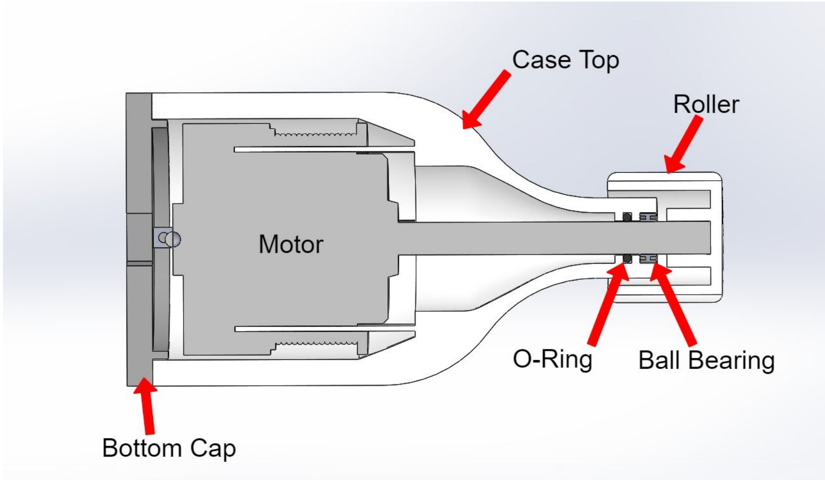

Figure 7.16: Section View of Redesigned Bicycle Generator

The new component list for the final bicycle generator design can be seen in Table 7.6 below. As with the prototype bicycle generator, the BDM analysis process was used with the improved generator design to determine the new manual assembly time and efficiency. Table 7.7 below shows the new estimates for the assembly time for the generator.

Number	Part Description	Dimensions (mm)	Quantity
1	Bottom Cap	57 diameter, 5 thickness	1
2	Waterproof Adhesive	-	1
3	RTV Silicone	-	1
4	Circuit Board	44 length, 24 width	1
5	Adhesive	-	1
6	Roller	22 length, 22 diameter	1
7	Adhesive	-	1
8	DC Motor	40 length, 45 diameter	1
9	Bearing	10 diameter, 3 thickness	1
10	O-ring	6 diameter	1
11	Case Top	98 length, 57 diameter	1

Table 7.6: Redesigned Component Table for Bicycle Generator

Number	Part Description	Number of Identical Operations	Symmetry (alpha/beta, degree/degree)	Manual Handling Code	Manual Handling Time (s)	Manual Insertion Code	Manual Insertion Time (s)	Total Assembly Time (s)	Theoretical Minimum Number of Parts
1	Bottom Cap	1	360/360	3-0	1.95	3-0	2	3.95	1
2	Waterproof Adhesive	1	0/0	0-0	1.13	3-0	2	3.13	1
3	RTV Silicone	1	0/0	0-0	1.13	3-0	2	3.13	1
4	Circuit Board	1	360/360	3-0	1.95	3-0	2	3.95	1
5	Adhesive	1	0/0	0-0	1.13	3-0	2	3.13	1
6	Roller	1	360/360	3-0	1.95	3-4	6	7.95	1
7	Adhesive	1	0/0	0-0	1.13	3-0	2	3.13	1
8	DC Motor	1	360/0	1-0	1.5	3-1	5	6.5	1
9	Bearing	1	360/0	1-0	1.5	3-1	5	6.5	1
10	O-ring	1	180/0	0-1	1.43	3-4	6	7.43	1
11	Case Top	1	360/0	1-0	1.5	3-0	2	3.5	1
Total Product Assembly Time (s)								52.3	-
Total Theoretical Minimum Number of Parts									11

Table 7.7: Manual Assembly Time for Redesigned Bicycle Generator

As shown in Table 7.6 above, the new total estimated assembly time for the bicycle generator is 52.3 seconds. This is a major improvement over the prototype assembly time, which was 134.13 seconds. Due to the addition of water- and dustproofing components, such as the O-ring and waterproof adhesive, the theoretical minimum number of parts actually increased in the redesign. However, the total number of components decreased from 16 to 11, and now the theoretical number of parts matches the number of components. The new manual design efficiency was calculated as:

$$E_m = \frac{3*11}{52.3} = 0.631$$

The manual design efficiency of the redesigned bicycle generator is 63.1%, which is a vast improvement from the 15.7% efficiency of the prototype generator. The new percentage is still not the most efficient the design could probably be, but for an inexpensive product, it is a fairly good and achievable efficiency if the bicycle generator were to ever be manufactured. The new steps for manually assembling the redesigned bicycle generator are shown below.

1) Fix the Case Top to the workspace.
2) Insert the O-ring into the Case Top.
3) Insert the waterproof bearing into the Case Top.
4) Insert the DC motor into the Case Top so that the shaft protrudes out the Case Top's spout.
5) Apply adhesive to the end of the motor's shaft.
6) Insert the roller onto the end of the shaft with the adhesive.
7) Apply adhesive to the Bottom Cap.
8) Adhere the circuit board to the Bottom Cap.
9) Use RTV silicone to seal the USB port hole to the Bottom Cap.
10) Apply waterproof adhesive to the edges and lip of the Bottom Cap.
11) Insert the Bottom Cap into the Case Top and allow to fully dry.

7.4.2 Generator Case Durability Testing

To ensure that the bicycle generator would be durable enough to withstand being dropped, the team used SolidWorks simulation software to perform a drop test on the generator case. The drop test was conducted from a height of 2 meters, and the thickness of the case walls was ⅛ inches. The figures below show the results from the drop test of the redesigned bicycle generator.

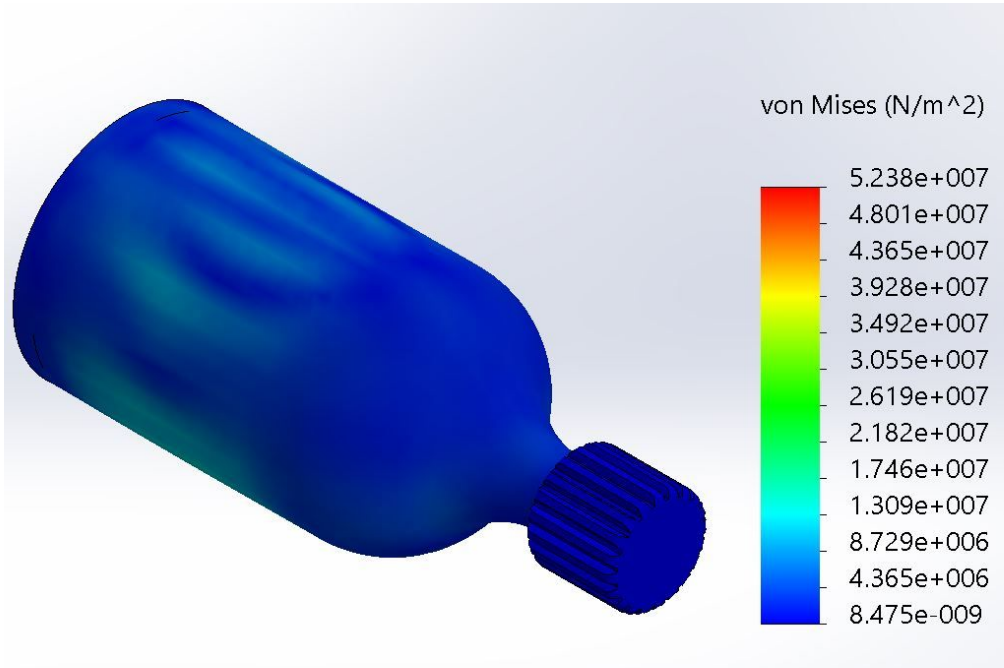

Figure 7.17: Isometric View of Drop Test Results

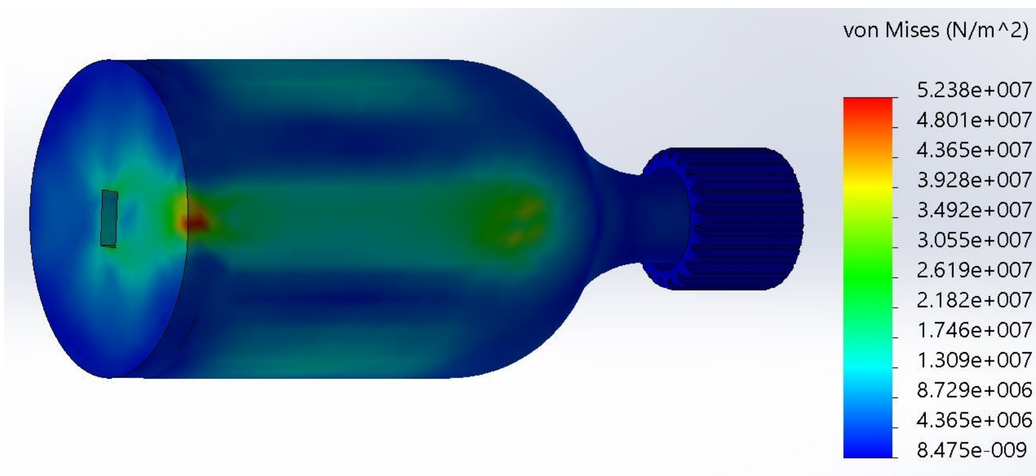

Figure 7.18: Bottom View of Drop Test Results

As can be seen in Figures 7.17 and 7.18, the majority of the stress caused by the drop occurs on the bottom of the case where it hits the ground, as would be expected. The highest stress calculated by the software occurs at the edge of the Bottom Cap. This means that it is important to sure that the Bottom Cap is thick enough to withstand being dropped, and that the Bottom Cap is well adhered to the rest of the case to ensure it does not fall off in the event that the generator is dropped. According to the simulation, the highest stress the case experiences during a two meter drop is 52.38 MPa. The case would be constructed out of ABS plastic, which can have a yield strength of up to 65 MPa (MatWeb (a), 2018). This means that a case made out of ABS would likely be able to withstand being dropped from a 2 meter height. However, if dropped from a higher height, the forces of the drop may prove to be too large for the case, and it could potentially break. As a result of this possibility, we recommend that the case be made out of a metal, such as an aluminum alloy. Aluminum 6061 has a yield strength of 276 MPa, which is more than enough strength to prevent the generator case from breaking upon being dropped (MatWeb (b), 2018).

7.4.3 Bicycle Generator Mount Concept

The prototype generator bicycle mount was not able to provide enough pressure on the generator to ensure that the roller made solid contact with the tire. To remedy this, the mount could be redesigned to incorporate either a spring-loaded mounting bracket or a locking mechanism that provides enough pressure on the roller. Many bicycle dynamos employ a spring-loaded mount that presses the generator's roller up against the bicycle tire with enough force to maintain good contact between the roller and wheel no matter the bicycle riding conditions. The team modelled a new concept bicycle generator Top Case component which incorporates a spring box to ensure better contact between the generator roller and the bicycle tire, as seen in Figure 7.19 below.

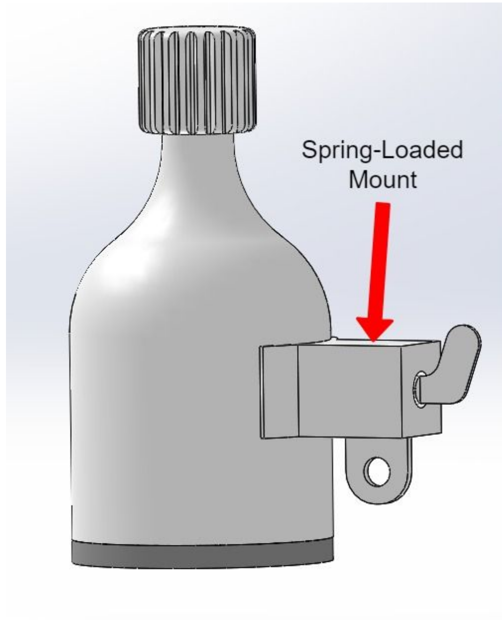

Figure 7.19: Generator Top Case Component with Spring Loaded Mount

7.5 Other System Components

7.5.1 Battery Pack and Book Light

In addition to the bicycle generator and its mount, the two other components of the lighting system that would be donated to the students in Vietnam are the battery pack and the book light. The battery pack would be a standard, durable battery pack containing the two batteries and the charging circuit components, as discussed in section 6. The current components of the charging circuit were too large to fit inside a compact battery pack, so only a concept battery pack was designed. For a modern appearance, the concept battery pack was given a simple rectangular shape and a metallic color, as seen below in Figure 7.20. The batteries and some of the circuitry inside the battery pack can be seen in Figure 7.21 below as well. There are LED charging lights on the side to indicate how charged the device is, and there is also the device's mini-USB charging port on the side. On top of the battery pack is a USB port for either a USB book light or another device that needs to be charged, such as a cell phone. When used with a light, the battery pack acts as a base for the light, preventing it from tipping over. The book light that would be donated to the students would be a generic USB light bought from a third-party retailer, and not designed by our team. The battery pack and book light setup can be seen below in Figure 7.22.

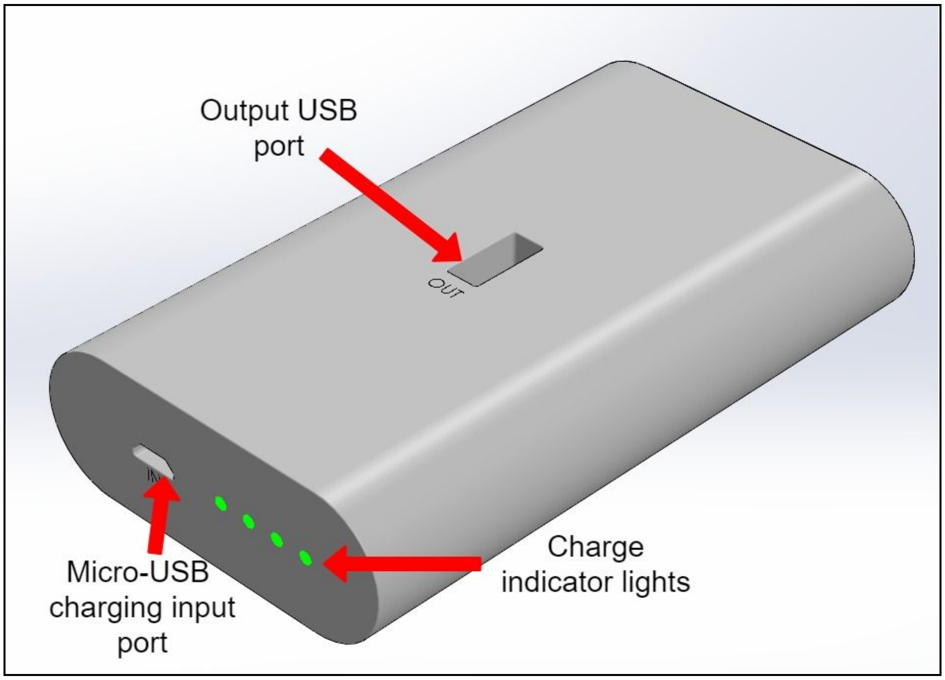

Figure 7.20: Concept Battery Pack

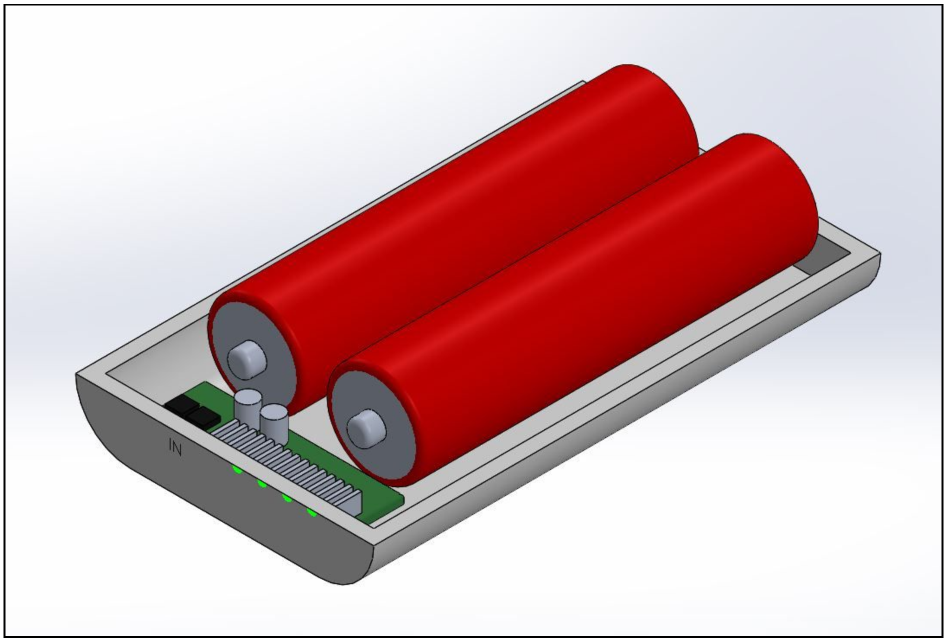

Figure 7.21: Inside the Battery Pack

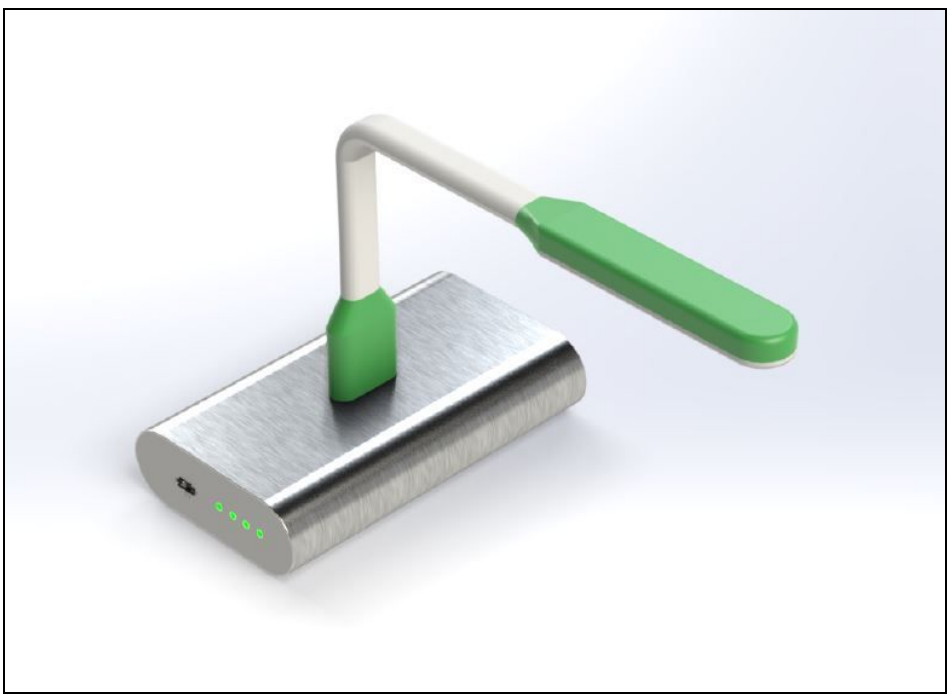

Figure 7.22: Concept battery pack with USB book light

8. Final Thoughts and Recommendations

8.1 Introduction

To conclude the project, we will discuss the results of the project of both the electrical and the mechanical aspects of the overall system and we shall make recommendations for future work on the system.

8.2 Brief Discussion of Results

The prototype bicycle generator worked as expected; the motor was powerful enough to produce a sufficient voltage to charge a battery pack, even though the measured voltage output was slightly lower than the predicted output voltage. When travelling at about 8 miles per hour, with the prototype generator, a user could expect to generate around 30 volts for charging the batteries. The one factor that needs to be improved with the bicycle generator is the mounting system on the bicycle. The prototype mounting system was not capable of ensuring solid contact between the generator roller and the bicycle tire, which lead to slippage of the roller on the tire. This is likely the main reason for measuring a lower output voltage from the generator than expected. To remedy this issue, it would be best to improve the design of the generator bicycle mount by employing a spring-loaded mount to help maintain better contact between the generator roller and the bicycle tire.

The DC-DC converters work well and the filtering circuit successfully worked with the generator, but the charge control circuit was not able to properly charge the 18650 batteries. With the charge control circuit unable to charge the battery, the system could not be integrated with the mechanical system so the whole system could not be tested as one.

The complete system that would be donated to the students of Tra Vinh, Vietnam, includes the redesigned bicycle generator system, the battery pack, and a book light. The bicycle generator system would be the one with a spring-loaded mount to help ensure that the generator's roller makes solid contact with the bicycle's tire. As seen in Figure 8.1 below, it is anticipated that the battery pack be attached to the bicycle with straps while being charged with the generator via a micro-USB cord (not pictured).

Figure 8.1: Bicycle Generator and Battery Pack Mounted on Bicycle

8.3 Recommendations for Future Work

For future work and iterations, there are a few suggestions and plans to implement to design and test a better overall system. On the electrical side, one suggestion is to design a filtering circuit using an inductor instead of a resistor to gain better efficiency. In order to execute a smaller circuit able to fit within the design battery case, smaller DC-DC converters should be used in the circuit design. Also, a charging circuit that is fully integrated without having to design the external circuitry or a more updated charge control IC should be used to mitigate all of the issues that arose with the BQ24278 circuit.

Although the circuit does not currently function, a different circuit board was ordered to try to replace the BQ24278. The board is an Icstation board that is an 5V, 1A 18650 battery charger that has a micro-USB output, as seen in Figure 8.2. This board protects against overcharging and over-discharging with an overcurrent protection of 3A and a cut-off charging voltage of 4.2V. The input voltage for this board is 5V, so the overall design will change to the boost-buck converter supplying 5V to the charging circuit. This board will replace the BQ24278 chip and external circuit and will be testing in the system.

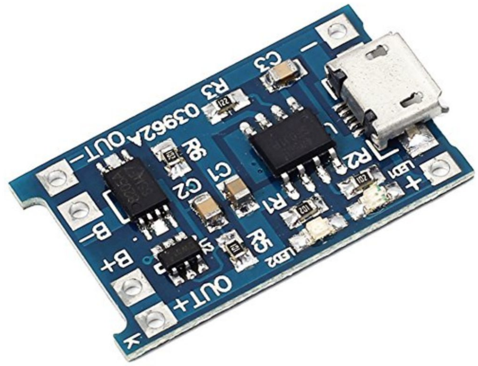

Figure 8.2: 5V, 1A 18650 Battery Charging Board

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Appendices A: Motor Testing and Selection

Large AC Motor- No Load

Title: Discovering the relation between rotations per minute and motor voltage

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

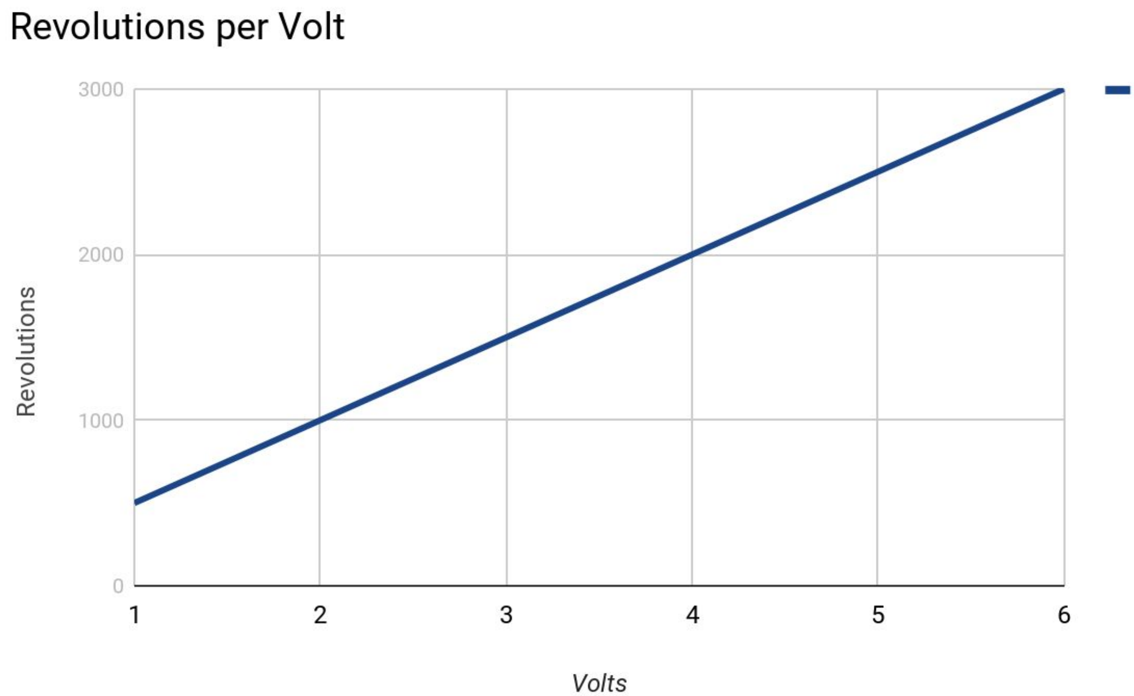
- Large AC Motor

Procedure: The name of the large motor, ML4108 500KV has specific meanings for each of the numbers. '41' and '08' are the diameter and height of the rotor inside of the motor and 500 is the number of rotations per volt with no load. Because the number of rotations are too high to count in a lab setting, we will calculate the estimated RPM of the motor using the specs and assume that the k constant is by rotations in a minute of the given voltage.

Results:

Voltage Input	Estimated RPM
1	500
2	1000
3	1500
3.5	1750
4	2000
4.5	2250
5	2500
5.5	2750
6	3000

Table A.1: RPM versus Input Motor Voltage



Graph A.1 RPM versus Input Motor Voltage

Discussions/Conclusions: after analyzing the graph, we know that we need to have 2500 rotations in order to get 5V out of the system with no load, so it is unpractical for a commuter that needs at least a 20Wh battery.

Large AC Motor- With Load

Title: Discovering the relation between rotations per minute and motor voltage WITH A LOAD

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Theory: connecting a load to the system will add another component that the voltage runs through, thus having another voltage drop. If there is another voltage drop then there is less voltage that goes to the motor. In terms of our project, this means that the same amount of pedaling will acquire less power to go to the battery itself, so the get the same power as the motor would without a load would mean that there is more pedaling needed to compensate for the voltage drop. Therefore, we expect the RPM values to be higher in comparison to the same testing without a load.

Procedure: connect a 10 ohm potentiometer in parallel to the motor. Connect the voltage supply to the potentiometer and oscilloscope to the motor. Attach the 3 inch gear to the shaft of the motor. Increase the power supply until the oscilloscope reads the desired voltage and then count the number of rotations the gear does in a minute to the corresponding voltages.

Results: Since the motor rotated faster than what we could measure in the lab, we could not get numbers for this test. There are no estimates that we could do either except that the number will be higher than the original calculations for no load.

Discussions/Conclusions: After this theoretical test, we can conclude that the large motor is highly impractical for our system.

Large DC Motor- No Load

Title: Discovering the relation between rotations per minute and motor voltage WITH NO LOAD

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

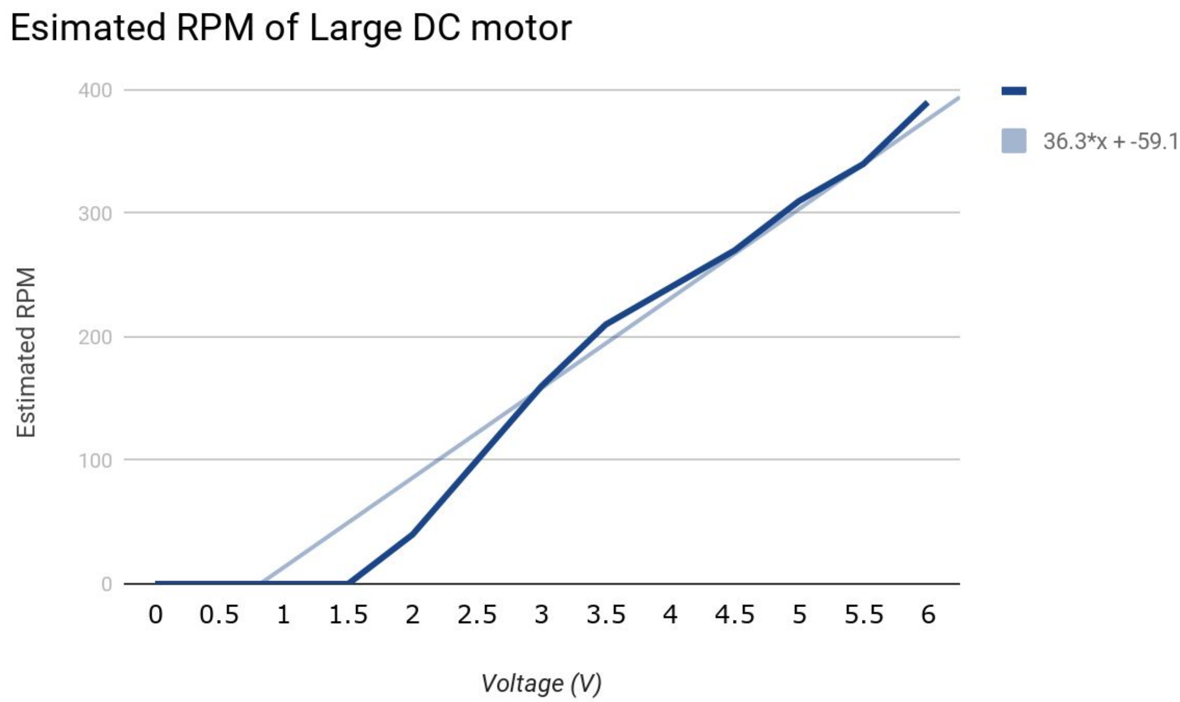
- Oscilloscope
- DC Power Supply
- Large DC Motor
- 3in Diameter Gear
- Timer

Procedure: Draw a straight line on the gear from the center to the edge. Attach the shaft of the motor to the gear. Attach the positive and negative output from the DC power supply to the corresponding terminals of the motor. To monitor the power supply, attach the oscilloscope to double check the input voltages and the accuracy of supplying the voltage. Starting from 0V, slowly increase the input voltage from the DC power supply and count how many times the line on the gear makes a complete rotation within 6 seconds. If the gear is spinning too quickly, attach a small wire from the gear to count how many times the wires gently hit a table by listening to the sound.

Results:

Voltage Input	Estimated RPM
1 V	Off
2 V	40
3 V	140
3.5 V	210
4 V	240
4.5 V	270
5 V	310
5.5 V	340
6 V	390

Table A.2: RPM versus Input Motor Voltage



Graph A.2 RPM versus Input Motor Voltage

Calculating k constant:
rise/run
390-140/6-3 = 250/3 = 83.3

Using the data points (3,140) and (6,390), the k value of the motor is 83.3. This means that on average, the increase in 1V results in an RPM increase of 83.3.

By using a line of best fit, the slope is 36.3.

Discussions/Conclusions: The graph was close to linear which was as expected. This experiment showed up that to get the desired voltage of between 5 and 6 V, the RPM would have to be 310 for 5V and 390 for 6V. Using the motor and gear ratio spreadsheet, we know that we would need a 2:1 or 2.5:1 gear ratio to satisfy this voltage need for the system if the student were to travel at the average commuter speed.

Large DC Motor- With Load

Title: Discovering the relation between rotations per minute and motor voltage WITH A LOAD

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

- Oscilloscope
- DC Power Supply
- Motor (DC MOTOR RS455PA-17150)
- 3in Diameter Gear
- 35 Ohm Potentiometer

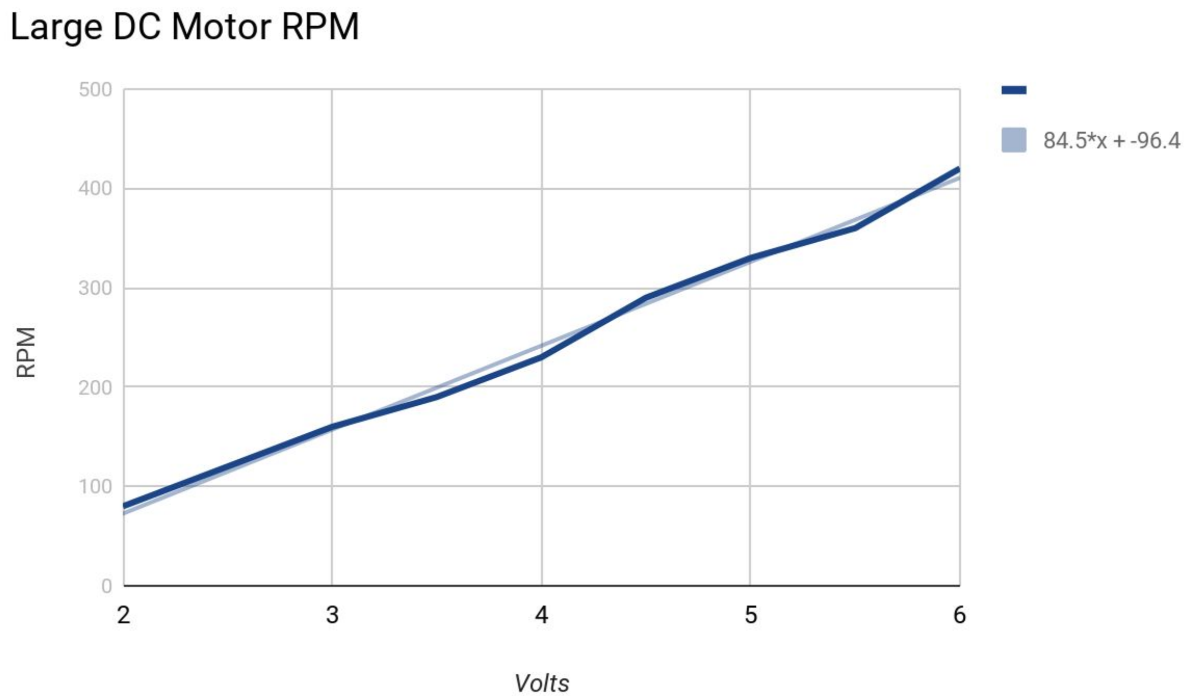
Procedure:

connect a 10 ohm potentiometer in parallel to the motor. Connect the voltage supply to the potentiometer and oscilloscope to the motor. Attach the 3 inch gear to the shaft of the motor. Increase the power supply until the oscilloscope reads the desired voltage and then count the number of rotations the gear does in a minute to the corresponding voltages.

Results:

Estimated RPM	Voltage Output
off	1
80	2
160	3
190	3.5
230	4
290	4.5
330	5
360	5.5
420	6

Table A.3: RPM versus Input Motor Voltage



Graph A.3 RPM versus Input Motor Voltage

Discussions/Conclusions: The graph was close to linear which was as expected. This experiment showed up that to get the desired voltage of between 5 and 6 V, the RPM would have to be 330 and 420 RPM.

Small AC Motor- No Load

Title: Discovering the relation between rotations per minute and motor voltage

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

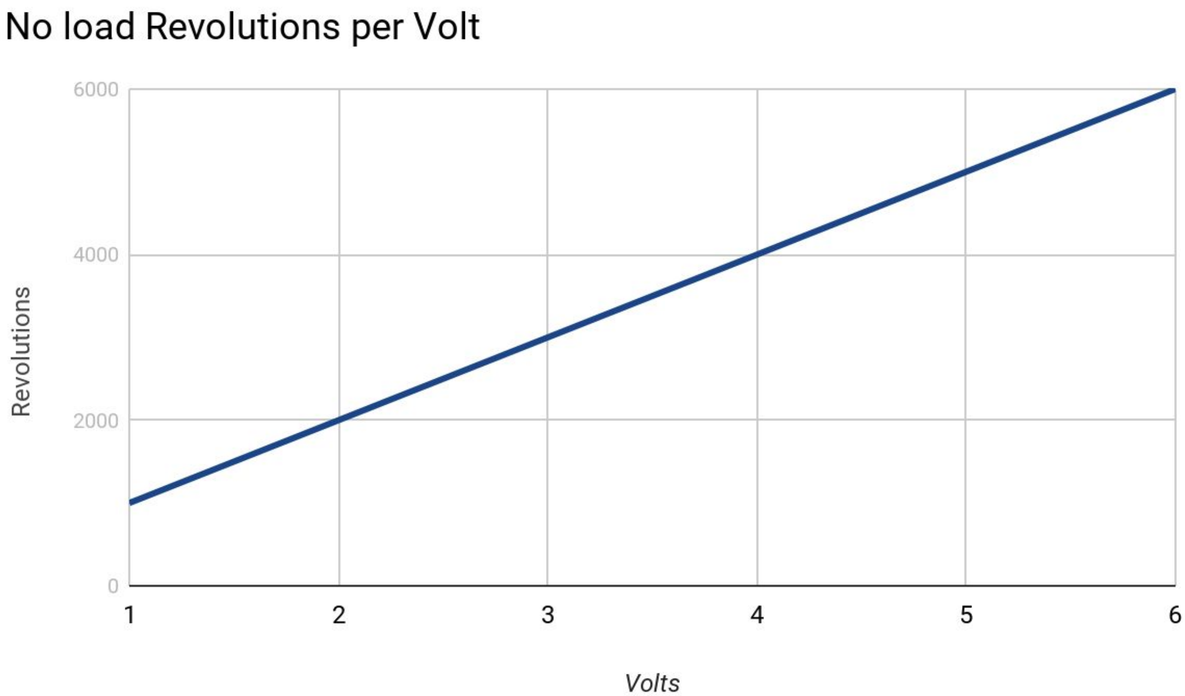
- Small AC Motor.

Procedure: The name of the small motor, A2212/13T 1000KV has specific meanings for each of the numbers. ‘22’ and ‘12’ are the diameter and height of the rotor inside of the motor, 13 is the number of wire turns around each pole inside the motor and 1000 is the number of rotations per volt with no load. Because the number of rotations are too high to count in a lab setting, we will calculate the estimated RPM of the motor using the specs and assume that the k constant is by rotations in a minute of the given voltage.

Results:

Voltage Input	Estimated RPM
1 V	1000
2 V	2000
3 V	3000
3.5 V	3500
4 V	4000
4.5 V	4500
5 V	5000
5.5 V	5500
6 V	6000

Table A.4: RPM versus Input Motor Voltage



Graph A.4 RPM versus Input Motor Voltage

Discussions/Conclusions: After analyzing this chart, we know that it will take 5000 turns on a bicycle to get 5V out of the motor. This is not practical for a commuting student that needs more than 20Wh battery.

Small AC Motor- With Load

Title: Discovering the relation between rotations per minute and motor voltage with a load

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Theory: connecting a load to the system will add another component that the voltage runs through, thus having another voltage drop. If there is another voltage drop then there is less voltage that goes to the motor. In terms of our project, this means that the same amount of pedaling will acquire less power to go to the battery itself, so the get the same power as the motor would without a load would mean that there is more pedaling needed to compensate for the voltage drop. Therefore, we expect the RPM values to be higher in comparison to the same testing without a load.

Procedure: connect a 10 ohm potentiometer in parallel to the motor. Connect the voltage supply to the potentiometer and oscilloscope to the motor. Attach the 3 inch gear to the shaft of the motor. Increase the power supply until the oscilloscope reads the desired voltage and then count the number of rotations the gear does in a minute to the corresponding voltages.

Results: Since the motor rotated faster than what we could measure in the lab, we could not get numbers for this test. There are no estimates that we could do either except that the number will be higher than the original calculations for no load.

Discussions/Conclusions: After this theoretical test, we can conclude that the small motor is highly impractical for our system.

Small DC Motor- No Load

Title: Discovering the relation between rotations per minute and motor voltage

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

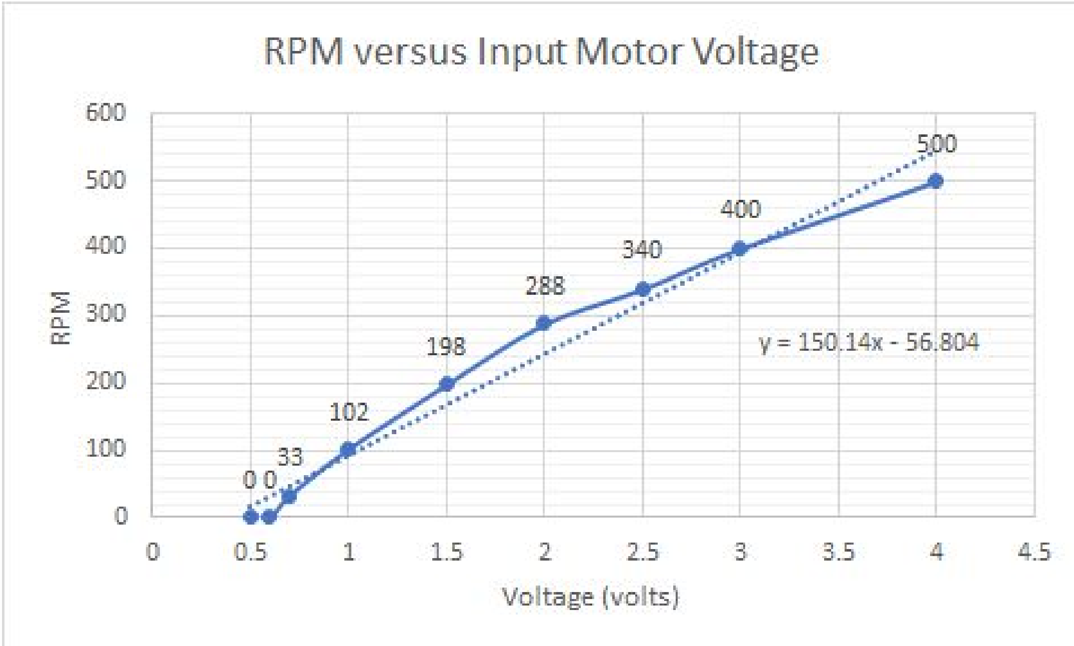
- Oscilloscope
- DC Power Supply
- Small DC Motor
- 3in Diameter Gear

Procedure: Draw a straight line on the gear from the center to the edge. Attach the shaft of the motor to the gear. Attach the positive and negative output from the DC power supply to the corresponding terminals of the motor. To monitor the power supply, attach the oscilloscope to double check the input voltages and the accuracy of supplying the voltage. Starting from 0V, slowly increase the input voltage from the DC power supply and count how many times the line on the gear makes a complete rotation within 6 seconds. If the gear is spinning too quickly, attach a small wire from the gear to count how many times the wires gently hit a table by listening to the sound.

Results:

Voltage Input	Estimated RPM
0.5 V	Off
0.6 V	Off
0.7 V	33 RPM
1 V	102 RPM
1.5 V	198 RPM
2 V	288 RPM
2.5 V	340 RPM
3 V	400 RPM
4 V	500 RPM

Table A.5: RPM versus Input Motor Voltage



Graph A.5 RPM versus Input Motor Voltage

Calculating k constant:
rise/run
500/4-0.7 =500/3.3 = 151.5151
288-102/1 = 186
500-33/4-0.7 = 141.5151

Using the data points (0.7, 33) and (4, 500), the k value of the motor is 141.52. This means that on average, the increase in 1V results in an RPM increase of 141.52.

By using a line of best fit, the slope is 150.14.

Discussions/Conclusions: The graph was close to linear which was as expected. This experiment showed up that to get the desired voltage of between 5 and 6 V, the RPM would have to be 650 for 5V and 800 for 6V.

Small DC Motor- With Load

Title: Discovering the relation between rotations per minute and motor voltage WITH A LOAD

Abstract: In this experiment, we needed to find out the correlation to RPM and the voltage of the motor to determine how fast the generator must spin to produce a usable amount of voltage to charge the battery pack. The expected results are a linear graph with the slope of the line to be the k constant of the motor. This constant will help us determine the needed RPM to produce the desired output voltage (in our case, 5-6V).

Equipment:

- Oscilloscope
- DC Power Supply
- Motor (DC MOTOR RS455PA-17150)
- 3in Diameter Gear
- 35 Ohm Potentiometer

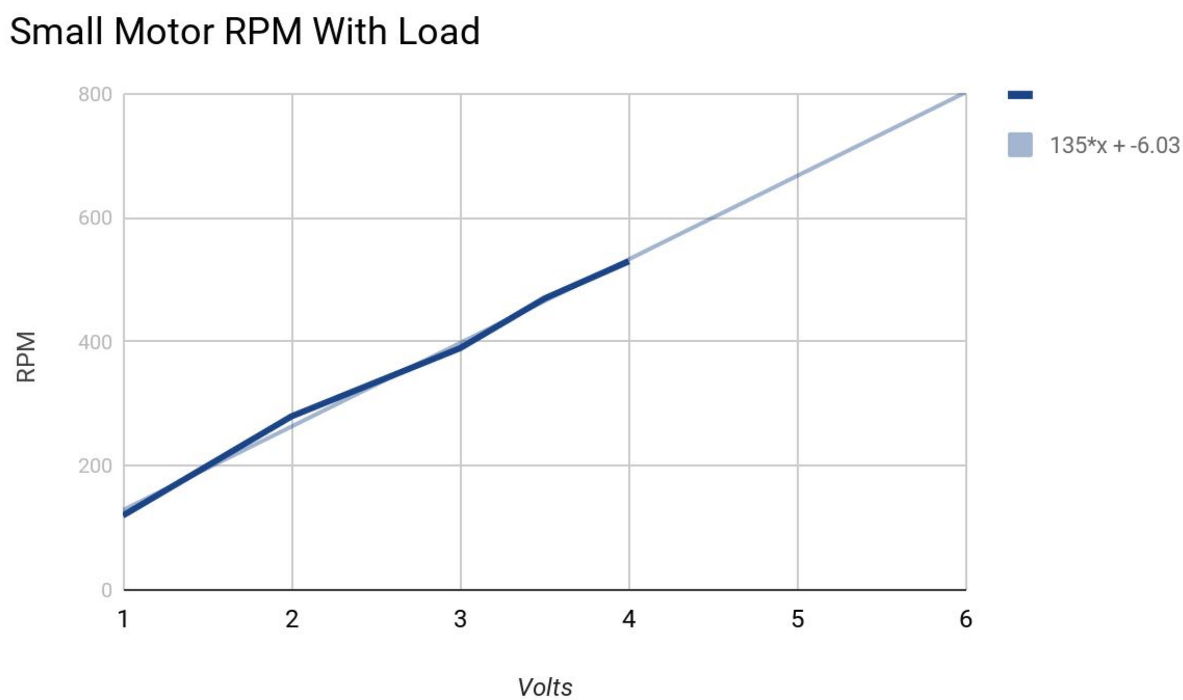
Procedure:

connect a 10 ohm potentiometer in parallel to the motor. Connect the voltage supply to the potentiometer and oscilloscope to the motor. Attach the 3 inch gear to the shaft of the motor. Increase the power supply until the oscilloscope reads the desired voltage and then count the number of rotations the gear does in a minute to the corresponding voltages.

Results:

Estimated RPM	Voltage Output
120	1
280	2
390	3
470	3.5
530	4
-	4.5
-	5
-	5.5
-	6

Table A.6: RPM versus Input Motor Voltage



Graph A.6 RPM versus Input Motor Voltage

After 4V it was too difficult to count the RPM accurately but by using the calculations that we got compared to the trend line of best fit, we can calculate 5V and 6V to be estimated at

RPM(5)= 135(5) - 6.03 = 668.97 = ~669
RPM(6) = 135(6) - 6.03 = 803.97 = ~804

Discussions/Conclusions: The graph was close to linear which was as expected. This experiment proved that to get the desired voltage of between 5 and 6 V, the RPM would have to be between 669 and 804 RPM.

Appendix B: BQ24278 Datasheet

Not Recommended For New Designs

2.5A, Single Input, Single Cell Switchmode Li-Ion BATTERY CHARGER with Power Path Management

Check for Samples: bq24278

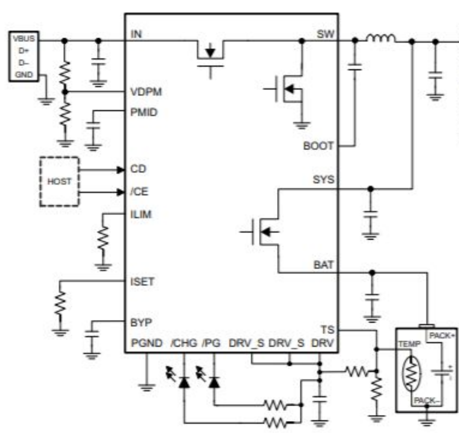
FEATURES

- High-Efficiency Switch Mode Charger with Separate Power Path Control
  - Instantly Startup System from a Deeply Discharged Battery or No Battery
- 20V input rating, with 10.5V Over-Voltage Protection (OVP)
- Integrated FETs for Up to 2.5A Charge Rate
- Highly Integrated Battery N-Channel MOSFET Controller for Power Path Management
- Safe and accurate Battery Management Functions
  - 0.5% Battery Regulation Accuracy
  - 10% Charge Current Accuracy
- Voltage-based, NTC Monitoring Input (TS)
  - Standard Temp Range
- Thermal Regulation Protection for Output Current Control
- Low Battery Leakage Current, BAT Short-Circuit Protection
- Soft-Start feature to reduce inrush current
- Thermal Shutdown and Protection
- Available in small 49-ball WCSP or QFN-24 packages

APPLICATIONS

- Handheld Products
- Portable Media Players
- Portable Equipment
- Netbook and Portable Internet Devices

APPLICATION SCHEMATIC



DESCRIPTION

The bq24278 highly integrated single cell Li-Ion battery charger and system power path management device targeted for space-limited, portable applications with high capacity batteries. The single cell charger operates from a dedicated charging source such as an AC adapter or Wireless Power.

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

DESCRIPTION (CONTINUED)

The power path management feature allows the bq24278 to power the system from a high efficiency DC to DC converter while simultaneously and independently charging the battery. The charger monitors the battery current at all times and reduces the charge current when the system load requires current above the input current limit. This allows for proper charge termination and timer operation. The system voltage is regulated to the battery voltage but will not drop below 3.5V. This minimum system voltage support enables the system to run with a defective or absent battery pack and enables instant system turn-on even with a totally discharged battery or no battery. The power-path management architecture also permits the battery to supplement the system current requirements when the adapter cannot deliver the peak system currents. This enables the use of a smaller adapter.

The battery is charged in three phases: conditioning, constant current and constant voltage. In all charge phases, an internal control loop monitors the IC junction temperature and reduces the charge current if the internal temperature threshold is exceeded. Additionally, the bq24278 offers a voltage-based battery pack thermistor monitoring input (TS) that monitors battery temperature for safe charging .

ORDERING INFORMATION

PART NUMBER	IN OVP	NTC MONITORING (TS)	JEITA COMPATIBLE	MINIMUM SYSTEM VOLTAGE	PACKAGE
bq24278YFFR	10.5 V	Yes	No	3.5 V	WCSP
bq24278YFFT	10.5 V	Yes	No	3.5 V	WCSP
bq24278RGER	10.5 V	Yes	No	3.5 V	QFN
bq24278RGET	10.5 V	Yes	No	3.5 V	QFN

ABSOLUTE MAXIMUM RATINGS

over operating free-air temperature range (unless otherwise noted)(1)

		MIN	MAX	UNIT
Pin voltage range (with respect to VSS)	IN	–2	20	V
	PMID, BYP, BOOT	–0.3	20	V
	SW	–0.7	12	V
	SYS, BAT, BGATE, DRV, $\overline{PG}$, $\overline{CHG}$, $\overline{CE}$, CD, TS, DRV_S, ILIM, ISET, VDPM	–0.3	7	V
BOOT to SW		–0.3	7	V
Output current (continuous)	SW		4.5	A
	SYS		3.5	A
Input current (continuous)	IN		2.75	A
Output sink current	$\overline{PG}$, $\overline{CHG}$		10	mA
Operating free-air temperature range		-40	85	°C
Junction temperature, T_J		-40	125	°C
Storage temperature, T_{STG}		–65	150	°C
Lead temperature (soldering, 10 s)			300	°C

(1) Stresses beyond those listed under absolute maximum ratings may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under recommended operating conditions is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability. All voltage values are with respect to the network ground terminal unless otherwise noted.

THERMAL INFORMATION

THERMAL METRIC[(1)]		bq24278		UNITS
		YFF (48 PINS)	QFN (24 PINS)	
θ_{JA}	Junction-to-ambient thermal resistance	49.8	32.6	°C/W
θ_{JCtop}	Junction-to-case (top) thermal resistance	0.2	30.5	
θ_{JB}	Junction-to-board thermal resistance	1.1	3.3	
ψ_{JT}	Junction-to-top characterization parameter	1.1	0.4	
ψ_{JB}	Junction-to-board characterization parameter	6.6	9.3	
θ_{JCbot}	Junction-to-case (bottom) thermal resistance	N/A	2.6	

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.

RECOMMENDED OPERATING CONDITIONS

		MIN	MAX	UNITS
V_{IN}	IN voltage range	4.2	18[(1)]	V
	IN operating range	4.2	10	
I_{IN}	Input current IN input		2.5	A
I_{SYS}	Ouput Current from SW, DC		3	A
I_{BAT}	Charging		2.5	A
	Discharging, using internal battery FET		2.5	
T_J	Operating junction temperature range	0	125	°C

(1) The inherent switching noise voltage spikes should not exceed the absolute maximum rating on either the BOOT or SW pins. A tight layout minimizes switching noise.

ELECTRICAL CHARACTERISTICS

Circuit of Figure 2, $VU_{VLO} < V_{IN} < V_{OVP}$ AND $V_{IN}>V_{BAT}+V_{SLP}$, T_J = 0°C–125°C and T_J = 25°C for typical values (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
I_{IN}	Input quiescent current	$V_{UVLO} < V_{IN} < V_{OVP}$ AND $V_{IN} > V_{BAT}+V_{SLP}$ PWM switching		15		mA
		$V_{UVLO} < V_{IN} < V_{OVP}$ AND $V_{IN} > V_{BAT}+V_{SLP}$ PWM NOT switching			5	
		0°C < T_J < 85°C, High-Z Mode			175	µA
$I_{BATLEAK}$	Leakage current from BAT to the supply	0°C< T_J < 85°C, V_{BAT} = 4.2V, V_{IN} = 0 V			5	µA
I_{BAT_HIZ}	Battery discharge current in High Impedance mode (BAT, SW, SYS)	0°C< T_J < 85°C, V_{BAT} = 4.2 V, V_{IN} = 0 V or 5 V, High-Z Mode			55	µA
POWER PATH MANAGEMENT						
$V_{SYS(REG)}$	System regulation voltage	$V_{BAT} < V_{MINSYS}$	3.6	3.7	3.82	V
$V_{SYSREGFETOFF}$		Battery FET turned off, Charge disable or termination	4.26	4.33	4.37	
V_{MINSYS}	Minimum system regulation voltage	$V_{BAT} < V_{MINSYS}$, Input current limit or VINDPM active	3.4	3.5	3.62	V
V_{BSUP1}	Enter supplement mode threshold	V_{BAT} > 2.5 V		V_{BAT} – 40mV		V
V_{BSUP2}	Exit supplement mode threshold	V_{BAT} > 2.5 V		V_{BAT} – 10mV		V
$I_{LIM(Discharge)}$	Current limit, discharge or supplement mode	Current monitored in internal FET only		7		A
$t_{DGL(SC1)}$	Deglitch time, OUT short circuit during discharge or supplement mode	Measured from ($V_{BAT} – V_{SYS}$) = 300 mV to V_{BGATE} = (VBAT – 600 mV)		250		µs
$t_{REC(SC1)}$	Recovery time, OUT short circuit during discharge or supplement mode			60		ms
	Battery range for BGATE operation		2.5		4.5	V

ELECTRICAL CHARACTERISTICS (continued)

Circuit of Figure 2, $VU_{VLO} < V_{IN} < V_{OVP}$ AND $V_{IN} > V_{BAT} + V_{SLP}$, T_J = 0°C–125°C and T_J = 25°C for typical values (unless otherwise noted)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
BATTERY CHARGER							
$R_{ON(BAT-SYS)}$	Internal battery charger MOSFET on-resistance	Measured from BAT to SYS, V_{BAT} = 4.2 V	YFF pkg		37	57	mΩ
			RGE pkg		50	70	
V_{BATREG}	Battery regulation voltage	T_A = 25°C		4.179	4.2	4.221	V
		$V_{WARM} < V_{TS} < V_{COOL}$		4.160	4.2	4.24	
		T_A = 25°C		4.04	4.06	4.08	
		$V_{HOT} < V_{TS} < V_{WARM}$		4.02	4.06	4.1	
I_{CHARGE}	Charge current programmable range	$I_{CHARGE} = \frac{K_{ISET}}{R_{ISET}}$		550		2500	mA
K_{ISET}	Programmable fast charge current factor	T_A = 0°C to 125°C, $V_{WARM} < V_{TS} < V_{COOL}$		400	490	560	AΩ
		T_A = 0°C to 125°C, $V_{COLD} < V_{TS} < V_{COOL}$		225	245	270	
$V_{BATSHRT}$	Battery short threshold	V_{BAT} Rising		2.9	3.0	3.1	V
$V_{BATSHRThys}$	Battery short threshold hysteresis	V_{BAT} Falling			100		mV
$I_{BATSHRT}$	Battery short current	$V_{BAT} < V_{BATSHRT}$			50.0		mA
$t_{DGL(BATSHRT)}$	Deglitch time for battery short to fast charge transition				32		ms
I_{TERM}	Termination charge current	I_{CHARGE} ≤ 1A		7	10	11.5	$\%I_{CHARGE}$
		I_{CHARGE} >1A		8	10	11	
$t_{DGL(TERM)}$	Deglitch time for charge termination	Both rising and falling, 2-mV over-drive, t_{RISE}, t_{FALL} = 100 ns			32		ms
V_{RCH}	Recharge threshold voltage	Below V_{BATREG}			120		mV
$t_{DGL(RCH)}$	Deglitch time	V_{BAT} falling below V_{RCH}, t_{FALL} = 100 ns			32		ms
I_{DETECT}	Battery detection current before charge done (sink current)				2.5		mA
t_{DETECT}	Battery detection time				250		ms
INPUT PROTECTION							
I_{INLIM}	Maximum input current limit programmable range for IN input	$I_{INLIM} = \frac{K_{ILIM}}{R_{ILIM}}$		1000		2500	mA
K_{ILIM}	Maximum input current factor for IN input			238	251	264	AΩ
$V_{IN\_DPM\_IN}$	VIN_DPM threshold programmable range for IN Input			4.2		10	V
	VDPM threshold			1.18	1.2	1.22	V
V_{DRV}	Internal bias regulator voltage			5	5.2	5.45	V
I_{DRV}	DRV Output current			10			mA
V_{DO_DRV}	DRV Dropout voltage ($V_{IN} - V_{DRV}$)	I_{IN} = 1A, V_{IN} = 5 V, I_{DRV} = 10 mA				450	mV
V_{UVLO}	IC active threshold voltage	V_{IN} rising		3.6	3.8	4.0	V
V_{UVLO_HYS}	IC active hysteresis	V_{IN} falling from above V_{UVLO}			150		mV
V_{SLP}	Sleep-mode entry threshold, V_{IN}-V_{BAT}	2.0 V ≤ V_{BAT} ≤ V_{OREG}, V_{IN} falling		0	40	100	mV
V_{SLP_EXIT}	Sleep-mode exit hysteresis	2.0 V ≤ V_{BAT} ≤ V_{OREG}		40	100	160	mV
	Deglitch time for supply rising above $V_{SLP}+V_{SLP\_EXIT}$	Rising voltage, 2-mV over drive, t_{RISE} = 100 ns			30		ms
V_{OVP}	Input supply OVP threshold voltage	IN, V_{IN} Rising		10.3	10.5	10.7	V
$V_{OVP(HYS)}$	V_{OVP} hysteresis	Supply falling from V_{OVP}			100		mV
V_{BOVP}	Battery OVP threshold voltage	V_{BAT} threshold over V_{OREG} to turn off charger during charge		1.025 × V_{BATREG}	1.05 × V_{BATREG}	1.075 × V_{BATREG}	V
	VB_{OVP} hysteresis	Lower limit for V_{BAT} falling from above V_{BOVP}			1		% of V_{BATREG}
$V_{BATUVLO}$	Battery UVLO threshold voltage				2.5		V
I_{LIMIT}	Cycle by Cycle current limit			4.1	4.9	5.6	A
$T_{SHUTDWN}$	Thermal shutdown	10C Hysteresis			165		C
T_{REG}	Thermal regulation threshold				120		C
	Safety Timer			324	360	396	min
$\overline{CE}$, CD, $\overline{PG}$, $\overline{CHG}$							
V_{IH}	Input high threshold			1.3			V
V_{IL}	Input low threshold					0.4	V
I_{IH}	High-level leakage current	$V_{\overline{CHG}} = V_{\overline{PG}}$ = 5 V				1	µA
V_{OL}	Low-level output saturation voltage	I_O = 10 mA, sink current				0.4	V

ELECTRICAL CHARACTERISTICS (continued)

Circuit of Figure 2, $VU_{VLO} < V_{IN} < V_{OVP}$ AND $V_{IN} > V_{BAT} + V_{SLP}$, T_J = 0°C–125°C and T_J = 25°C for typical values (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
PWM CONVERTER						
	Internal top reverse blocking MOSFET on-resistance	I_{IN_LIMIT} = 500 mA, Measured from V_{IN} to PMIDU		95	175	mΩ
	Internal top N-channel Switching MOSFET on-resistance	Measured from PMIDU to SW		100	175	mΩ
	Internal bottom N-channel MOSFET on-resistance	Measured from SW to PGND		65	115	mΩ
f_{OSC}	Oscillator frequency		1.35	1.50	1.65	MHz
D_{MAX}	Maximum duty cycle			95%		
D_{MIN}	Minimum duty cycle		0			
BATTERY-PACK NTC MONITOR						
V_{HOT}	High temperature threshold	V_{TS} falling	29.7	30	30.5	%VDRV
$V_{HYS(HOT)}$	Hysteresis on high threshold	V_{TS} rising		1		%VDRV
V_{COLD}	Low temperature threshold	V_{TS} rising	59.5	60	60.4	%VDRV
V_{WARM}	Warm temperature threshold	V_{TS} falling	37.9	38.3	39.6	%VDRV
$V_{HYS(WARM)}$	Hysteresis on warm threshold	V_{TS} rising		1		%VDRV
V_{COOL}	Cool temperature threshold	V_{TS} rising	56.0	56.5	56.9	%VDRV
$V_{HYS(COOL)}$	Hysteresis on cool threshold	V_{TS} falling		1		%VDRV
$V_{HYS(COLD)}$	Hysteresis on low threshold	V_{TS} falling		1		%VDRV
TSOFF	TS Disable threshold	V_{TS} rising, 2% V_{DRV} Hysteresis	70		73	%VDRV
$t_{DGL(TS)}$	Deglitch time on TS change			50		ms

PIN FUNCTIONS

PIN			I/O	DESCRIPTION
NAME	NUMBER			
	YFF	RGE		
IN	A1-A4	21	I	Input power supply. IN is connected to the external DC supply (AC adapter or alternate power source). Bypass IN to PGND with at least a 1μF ceramic capacitor.
AGND	A5-A7	22	I	Ground terminal. Connect to the thermal pad (for QFN only) and the ground plane of the circuit.
PMID	B1-B4	20	O	Reverse Blocking MOSFET and High Side MOSFET Connection Point for High Power Input. Bypass PMID to PGND with at least a 4.7μF ceramic capacitor. Use caution when connecting an external load to PMID. The PMID output is not current limited. Any short on PMID will result in damage to the IC.
BYP	B5-B7	23	O	Bypass for internal supply. Bypass BYP to GND with at least a 0.1μF ceramic capacitor.
SW	C1–C7	18	O	Inductor Connection. Connect to the switched side of the external inductor.
PGND	D1–D7	16, 17	—	Ground terminal for Switching FET. Connect to the thermal pad (for QFN only) and the ground plane of the circuit.
ILIM	E1	15	I	IN Input Current Limit Programming Input. Connect a resistor from ILIM to GND to program the input current limit for IN. The current limit is programmable from 1A to 2.5A.
CD	E2	2	I	IC Hardware Disable Input. Drive CD high to place the bq24278 in high-z mode. Drive CD low for normal operation.
VDPM	E3	1	I	Input DPM Programming Input. Connect a resistor divider from IN to PGND with VDPM connected to the center tap to program the Input Voltage based Dynamic Power Management (VIN_DPM) threshold. The input current is reduced to maintain the supply voltage at $V_{IN\_}DPM$. *See the Input Voltage based Dynamic Power* Management section for a detailed explanation.
$\overline{CE}$	E4	24	I	Charge Enable Input. $\overline{CE}$ is used to disable or enable the charge process. A low logic level (0) enables charging and a high logic level (1) disables charging. When charging is disabled, the SYS output remains in regulation, but BAT is disconnected from SYS. Supplement mode is still available if the system load demands cannot be met by the supply.
DRV_S	E5, E6	3, 4	I	Supply for Internal Circuits. Connect DRV_S to DRV directly.
BOOT	E7	19	I	High Side MOSFET Gate Driver Supply. Connect a 0.01μF ceramic capacitor (voltage rating > 10V) from BOOT to SW to supply the gate drive for the high side MOSFETs.
SYS	F1–F4	13,14	I/O	System Voltage Sense and Charger FET Connection. Connect SYS to the system output at the output bulk capacitors. Bypass SYS locally with 1μF.
BGATE	F5	10	O	External Discharge MOSFET Gate Connection. BGATE drives an external P-Channel MOSFET to provide a very low resistance discharge path. Connect BGATE to the gate of the external MOSFET. BGATE is low during supplement mode and when no input is connected.
$\overline{PG}$	F6	7	I	Power Good Open Drain Output. /PG is pulled low when a valid supply is connected to IN. A valid supply is between V_{BAT}+V_{SLP} and V_{OVP}. If no supply is connected or the supply is out of this range, $\overline{PG}$ is high impedance.
DRV	F7	6	O	Gate Drive Supply. DRV is the bias supply for the gate drive of the internal MOSFETs. bypass DRV to PGND with a 1μF ceramic capacitor. DRV may be used to drive external loads up to 10mA. DRV is active whenever the input is connected and $V_{SUPPLY} > V_{UVLO}$ and V_{SUPPLY} > (V_{BAT} + V_{SLP})
BAT	G1–G4	11, 12	I/O	Battery Connection. Connect to the positive terminal of the battery. Additionally, bypass BAT to GND with a 1μF capacitor.
TS	G5	9	I	Battery Pack NTC Monitor. Connect TS to the center tap of a resistor divider from DRV to GND. The NTC is connected from TS to GND. The TS function in the bq24278 provides 2 thresholds for Hot/ Cold shutoff, with 2 additional thresholds for JEITA compliance. See the *NTC Monitor* section for more details on operation and selecting the resistor values.
$\overline{CHG}$	G6	8	O	Charge Status Open Drain Output. $\overline{CHG}$ is pulled low when a charge cycle starts and remains low while charging. $\overline{CHG}$ is high impedance when the charging terminates and when no supply exists. $\overline{CHG}$ does not indicate recharge cycles.
ISET	G7	5	I	Charge Current Programming Input. Connect a resistor from ISET to GND to program the fast charge current. The charge current is programmable from 550mA to 2.5A.
Thermal Pad	—	Pad	—	There is an internal electrical connection between the exposed thermal pad and the VSS pin of the device. The thermal pad must be connected to the same potential as the VSS pin on the printed circuit board. Do not use the thermal pad as the primary ground input for the device. VSS pin must be connected to ground at all times.

TYPICAL APPLICATION CIRCUIT

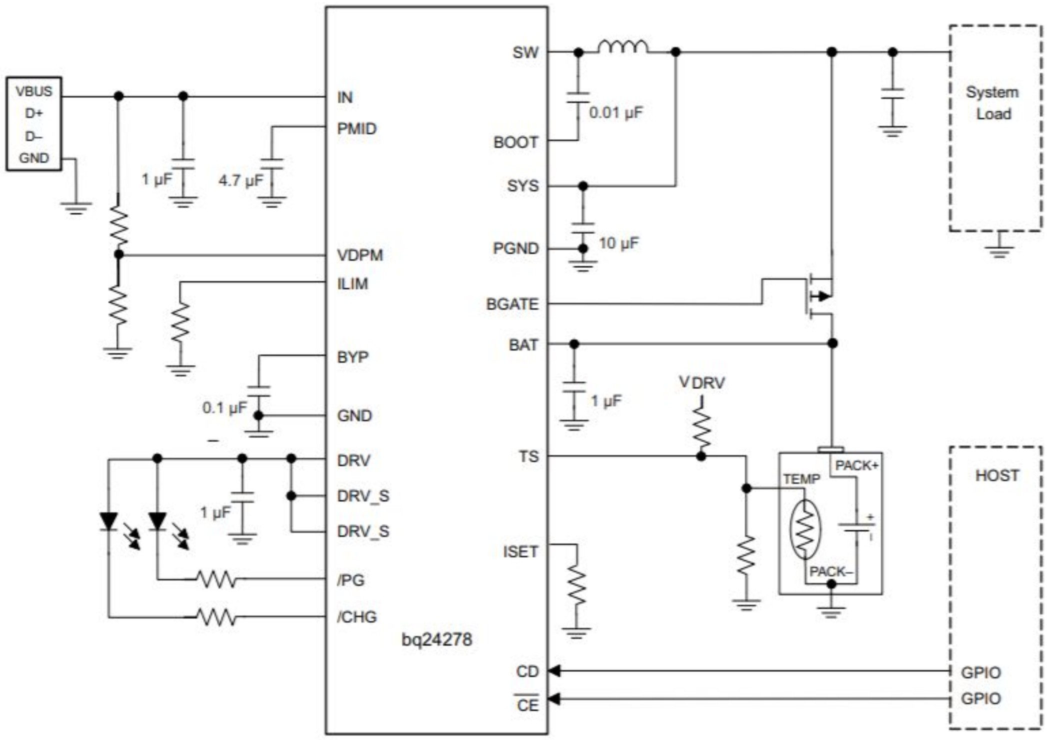


Figure 1. bq24278 Application Circuit, External Discharge FET Connected

DETAILED DESCRIPTION

The bq24278 is a highly integrated single cell Li-Ion battery charger and system power path management devices targeted for space-limited, portable applications with high capacity batteries. The power path management feature allows the bq24278 to power the system from a high efficiency DC to DC converter while simultaneously and independently charging the battery. The charger monitors the battery current at all times and reduces the charge current when the system load requires current above the input current limit. This allows for proper charge termination and enables the system to run with a defective or absent battery pack. Additionally, this enables instant system turn-on even with a totally discharged battery or no battery. The power-path management architecture also permits the battery to supplement the system current requirements when the adapter cannot deliver the peak system currents. This enables the use of a smaller adapter. The battery is charged in three phases: conditioning, constant current and constant voltage. In all charge phases, an internal control loop monitors the IC junction temperature and reduces the charge current if the internal temperature threshold is exceeded.

Charge Mode Operation

Charge Profile

Charging is done through the internal battery MOSFET. When the battery voltage is above 3.5V, the system output (SYS) is connected to the battery to maximize the charging efficiency. There are 5 loops that influence the charge current; constant current loop (CC), constant voltage loop (CV), thermal regulation loop, minimum system voltage loop (MINSYS) and input voltage dynamic power management loop (V_{IN-DPM}). During the charging process, all five loops are enabled and the dominant one takes control. The bq24278 supports a precision Li-Ion or Li-Polymer charging system for single-cell applications. The minimum system output feature regulates the system voltage to a minimum of $V_{SYS(REG)}$, so that startup is enabled even for a missing or deeply discharged battery. Figure 2 shows a typical charge profile including the minimum system output voltage feature.

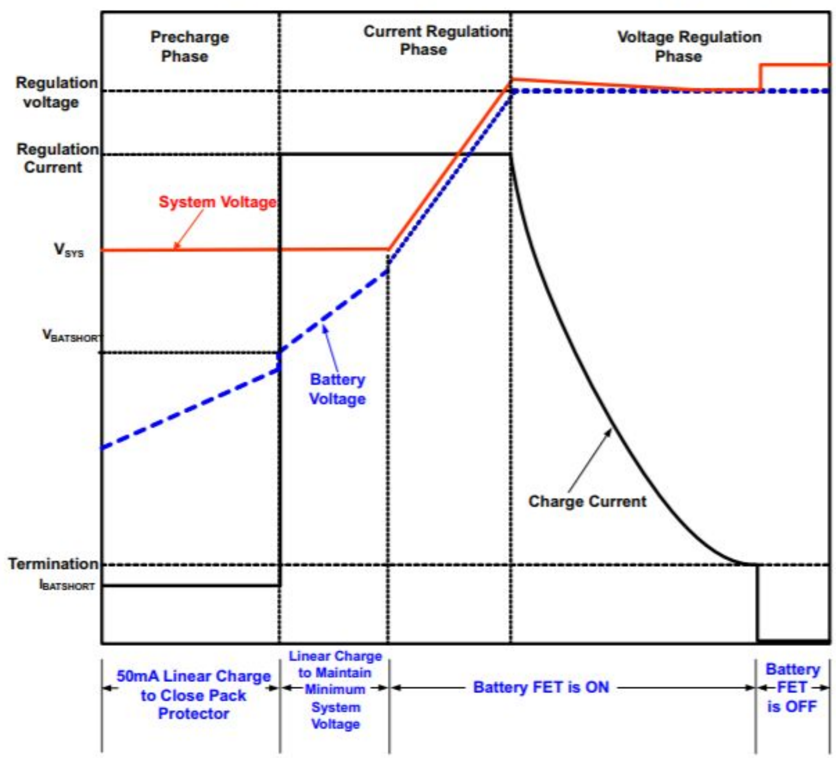


Figure 2. Typical Charging Profile of bq24278

PWM Controller in Charge Mode

The bq24278 provides an integrated, fixed 1.5 MHz frequency voltage-mode controller with to power the system and supply the charge current. The converter is internally compensated and provides enough phase margin for stable operation, allowing the use of small ceramic capacitors with very low ESR.

The bq24278 input scheme prevents battery discharge when the supply voltage is lower than V_{BAT}. The high-side N-MOSFET (Q1) switches to control the power delivered to SYS. The DRV LDO supplies the gate drive for the internal MOSFETs. The high-side MOSFET is supplied by a boot strap circuit with external boot-strap capacitor (BST).

The input is protected from short circuit by a cycle-by-cycle current limit that is sensed through the high-side MOSFET. The threshold is set to a nominal 5-A peak current. The input also utilizes an input current limit that limits the current from the power source.

Battery Charging Process

When the battery is deeply discharged or shorted, the bq24278 applies a 50mA current to charge the battery voltage up to acceptable charging levels. During this time, the battery FET is linearly regulated to maintain the system output regulation at $V_{SYS(REG)}$. Once the battery rises above V_{SHORT}, the charge current increases to the fastcharge current setting. The SYS voltage is regulated to $V_{SYS(REG)}$ while the battery is linearly charged through the battery FET. Additionally, the thermal regulation loop reduces the charge current to maintain the die temperature at safe levels. Under normal conditions, the time spent in this region is a very short percentage of the total charging time, so if the charge current is reduced, the reduced charge rate does not have a major negative effect on total charge time. If the current limit for the SYS output is reached (limited by the input current limit, or V_{IN_DPM}), the charge current is reduced to provide the system with all the current that is needed. If the charge current is reduced to 0mA, pulling further current from SYS causes the output to fall to the battery voltage and enter supplement mode (see the "*Dynamic Power Path Management*" section for more details).

Once the battery is charged enough to where the system voltage begins to rise above V_{SYSREG} (depends on the charge current setting), the battery FET is turned on fully and the battery is charged with the programmed charge current programmed using the ISET input, I_{CHARGE}. The slew rate for fast charge current is controlled to minimize the current and voltage over-shoot during transient. The charge current is programmed by connecting a resistor from ISET to GND. The value for R_{ISET} is calculated using Equation 1.

$$R_{ISET} = \frac{K_{ISET}}{I_{CHARGE}} \quad (1)$$

Where I_{CHARGE} is the programmed fast charge current and K_{ISET} is the programming factor found in the Electrical Characteristics table.

The charge current is regulated to I_{CHARGE} until the battery is charged to the regulation voltage. Once the battery voltage is close to the regulation voltage, V_{BATREG}, the charge current is tapered down as shown in Figure 2 while the SYS output remains connected to the battery. The voltage regulation feedback occurs by monitoring the battery-pack voltage between the BAT and PGND pins.

The bq24278 monitors the charging current during the voltage regulation phase. Once the termination threshold, I_{TERM}, is detected and the battery voltage is above the recharge threshold, the bq24278 terminates charge and turns off the battery charging FET and begins battery detection. The system output is regulated to the $V_{BAT(REG)}$ voltage and supports the full current available from the input and the battery supplement mode (see the "*Dynamic Power Path Management*" section for more details) is still available.

A charge cycle is initiated when one of the following conditions is detected:

1. The battery voltage falls below the $V_{BAT(REG)}$-V_{RCH} threshold.
2. V_{IN} Power-on reset (POR)
3. $\overline{CE}$ toggle
4. Toggle Hi-Impedance mode (using CD)

If the battery voltage is ever greater than $V_{BAT(REG)}$, the PWM converter is turned off and the battery is discharged to $V_{BAT(REG)}$. This prevents further overcharging the battery and allows the battery to discharge to safe operating levels.

Battery Detection

When termination conditions are met, a battery detection cycle is started. During battery detection, I_{DETECT} is pulled from V_{BAT} for t_{DETECT} to verify there is a battery. If the battery voltage remains above V_{DETECT} for the full duration of t_{DETECT}, a battery is determined to be present and the IC enters "Charge Done". If V_{BAT} falls below V_{DETECT}, a "Battery Not Present" fault is signaled and battery detection continues. During the next cycle of battery detection, the bq24278 turns on $I_{BATSHORT}$ for t_{DETECT}. If V_{BAT} rises to V_{DETECT}, the current source is turned off and after t_{DETECT}, the battery detection continues through another current sink cycle. Battery detection continues until charge is disabled or a battery is detected. Once a battery is detected, the fault status clears and a new charge cycle begins. Battery detection is disabled when termination is disabled.

Dynamic Power Path Management

The bq24278 features a SYS output that powers the external system load connected to the battery. This output is active whenever a source is connected to IN or BAT. The following sections discuss the behavior of SYS with a source connected to the supply or a battery source only.

Input Source Connected

When a source is connected to IN, and the bq24278 is enabled, the buck converter starts up. If charging is enabled using $\overline{CE}$, the charge cycle is initiated. When V_{BAT} > 3.5V, the SYS output is connected to V_{BAT}. If the SYS voltage falls to $V_{SYS(REG)}$, it is regulated to that point to maintain the system output even with a deeply discharged or absent battery. In this mode, the SYS output voltage is regulated by the buck converter and the battery FET is linearly regulated to regulate the charge current into the battery. The current from the supply is shared between charging the battery and powering the system load at SYS. The dynamic power path management (DPPM) circuitry of the bq24278 monitors the SYS voltage continuously and if V_{SYS} falls to V_{MINSYS}, adjusts charge current to maintain the load on SYS while preventing the system voltage from crashing. If the charge current is reduced to zero and the load increases further, the bq24278 enters battery supplement mode. During supplement mode, the battery FET is turned on and the battery supplements the system load. When the charge current is reduced by the DPPM regulation loop, the safety timer runs at half speed, so that it is twice a long. This prevents false safety timer faults. See the *Safety Timer* section for more details.

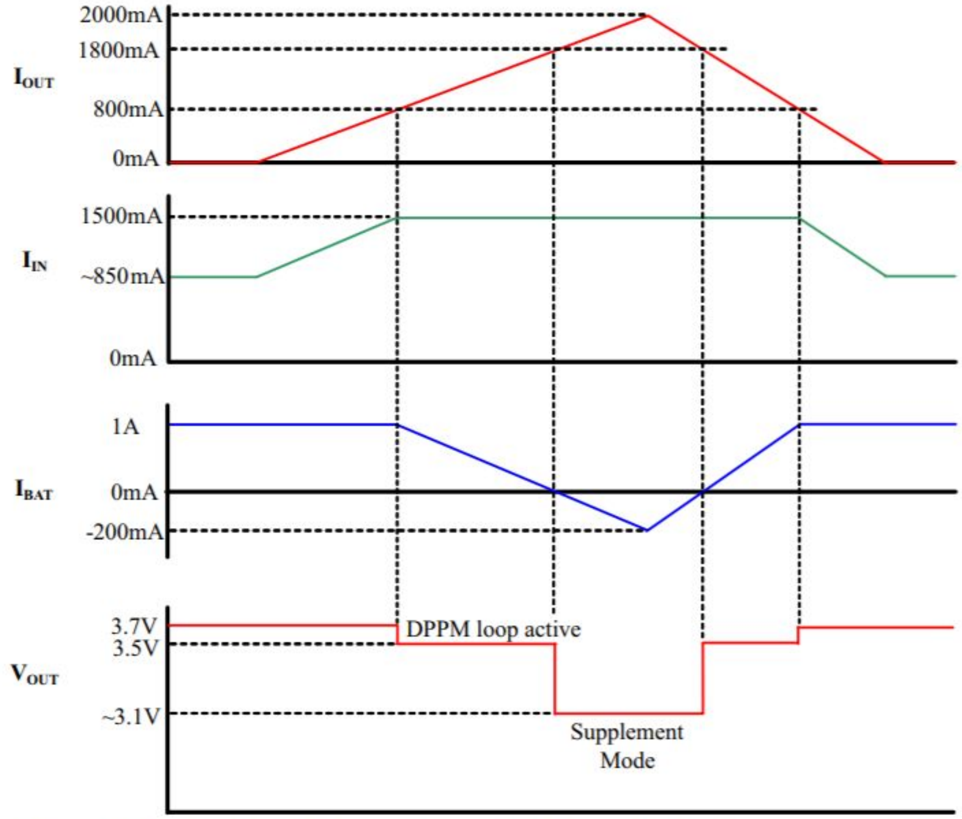


Figure 3. Example DPPM Response (V_{Supply}=5V, V_{BAT} = 3.1V, 1.5A Input current limit)

If the $V_{BAT(REG)}$ threshold is ever less than the battery voltage, the battery FET is turned off to allow the battery to relax down to $V_{BAT(REG)}$ and the SYS output is regulated to $V_{SYSREG(FETOFF)}$. If the battery is ever above V_{BOVP}, the battery OVP circuit shuts the PWM converter off and the battery FET is turned on to discharge the battery to safe operating levels.

The input current limit for IN is programmable using the ILIM input. Connect a resistor from ILIM to GND to set the maximum input current limit. The programmable range for the IN input current limit is 1000mA to 2.5A. R_{ILIM} is calculated using Equation 2:

$$R_{ILIM} = \frac{K_{ILIM}}{I_{IN\_LIM}} \quad (2)$$

Where I_{IN_LIM} is the programmed input current limit and K_{ILIM} is the programming factor found in the Electrical Characteristics table.

Battery Only Connected

When the battery is connected with no input source, the battery FET is turned on similar to supplement mode. In this mode, the current is not regulated; however, there is a short circuit current limit. If the short circuit limit is reached, the battery FET is turned off for the deglitch time. After the deglitch time, the battery FET is turned on to test and see if the short has been removed. If it has not, the FET turns off and the process repeats until the short is removed.

Battery Discharge FET (BGATE)

The bq24278 contains a MOSFET driver to drive an external P-Channel MOSFET between the battery and the system output. This external FET provides a low impedance path for supply the system from the battery. Connect BGATE to the gate of the external discharge MOSFET. BGATE is on under the following conditions:

1. No valid input supply connected.
2. CD=high (High-Impedance Mode)

This FET is optional and runs in parallel with the internal charge FET during discharge. Note that this FET is not protected by the short circuit current limit.

Safety Timer

At the beginning of charging process, the bq24278 starts the 6 hour safety timer. This timer is active during the entire charging process. If charging has not terminated before the safety timer expires, the charge cycle is terminated and the battery FET is turned off. A new charge cycle must be entered using $\overline{CE}$ or High Impedance mode or input power must be toggled in order to clear the safety timer fault.

During the fast charge phase, several events increase the timer durations.

1. The system load current reduces the available charging current
2. The input current is reduced because the V_{INDPM} loop is preventing the supply from crashing.
3. The device has entered thermal regulation because the IC junction temperature has exceed $T_{J(REG)}$

During these events, the timer is slowed by half to extend the timer and prevent any false timer faults. Starting a new charge cycle by toggling the input, toggling the $\overline{CE}$ pin to disable/enable charge, resets the safety timer. Additionally, thermal shutdown events cause the safety timer to reset.

LDO Output (DRV)

The bq24278 contains a linear regulator (DRV) that is used to supply the internal MOSFET drivers and other circuitry. Additionally, DRV supplies up to 10mA external loads to power the STAT LED or other external circuitry. The LDO is on whenever a supply is connected to the input of the. The DRV is disabled under the following conditions:

1. V_{IN} < UVLO
2. $V_{IN} < V_{BAT} + V_{SLP}$
3. Thermal Shutdown

External NTC Monitoring (TS)

The I^2C interface allows the user to easily implement the JEITA standard for systems where the battery pack thermistor is monitored by the host. Additionally, the bq24278 provides a flexible, voltage-based TS input for monitoring the battery pack NTC thermistor, Figure 4. The voltage at TS is monitored to determine that the battery is at a safe temperature during charging. The bq24278 enables the user to easily implement the JEITA standard for charging temperature. The JEITA specification is shown in Figure 5.

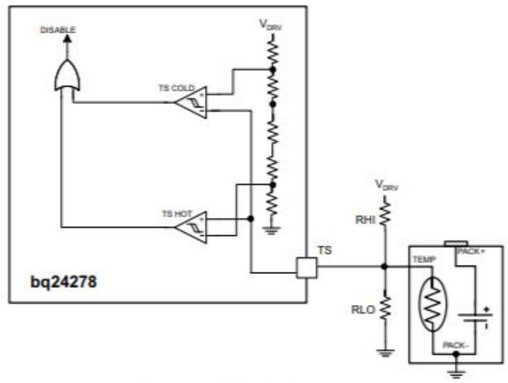


Figure 4. TS Circuit

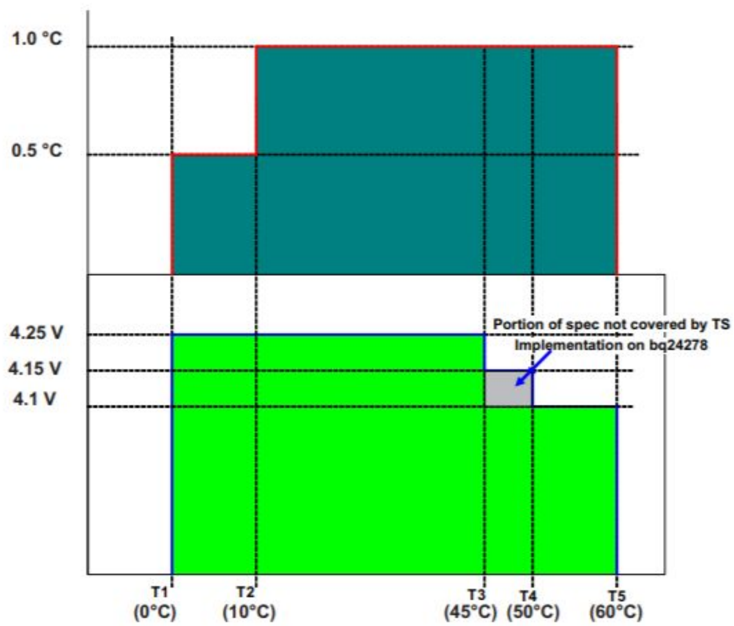


Figure 5. Charge Current During TS Conditions

To satisfy the JEITA requirements, four temperature thresholds are monitored; the cold battery threshold; the cold battery threshold (T_{NTC} < 0°C), the cool battery threshold (0°C < T_{NTC} < 10°C), the warm battery threshold (45°C < T_{NTC} < 60°C) and the hot battery threshold (T_{NTC} > 60°C). These temperatures correspond to the V_{COLD}, V_{COOL}, V_{WARM}, and V_{HOT} thresholds. Charging is suspended and timers are suspended when $V_{TS} < V_{HOT}$ or $V_{TS} > V_{COLD}$. When $V_{HOT} < V_{TS} < V_{WARM}$, the battery regulation voltage is reduced by 140 mV from the programmed regulation threshold. When $V_{COOL} < V_{TS} < V_{COLD}$, the charging current is reduced to half of the programmed charge current.

The TS function is voltage based for maximum flexibility. Connect a resistor divider from DRV to GND with TS connected to the center tap to set the threshold. The connections are shown in Figure 10. The resistor values are calculated using the following equations:

$$RLO = \frac{V_{DRV} \times RCOLD \times RHOT \times \left[\frac{1}{V_{COLD}} - \frac{1}{V_{HOT}} \right]}{RHOT \times \left[\frac{V_{DRV}}{V_{HOT}} - 1 \right] - RCOLD \times \left[\frac{V_{DRV}}{V_{COLD}} - 1 \right]} \quad (3)$$

$$RHI = \frac{\frac{V_{DRV}}{V_{COLD}} - 1}{\frac{1}{RLO} + \frac{1}{RCOLD}} \quad (4)$$

Where:

$V_{COLD} = 0.60 \times V_{DRV}$

$V_{HOT} = 0.30 \times V_{DRV}$

Where RHOT is the NTC resistance at the hot temperature and RCOLD is the NTC resistance at cold temperature.

The WARM and COOL thresholds are not independently programmable. The COOL and WARM NTC resistances for a selected resistor divider are calculated using the following equations:

$$RCOOL = \frac{RLO \times 0.564 \times RHI}{RLO - RLO \times 0.564 - RHI \times 0.564} \quad (5)$$

$$RWARM = \frac{RLO \times 0.383 \times RHI}{RLO - RLO \times 0.383 - RHI \times 0.383} \quad (6)$$

Thermal Regulation and Protection

During the charging process, to prevent the IC from overheating, bq24278 monitor the junction temperature, T_J, of the die and begins to taper down the charge current once T_J reaches the thermal regulation threshold, T_{CF}. The charge current is reduced to zero when the junction temperature increases about 10°C above TCF. Once the charge current is reduced, the system current is reduced while the battery supplements the load to supply the system. This may cause a thermal shutdown of the bq24278 if the die temperature rises too high. At any state, if T_J exceeds T_{SHTDWN}, bq24278 suspends charging and disables the buck converter. During thermal shutdown mode, PWM is turned off, and the timer is reset. The charging cycle resets when T_J falls below T_{SHTDWN} by approximately 10°C.

Input Voltage Protection in Charge Mode

Sleep Mode

The bq24278 enters the low-power sleep mode if the voltage on VIN falls below sleep-mode entry threshold, $V_{BAT}+V_{SLP}$, and V_{VBUS} is higher than the undervoltage lockout threshold, V_{UVLO}. This feature prevents draining the battery during the absence of V_{IN}. When $V_{IN} < V_{BAT} + V_{SLP}$, the bq24278 turns off the PWM converter, and turns the battery FET and BGATE on. Once $V_{IN} > V_{BAT} + V_{SLP}$, the device initiates a new charge cycle.

Input Voltage Based DPM

During normal charging process, if the input power source is not able to support the programmed or default charging current, the supply voltage decreases. Once the supply drops to V_{IN_DPM} (set by VDPM), the input current limit is reduced down to prevent the further drop of the supply. This feature ensures IC compatibility with adapters with different current capabilities without a hardware change. Figure 6 shows the V_{IN-DPM} behavior to a current limited source. In this figure the input source has a 750mA current limit and the charging is set to 750mA. The SYS load is then increased to 1.2A.

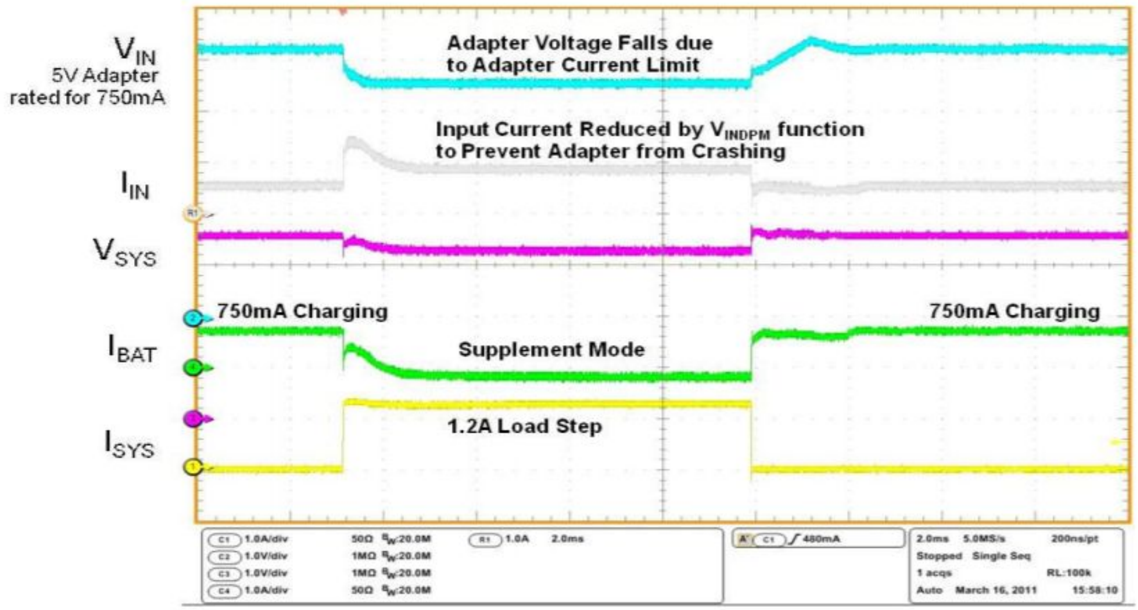


Figure 6. bq24278 $V_{IN\text{-}DPM}$

The VINDPM threshold for the IN input is set using a resistor divider with VDPM connected to the center tap. Select 10kΩ for the bottom resistor. The top resistor is selected using Equation 7:

$$RTOP = \frac{10k\Omega \times (V_{INDPM} - V_{DPM})}{V_{DPM}} \tag{7}$$

Where V_{INDPM} is the desired V_{INDPM} threshold and V_{DPM} is the regulation threshold specified in the Electrical Characteristics table.

Bad Source Detection

When a source is connected to IN, the bq24278 runs a Bad Source Detection procedure to determine if the source is strong enough to provide some current to charge the battery. A current sink is turned on (70mA) for 32ms. If the source is valid after the 32ms ($V_{BADSOURCE} < V_{IN} < V_{OVP}$), the buck converter starts up and normal operation continues. If the supply voltage falls below V_{BAD_SOURCE} during the detection, the current sink shuts off for 2s and then retries. The detection circuits retries continuously until a valid source is detected after the detection time. If during normal operation the source falls to V_{BAD_SOURCE}, the bq24278 turns off the PWM converter, turns the battery FET on and runs the bad source detection. Once a good source is detected, the device returns to normal operation.

Input Over-Voltage Protection

The bq24278 provides over-voltage protection on the input that protects downstream circuitry. The built-in input over-voltage protection to protect the device and other components against damage from overvoltage on the input supply (Voltage from V_{IN} to PGND). When $V_{IN} > V_{OVP}$, the bq24278 turns off the PWM converter, suspends the charging cycle and turns the battery FET on. Once the OVP fault is removed, the device returns to the operation it was in prior to the OVP fault.

Status Indicators ($\overline{CHG}$, $\overline{PG}$)

The bq24278 contains two open-drain outputs that signal its status. The $\overline{PG}$ output indicates that a valid input source is connected to IN. $\overline{PG}$ is low when ($V_{BAT}+V_{SLP}$) < V_{IN} < V_{OVP}. When there is no supply connected to the input within this range, $\overline{PG}$ is high impedance. Table 1 illustrates the $\overline{PG}$ behavior under different conditions.

The $\overline{CHG}$ output indicates new charge cycles. When a new charge cycle is initiated by $\overline{CE}$, toggling High Impedance mode or toggling the input power, $\overline{CHG}$ goes low and remains low until termination. After termination, $\overline{CHG}$ remains high impedance until a new charge cycle is initiated. $\overline{CHG}$ does not go low during recharge cycles. Table 2 illustrates the $\overline{CHG}$ behavior under different conditions.

Connect $\overline{PG}$ and $\overline{CHG}$ to the DRV output through an LED for visual indication, or connect through a 100kΩ pullup to the required logic rail for host indication.

Table 1. $\overline{PG}$ Status Indicator

CHARGE STATE	$\overline{PG}$ BEHAVIOR
$V_{IN} < V_{UVLO}$	High-Impedance
$V_{IN} < (V_{BAT}+V_{SLP})$	High-Impedance
$(V_{BAT}+V_{SLP}) < V_{IN} < V_{OVP}$	Low
$V_{IN} > V_{OVP}$	High-Impedance

Table 2. $\overline{CHG}$ Status Indicator

CHARGE STATE	$\overline{CHG}$ BEHAVIOR
Charge in progress	Low (first charge cycle) High-Impedance (recharge cycles)
Charging suspended by thermal loop	
Charge Done	High-Impedance
Recharge Cycle after Termination	
Timer Fault	
No Valid Supply, $V_{IN}>V_{OVP}$ or $V_{IN} < V_{SLEEP}$	
No Battery Present	

APPLICATION INFORMATION

Output Inductor and Capacitor Selection Guidelines

When selecting an inductor, several attributes must be examined to find the right part for the application. First, the inductance value should be selected. The bq24278 is designed to work with 1.5µH to 2.2µH inductors. The chosen value will have an effect on efficiency and package size. Due to the smaller current ripple, some efficiency gain is reached using the 2.2µH inductor, however, due to the physical size of the inductor, this may not be a viable option. The 1.5µH inductor provides a good tradeoff between size and efficiency.

Once the inductance has been selected, the peak current must be calculated in order to choose the current rating of the inductor. Use Equation 8 to calculate the peak current.

$$I_{PEAK} = I_{LOAD(MAX)} \times \left(1 + \frac{\%_{RIPPPLE}}{2}\right) \quad (8)$$

The inductor selected must have a saturation current rating less than or equal to the calculated I_{PEAK}. Due to the high currents possible with the bq24278, a thermal analysis must also be done for the inductor. Many inductors have 40°C temperature rise rating. This is the DC current that will cause a 40°C temperature rise above the ambient temperature in the inductor. For this analysis, the typical load current may be used adjusted for the duty cycle of the load transients. For example, if the application requires a 1.5A DC load with peaks at 2.5A 20% of the time, a Δ40°C temperature rise current must be greater than 1.7A:

$$I_{TEMPRISE} = I_{LOAD} + D \times)I_{PEAK} - I_{LOAD}) = 1.5\text{ A} + 0.2 \times (2.5\text{ A} - 1.5\text{ A}) = 1.7\text{ A} \quad (9)$$

The bq24278 provides internal loop compensation. Using this scheme, the bq24278 is stable with 10µF to 200µF of local capacitance. The capacitance on the SYS rail can be higher if distributed amongst the rail. To reduce the output voltage ripple, a ceramic capacitor with the capacitance between 10µF and 47µF is recommended for local bypass to SYS.

Appendix C: NTC Thermistor Datasheet

VISHAY. www.vishay.com

NTCLE100E3

Vishay BCcomponents

ELECTRICAL DATA AND ORDERING INFORMATION

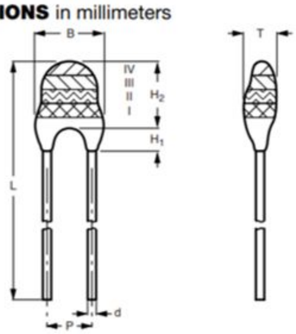
R_{25} (Ω)	R_{25}-TOL. (± %)	$B_{25/85}$ (K)	$B_{25/85}$-TOL. (± %)	UL RECOGNIZED (Y/N)	SAP MATERIAL NUMBER NTCLE100E3....B0/T1/T2 RoHS COMPLIANT WITH EXEMPTIONS (1)	SAP MATERIAL NUMBER NTCLE100E3....B0A/T1A/T2A RoHS COMPLIANT WITHOUT EXEMPTIONS (1)	COLOR CODE (2) I	II	III
330	2, 3, 5	3560	1.5	Y	331*B0	331*B0A	Orange	Orange	Brown
470	2, 3, 5	3560	1.5	Y	471*B0	471*B0A	Yellow	Violet	Brown
680	2, 3, 5	3560	1.5	Y	681*B0	681*B0A	Blue	Grey	Brown
1000	2, 3, 5	3528	0.5	Y	102*B0	102*B0A	Brown	Black	Red
1500	2, 3, 5	3528	0.5	Y	152*B0	152*B0A	Brown	Green	Red
2000	2, 3, 5	3528	0.5	Y	202*B0	202*B0A	Red	Black	Red
2200	2, 3, 5	3977	0.75	Y	222*B0	222*B0A	Red	Red	Red
2700	2, 3, 5	3977	0.75	Y	272*B0	272*B0A	Red	violet	Red
3300	2, 3, 5	3977	0.75	Y	332*B0	332*B0A	Orange	Orange	Red
4700	2, 3, 5	3977	0.75	Y	472*B0	472*B0A	Yellow	Violet	Red
5000	2, 3, 5	3977	0.75	Y	502*B0	502*B0A	Green	Black	Red
6800	2, 3, 5	3977	0.75	Y	682*B0	682*B0A	Blue	Grey	Red
10 000	2, 3, 5	3977	0.75	Y	103*B0	103*B0A	Brown	Black	Orange
12 000	2, 3, 5	3740	2	Y	123*B0	123*B0A	Brown	Red	Orange
15 000	2, 3, 5	3740	2	Y	153*B0	153*B0A	Brown	Green	Orange
22 000	2, 3, 5	3740	2	Y	223*B0	223*B0A	Red	Red	Orange
33 000	2, 3, 5	4090	1.5	Y	333*B0	333*B0A	Orange	Orange	Orange
47 000	2, 3, 5	4090	1.5	Y	473*B0	473*B0A	Yellow	Violet	Orange
50 000	2, 3, 5	4190	1.5	Y	503*B0	503*B0A	Green	Black	Orange
68 000	2, 3, 5	4190	1.5	Y	683*B0	683*B0A	Blue	Grey	Orange
100 000	2, 3, 5	4190	1.5	Y	104*B0	104*B0A	Brown	Black	Yellow
150 000	2, 3, 5	4370	2.5	Y	154*B0	154*B0A	Brown	Green	Yellow
220 000	2, 3, 5	4370	2.5	Y	224*B0	224*B0A	Red	Red	Yellow
330 000	2, 3, 5	4570	1.5	N	334*B0	334*B0A	Orange	Orange	Yellow
470 000	2, 3, 5	4570	1.5	N	474*B0	474*B0A	Yellow	Violet	Yellow

Notes

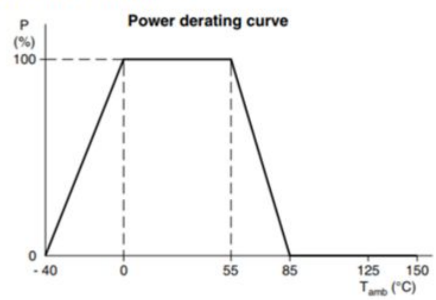
(1) Replace * in SAP by J for 5 %, H for 3 %, G for 2 %.

(2) For R_{25} ± 2 % band IV is red, ± 3 % band IV is orange, ± 5 % band IV is gold.

DIMENSIONS in millimeters



POWER DERATING



Note

- Zero power is considered as measuring power max. 1 % of max. power. Voltage on the NTC should always be below 50 V_{DC}.

PHYSICAL DIMENSIONS FOR RELEVANT TYPE (all dimensions in millimeters)

R_{25}-VALUE	$B_{MAX.}$	d	H_1 MIN.	H_1 MAX.	$H_{2\ MAX.}$	L	P	$T_{MAX.}$
3.3 Ω to 220 Ω	5.0	0.6 ± 0.06	1.0	4.0	6.0	24 ± 1.5	2.54	4.0
330 Ω to 470 kΩ	3.3 ± 0.5	0.6 ± 0.06	1.0	3.0	6.0	24 ± 1.5	2.54	3.0

Revision: 22-Dec-16 2 Document Number: 29049

For technical questions, contact: nlr@vishay.com

For complete Curve Computation, visit: www.vishay.com/thermistors/ntc-curve-list/

RESISTANCE VALUES AT INTERMEDIATE TEMPERATURES WITH R_{25} AT (2.2, 2.7, 3.3, 4.7, 5.0, 6.8, 10) kΩ

T_{OPER} (°C)	PART NUMBER NTCLE100E3222*** R_T (Ω)	PART NUMBER NTCLE100E3272*** R_T (Ω)	PART NUMBER NTCLE100E3332*** R_T (Ω)	PART NUMBER NTCLE100E3472*** R_T (Ω)	PART NUMBER NTCLE100E3502*** R_T (Ω)	PART NUMBER NTCLE100E3682*** R_T (Ω)	PART NUMBER NTCLE100E3103*** R_T (Ω)	TCR (%/K)	$\Delta R/R$ DUE TO $B_{tol.}$ (%)
-40	73 061	89 665	109 591	156 084	166 047	225 824	332 094	-6.62	2.79
-35	52 778	64 773	79 167	112 753	119 950	163 132	239 900	-6.39	2.52
-30	38 544	47 304	57 816	82 344	87 600	119 136	175 200	-6.18	2.26
-25	28 443	34 907	42 665	60 765	64 643	87 915	129 287	-5.98	2.02
-20	21 199	26 017	31 798	45 288	48 179	65 524	96 358	-5.78	1.78
-15	15 950	19 575	23 925	34 075	36 250	49 300	72 500	-5.60	1.55
-10	12 110	14 862	18 165	25 872	27 523	37 431	55 046	-5.42	1.33
-5	9275	11 382	13 912	19 814	21 078	28 667	42 157	-5.25	1.12
0	7162	8790	10 743	15 300	16 277	22 137	32 554	-5.09	0.92
5	5574	6841	8362	11 909	12 669	17 230	25 339	-4.93	0.72
10	4372	5365	6558	9340	9936	13 513	19 872	-4.79	0.53
15	3454	4239	5180	7378	7849	10 675	15 698	-4.64	0.35
20	2747	3372	4121	5869	6244	8492	12 488	-4.51	0.17
25	2200	2700	3300	4700	5000	6800	10 000	-4.38	0.00
30	1773	2176	2659	3788	4030	5480	8059	-4.25	0.17
35	1438	1764	2156	3071	3267	4444	6535	-4.13	0.32
40	1173	1439	1759	2505	2665	3624	5330	-4.02	0.48
45	961.8	1180	1443	2055	2186	2973	4372	-3.91	0.63
50	793.2	973.4	1190	1694	1803	2452	3605	-3.80	0.77
55	657.5	806.9	986.3	1405	1494	2032	2989	-3.70	0.91
60	547.8	672.3	821.7	1170	1245	1693	2490	-3.60	1.05
65	458.6	562.8	687.9	979.7	1042	1417	2084	-3.51	1.18
70	385.7	473.3	578.5	823.9	876.5	1192	1753	-3.42	1.31
75	325.8	399.8	488.7	696.0	740.5	1007	1481	-3.33	1.44
80	276.4	339.2	414.6	590.5	628.2	854.3	1256	-3.25	1.56
85	235.5	289.0	353.2	503.0	535.2	727.8	1070	-3.17	1.68
90	201.4	247.2	302.1	430.2	457.7	622.5	915.4	-3.09	1.79
95	172.9	212.2	259.4	369.4	393.0	534.5	786.0	-3.01	1.90
100	149.0	182.9	223.5	318.3	338.6	460.6	677.3	-2.94	2.01
105	128.9	158.2	193.3	275.3	292.9	398.3	585.7	-2.87	2.12
110	111.8	137.2	167.7	238.9	254.2	345.7	508.3	-2.80	2.22
115	97.37	119.5	146.1	208.0	221.3	301.0	442.6	-2.74	2.32
120	85.05	104.4	127.6	181.7	193.3	262.9	386.6	-2.67	2.42
125	74.52	91.46	111.8	159.2	169.4	230.3	338.7	-2.61	2.51
130	65.49	80.38	98.24	139.9	148.8	202.4	297.7	-2.55	2.61
135	57.72	70.84	86.59	123.3	131.2	178.4	262.4	-2.50	2.70
140	51.02	62.62	76.53	109.0	116.0	157.7	231.9	-2.44	2.78
145	45.22	55.49	67.83	96.60	102.8	139.8	205.5	-2.39	2.87
150	40.18	49.31	60.27	85.84	91.32	124.2	182.6	-2.34	2.96

Appendix D: Boothroyd-Dewhurst Method Assembly Time Tables

MANUAL HANDLING — ESTIMATED TIMES (seconds)

Key: ONE HAND — parts can be grasped and manipulated by one hand without the aid of grasping tools

		parts are easy to grasp and manipulate					parts present handling difficulties (1)				
		thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
$(\alpha + \beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
$360° \le (\alpha + \beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
$540° \le (\alpha + \beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
$(\alpha + \beta) = 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

Key: ONE HAND with GRASPING AIDS — parts can be grasped and manipulated by one hand but only with the use of grasping tools

		parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
		parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
		parts are easy to grasp and manipulate		parts present handling difficulties (1)		parts are easy to grasp and manipulate		parts present handling difficulties (1)			
		thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm		
		0	1	2	3	4	5	6	7	8	9
$\alpha \le 180°$, $0 \le \beta \le 180°$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
$\alpha \le 180°$, $\beta = 360°$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
$\alpha = 360°$, $0 \le \beta \le 180°$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
$\alpha = 360°$, $\beta = 360°$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

Key: TWO HANDS for MANIPULATION

		parts present no additional handling difficulties					parts present additional handling difficulties (e.g., sticky, delicate, slippery, etc.)(1)				
		$\alpha \le 180°$			$\alpha = 360°$		$\alpha \le 180°$			$\alpha = 360°$	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary)(2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

Key: TWO HANDS required for LARGE SIZE

		parts can be handled by one person without mechanical assistance									two persons or mechanical assistance required for parts manipulation
		parts do not severely nest or tangle and are not flexible								parts severely nest or tangle or are flexible (2)	
		part weight < 10 lb				parts are heavy (> 10 lb)					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$		
		0	1	2	3	4	5	6	7	8	9
two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

Based on Geoffrey Boothroyd, Peter Dewhurst, Winston Anthony Knight, Product Design for Manufacture and Assembly, M. Dekker, 1994

Table D.1: Estimated Manual Assembly Handling Times

MANUAL INSERTION — ESTIMATED TIMES (seconds)

Key: PART ADDED but NOT SECURED

		after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
		easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
		no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
		0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately: part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

Key: PART SECURED IMMEDIATELY

		no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion: plastic bending or torsion			plastic deformation immediately after insertion: rivetting or similar operation			screw tightening immediately after insertion (6)	
		easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	not easy to align or position during assembly: no resistance to insertion	not easy to align or position during assembly: resistance to insertion (5)	easy to align and position during assembly (4)	not easy to align or position during assembly: no resistance to insertion	not easy to align or position during assembly: resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
		0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately: part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access or restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

Key: SEPARATE OPERATION

		mechanical fastening processes (part(s) already in place but not secured immediately after insertion): none or localized plastic deformation			mechanical fastening processes: bulk plastic deformation (large proportion of part is plastically deformed during fastening)	non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion): metallurgical processes			non-mechanical fastening processes	non-fastening processes	
		bending or similar processes	rivetting or similar processes	screw tightening (6) or other processes		no additional material required (e.g. resistance, friction welding, etc.)	additional material required: soldering processes	additional material required: weld/braze processes	chemical processes (e.g. adhesive bonding, etc.)	manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of part(s), etc.)	other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place	9	4	7	5	3.5	7	8	12	12	9	12

Table D.2: Table D.1: Estimated Manual Assembly Insertion Times