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Green Road

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Green Road:
Harvesting Wasted Vehicular Kinetic Energy from Transportation Infrastructure

A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Electrical and Computer Engineering by:

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Abstract

In this project, we designed and implemented a prototype device that harvests vehicular kinetic energy and converts it to electrical energy. The proposed solution is a three phase permanent magnetic generator capable of producing 15 volts from a car moving 60 mph while only imposing .06 Gs on the vehicle. This energy is fed through a custom built circuit that converts the voltage from AC to DC and can power roadside infrastructure.

Acknowledgements

We would first like to acknowledge our Advisor, Professor Alexander Wyglinski, for his continual guidance and support throughout the duration of our project. He has provided unwavering support and direction, making our project possible. Our team would also like to express our gratitude towards the Electrical and Computer Engineering department and faculty at Worcester Polytechnic Institute for providing the financial assistance and laboratories necessary for our project.

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Executive Summary

There are 8.6 million lane miles of roadway that cover the United States. These roads have seen few significant advancements and are being used in only one dimension. We wanted to use all this space for something more than just a surface to drive on and because of the increasing desire in this country for green and alternative energies that require more and more room, a "Green Road" just made sense. After finding that the average American driver drives 13,000 miles a year, we wondered if we could utilize some kinetic energy from all these vehicles on the roadway to create useful electrical power.

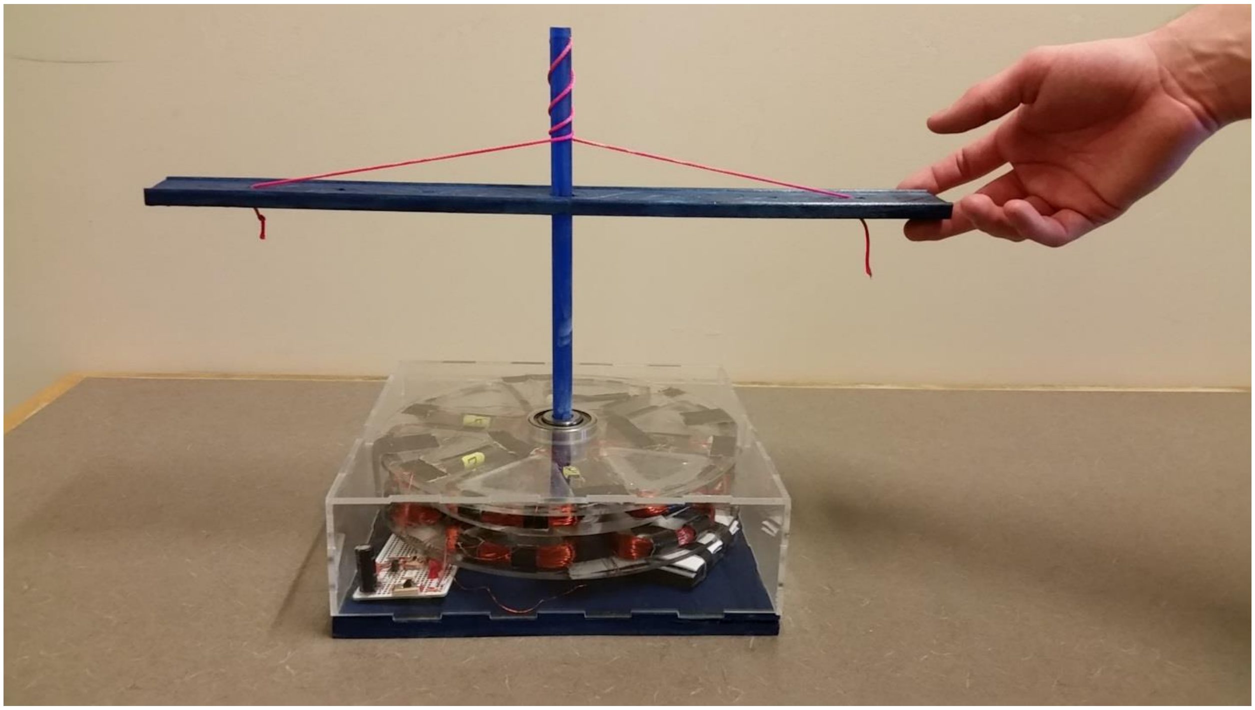
To begin this project we needed to look at the current infrastructure and see how we could best tailor to it. In many places roads are only a few feet thick meaning that any device in the road cannot be more than that. Lanes are also 9-12 feet wide so a device in the roadway would have to be large enough to account for vehicles moving around the lane. We also realized that feeding electricity back into the grid can be problematic, luckily the lights on the side of the road require lots of power. The almost 500,000 lights in Massachusetts require over 300 GWh/yr. If our proposed device could take these off the grid it could save millions of dollars a year.

For our design we decided to build a permanent magnet generator that would capture the weight and velocity of the car and convert that energy into usable electricity to power the streets. The design was based on Faraday's Law that was simulated in Mathematica to better understand the values for each parameter being: coil size, number of turns, magnetic strength, number of magnets, number of coils in parallel, and rotor spin rate. The generator was built and then tested

based on these prerequisites. The final output was only roughly 65% of the expected value but the generator was still powerful enough to power the boost converter, thus powering the lights.

The circuit used for our final design is very simple and is widely used for converting AC to DC. The waveform from each phase was passed through a full wave rectifier and then moves on to the smoothing capacitor that would finish converting to a DC signal. The signal was finally boosted to a 20 volt DC signal to successfully power the street lights. The circuit did work as intended and would boost the final signal to roughly 22V.

Finally all the parts of the project were put together. A pump drill was added to the generator to properly simulate a mechanical force hitting the device. The generator would output a 15V sine wave with a rotor spin rate of roughly 4.5 rev/sec. This signal would then properly become rectified and became boosted to 22V to then go on and power the LED arrays.



1.0 Introduction

Interest in renewable energies has grown in the past few decades. After the energy crisis in the 1970's and the creation of the Department of Energy there has been a push from the American populace and government to replace energy from fossil fuels with cleaner alternatives [1]. One of the main setbacks when developing a grid on clean energy is that many of the currently available energy options require large amounts of land to be effective sources of power [2]. This means that considerably sized swaths of land need to be cleared of foliage so that "green" energy can be installed. The good news is that the United States already has a huge amount of space in the form of our roadways. The U.S. has over 4 million miles of roadway [3] that are in need of updating and waiting to be utilized for energy. Currently the U.S. spends the majority of its power on fossil fuels, but there has recently been a decline in their use and a rise in other renewables [4]. A chart of these relationships can be seen in Figure 1 below,

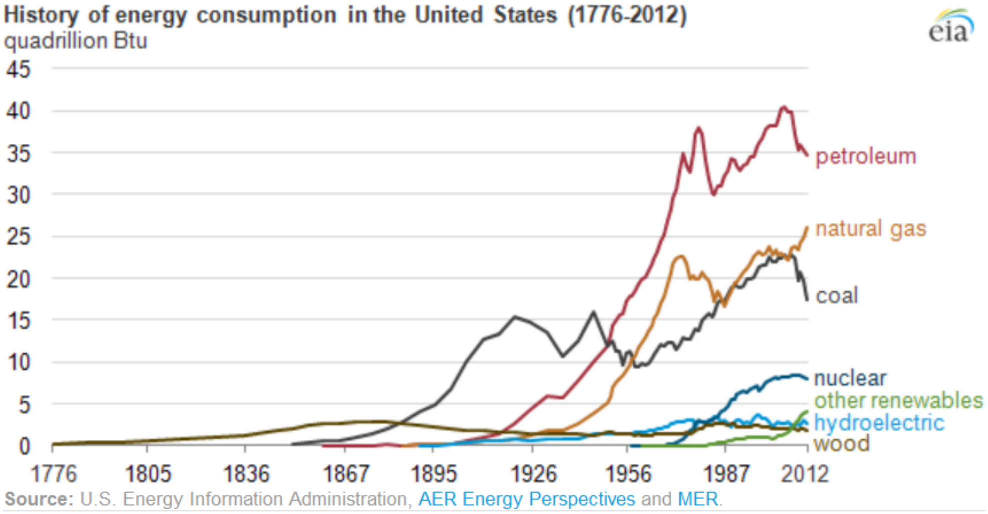


Figure 1: The history of energy consumption in the United States. Petroleum is the largest portion but is on the decline. Renewable energies are beginning to rise [4].

There are currently a few companies that are attempting to fill this niche market and use this space; Solar Roadways, Highway Energy Systems Ltd, and New Energy Technologies Inc. These companies are new startups and are mainly still in the research and development stage. Solar Roadways is by far the most developed company that has received lots of support for their innovative design. The solar roadway is a modular system of specifically engineered solar panels that can be walked and driven upon. The system does more than just produce power, it also makes the roadway more “intelligent” by having the ability to change embedded LED lights for lines and signage. The modular design also makes maintenance faster [5]. While Solar Roadways seems like a great solution there are some concerns with the product, the main being durability and safety. Many people are skeptical of the claim that the solar panels can take the strain of being driven on by not just cars, but cargo trucks as well [6]. There is also doubt that the roads will have as much traction as a traditional asphalt roadway. Finally, there are some predictions that for every road to be covered it would cost around $56 trillion [7].

Another one of these small companies, Highway Energy Systems, uses the road in a different way. This company uses the kinetic energy from vehicles to produce power. They do this by placing what they call an Electro-Kinetic Road Ramp that acts as a speed bump for vehicles. The company claims that their device can produce anywhere between 5 and 50 kWhs depending on traffic [8]. This device would be great if implemented in areas where speed bumps are required, however, one of these systems can cost over $23,000. Clearly this is not a particularly economical option.

New Energy Technologies is another company that produces a “kinetic energy recovery device” called MotionPower Express. This system captures unused kinetic energy of vehicles where they must slow or stop. The device works best when vehicles are traveling faster than 15 mph and are slowing. New Energy tested this product in 2010 in the city of Roanoke Virginia where of a total of 580 cars passed over it in 6 hours. This produced enough energy to power an average American home for a full day. The MotionPower speed bump is estimated to cost between $1500 and $2000 with a return on investment in two to three years [9]. This product seems much more economically viable and could be used by businesses in their parking lots to offset energy costs.

Clearly there is a serious opportunity to grab the market on utilizing the roadways for electricity production. The current competition has a few interesting products, each with their own advantage and disadvantages. To effectively compete we learned from each to create an affordable device that is able to be implemented into the roadway, capable of generating electricity and storing it. This device utilizes the kinetic energy of passing vehicles while they are driving at regular speeds. It is designed in a way that allows for easy maintenance and implementation of future advancements. Our system will make a less than 5% increase in the current upfront cost of paving a road.

1.1 Contributions of MQP

In this Major Qualifying Project the group:

- Produced a small permanent magnet generator that is viable for use in a roadway.
- A custom power circuit built for this generator that converts the AC source into a DC output to light up an LED array.
- Simple calculations to address the safety of our device and its viability in the marketplace

1.2 MQP Report Organization

The following report is broken down into four main sections. Section 2.0 introduces some fundamental concepts involved in the creation and justification of the project. This section discusses various aspects of road infrastructure, gives background information on induction coils and generators, and then delves into market research and prior art. The next section, section 3.0, discusses the proposed design and the product requirements. This section includes the customer requirements, product specifications, and the proposed approach. In the proposed approach there is a comparison of a permanent magnet generator to an induction generator. There is also detailed designs of the generator and circuit. Section 4.0 is the methodology and implementation part of the report. This section shows the building and implementation our initial and revised permanent magnet generator design as well as the power circuit. Finally, in section 5.0, our results are discussed.

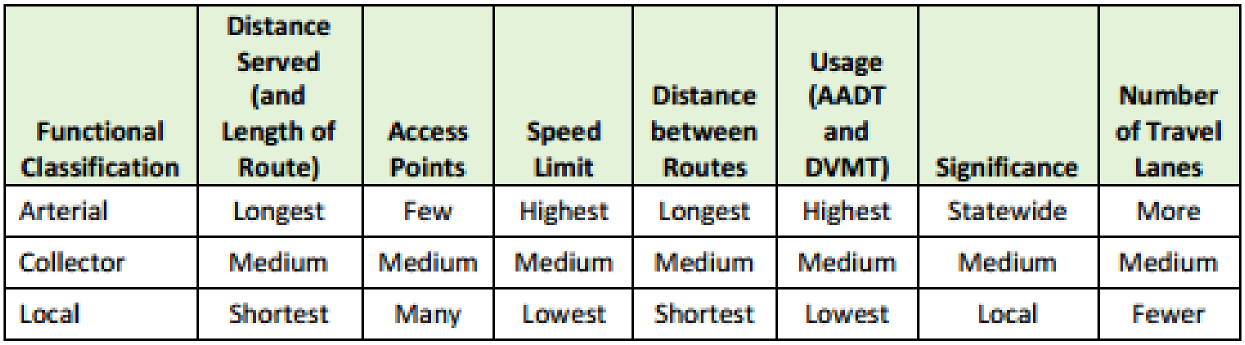
2.0 Fundamental Concepts

2.1 Road Infrastructure

Over the course of the 20th century, roads, the largest and most important parts of our civil infrastructure, have not seen any significant advancements. There has recently been much interest from the government to find a way to update these aging roadways. The amount of space that roads occupy, if used effectively has the potential to produce a profitable amount of power. We planned on developing a cost effective system that could be implemented on roadways to produce this power from the traffic that already exists.

When deciding where to place our device we must factor in what type of road we would implement it on. Our device needs to be on a roadway with large amounts of traffic and high speeds to be most effective. In the United States roads fall into three categories: Arterial, Collector, and Local. The roadways in these categories vary by mobility and accessibility. Simply put “roadways that provide a high level of mobility are called ‘Arterials’; those that provide a high level of accessibility are called ‘Locals’; and those that provide a more balanced blend of mobility and access are called ‘Collectors [10].’” The Arterial category encompasses interstates, freeways, and expressways, which take on 71.7% of all travel in the United States [11]. The Arterial roadways allow motorists to drive at higher speeds. The table below breaks down the relationship between roadway classifications and characteristics.

Table 1: Relationship between Roadway Classifications and Characteristics. Arterial roads have the highest speed limits and the most traffic [10].



Functional Classification	Distance Served (and Length of Route)	Access Points	Speed Limit	Distance between Routes	Usage (AADT and DVMT)	Significance	Number of Travel Lanes
Arterial	Longest	Few	Highest	Longest	Highest	Statewide	More
Collector	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Local	Shortest	Many	Lowest	Shortest	Lowest	Local	Fewer

By looking at this table it is clear that Arterial roadways would make the most sense for a device that uses a vehicle’s kinetic energy to produce power. However, Arterial roads are largely controlled by the federal level of government. This means it may be more difficult to be cleared to work on these roads than Collector and Local roads which are controlled by the state and local governments. Also, because our product is new and unproven, it may be more difficult to test in a high traffic area.

In addition to the speed limit and usage of the road we must also look at how the road is built, this will help us decide on constraints for our device. When constructing a road there are four main layers that can vary in thickness. This top layer is the surface layer and consists of a thin spread of asphalt that can be easily paved over. This layer is usually 1.5 inches thick. Under this surface section is another asphalt base. This base can vary from 2.5 to 3.5 inches thick and can also vary in materials. The next layer is the aggregate base that can vary from 8 to 10 inches thick [12]. Finally, beneath the aggregate base is the subgrade. This can vary greatly in size but should not be touched by us as it could affect the stability of the roadway. A cross section comparison of vary road thicknesses can be seen in Figure 2.

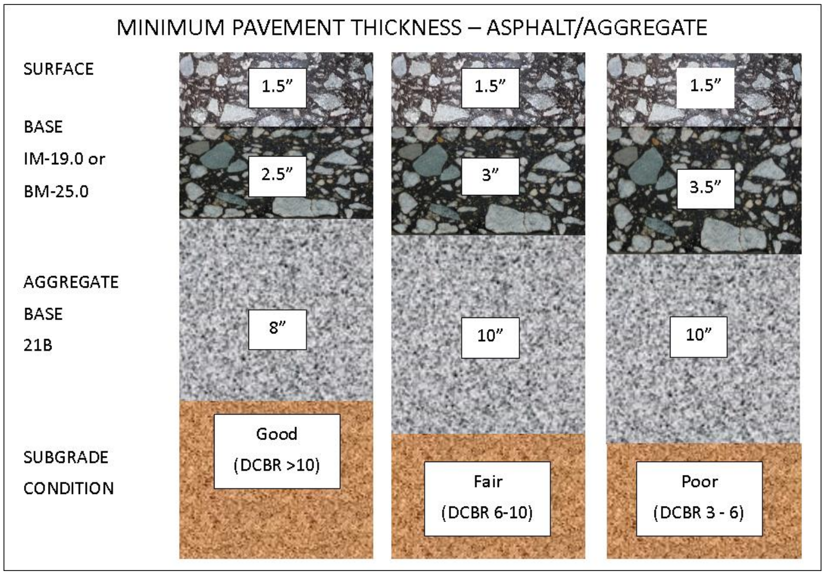


Figure 2: A cross-section comparison of vary road thickness and the materials used for each layer [12].

Most roadways follow these standards for thickness, and because our device would have to fit in the base and aggregate base layers, this leaves us with on 10.5 to 13.5 inches of space.

High quality lighting along roadways is beneficial as it cuts down on nighttime vehicular crashes, particularly on freeways. In an independent study it was found that the average night/day crash ratio of a well-lit freeway was 1.43, for unlit freeways that ratio increased to 2.37 [13]. Clearly adding light to illuminate roadways in dark conditions improves the safety of drivers. Traffic and safety are not the only factors that go into the design decisions when placing road side lighting, presence of overhead distribution and transmission lines as well as the availability of power are two other main factors [14]. If we could implement our device to work properly in places where lighting would be beneficial, but power is difficult to get, we could help expand our lighting system. There are also some dangers associated with roadway lights. Light pollution and loss of night vision are two of the major concerns. Due to these dangers, lights on freeways, our ideal point of implementation, are used sparingly, usually at a freeway junction or exit ramp. So if we wanted to deploy our device to produce power for roadway lighting it should be close to one of these points.

Figure 3: On the left is a road lit by new LED Street Lights, on the right is the same road using old high pressure sodium lights. The new lights clearly increase visibility while using much less energy [13].

There are approximately 496,000 municipal street lights being used in Massachusetts that use about 305 GWh/yr [13]. With an average cost of $0.14 a kWh[15] running these lights could cost the state over $42,000,000 a year. Currently there is a nationwide push to replace the old high pressure sodium (HPS) and metal halide (MH) street lights with newer, more energy efficient LED. Lights. These LED lights have the added benefit of reduced light pollution, and produce a more natural white light. The high pressure sodium (HPS) lights used today draw 97 W and use 425 kWh/yr. With the new 3-array LED the power draw drops to 72 W and only uses 311 kWh/yr, and with 2-array LED the power draw is even lower at 48 W and uses only 210 kWh/yr [16]. Some LED street lights are able to operate on as little as 20 W. Even with the advancements of LED technology running these lights every day is expensive. A device that could power a street light using only the wasted kinetic energy of traffic would help cut down on the cost.

2.2 Induction Coils and Induction Machines

Induction coils were one of the first developments using the concept of electromagnetism. In the early 1800s, induction coils were developed twice independently by both Michael Faraday and also Joseph Henry [17]. Their systems were originally used to wirelessly transfer a current from one coil to another coil. This was done using the magnetic field produced from one of the coils. This concept was used to then create magneto-electric machines which we able to produce voltages from a magnetic field. Since these discoveries inductors have been used heavily to produce power mainly from a mechanical input.

Michael Faraday's contributions towards the use of inductors make him one of the founding fathers of Electrical Engineering [17]. His main contributions dealing with how magnetic fields affect voltage induced within coils. Prior to Faraday’s find, Faraday knew that current through a coil produced a magnetic field but his ability to discover that coils worked in both ways is what made him famous.

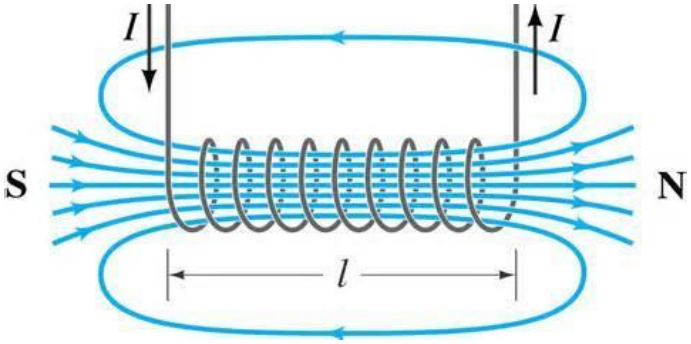


Figure 4: Solenoids and Magnetic Fields showing the relationship between current within a solenoid and the resulting magnetic field [17].

The basic law stated that, “An electric field is created within a conduction as a result of a changing magnetic field [18].” Faraday next had to discover the relationship between the magnetic field and the current and voltage within the solenoid. This was quite difficult at the time since induction coils weren’t very well understood at the time. He was able to relate the two using the basic properties of the coil namely, length, number of turns, diameter, and resistance. Using these constants Faraday found the relationship to be:

$$V = -N\frac{\Delta\Phi}{\Delta t}$$

Equation 1: Faraday’s Law demonstrating how a changing magnetic field can produce a voltage.

The equation above simply states that a change in magnetic flux, area and magnetic field, over time will cause a voltage within a solenoid proportional to the number of turns of the coil. This means that the more turns a coil has the more voltage generated. The solenoid and a magnet is a very simple way of producing power and is the basis of all induction generators [18].

Since electromagnetism works in both directions, when a magnetic field induces a current within a coil Lenz found that something strange happens with that coil. Lenz, in 1834, was trying to relate natural laws of physics laid out by Newton to the work done by electrical engineers. Between Newton’s third law and the conservation of energy Lenz found that something unique must happen with Coils. This was due to a lack of noticeable reaction that took place during a changing magnetic field. So Lenz found that when a Voltage is induced within a coil, that voltage again induces a magnetic field opposing the original field. This was an important find since this effect causes a braking effect for moving magnets. This find is what added the negative sign into Faraday's Law [19].

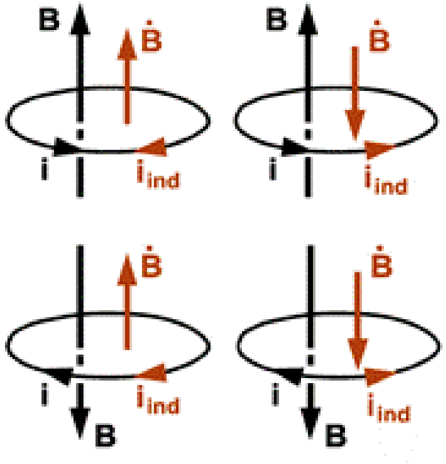


Figure 5: Lenz Law displaying the relationship between magnetic fields and induced magnetic fields along with the resulting current involved [20].

Lenz Law is a simple phenomenon that takes place when working with coils. Since a magnetic field through a loop creates a current in the loop and a current can create a magnetic field this interaction can take place iterate itself infinitely. When a current is imposed upon a loop a magnetic flux is also produced at the same time. Depending on the orientation of that new magnetic field a new current is induced. Sometimes this new current counters the original current thus hindering the output current of the coil. This can also work in the other way as well. The resulting magnetic field can end up boosting the original current [20]. When it came to building a generator Lenz law works in favor of power output. Since so many coils are involved in a generator, all of their magnetic fields come into play and end up boosting the output current of the system.

The induction generator, uses the basic principles laid out by Faraday to convert a mechanical force to an electrical force. This was originally done in single phase but Siemens in 1856 and used for railways, but this was very inefficient. An efficient generator wasn't developed until after Maxwell collected all information regarding electromagnetism and found their connections to one another. Using this newly sorted information, Tesla was able to developed designs for the first 3-phase induction generator which is still very heavily used to this day [21].

Induction generators in theory can be used as a motor and also as a generator since electromagnetism works in both ways. The system is built with two components, rotor and stator. The rotor is made up of a rotatable wheel which has electromagnets on it, this device usually accounts for the mechanical aspect of the, two way, electromechanical conversion device. This is most typically called a squirrel cage rotor since the design of coils that make up the electromagnets looks like a cage.

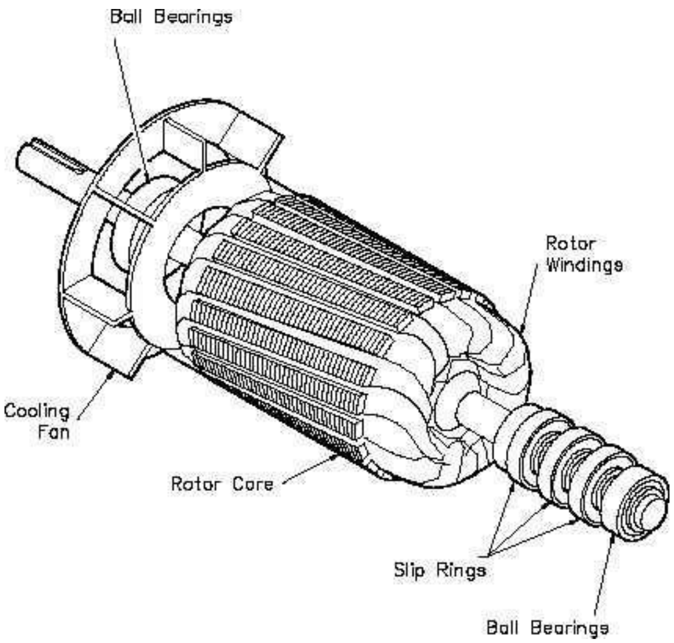


Figure 6: Rotor for Induction motor shaped in such a way to minimize startup force and tightly wound coils placed to act as the magnetic field for energy production [22].

The stator is the rotors counterpart and is responsible for electricity that is produced since the stator is made up of the coils that either have current induced within it from the electromagnet, or the produce a magnetic field from a current. Stators mostly have 3 sets of coils within them to allow for three currents to be produced. Each coil is wrapped around a magnetic core to boost the magnetic field sensitivity allowing the coils to produce more power.

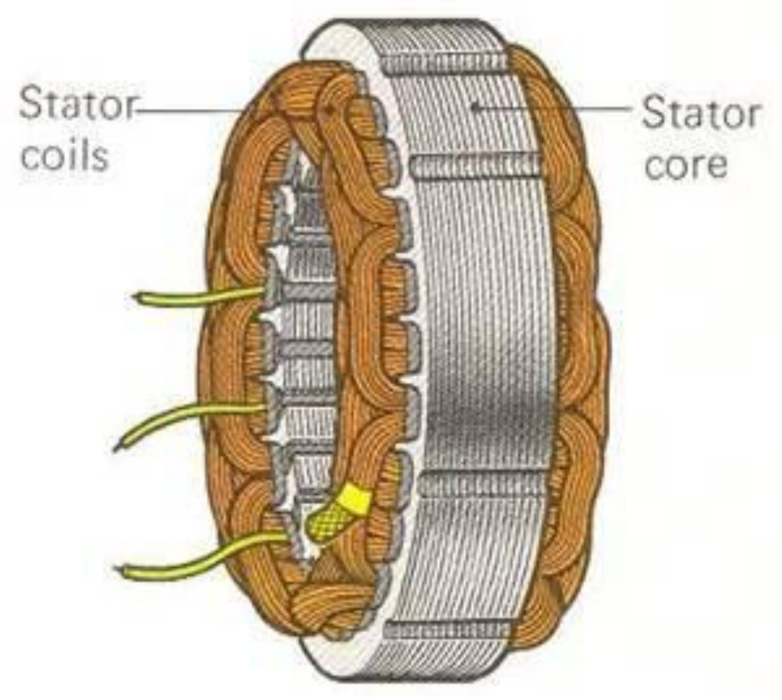


Figure 7: Typical 3-phase induction motor stator with an iron core to maximize the magnetic flux potential. Along with tightly wound coils that are located to reduce size. [23].

The 3-Phase induction generator is considered by many to be one of the most important inventions for the modern era. This generator produces three AC signals which are all 120 degrees out of phase. Which allows the signal to be sent a very far distance with much less losses. The 3-phase system also removed the need for a neutral ground wire since the sum of the three currents in the wires added to exactly zero amps. Typically these generators have upwards of 90% efficiency. But will need roughly 50 to 60 Hz of input to be able to produce the rated power [24]. This usually forces designers to use a gearbox to adjust the rotation on the input or output which may yield high prices [25].

The permanent magnet generator also uses the fundamentals of electromagnetism put forth by Michael Faraday. The difference between the permanent magnet generator and the induction generator is that, where and induction generator uses rotor windings to generate a magnetic field, a permanent magnet motor uses permanent magnets on its rotor. The use of permanent magnets improves control of the rotational velocity of the rotor. Below is a diagram that displays the differences between a permanent magnet generator and an induction motor [26].

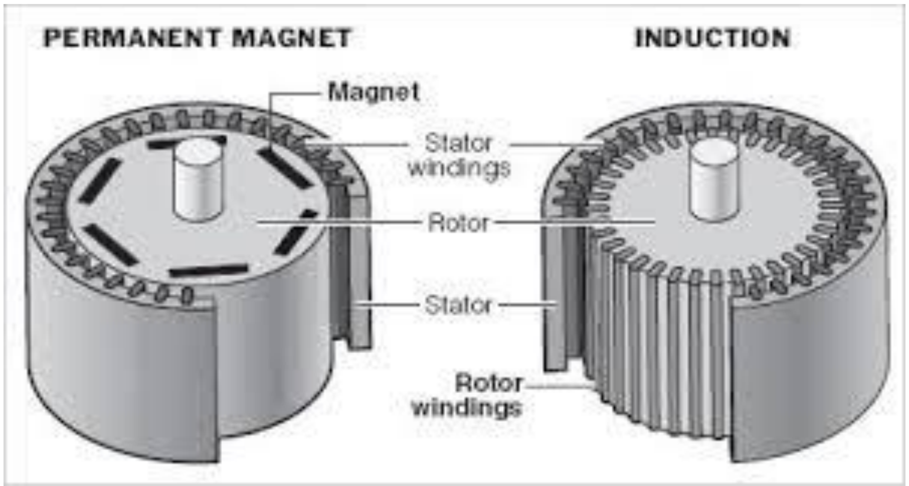


Figure 8: The Difference between a permanent magnet generator and induction generator is shown above. The Permanent Magnet Generator is depicted on the left, while the Induction Generator is on the right [26].

The reason for the containment of rotational velocity of the rotor in permanent magnet motors is that the rotor spins at the same velocity as its internal magnetic field. This makes permanent magnet motors a favorable option for converting mechanical input energy and torque into electrical energy.

$$N = \frac{120 * f}{P}$$

Equation 2: Synchronous speed calculations using number of poles and generator frequency.

Above is the formula used to determine the motor’s synchronous speed. This is used to find N, the generator’s synchronous speed, using the frequency and the number of poles [27].

2.3 Green Road Technologies

To help finalize a design for our project we researched different technologies with a similar application. We looked into how these technologies decreased the carbon footprint, how they impacted the roadway’s functionality, and how major the installation process would be. We used these three attributes to decide on how to make our product the most competitive.

One of the first potential competitors we encountered was a company called Solar Roadways, which has developed a modular system that replaces all roadways, parking lots, sidewalks, and bike paths with smart micro processing interlocking hexagonal solar panels this can be seen in Figure 9. These panels are individually replaceable if one malfunctions without compromising the rest of the system. One 4’x4’ solar panel can produce 36 watts of power and cost under $10,000 to make and install [28]. Along with the solar aspect of the panel it also contains heating elements that keep the surface temperature a few degrees above freezing. It also has a series of LED lights on the circuit board that can be programmed to make road lanes, warning signs, parking lot configurations, etc. After the energy is produced it feeds into a decentralized power grid.

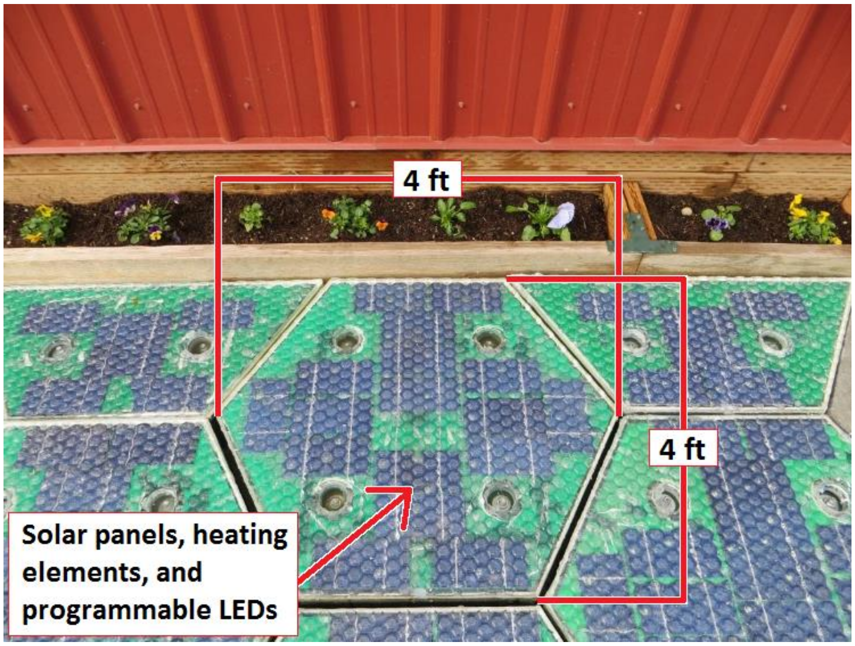


Figure 9: Solar Roadway's hexagonal panels, each is 4 feet wide and contains a heating element and programmable LEDs. [28]

In term of our proposed system, Solar Roadways are one of our major competitors. This is because there are many aspects of their system that correlate or are similar to our project. The main component that is similar that we would also like to implement is how their system is modular. Making our system modular would make the installation and repairs easier and quicker compared to the current maintenance system in the United States for asphalt roads, increasing our profit. Another similarity is that the power that our system produces would ultimately be used to power a connected load. This would be done through a decentralized power grid system, similar to Solar Roadways. For example, our system in highways could power the street lamps on either side. Excess power produced by our system can feed surrounding areas instead of putting it into one central location, like a power plant, and then sending it out via transmission lines over long distance, which leads to substantial loss. In the distant future we would also like to have some type of programmable LED light system, but we were primarily focused on power production.

Another competitor we found during our research that focuses mainly on making a modular system was a company called VolkerWessels. They have designed a product called PlasticRoad, that they are hoping one day will replace roadways. There idea is to use 100% recycled plastic to manufacture lightweight prefabricated road parts that interconnect with each other to make one road like structure. The prefabricated production and the lightweight design also make the construction of a PlasticRoad into a much simpler task. Using recycled material will help eliminate the threat that plastic has on our environment. Their design also features a 'hollow' space that can be used to store rainwater or be for cables and pipes. In the future they plan on adding new innovations such as power generation and heated roads [29].

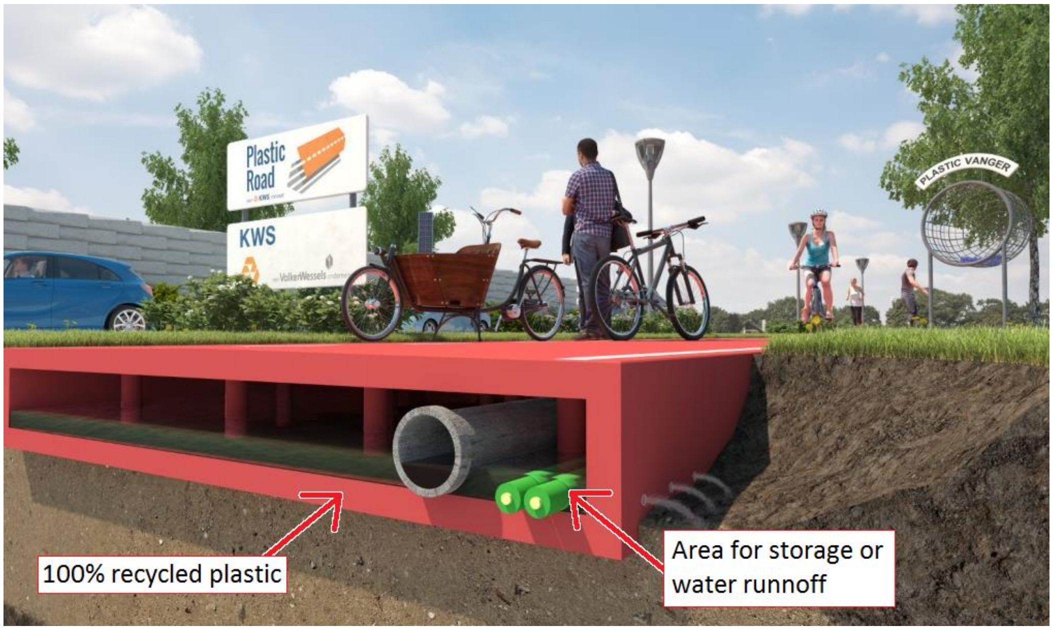


Figure 10: An artist's rendition of VolkerWessels Plastic Roadway. The road is made of 100% recycled plastic and is totally module [29].

The main reason why VolkerWessels is our competitor is because their system is modular just like ours inspires to be. Like we said in the previous section on Solar Roadways, Making our system modular would make the construction of the system faster and it will have less maintenance time as well. In the U.S., over $120 billion is lost each year because people are sitting in traffic due to road construction and maintenance [30]. We would also like to also prefabricate our design, this way everything would be built off-site and then quickly set up. This is another factor to faster installation time.

The company Highway Energy Services Ltd. manufactures a ramp that generates free electrical energy when passing traffic drives over it, they call it the Electro-Kinetic Road Ramp. The ramp was invented by the director of the company Peter Hughes, an electrical and mechanical engineer. When interviewed by a team of scientist that were with Cambridge University's Institute of Continuing Education (ICE), Peter Hughes said the amount of electricity the system produces depends on the amount of traffic and their comparative weight, but under normal traffic conditions it can produce between 5 kilowatt hours and anything up to 50 kilowatt hours [31]. The Ramp requires the minimum of maintenance and may be used for generating electricity to power street lighting, traffic lights or road signs, with the surplus being fed into the national grid [32]. It can also store electricity within a storage battery for future use. Hughes states that “We charge storage batteries during the periods when we have very heavy traffic flow. When the traffic is light, we then use the storage battery facility to continue to power the lights [33]. To build one of these systems and implement them into the roads, it costs a little bit more than $23,000.

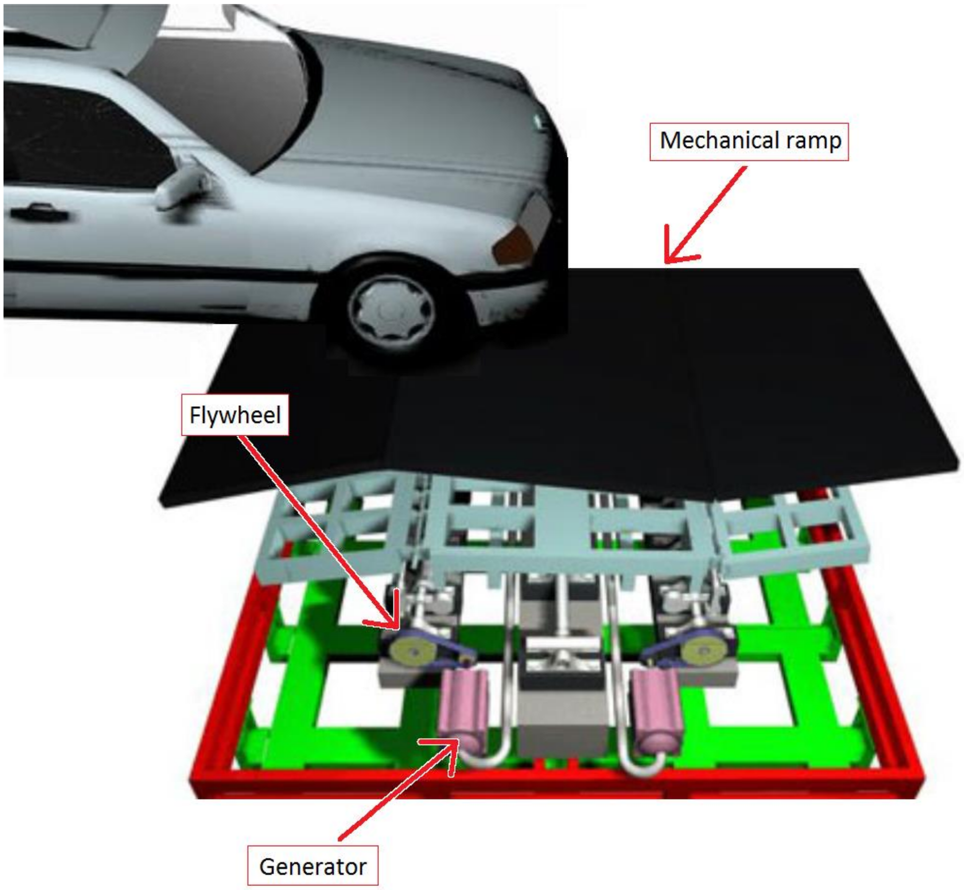


Figure 11: This is an artist rendition of Electro-Kinetic Road Ramp. When the car drives over the mechanical ramp, the flywheel is spun resulting in an output of electrical voltage from the generator [33].

In terms of our proposed system, we wanted a way to convert kinetic energy to electric energy and we could possible use something similar to what the Electro-kinetic road ramp did. Their system is made up of metal plates in the road that move up and down, in a see-saw motion, as traffic passes over them. The movement of the plates drives a specially developed flywheel, which in turn drives a generator to produce electricity [34]. We also wanted a car to drive over or onto our system that in turns moves something that generates electricity.

Since New Energy Technologies' MotionPower™-Express system did not provide us with a lot of information we continued our search of a speed bump like apparatus. We came across a patent of the Electric Power Generating Speed Bump invented by Victor Dmitriev[35]. While acting like a normal speed bump (forcing cars to slow down), it converts the kinetic energy and weight force of the car that drive over the speed bump to electric energy. The electric energy is generated by linear electric generator (which is installed inside the speed bump) when the wheels of a vehicle roll over the speed bump. The way the energy is generated is fairly simple. When wheels of a car drive over the speed bump, the weight and motion of the car make the upper surface of the speed bump move downwards, that energy of the downward movement makes a linear electromagnetic generator to generate electric energy, which can be seen in Figure 12. The same thing happens when the car rolls off the speed bump.

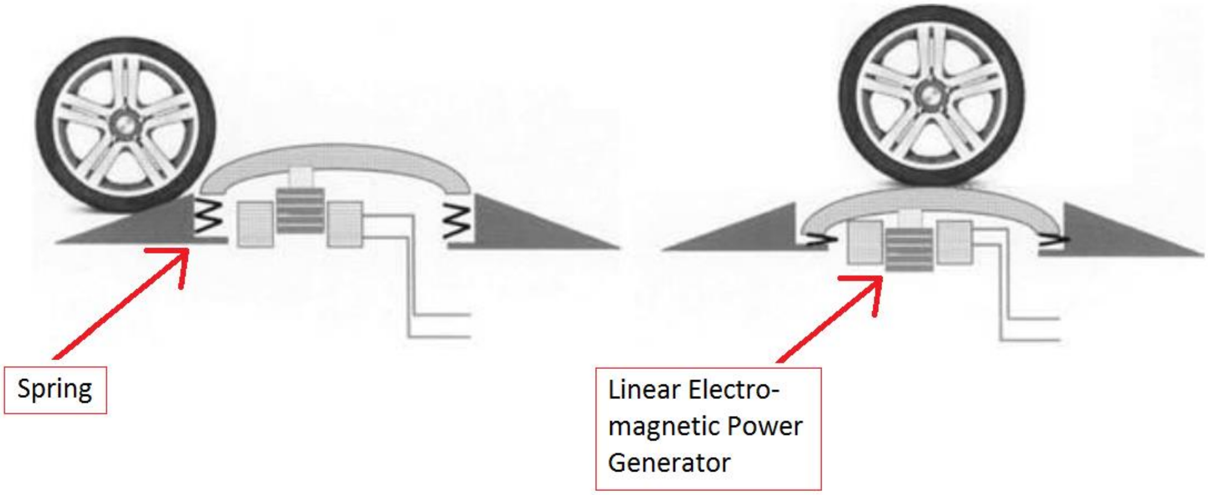


Figure 12: This is an artist rendition of Electric Power Generating Speed Bump. Weight of the car compresses springs moving a linear electromagnetic generator resulting in electric voltage [36].

This product is extremely relevant to our project so it is important to understand what Victor Dmitriev did in order to learn from his mistakes and further our project. One of our main goals is to produce power from the kinetic energy of a moving vehicle and change it into electric energy. Not only did the product Electric Power Generating Speed Bump do this, it used the mechanism, electro-magnetic generator which is extremely similar to our magnet and induction idea. An electro-magnetic generator is a device that converts mechanical energy into electrical energy using electromagnetic induction [37].

2.4 Chapter Summary

If we want our device to power streetlights as cars pass by it should be located in an area where street lighting is most prevalent. From what was discussed previously in section *2.1 Road Infrastructure,* exit and junction ramps on arterial roads (freeways) would be our best option. This is because arterial roads allow for higher rates of speed and streetlights are used only around these ramps. If our device could remove streetlights from the power grid then it could save millions of dollars a year.

Looking back on all designs mentioned in section *2.2 Induction Coils and Induction Machines*, it seemed as though the most viable approach to take was the permanent magnet motor. One primary concern with both the induction and permanent magnet generators was the mechanical aspect. To deal with this we would probably require a gearbox to be able to get the rotor to spin at a usable speed. In this case, the permanent magnet generator would work better because it does not need to rotate at very high and consistent speed. Although these mechanical complications were definite concerns, we were keeping our primary focus on the electrical aspect of the project. Another pro of the permanent magnet generator in the very simple design, it does not require the electromagnets or brushes required by an induction generator. Because of the reasons stated above, we decided that a permanent magnet generator was the most effective way of powering the array of LEDs.

From the section *2.3 Green Road Technologies*, there were a couple conclusions that we could draw. First, we wanted our device to be Modular. Our product could be made off site then placed in at a later time. This would make the installation and repairs easier and quicker compared to the current maintenance system in the United States for asphalt roads, increasing our profit. Second, for our device to produce power with each vehicle pass it was important that we have a mechanical device capable of taking kinetic energy then feed that into our product and create electrical energy. As of right now we have decide to keep the mechanical aspect of our project to a minimum to focus on the electrical part but having a mechanical device to move our magnet to then produce energy was still very important.

3.0 Proposed Design and Product Requirements

The first step we took was to establish the market we planned to target, the Massachusetts Department of Transportation (DOT). As the DOT oversees all road work and is responsible for contracting any jobs, our goal was to appeal to the DOT by developing an environmentally friendly, and fiscally advantageous alternative to the current option.

3.1 Customer Requirements

After researching the costs of the current methods used by the Massachusetts DOT, we determined the customer requirements that we would need in order to create an effective and competitive product. These customer requirements are listed in Table 2.

Table 2: Customer requirements and reasoning for a "Green Road"

Requirement	**Reasoning**
Durability:	Our product will be regularly subject to inclement weather conditions and significant physical stress, and repairs would not be a very simple procedure, therefore, it must be durable enough to withstand these conditions for years while still being able to generate power.
Safety:	With the millions of people on the roads every day, it is imperative that our product is just as safe to drive on as the current pavement. No product that endangers drivers is marketable to the Department of Transportation.
Effect on Traffic Flow:	One of our objectives is for our product not to affect traffic patterns. In order for this to be true, our product must not require cars to slow down.
Cost:	The cost of our product must be relatively close to the current cost of roadways in order to be competitive. While we plan on our product costing slightly more, we will compensate for this with the power generated by our road.
Size:	The size of our product is important because the surface of roads have a limited depth and width.
Maintenance:	Maintaining our product cannot be much more difficult to maintain than current roads. Not only does our road need to be affordable, but it should not require excessive training or time to conduct road maintenance.

Our project could be the best in the world but we would not be able to get anywhere with it without funding. As of right now the Electrical and Computer Engineering Department at Worcester Polytechnic Institute has given us a budget of $500. While this was enough to get us started on building and testing, we needed to research other possible future investors to help us along our way.

We first looked to the federal government for help. There are many different types of grants and funding for different types of businesses and projects. We would focus on applying to those that are focused on road construction and the production of renewable energy. The Department of Transportation give out funding to those types of projects. For example The Surface Transportation Program (STP) of Federal Highway Administration provides flexible funding that may for projects to maintain and improve the conditions and performance on any Federal-aid highway [38]. Also, we have learned that the average global subsidy for renewable energies came to be 5.0cents/kWh[39]. This support for renewable energy sources would greatly help us achieve our goal.

3.2 Product Specifications

Once we determined our customer requirements, our next step was to use these in order to establish our quantitative product specifications. These product specifications are shown in Table 3.

Table 3: Product specification and reasoning.

Specification	**Reasoning**
A life expectancy of 25 years	In order to be cost effective, and to reduce maintenance, our device should have a life expectancy longer than that of the road.
Surface of the road does not increase accident frequency	Safety is integral. If our product increases the accident rate, regardless of the energy created, it will not be worth implementing.
Must generate 10 watts per car per lane mile	Our generator must be capable of powering the LED street lights.
Must decrease carbon footprint by more than its installation causes	The purpose of our generator is to generate green energy. If the installation of our generator causes a larger carbon footprint than the generator makes up for, then our device is not truly generating green energy.
Less than a 5% increase in upfront cost of paving a road	Implementing our generator would obviously increase the cost of road construction. We aim to not increase this by more than 5% of its current cost.
Maintenance of our road cannot be more frequent or costly than the current roads	It is important that the addition of our generator not be more of a hassle than any other road as maintenance would drive up costs and labor.

As a team of four electrical and computer engineers, we were not fully able to analyze and design the most effective mechanical system. Instead, we calculated the input energy of a car, assuming an efficiency rating of 20 percent, and will simulate this input in order to test the effectiveness of our generator.

3.3 Proposed Approach

The method that we chose involved embedding a permanent magnet generator into the road, and implementing a mechanical device to convert the kinetic input of the car into usable rotational energy for the generator. This is depicted in Figure 13 below.

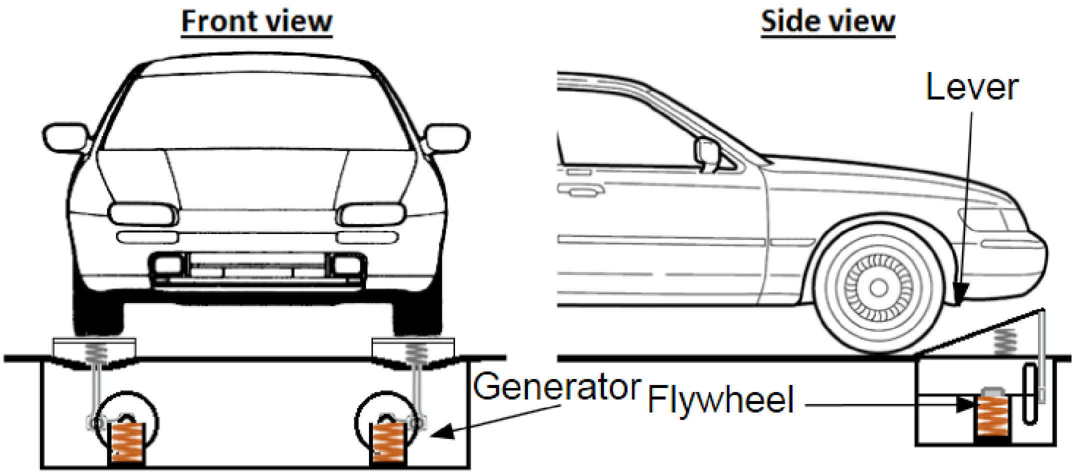


Figure 13: This is an artist's rendition of how we plan on implementing our device into the road's surface. The vehicle drives over the lever, causing the rotor to spin.

This device would use the kinetic input to create usable electrical energy. Instead of feeding this energy back into the grid, we decided that it would be far less complex and less expensive if we used the electricity produced to power something local. We aim to use our generator to power as many street lights as possible which would take them of the grid and save a substantial amount of power.

3.3.1 Design Choice - Permanent Magnet versus Induction Generator

One of the most important decisions made was the one about how the power would be converted from mechanical to electrical. The Induction generator was more use when it comes to power production, this was because it offers much more power from being more highly developed and understood. But Induction generators have to spin at much higher speeds to be able to produce it power. If an induction generator was used it would also need an input current to be able to produce its power since its rotor is a glorified electromagnet. The induction motor if used would have been very difficult to build and most likely just be purchased as a whole, that price would have been higher than to make a PMSG from scratch.

The main reasons that it was decided to use the permanent magnet generator were due to the size and maintenance. One of the main aspects of this product was that it fits in the road so that it will be able to do its job. The size has to be very small especially when it comes to height, since most layers of the pavement are only about three inches. Lastly, the generator has to be very easy to maintain, thus the solid aspect of the PMSG makes it much easier to fix. If a magnet were to act up it could simply be replaced. While the induction generator is much more difficult to take apart and all the coils are almost impossible to fix since they are incredibly tangled to save space. The PMSG just made more sense to use since it could be made with all of the specifications that are needed for use in the roadways.

3.3.2 Design Choice - Generator Design

We decided to use a three-phase permanent magnet generator that would use twelve coils of copper wire. Due to our size constraints, as the generator must be able to fit within the road, the generator will be vertically oriented with three separate levels. The stator will consist of both the bottom and the top levels, and will have six triangular coils, each with 3.5” sides. The middle level will be the rotor, and will include ten magnets and use the mechanical energy input by the car to rotate between the coils. We decided upon these specifications because of our Mathematica code. We found that this generator will achieve our desired output voltage in the most cost efficient way. Below are diagrams that illustrate the three levels of our design.

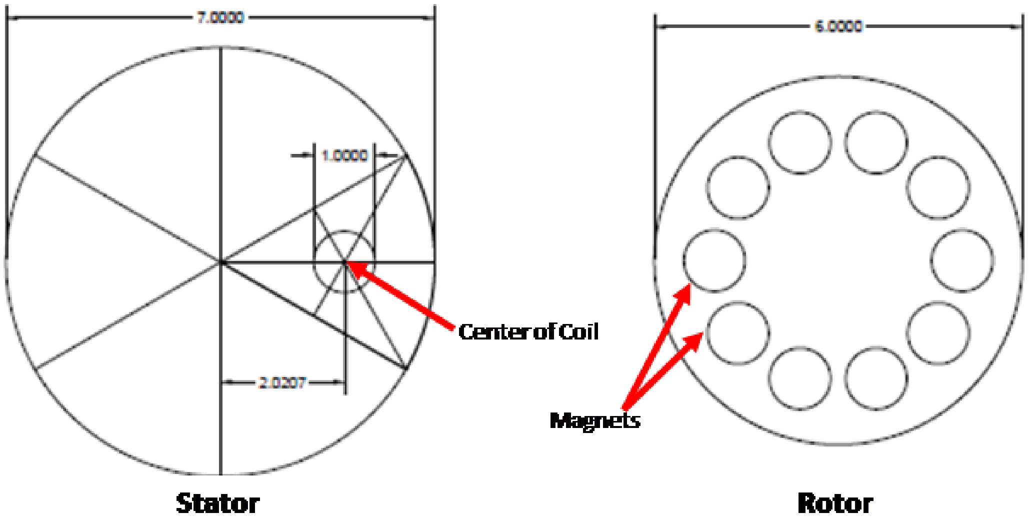
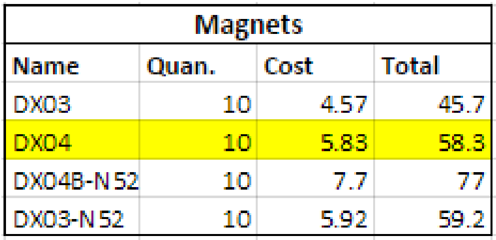


Figure 14: This is the AutoCAD drawings of the rotor and stator of our permanent magnet generator. The stator is displayed on the left, while the rotor is shown on the right.

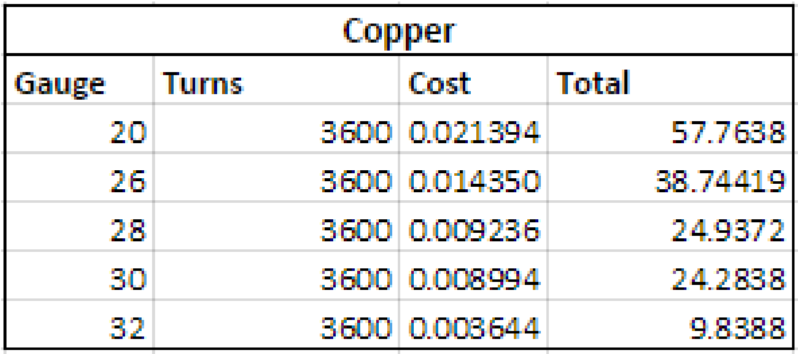
Once our team had decided on our design, we calculated the effectiveness of many potential magnets in order to calculate our product's return on investment. The tables below are the costs of the four magnets that we considered for our generator, as well as the other material costs of our product.

Table 4: A table of the various magnets we considered and their costs.



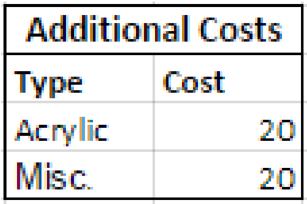
Magnets			
Name	Quan.	Cost	Total
DX03	10	4.57	45.7
DX04	10	5.83	58.3
DX04B-N52	10	7.7	77
DX03-N52	10	5.92	59.2

Table 5: The price of different gauges of copper wire, and the price of the amount that we would need for our generator.



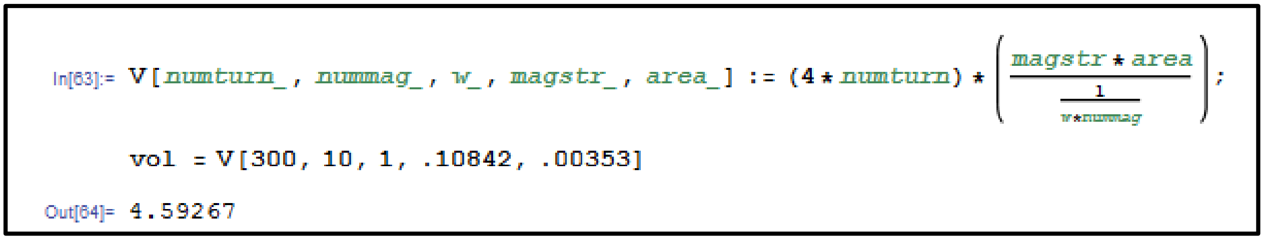
Copper			
Gauge	**Turns**	**Cost**	**Total**
20	3600	0.021394	57.7638
26	3600	0.014350	38.74419
28	3600	0.009236	24.9372
30	3600	0.008994	24.2838
32	3600	0.003644	9.8388

Table 6: Our estimated cost of acrylic and other miscellaneous materials that we used.



Additional Costs	
Type	**Cost**
Acrylic	20
Misc.	20

Once we found the material costs of our generator, we calculated the output voltage that we would receive for each magnet at three phases and six phases, as well as at different distances from the coils. These calculations were performed in Mathematica, using the following code:

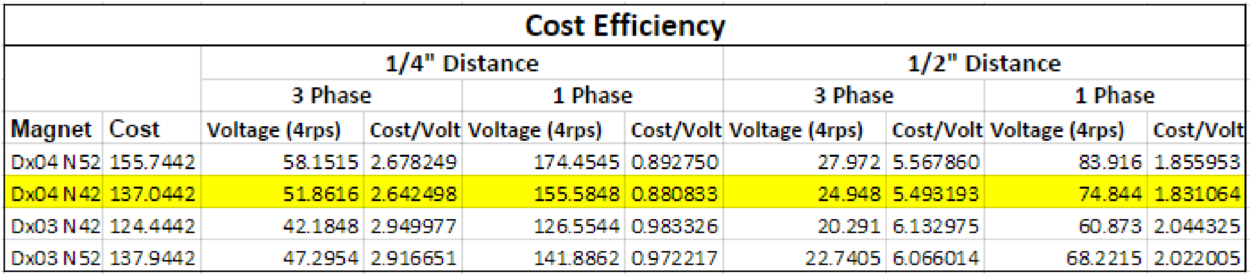


```
In[63]:= V[numturn_, nummag_, w_, magstr_, area_] := (4*numturn)*(magstr*area / (1 / w*nummag));

         vol  = V[300, 10, 1, .10842, .00353]

Out[64]= 4.59267
```

Figure 15: Actual code used in Mathematica to determine output voltages based on Faraday's law. Used to determine the theoretical Output.

We then divided our total cost by the output voltages to receive the cost per volt that our generator would generate. The table below shows our results.

Table 7: Calculations of the cost per volt that we would get from using various magnets and phases. We used the price of materials and divided it by our output voltage that we found using Mathematica.



Cost Efficiency									
		1/4" Distance				1/2" Distance			
		3 Phase		1 Phase		3 Phase		1 Phase	
Magnet	Cost	Voltage (4rps)	Cost/Volt	Voltage (4rps)	Cost/Volt	Voltage (4rps)	Cost/Volt	Voltage (4rps)	Cost/Volt
Dx04 N52	155.7442	58.1515	2.678249	174.4545	0.892750	27.972	5.567860	83.916	1.855953
Dx04 N42	137.0442	51.8616	2.642498	155.5848	0.880833	24.948	5.493193	74.844	1.831064
Dx03 N42	124.4442	42.1848	2.949977	126.5544	0.983326	20.291	6.132975	60.873	2.044325
Dx03 N52	137.9442	47.2954	2.916651	141.8862	0.972217	22.7405	6.066014	68.2215	2.022005

These calculations show that the Dx04 N42 magnet was the best choice, as it was the most cost-effective in all scenarios. Not only did this allow us to decide on the correct magnet, but it also shows that we will produce more than enough energy to power a street light, assuming 60 rpm, or 1 revolution per second which was a very conservative assumption.

In order to take the power that the team will get from the permanent magnet generator and use it to power an array of LEDs, an analog power circuit was required. This circuit will need to convert the alternating current (AC) to direct current. Below is a Block diagram of what was needed to do this conversion. The first block represent the one phase of the permanent magnet generator which generate AC power. Then that power was transferred into the next block. The next block would be some type of rectifier that could take that AC current and/ or voltage and convert it to DC. The next block in the block diagram represent a component that will smooth out this voltage and make the output manageable for an array of LEDs to use to power up, like a smoothing capacitor. These components alone were not enough to power an array of LEDs another block was needed. This was because the output of a rectifier it not also a constant voltage or current. So the next block was some sort of voltage booster, this could ether be a transformer or a boost converter. Finally, the next and final block represent an array of LEDs placed in parallel to the rest of the circuit.

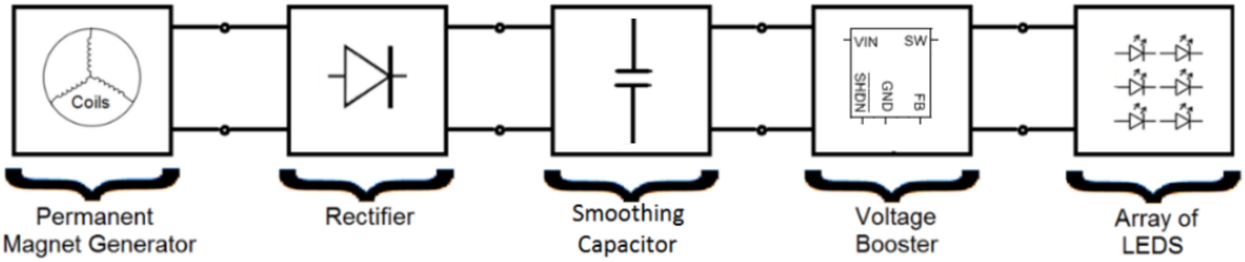


Figure 16: Block diagram of the overall power circuit, it has 3 main sections, the rectifier, smoothing capacitor, and voltage booster.

The full-wave rectifier is a very useful power component that takes an ac voltage or current and converts it to a dc voltage or current. This will be ideal for our application because we need to take the ac power produced by our permanent magnet generator and use it to power our LED array which takes dc. An example of a full-wave rectifier can be seen in Figure 17 below.

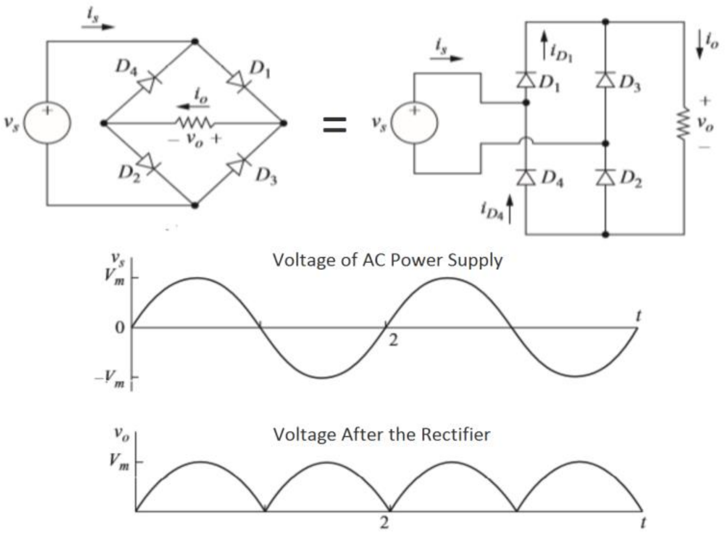


Figure 17: This is an example of Full-Wave Rectifier using 4 diodes with a resistive load. The waveform can be seen in the bottom graph [40].

The smoothing capacitor converts the full-wave rippled output of the rectifier into a smooth DC output voltage. Generally for DC power supply circuits the smoothing capacitor is an Aluminum Electrolytic type that has a capacitance value of 100uF or more with repeated DC voltage pulses from the rectifier charging up the capacitor to peak voltage [41]. Below in Figure 18 is an example of a simple rectifier plus smoothing capacitor circuit and its resulting waveform. This was what we expect our results to look like, out of both the Multisim simulations and the physical analog test.

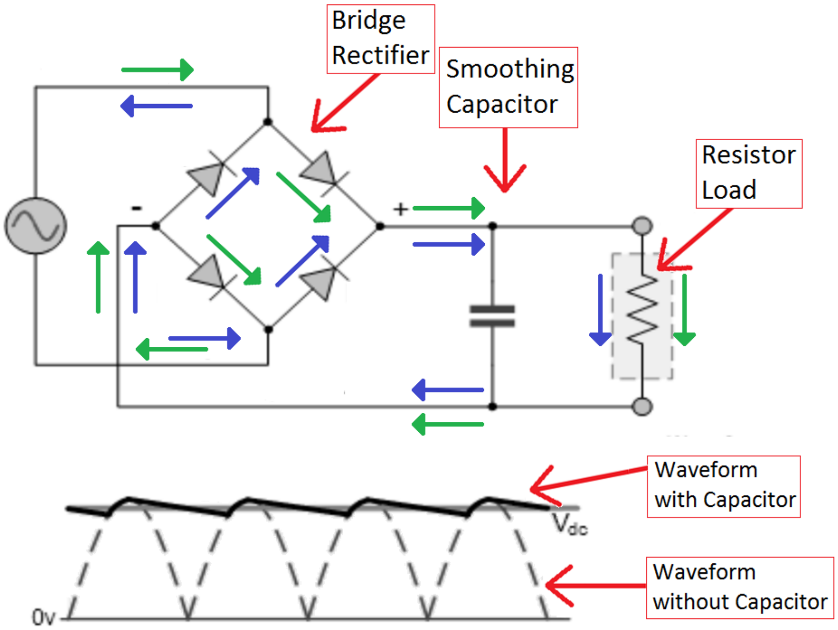


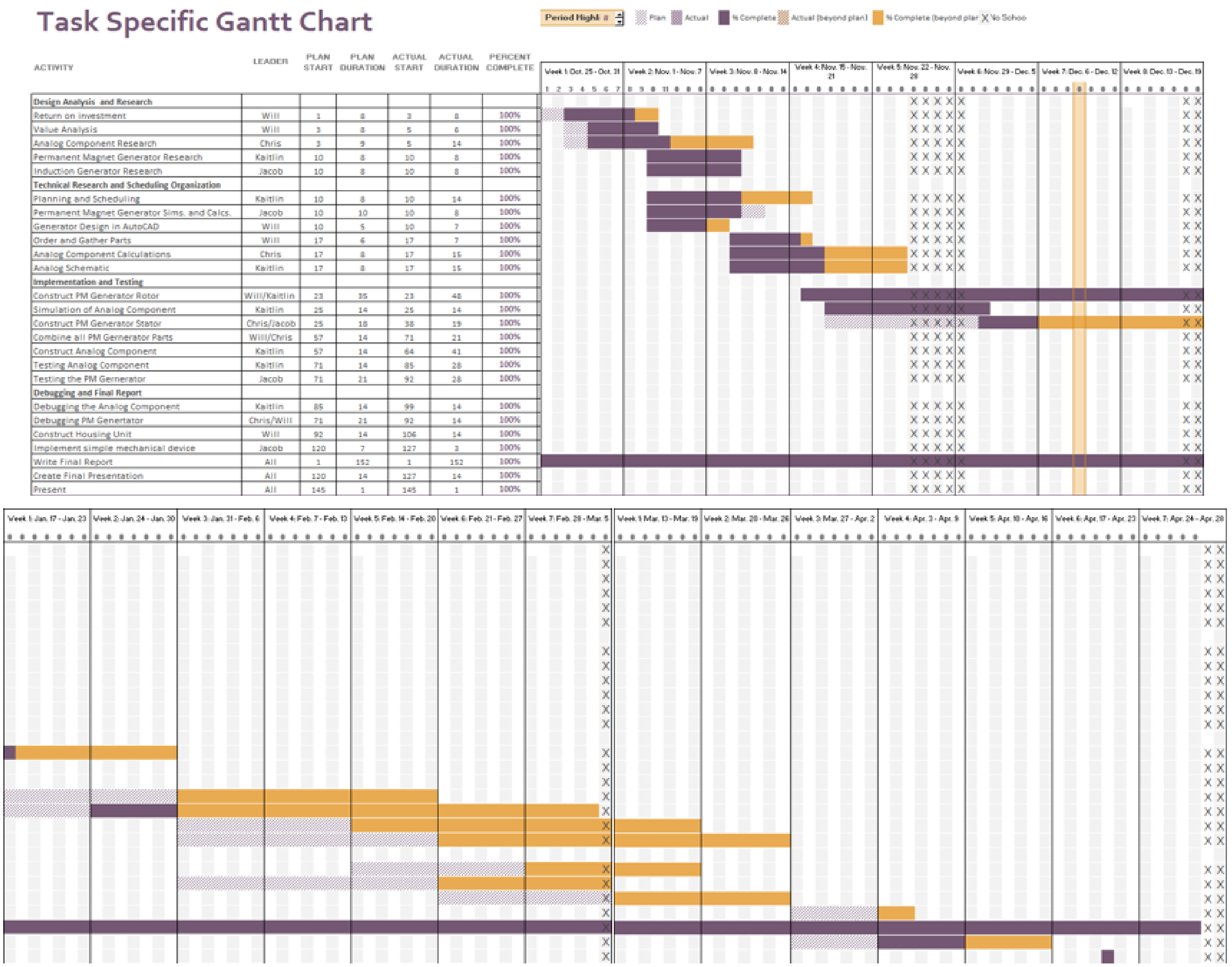
Figure 18: This is a rectifier and smoothing capacitor circuit, the capacitor makes the waveform closer to a DC signal [41].

3.4 Project Logistics

In any project environment where group work is required it was important to consider and establish a set of project goals and tasks that each member will abide by. Thus, by maintaining proper project management and scheduling, it will be possible to meet the set deadlines and milestones that the group needs to meet. An effective way of managing the progress of collective tasks and keeping track of upcoming deadlines or milestones was through the use of a Gantt chart. The Gantt chart can been seen in Figure 19.

This Gantt chart was used to track the progress of project work through various stages. The entire design process has been separated into five major components: design analysis and research, technical research and scheduling organization, implementation and testing, and debugging and final report. In using a Gantt chart, the design team expects that tasks and responsibilities will be completed in a timely and efficient manner. Despite dedicating a lot of review to time management such that delays may be minimized, the design team was nonetheless taking the extra precaution to incorporate extra time in case of unexpected delays or problems.

The tasks for the group was laid out in a plain, clear fashion, so as not to cause confusion at a later time, and communication has remained constant to ensure that each member was not only actively completing their work, but will constantly be reminded of upcoming deadlines and the potential consequences of missing them.



Task Specific Gantt Chart

ACTIVITY	LEADER	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Design Analysis and Research						
Return on investment	Will	1	8	3	8	100%
Value Analysis	Will	3	8	5	6	100%
Analog Component Research	Chris	3	9	5	14	100%
Permanent Magnet Generator Research	Kaitlin	10	8	10	8	100%
Induction Generator Research	Jacob	10	8	10	8	100%
Technical Research and Scheduling Organization						
Planning and Scheduling	Kaitlin	10	8	10	14	100%
Permanent Magnet Generator Sims. and Calcs.	Jacob	10	10	10	8	100%
Generator Design in AutoCAD	Will	10	5	10	7	100%
Order and Gather Parts	Will	17	6	17	7	100%
Analog Component Calculations	Chris	17	8	17	15	100%
Analog Schematic	Kaitlin	17	8	17	15	100%
Implementation and Testing						
Construct PM Generator Rotor	Will/Kaitlin	23	35	23	48	100%
Simulation of Analog Component	Kaitlin	25	14	25	14	100%
Construct PM Generator Stator	Chris/Jacob	25	18	38	19	100%
Combine all PM Gernerator Parts	Will/Chris	57	14	71	21	100%
Construct Analog Component	Kaitlin	57	14	64	41	100%
Testing Analog Component	Kaitlin	71	14	85	28	100%
Testing the PM Gernerator	Jacob	71	21	92	28	100%
Debugging and Final Report						
Debugging the Analog Component	Kaitlin	85	14	99	14	100%
Debugging PM Genertator	Chris/Will	71	21	92	14	100%
Construct Housing Unit	Will	92	14	106	14	100%
Implement simple mechanical device	Jacob	120	7	127	3	100%
Write Final Report	All	1	152	1	152	100%
Create Final Presentation	All	120	14	127	14	100%
Present	All	145	1	145	1	100%

Figure 19: Task specific Gantt chart, a broken down schedule for all the tasks associated with completing the project.

3.5 Chapter Summary

Before we could decide on the specifications of our product, we found out the customer requirements that we would be working with. From these customer requirements we developed several product specifications that we could use as guidelines in order to determine the exact specifications of our generator. Our next step was to figure out the restricting factors of our generator based on the roads limited amount of space. We were able to use these product specifications to come up with our design, as well as analyze the most cost effective materials we would use.

Using these specifications for the generator we came up with our circuit specifications. This circuit converted the AC to DC voltage to power some type of road infrastructure. To do this our circuit needed to take the AC voltage output of the permanent magnet generator and convert it to DC through a rectifier. This smoothed the AC to a nice DC value. This voltage was then needed to be boosted in order to achieve our desired output voltage.

A Gantt chart acts as an effective visual scheduler that tracks progress, dependencies and tasks in an orderly fashion for easy interpretation. Using the Gantt chart we made, we were able to make sure that we got everything done in a timely manner. Everyone was assigned to different tasks to help spread the workload out.

4.0 Methodology and Implementation

After in-depth research on various ways to generate the required amount of power for an array of LED’s, approximately 35 watts, we determined that the best approach to take would be to use a permanent magnet generator. Once this was decided we began developing a design that would most effectively utilize the limited amount of space that we had to implement our generator.

4.1 Initial Permanent Magnet Design

Prior to building the generator it was crucial to develop a function that would be able to determine the specifics for the generator. These criteria included: number of turns, number of magnets, spin rate of rotor, strength of magnets, and number of coils. With the Mathematica code used all of the following variables were able to be tested to see what parameters gave us our desired outcome.

To simplify the process of finding the specifics of the generator, number of magnets and coils were chosen beforehand. Then the outcome properties: current, voltage, and power, were plotted with a slider which controlled spin rate to be able to see how the generator acted if the spin differed under different mechanical loads. From here turns and magnet strength were tested to see what values offered the needed output.

The code was fairly simple and can be seen in Appendix A. At the beginning of the code variables were set to be the rotational inertia of the rotor and the rough inductance of the coils. With this information, conservation of energy was used to very roughly determine the maximum current that could be expected out of the generator. This calculation was not very important at this time since the current produced is based on the rest of the circuit, and as long as the maximum current was well above what was needed it was not an issue. The voltage was calculated much more accurately using Faraday's law. Faraday set out the basic parameters that are used in developing a motor and generator by defining how induction coils react to changes in magnetic fields.

After deciding on our design we had to begin construction on our prototype. The first step of the building process was to design our rotor in AutoCAD. Our rotor's initial design had a 5" diameter with 8 holes of 1" diameter for the magnets to be placed in alternating orientation in order to increase the rate of change of the magnetic field and more effective generator. Once the AutoCAD of the rotor was completed we used the laser-cutter to cut it out of the ¼" piece of acrylic. Below is a picture of this rotor:

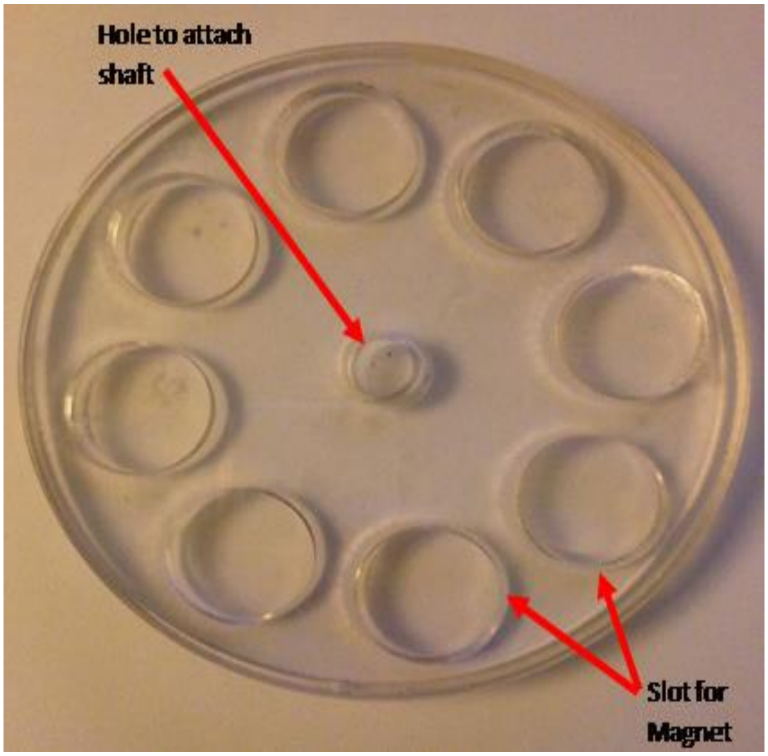


Figure 20: This shows our initial rotor design. While our final design uses ten magnets, this design only used eight magnets.

Once the rotor was completed we began the coiling process. This was done using a PVC pipe of 1" diameter, gorilla tape, and vice grips. The vice grips were used to secure one end of the wire to the pipe as it was tightly wound around the pipe. Once we had achieved 200 turns in a coil, we slid it off the pipe and used the gorilla tape to keep the coil tight. Once a few coils were completed we brought them to the lab to test how effective they were going to be in our generator. It quickly became apparent that the output of the coils would not be adequate. A picture of our original coils can be seen in Figure 21.

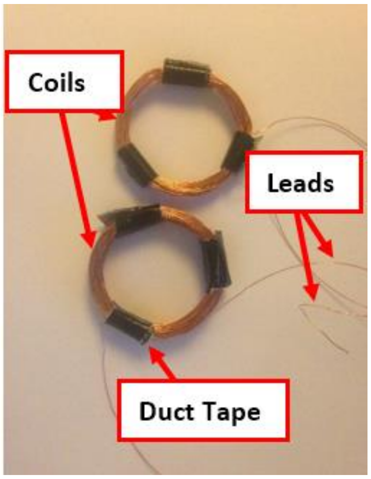


Figure 21: Here are two of the original coils that we used for testing. Each of them is 1" in diameter and has 200 turns.

Shortly after a couple of coils were made with varying numbers of turns, 100,150, and 200, they were all tested using the small impromptu rotor that was loaded on an axle, then hand spun at roughly 1 rotations per second while the holding the coil a quarter of an inch away from one another. The coil was then attached to an oscilloscope and max voltage was tested. A voltage of roughly 1V was expected from at least the 200 turn coil but instead all of the coils only were able to produce a maximum of .02V which was a massive discrepancy. This test was repeated several times with all four of the coils produced with similar results.

This large difference quickly moved the focus onto the code to try to explain what has gone wrong. This lead to an error in the code that explained what went wrong. The code was accidentally written for the area of the coil being in meters instead of centimeters. This was the main problem that lead to a lack of voltage. This lead to an update of the simulation.

4.2 Revised Permanent Magnet Design

Once the error in the code was found several changes had to be made to the code to yield trusted results. The first change made was the most important one, adding the area of the coil in square meters to the faraday function. This brought the voltage down significantly, by a factor of roughly 1000. The next change made to the code was just to update the voltage frequency based on how fast the rotor was spinning and also the number of magnets in use.

With all these changes made, and after finding several mistakes that reduced our expected voltage, changes to all of the variables had to be tested so that we could try to get back to the original voltage we calculated. Luckily, during our rechecking process, another error was found in our calculation for the strength of the magnets making them off by a factor of 10. This was helpful in getting back to the voltage we had originally expected. Next, the coil size was taken into account and their shape was taken into consideration. It was very important for the motor to maintain its small size therefore the coils were made more into a triangle to maximize the area of the stator coils while keeping the same size of the overall stator. This area maximization increased the size by a factor of 4. The final changes that were made to help restore the original plan were to increase the number of magnets used and also increasing the number of turns used from 150 per coil to 300 per coil. These changes made the smallest changes but were crucial to the final outcome. With all these changes only one more change needed to be made, that was to make the rotor spin slightly faster.

Just as beforehand, the first step of the building process was to design our rotor in AutoCAD. The new rotor was slightly larger than our prior model. It has a 6” diameter and 10 holes of 1” diameter as this design incorporates 10 magnets instead of the 8 of the prior design. With the AutoCAD complete, we used the laser-cutter again to create the rotor. Below is our AutoCAD design of the rotor, as well as an image of the rotor.

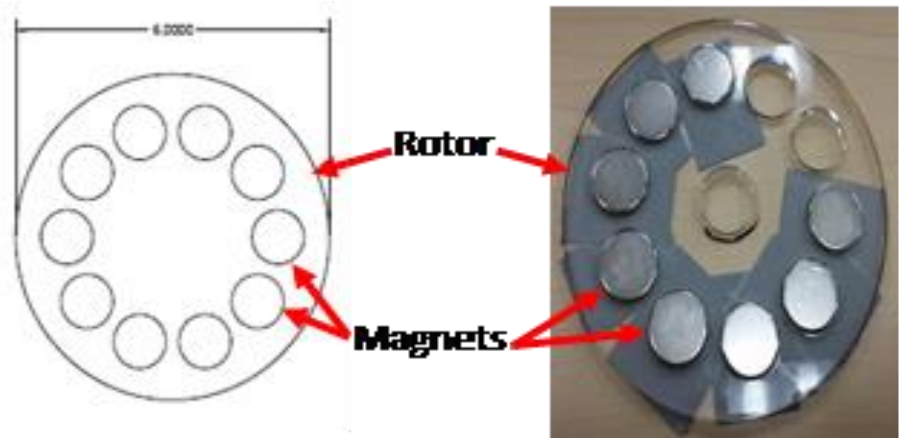


Figure 22: On the left is an AutoCAD rendering of our rotor. On the right is a picture of our rotor with eight of the ten magnets in place, being held with duct tape while the glue dries.

Once the rotor was constructed, we began working on the stator. In order to maximize the generator’s output, the coils of the generator need to be in the shape of an arced wedge. This meant that our old method of coiling would not be possible. To achieve this triangular shape, with sides of 3” and an arc of 3.5”, we had to create our own contraption to wind the wire around. We did this by drilling four holes into a piece of plywood in the desired shape, and inserting dowels that protrude from the wood to coil around. Our jig is shown below in Figure 23.

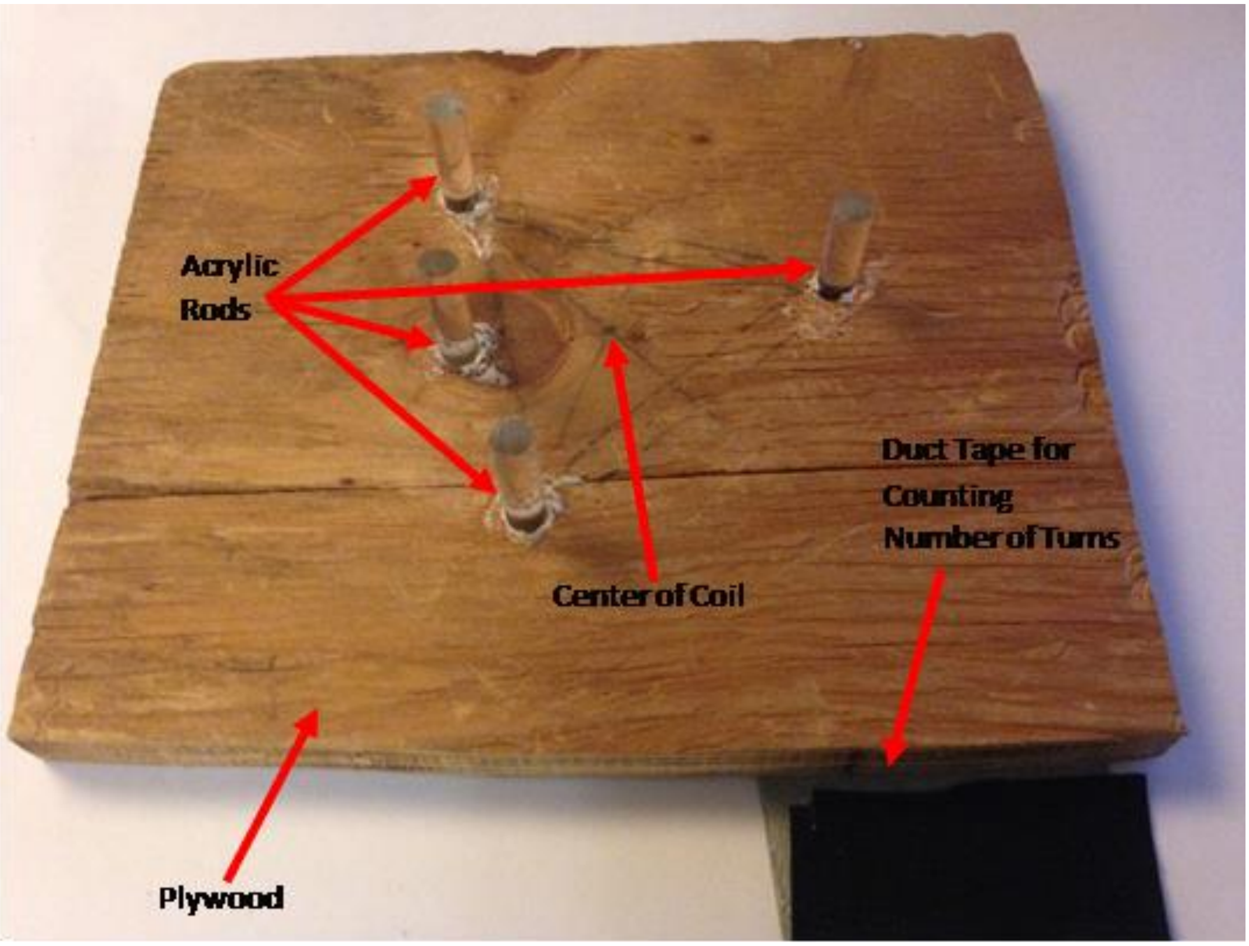


Figure 23: Here is an image of the wooden jig we used to create our coils.

The jig that we had made provided us with a frame to coil the wire around, however we still had no effective method to coil the wire in a reasonable amount of time. A lathe would have been ideal, however, with the shape of our jig, we knew that it would be a very unsafe procedure, so we were forced to come up with an alternative technique. We attached three magnets to the tip of a power drill, and put another two magnets on the other side of the jig, securing it in place. We then attached one end of the wire to the jig and another person was responsible for holding the wire as the jig was turned with the power drill. A picture of this can be seen below in Figure 24.

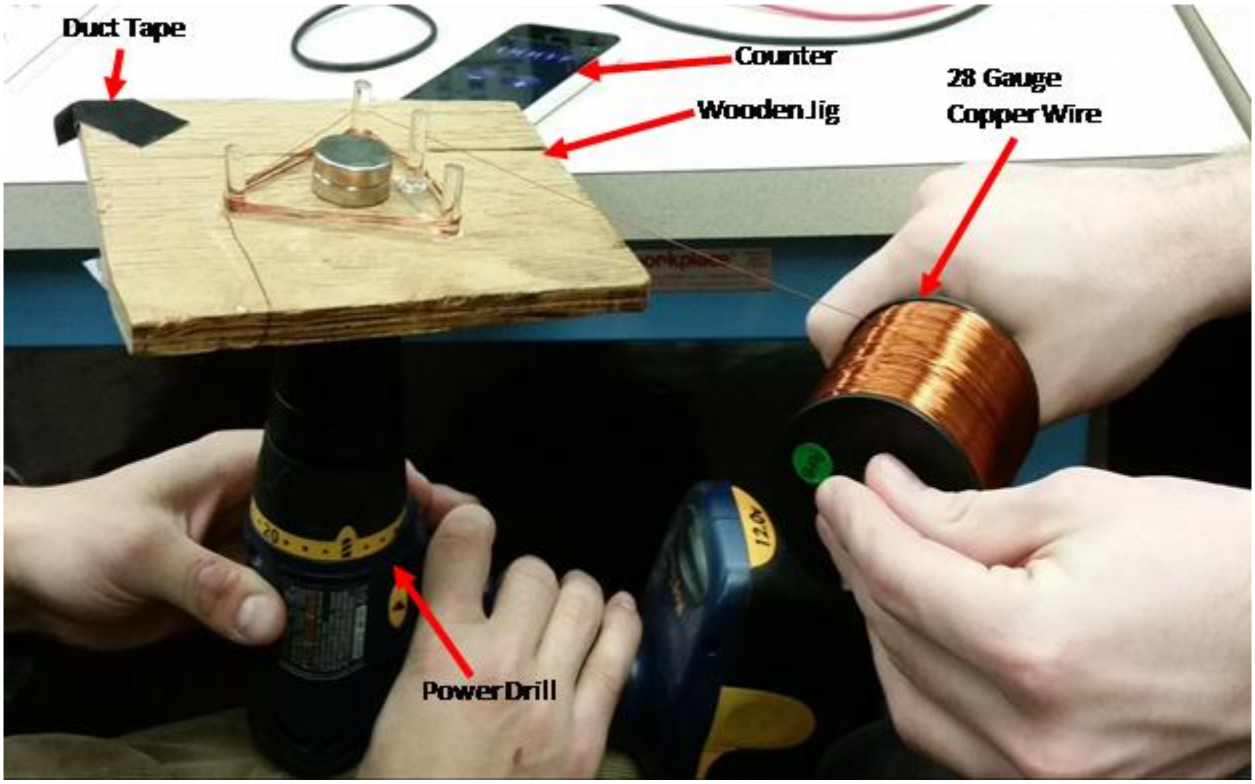


Figure 24: This picture shows our method of creating our coils. We used the wooden jig keep their shape, the drill to turn it, and the counter to count the number of turns.

After 300 turns of a coil, we had to figure out a method of removing the wire from the jig without losing its shape and turn density. We did this by slipping small strips of gorilla tape under the coils and attaching them to the coils sides before removing the coil from the jig.

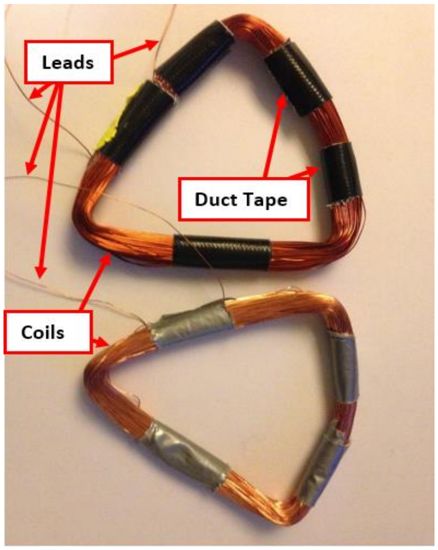


Figure 25: On top is the magnet wire coil, and on bottom is the bare copper wire coil.

Shown above is a picture of our initial coil with bare copper wire, and a coil of magnetic wire. At first we used the bare copper wire for our coils, however we quickly realized that this was ineffective as it meant that the coils simply acted as a single larger wire. Once we realized this we ordered magnetic wire which has a thin layer of insulation around it. While this insulation was necessary, it meant that we needed to strip the leads of the coils and solder them to make the copper accessible. Below are images of stripping and soldering the leads, as well as our completed twelve coils.

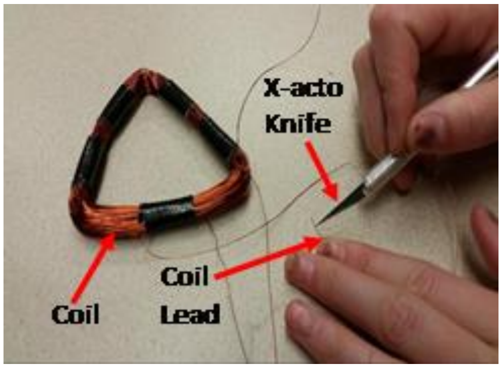


Figure 26: This shows us stripping the coil leads.

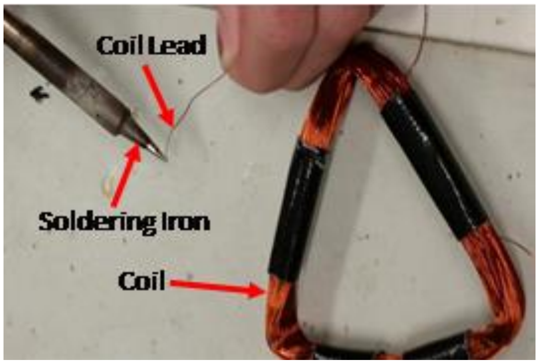


Figure 27: This shows us tinting the coil leads

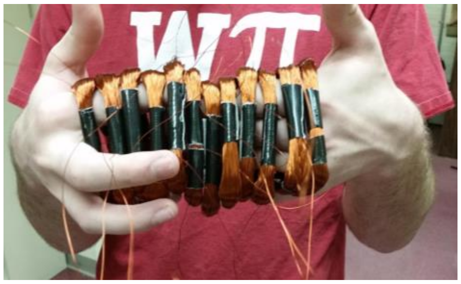


Figure 28: Our twelve coils are shown here. Each of them is three-hundred turns of 28 AWG copper wire.

With the completion of all twelve of our coils, we started putting the separate pieces together. Placing six coils onto each half of the stator. Figure 29 below shows one half of our stator.

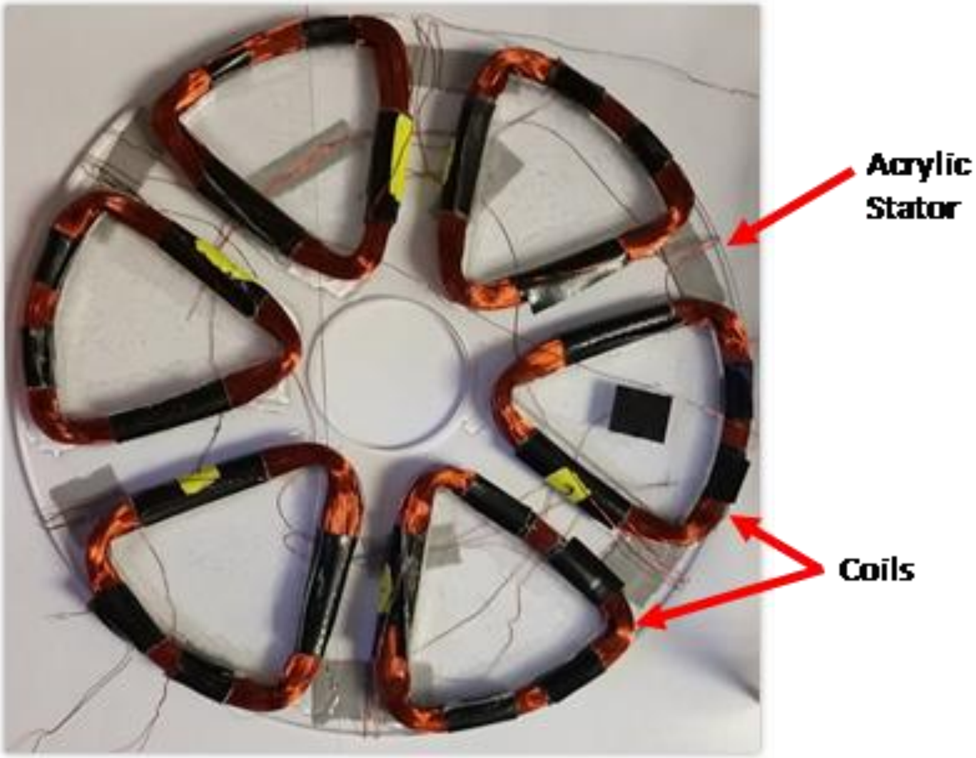


Figure 29: This depicts one half of our stator with six of the coils secured to it. On our generator one of these is above and below our rotor to maximize its output.

We also attached our ball bearings, shaft collar, and rotor to the shaft. Below is a picture of the completed rotor:

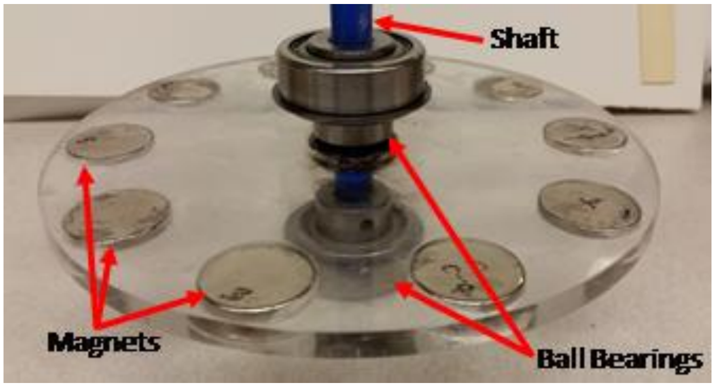


Figure 30: This is an image of our finished rotor attached to the shaft and the ball bearings.

The finished rotor provided us with the final dimensions of the generator's case. With the dimensions we revised our AutoCAD drawings and again used the laser cutter to cut the sides and top of the case, with a plywood base to accommodate the ball bearing. After we cut the sides and top of the case, we glued them together, keeping the plywood base separate from the acrylic. For the plywood base, we used the laser cutter to ensure our base's dimensions match the acrylic case perfectly. Below is a picture of the unfinished case:

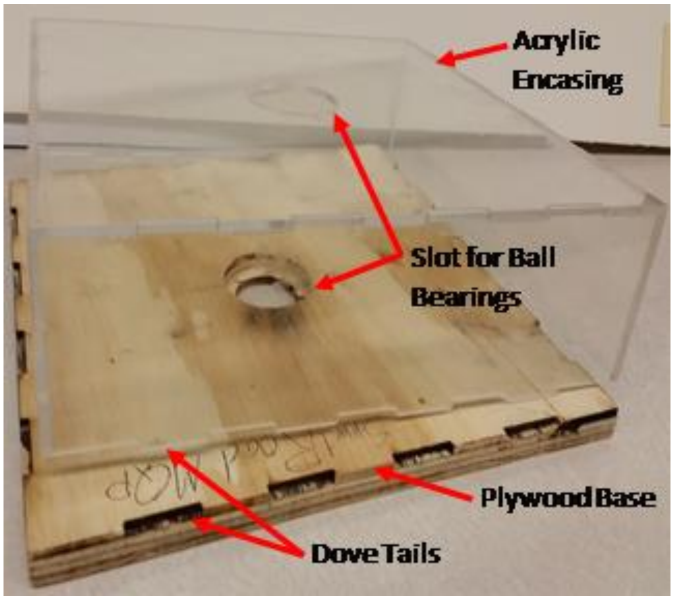


Figure 31: We built this acrylic encasing and plywood base for added stability and structural support.

After the case was constructed, we combined all of our parts to construct our permanent magnet generator. Below are pictures of this process:

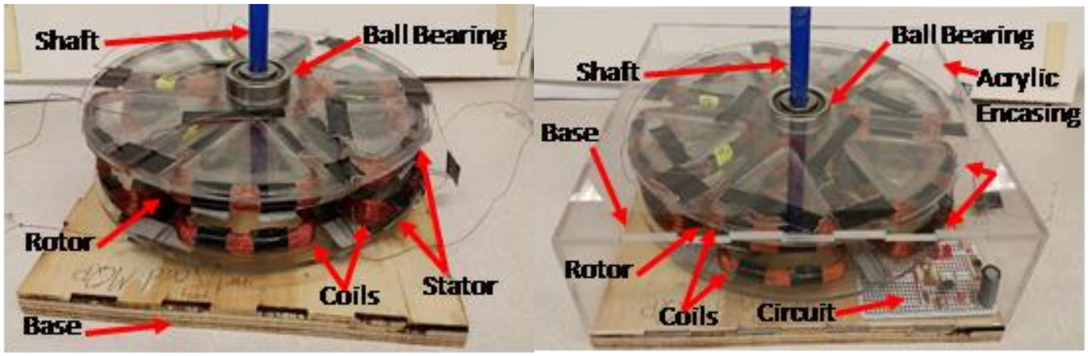


Figure 32 and Figure 33: On the left is a picture of our permanent magnet generator on the plywood base without its acrylic encasing, and on the right is a picture of it with its acrylic encasing.

4.3 Power Circuit Design

Below in Figure 34 is the first working simulation schematic design we envisioned, during the testing phase of our project. When this circuit was tested in the simulation software, Multisim, we found that it works fully, the only problem was that the current was smaller than we would have liked.

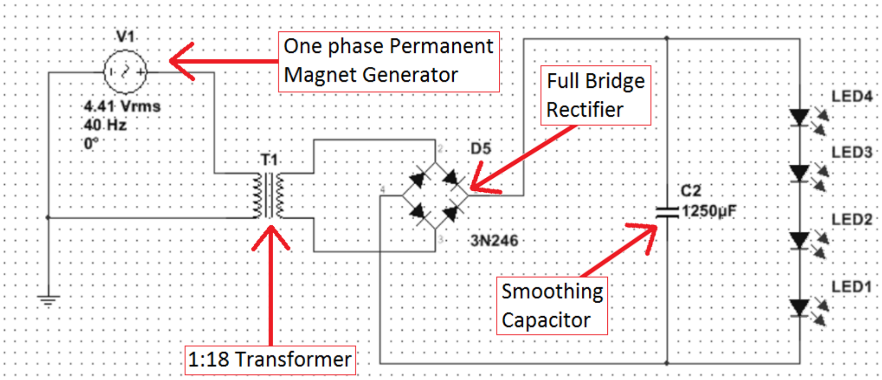


Figure 34: Original power circuit schematic consists of a 1:18 transformer, a full wave rectifier, and a smoothing capacitor to power an array of LEDs.

When stepping up the voltage of a circuit there are two different methods that can be used. The first method is to add a transformer before the rectifier, the second is a boost converter after a smooth dc voltage is created. When deciding on which to use there were two main factors that we took into consideration: the cost of the component and the difficulty in implementation.

The cost of the component was an important factor when deciding on which route to go because we still wanted our product to be very cheap. If we have to spend a considerable amount of money on only one component it would make reaching this goal much more difficult.

When considering the cost of a transformer we looked at online retailers that had transformers that were similar to what we need. The online retailer Automationdirect, sells many transformers that could properly boost the voltage, but each of these has a cost of over $50.00 [42]. This was more expensive than we had preferred.

In contrast, DC/DC boost converters were very cheap when looking for one that will work in our range. The online retailer SparkFun has multiple boost converters that could work for our application and most cost less than $15.00 [43]. This was a large difference in cost, making the boost converter the preferred approach.

When gauging the difficulty of implementation we looked at three areas; complexity of circuit installation, operational requirements, and difficulty of acquisition.

The transformer would have been very easy to install into our current power circuit, having only four leads to worry about. The transformer struggles with its operational requirements. When operating a transformer it should only be used at, or above its rated frequency. While a 60 Hz transformer would work fine at 120 Hz, it could become damaged if used at 40 Hz. This could be a huge problem when used with our device as the frequency could be inconsistent due to varying vehicle speeds. Finally, we found that it was extremely difficult to find a stock 1:18 transformer. This means that we would likely have to get one custom made or make one ourselves.

Boost converters were more difficult to install into the circuit, requiring a pulse to turn the switch on and off. This means that there were a few more components that would need to be installed. However, the boost converter does not have any restrictive operational requirements other than a max tolerable voltage. This was much better for our application because this would mean that we would not need to worry about the frequency created by our generator. In addition, boost converters of all sizes were readily available in stock from various retailers.

The reasons stated above make it easy to come to the conclusion that a DC/DC boost converter was the correct choice for our project. While a boost converter may be more difficult to install than a transformer, it is very forgiving operational requirements make it easier to use in the end. A transformer would require the frequency of the generator to be too consistent. This would be very difficult to achieve under the conditions we were using the device for. Additionally, the booster was more convenient to order and much less expensive.

When deciding on which booster to use there were only a few requirements:

1. Must have a possible output voltage of at least 24 V
2. Must tolerate currents of 1 to 2 A

Taking these requirements into consideration, we were able to find a suitable boost converter available from Digi-Key. The boost converter we selected was the LMR54010XMFE/NOPBCT for $1.89. The main datasheet information for this component can be seen in Appendix C.

Below in Figure 35 is the final schematic of power circuit that takes in AC voltage, converts that voltage to DC voltage and boost up the voltage and current to power a series of LEDs.

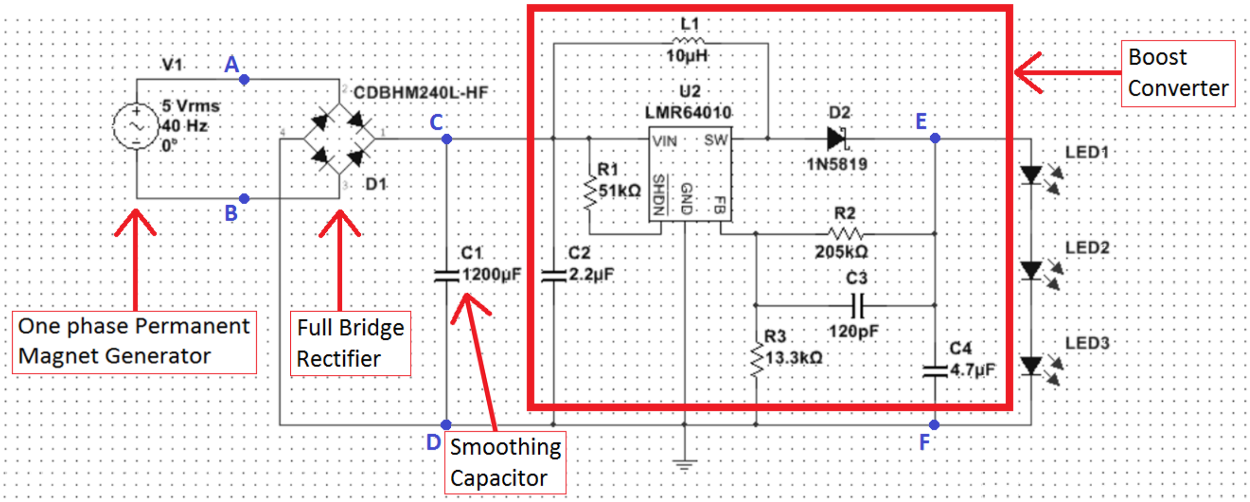


Figure 35: the final schematic of power circuit that takes in AC voltage, converts that voltage to DC voltage and boost up the voltage and current to power a series of LEDs.

The first section of our power circuit was a full-wave diode bridge rectifier. A full-wave rectifier is meant to produce a voltage or current that is purely dc. In our application the full-wave rectifier will be taking the ac voltage and current produced by our permanent magnet generator and converting it into a dc voltage that would turn on the LED array. We chose to use the 3N246 diodes for the simulation because they have a breakdown voltage high enough to deal with the potential voltages coming from the generator.

The second portion of our circuit was the smoothing capacitor. This capacitor charges up when the voltage from the rectifier rises above that of the capacitor and then as the rectifier voltage falls, the capacitor provides the required current from its stored charge. However, there were two important parameters to consider when we chose a suitable smoothing capacitor and these were its *Working Voltage*, which must be higher than the no-load output value of the rectifier and its *Capacitance Value*, which determines the amount of ripple that will appear superimposed on top of the DC voltage [44]. When choosing a value for the smoothing capacitor we chose a capacitor with a value of 1250 uF to ensure that the voltage was still high and that the current was substantial enough to power the array of LEDS. Also a nice rule of thumb to use is to use a capacitor with1000 uF per 1A [45].

The third section of our circuit was the boost converter. The boost converter we chose was a 1A Step-Up Voltage Regulator, meaning it is a DC-to-DC power converter that steps up its input voltage (supply) to its output (load). Using the help of datasheet and our specifications we chose the values for the components around the boost converter. We wanted the output voltage to be about 20 volts and in the datasheet there was a Basic Application Circuit for if the input was 5 volts and the output was 20 volts, this can be seen in the Appendix C page 2. We used the values of all the capacitors, inductors, and resistors from this circuit.

After successfully designing our final schematic in Multisim we wanted to build our circuit on a physical breadboard. The breadboard that we used manufactured by Twin Industries. Breadboards are ideal for electronic projects, rapid prototyping, and educational programs. We used it to build a temporary circuit for testing so no problems would occur when final implementation of our circuit was done. Below in Figure 36 is the breadboard we used for testing.

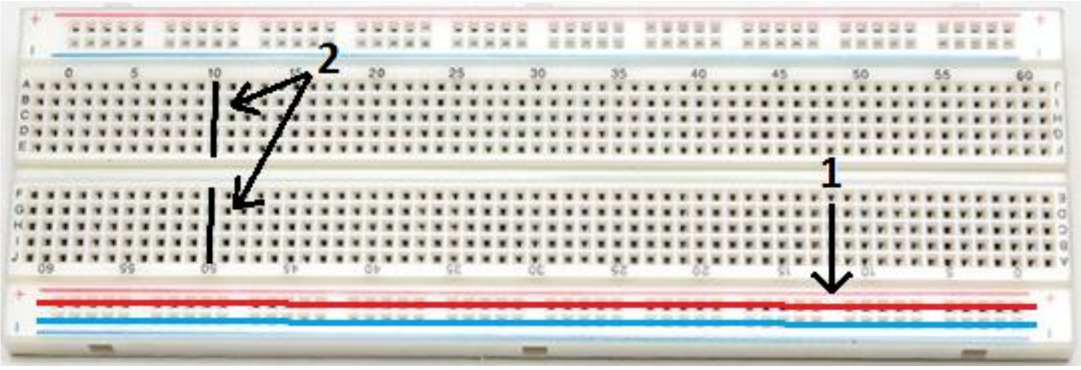


Figure 36: Twin Industries breadboard used for testing. The top and bottom rows are linked horizontally, indicated by the number 1. The other holes are linked vertically indicated by the number 2.

Breadboards have many connector holes arranged on a grid. The leads of most components can be pushed straight into the holes. When inserting ICs, like the rectifier and boost converter in our circuit, they are inserted across the central gap allowing no lead to be connected unintentionally. Wire links can be made with single-core plastic-coated wire of 0.6mm diameter (the standard size). Stranded wire was not suitable because it crumples when pushed into a hole and it could have potentially damaged the board if strands had broken off. The top and bottom rows are linked horizontally all the way across, this can be seen in Figure 36 indicated by the number 1. The power source of a circuit is typically connected to these rows. The other holes are linked vertically in blocks of 5 with no link across the center indicated by the number 2 in Figure 36. Notice how there are separate blocks of connections to each pin of ICs.

When constructing our breadboard circuit we made it in sections. The first section was the rectifier and smoothing capacitor. The second section was the boost converter circuit. Then we connected them together for the final circuit and tests. Figure 37 is the first section of the final circuit we built with a load of a resistor of 10 kΩ and red diffused LED. Since the rectifier that we ordered was a surface mount and extremely small, we engineered a wooden stabilizer. The reasoning behind building this stabilizer was because soldering wires directly onto the rectifier would increase the risk of breaking a lead off or burning out the component itself by holding the soldering iron onto it for too long. To build the stabilizer, we cut a piece of wood about 1/8th of inch thick and used copper foil, with adhesive tape on one side and copper on the other, to make contacts for each lead to be placed on. Then we soldered on leads and extra wires onto the contacts, these wires could then be place into the breadboard. After we tested and found that our circuit worked, results can be seen in section 5.0.

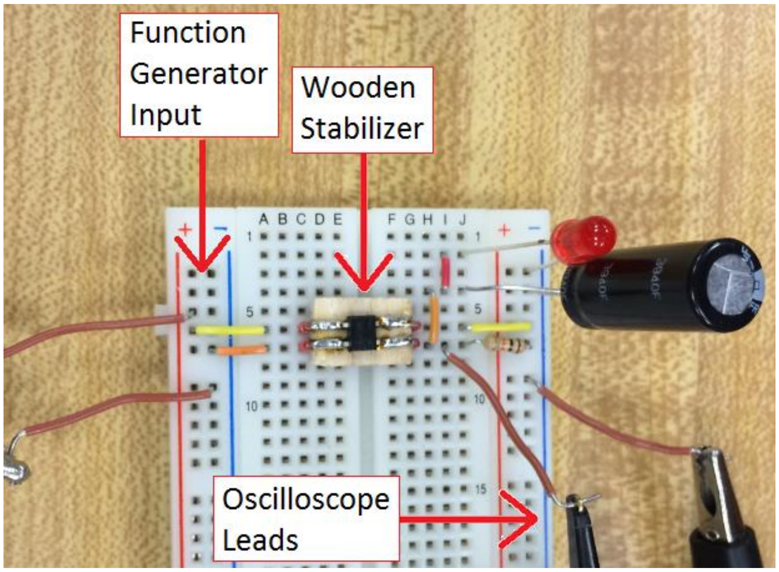


Figure 37: Displayed is a rectifier circuit on the breadboard. The component is attached to a function generator for testing.

Figure 37 is the second section of the final circuit we built. The boost converter was ordered as a surface mount just like the rectifier, so we had to make another wooden stabilizer. We cut another piece of wood and used copper foil, with adhesive tape on one side and copper on the other, to make contacts for each lead to be placed on. Then we soldered on leads and extra wires onto the contacts, these wires could then be place into the breadboard. After testing if the circuit worked we moved onto combining the two sections together and testing if the circuit worked as a whole.

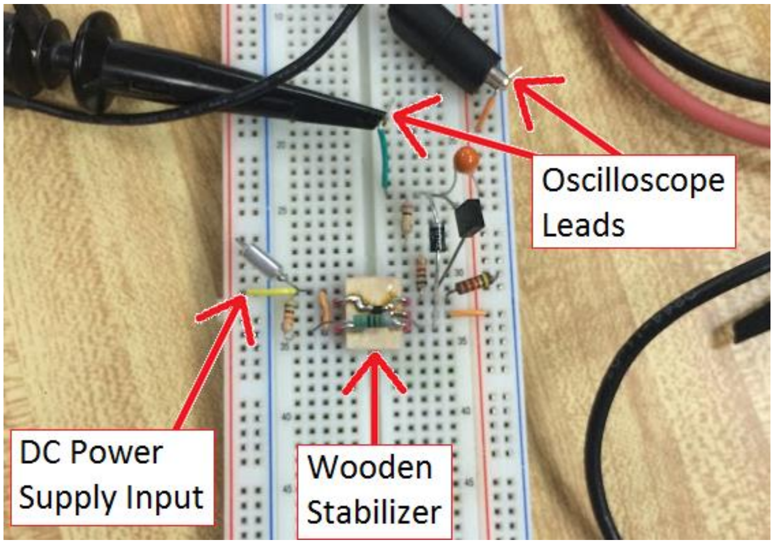
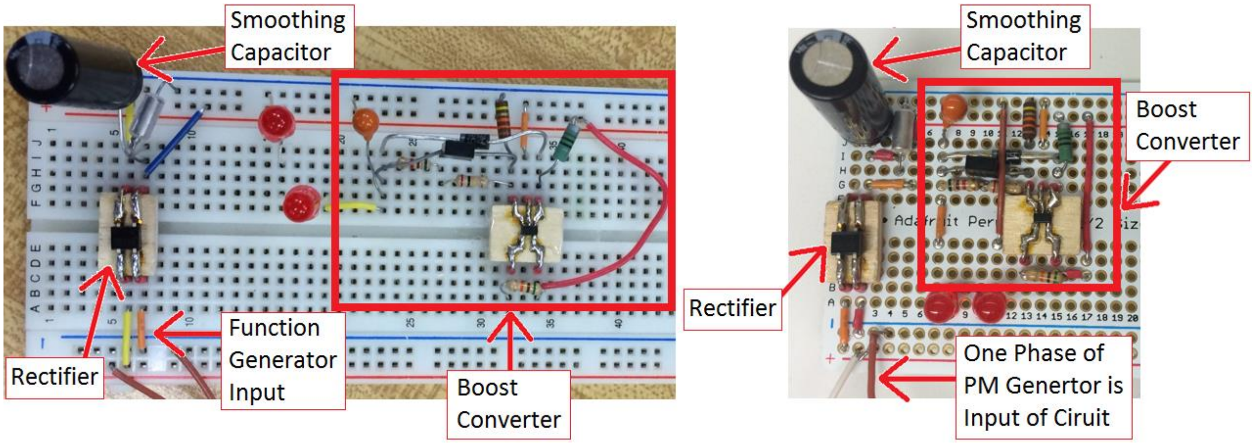


Figure 38: Displayed is the boost converter circuit on the breadboard attached to a DC power supply and an oscilloscope.

Next we combined the two sections together on the breadboard and tested if the circuit works the way it was supposed to; to take in an AC voltage, convert it to DC voltage and boost the voltage up. This circuit can be seen in Figure 38. After we tested and fully debugged our final power circuit, we constructed the same circuit onto a soldering board, this can be seen in Figure 40.



Figures 39-40: This depicts our final circuit on the breadboard (left) and a soldering board (right).

4.4 Chapter Summary

Upon building the coils for the originally design generator and testing their output voltage, it was determined that their voltage was nowhere near what was expected. This discovery lead to an investigation of the theoretical code, which eventually found a mistake in the code. Sadly, the equation used needed square meters instead of square centimeters for an input value along with some smaller coefficient errors. Changes were made to the code to allow for the true output voltage to be determined. Then using this new code new coefficients were used tested to allow for a generator that would produce the needed voltage.

While our generator produced an AC current, the LEDs that we planned on powering require DC current, therefore, we decided to feed the generator’s output through a full-wave rectifier. The output of this was then fed through a smoothing capacitor to achieve this desired DC current. This current was then fed into a boost converter in order to achieve the desired voltage to power the LEDs.

5.0 Results

5.1 Generator Testing and Results

Upon finishing the generator, testing the relationship between the rotor spin rate and output voltage was crucial. Since their relationship was known to be linear from faraday's law that ratio was important to know. Upon testing, the shaft was simple spun by hand with each phase independently hooked up to an oscilloscope. The oscilloscope automatically read average frequency for the window of phase 1, along with the average voltage for each phase. Since the relationship between voltage and frequency are linear the average was an acceptable reading. Also because the coils all had induced voltages from the same rotor, the frequency output held true for the other phases as well, the output voltage can be seen in figure 41.

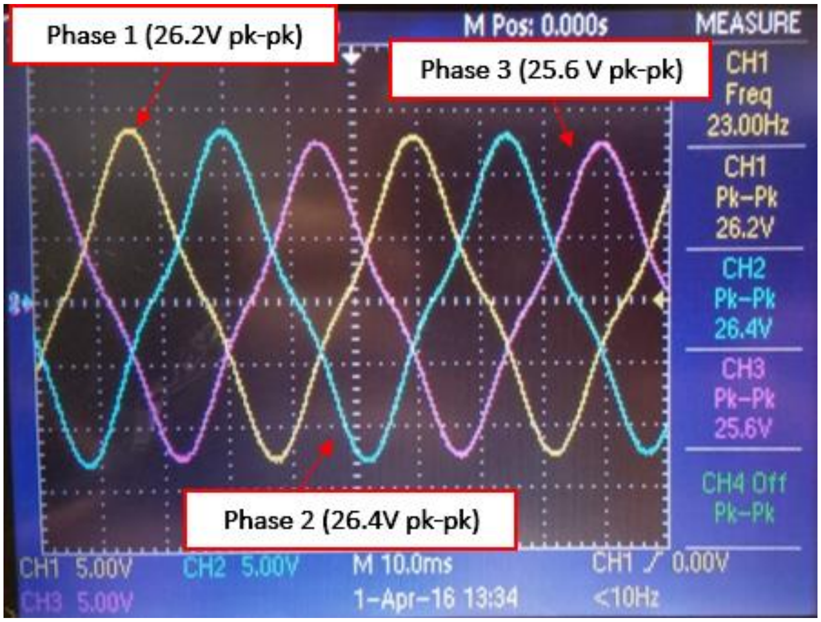


Figure 41: The output voltages of all three phases of the permanent magnet generator. Each phase is displaced 120^0.

After the generator was spun by hand the same process was repeated but with a pump drill. This waveform looked quite different from the hand spun data. This waveform looks more like and extended impulse that gradually died down due to the inertia from the rotor. The oscilloscope was again used to measure average voltage and frequency from the impulse along with counting each impulse by hand to capture both the up and down stroke of the pump drill.

Once all the data was collected the information was then all inserted into one single scatter plot to be able to determine the linear line of best fit along with comparing the expected outcome to the actual results. For a full list of testing values see Appendix D, the plot looks as follows:

Theory Line

Tested bullet points
~ 70% of theory

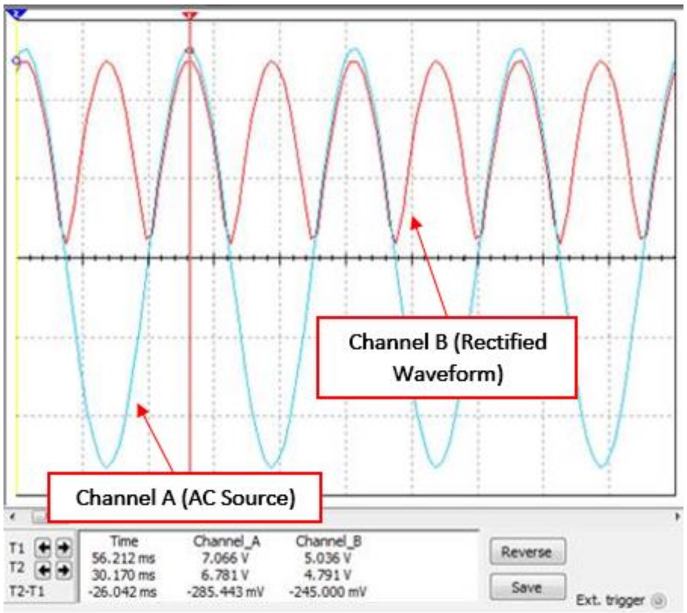
Original guess
from testing coils
individually

Figure 42: A graph of the generator performance. All three phases are represented as well as our theoretical and original testing lines.

As one can see, the expected relationship was to be about 4.59 volts per rotor spin rate, while the outcome of the rotor came out to be an average 2.99 volts per rotor spin rate, which makes for a 65% efficient generator. However this value was still greater than initial testing values predicted. These values were estimated based off of initial voltage reading taken from each coil independently. For a full list of coil results see Appendix E.

5.2 Circuit Testing and Results

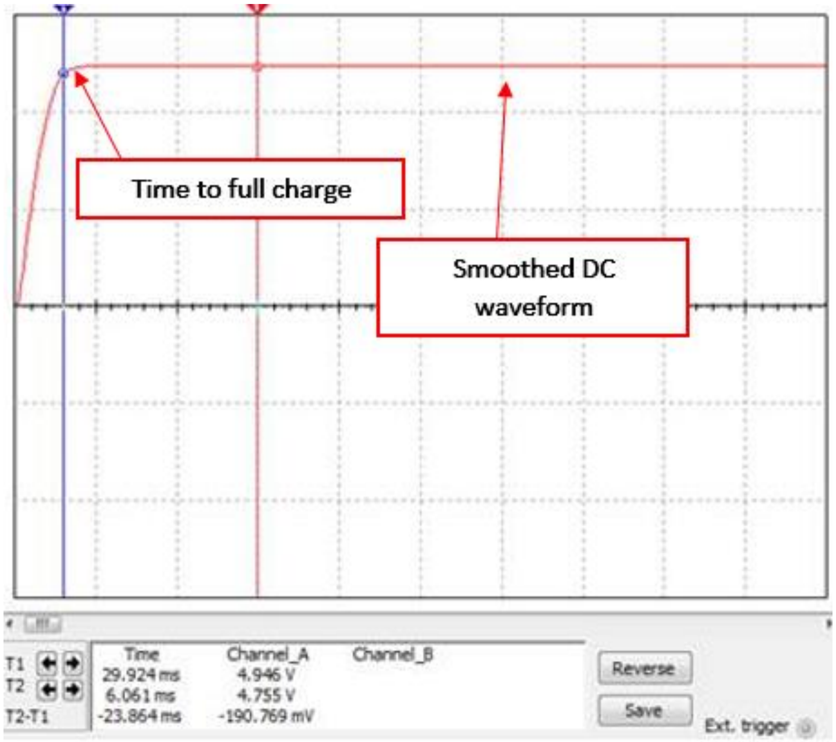
Once the final circuit was decided upon in the computer program Multisim, it needed to be tested in order to determine whether or not there would be any future problems when implementing the circuit onto the test breadboard. To do this we placed the first probe (Channel A) of an oscilloscope on nodes A and B and the second probe (Channel B) on nodes C and D that can be seen in Figure 35 in section *4.3 Power Circuit Design*. We then removed the smoothing capacitor and ran the simulation. The oscilloscope showed the DC waveform after going through the rectifier, this can be seen in Figure 43.



	Time	Channel_A	Channel_B
T1	56.212 ms	7.066 V	5.036 V
T2	30.170 ms	6.781 V	4.791 V
T2-T1	-26.042 ms	-285.443 mV	-245.000 mV

Figure 43: Simulated AC waveform as a result of the rectifier. Channel A is the AC voltage before entering the rectifier (blue line) and Channel B is the fully rectified wave (red line).

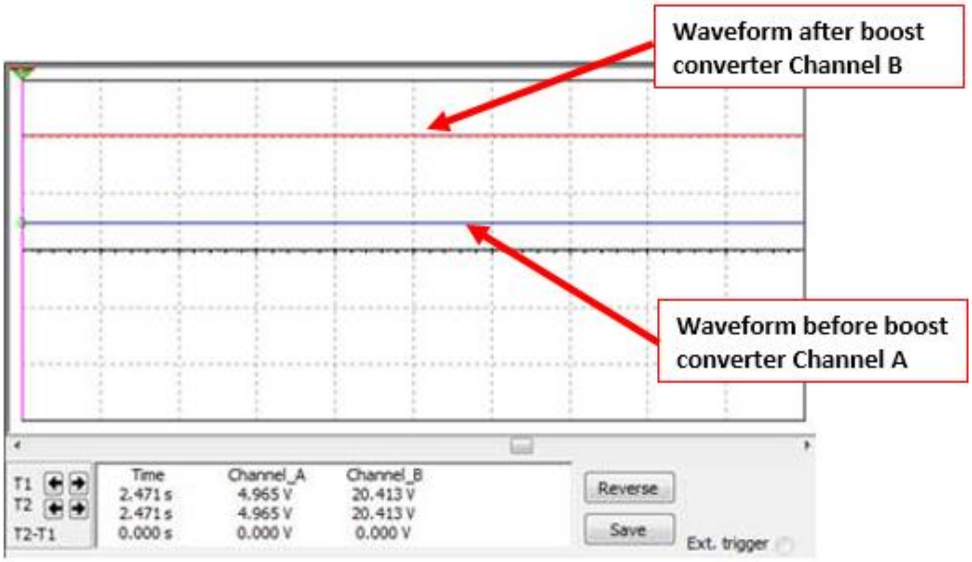
When simulating the circuit we found that the full-wave bridge rectifier gave us a greater mean DC value with less superimposed ripple while the output waveform was twice that of the frequency of the input supply frequency. We could therefore increase its average DC output level even higher by connecting a suitable smoothing capacitor across the output. So we added the smoothing capacitor back into the circuit and used the first probe of the oscilloscope to see the resulting waveform. We placed the probe on nodes B and C and ran the simulation. Figure 44 shows our results.



	Time	Channel_A	Channel_B
T1	29.924 ms	4.946 V	
T2	6.061 ms	4.755 V	
T2-T1	-23.864 ms	-190.769 mV	

Figure 44: The simulated DC waveform as a result of inserting the capacitor after the rectifier.

Next we needed to test the function of the boost converter. We executed this by connecting the different oscilloscope channels to different nodes. Channel A was connected to nodes C and D and channel B was connected to nodes E and F. This was to observe if our design for the boost converter would take in a DC value of 5 volts and boost it to 20 volts. Our results can be seen in Figure 45 below, this figure shows that our circuit for the boost converter works properly.


Waveform after boost converter Channel B

Waveform before boost converter Channel A

	Time	Channel_A	Channel_B
T1	2.471 s	4.965 V	20.413 V
T2	2.471 s	4.965 V	20.413 V
T2-T1	0.000 s	0.000 V	0.000 V

Figure 45: The simulated DC waveforms of the input and output of the boost converter boosted from 5V (Channel A, Blue) to 20V (Channel B, Red).

Once testing through Multisim was successful, we moved onto testing our circuit on the breadboard. Similarly to how we tested the circuit in Multisim, we tested our circuit in two sections. The first section was testing only the rectifier without the smoothing capacitor. When initially testing this portion of the final circuit we were having difficulties getting the rectifier to act like a full wave rectifier. It was acting like a half wave rectifier, which we discovered was because of two diodes in the rectifier had gotten fried during soldering. We fixed this problem by just replacing the broken component with a new one. Below in Figure 46 the final result can be seen. We connected a single channel function generator to the inputs of the rectifier. The function generator was set to have an amplitude of 10 volts peak to peak with a frequency of 10 Hz. We connected a resistor of 10 kΩ at the output of the rectifier to have something to bear the load. Next we connected channel 2 of a four channel digital storage oscilloscope across the resistor.

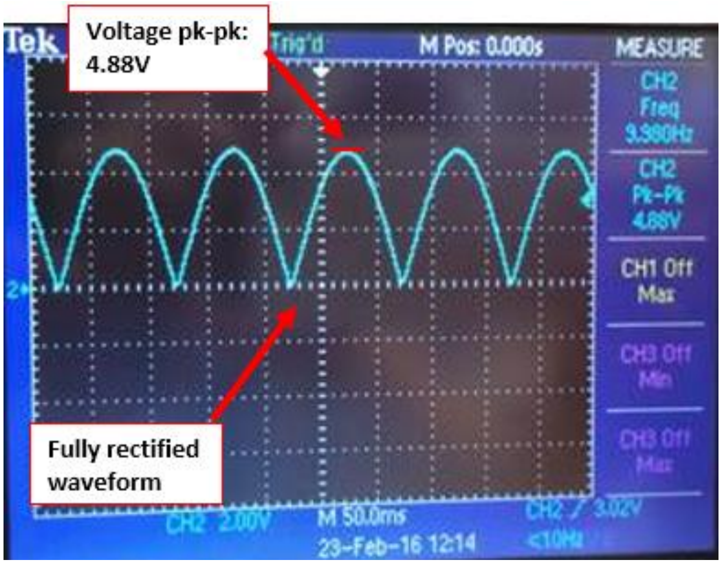


Figure 46: The waveform after going through our full wave rectifier.

Next we needed to test if adding the smoothing capacitor in parallel with the 10 kΩ resistor would be enough to take the waveform out of the rectifier and smooth it out to a nice DC value. The input of the function generator was set to have an amplitude of 10 volts peak to peak with a frequency of 10 Hz. Channel 2 of the oscilloscope was placed across the smoothing capacitor, as seen in Figure 37 of section *4.4 Power Circuit Design*.

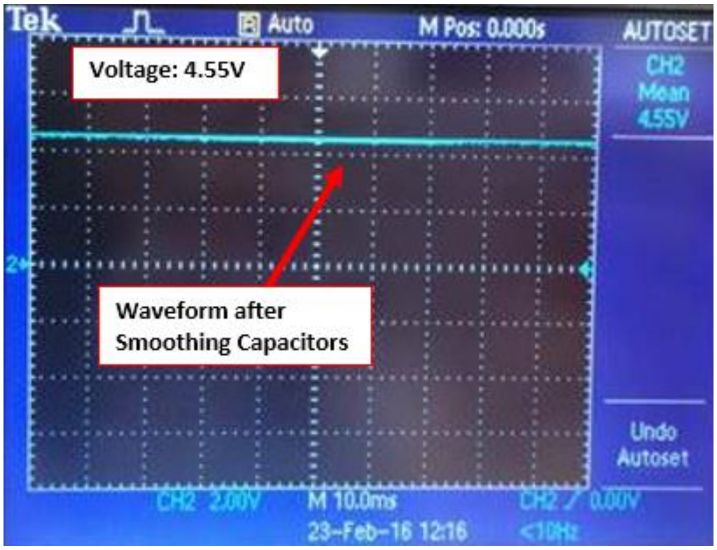


Figure 47: The DC waveform as a result of inserting the capacitor after the rectifier.

Finally the next portion of the circuit we tested was the boost converter. We connected the input of the boost converter to a DC power supply and set the voltage to volts. Then we the four channel digital storage oscilloscope to the circuit to observes the input and output waveforms. Channel 2 of the oscilloscope was connected to the input of the boost converter, while channel 1 of the oscilloscope was connected across the 4.7 μF capacitor to record the output. The resulting waveforms can be observed in Figure 48 below.

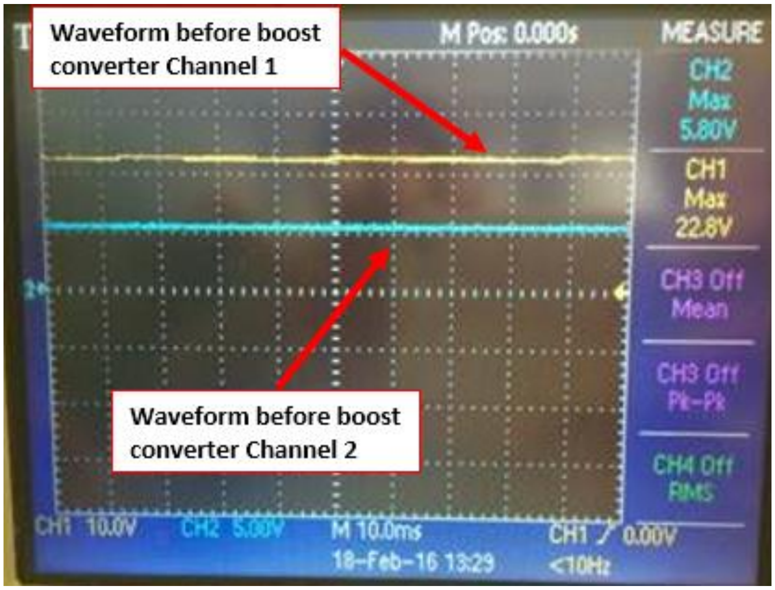


Figure 48: The DC waveforms of the input and output of the boost converter. The waveform is boosted from 5V (blue) to 20V (yellow).

The next step in testing the circuit was to combine the two sections we tested individually, the rectifier plus the smoothing capacitor and the boost converter, and make sure the circuit works as a whole. We connected the input of the rectifier to the function generator set to 10 volts peak to peak with a frequency of 10 Hz and connected the input of the boost converter to the output of the rectifier. We also added two red LEDs to the output so we could physically see that the circuit was working. It took a couple times debugging the circuit to make sure all the wires were where they were supposed to be and for this LEDs to light, but in the end the circuit worked correctly.

5.3 Chapter Summary

Upon finishing the construction of the generator extensive testing was done. This testing was purely to compare the spin rate with the output voltage of the generator. The rotor was spun many times with several different frequencies in order to fill out a scatter plot. This procedure was then repeated except this time using a pump drill to acquire a more consistent output. This test was repeated numerous time to acquire a large sample size. The resulting ratio turned out to be 2.99 V/Rev/s. These numbers we then compared to the theoretical ratio which was calculated to be 4.59V/Rev/s base on our Mathematica code. This led to our rotor being 65% the threshold. However the voltage was significantly higher than the original testing of the coils predicted.

When comparing the results of the Multisim simulations to the results of the breadboard testing, it was clear that there was not a lot of variation. The results when testing the rectifier for both Mutism and the breadboard were a success. In Multisim the amplitude of the rectified wave was around 5.036 volts. The amplitude of the rectified wave when testing it on the breadboard was about 4.88 volts. This was a difference of 0.156 volt which could be expected due to imperfections in the experimentation process. When adding the smoothing capacitor in Multisim, the DC value was 4.946 volts and on the breadboard it was 4.55 volts, this was a difference of 0.396 volts. It makes sense that the simulated voltages were closer to the 5 volts inputted into the rectifier. The results when testing the boost converter were also a success. In Multisim the DC voltage outputted of the boost converter circuit was about 20.413 volts and when testing the circuit on the breadboard the output voltage was about 22.8 volts. Both of these results were close to what we wanted; an output of 20 volts.

6.0 Conclusion and Future Work

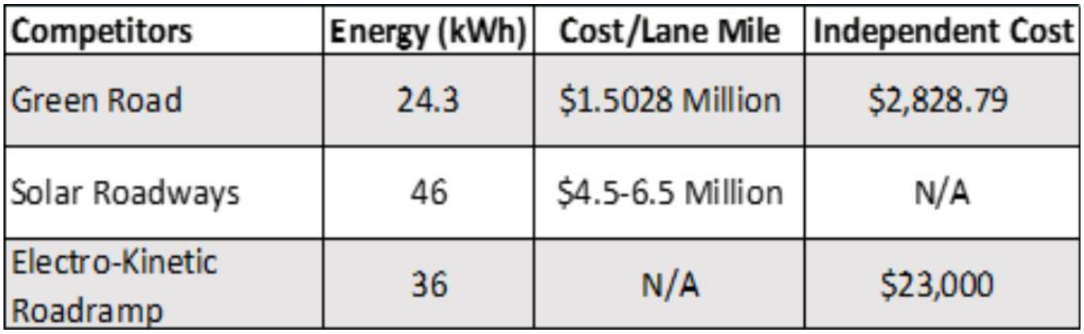
Ultimately we accomplished our goal of creating a device capable of being implemented into the surface of a road that is able to generate enough power to light an array of LEDs. We were able to construct our generator, and successfully fed the generator's output through a custom circuit to convert its AC waveform into enough DC Power to illuminate the roadway. Although the device was constructed, and yielded positive results, we were unable to fully explore the integration of our product into the roads surface.

6.1 Conclusion

We faced numerous challenges that forced us to adapt our approach of creating a roadway capable of converting lost kinetic energy from vehicles into usable electricity. We considered a variety of possible methods before we ultimately settled on using a permanent magnet generator to complete this task. We found that the permanent magnet generator was the most cost effective, and efficient option.

We began testing our generator and circuit upon their completion, and found that we had achieved our goal of 15 volts, enough to power an LED street light. After accomplishing our desired voltage, we performed a cost analysis of our prototype versus our competitors. This can be seen in Table 8.

Table 8: Final cost comparison of our Green Road versus our two main competitors, Solar Roadways and Electro-Kinetic Roadramp



Competitors	Energy (kWh)	Cost/Lane Mile	Independent Cost
Green Road	24.3	$1.5028 Million	$2,828.79
Solar Roadways	46	$4.5-6.5 Million	N/A
Electro-Kinetic Roadramp	36	N/A	$23,000

6.2 Future Work

The issue we ran into was that our team only included electrical and computer engineers, meaning that none of us were knowledgeable about roadways or how to implement a mechanical device to use a vehicle’s downward force to into enough rotational force to turn our generator. We recommend:

- The next team that plans on continuing this project should include a civil, and mechanical engineer.
- The future focus should be on producing a viable mechanical solution.
- The permanent magnet generator should be further tested for wear and tear.

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Appendix A – Old Mathematica Code

Iner =6.548*10^{-4};
//Defined the Rotational Inertia of the Stator

L = .001661;
//Defined the Inductance of the Rotor

KE[In_,w_]:=.5*In*w^{2};
//Set up function for the Rotational Kinetic Energy (RKE) of the Stator based on its inertia and how fast it was spinning

KE[Iner,1]
// tested RKE function

curr= $\sqrt{\frac{2*\mathrm{KE}[\mathrm{Iner}, 4]}{L}}$
//Tested conservation of energy for Rotor-Stator to find Current. RKE=Energy in Coil. Solved for current

V[numturn_,nummag_,w_,magstr_,]:=(4*numturn)*((2*magstr)/(1/(w*nummag))); //Set up function to find voltage produced by the Coils using Faradays Law. Function set up to handle input of Number of turns for the coils, Number of magnets in the rotor, how fast it is spinning, Magnet Strength.

vol =V[300,8,2,.00825]
//tested the Function.

Volt[t_,w_]:=V[300,8,w,.00825]*Sin[2*π*t*8];
//Used Function V to be able to set up a proper voltage function that produces the proper sin wave. This is now a function of Time, Also put spin rate to the outside function to be able to see how spin rate effects our project. Frequency is based on number of magnets.

Current[t_,w_]:= $\sqrt{\frac{2*\mathrm{KE}[\mathrm{Iner}, w]}{L}}$ *Sin[2*π*t*8-π/2];
//Did the same process for current.

```
Manipulate[Show[Plot[{Volt[t,w],Current[t,w],Volt[t,w]*Current[t,w],Tooltip[First[FindMaximum[Volt[t,w] Current[t,w],{t,0}]]]},{t,0,.5},
  PlotRange->{{0,..5},{-300,300}},
  PlotLegends->{"Voltage (V)","Current (A)","Power (W)","Max Power (W)"}]],{{w,1},0,5},{w,Range[5]}]
```

//Plotted Voltage/Current/Power/Max Power on the same plot and allowed for user to see different spin rates. Plot is labeled and also has a dynamic slider to allow for spin rate adjustment.

Appendix B – New Mathematica Code

Iner =6.548*10^{-4};
//Defined the Rotational Inertia of the Stator

L = .001661;
//Defined the Inductance of the Rotor

KE[In_,w_]:=.5*In*w^{2};
//Set up function for the Rotational Kinetic Energy (RKE) of the Stator based on its inertia and how fast it was spinning

KE[Iner,1]
// tested RKE function

curr= $\sqrt{\frac{2*\mathrm{KE}[\mathrm{Iner},4]}{L}}$
//Tested conservation of energy for Rotor-Stator to find Current. RKE=Energy in Coil. Solved for current

V[numturn_,nummag_,w_,magstr_,area_]:=(4*numturn)*((1*magstr*area)/(1/(w*nummag)));
//Set up function to find voltage produced by the Coils using Faradays Law. Function set up to handle input of Number of turns for the coils, Number of magnets in the rotor, how fast it is spinning, Magnet Strength, and Coil area.

vol =V[300,10,10,.00825,.00315]
//tested the Function.

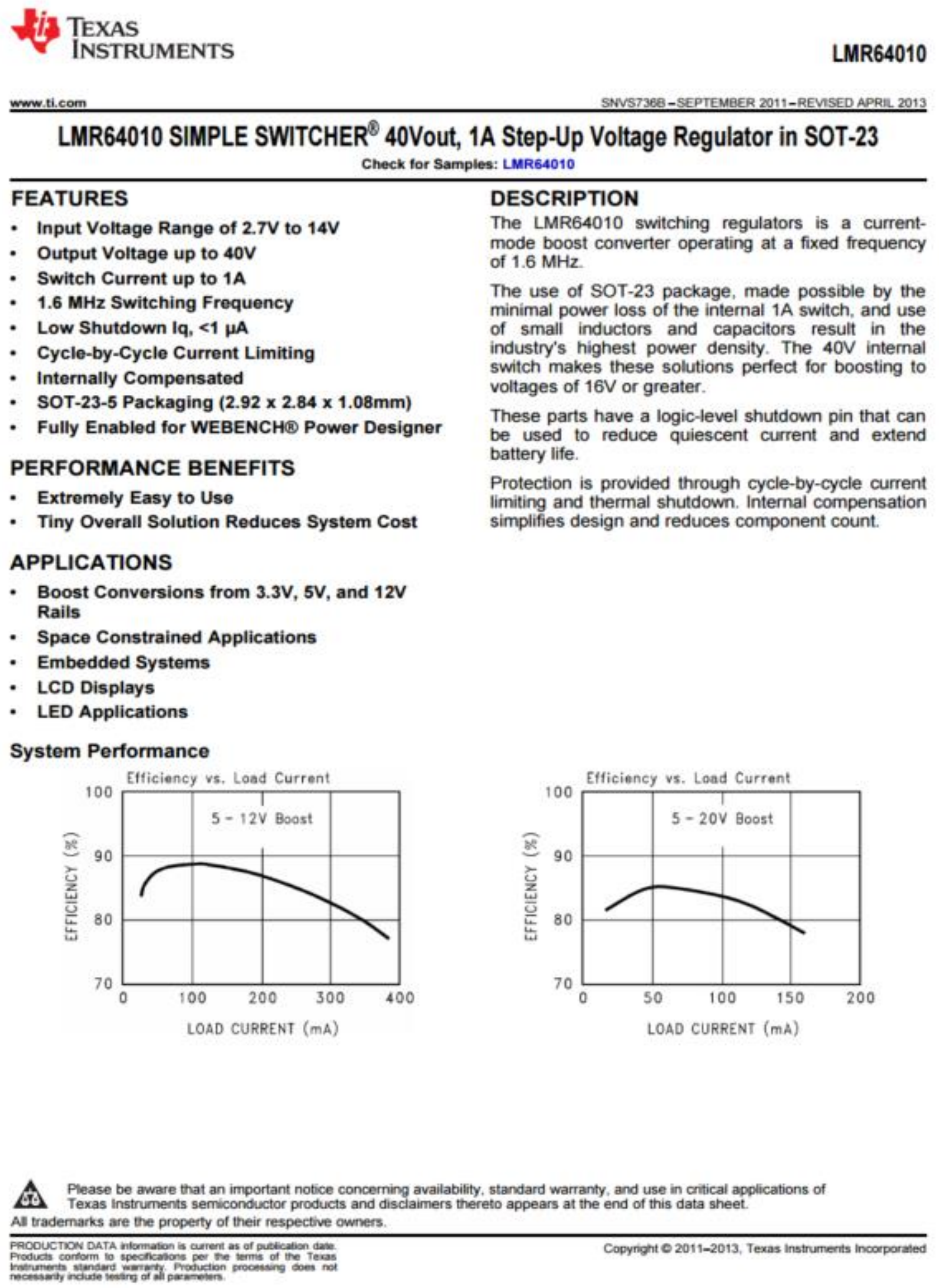
Volt[t_,w_]:=V[300,10,w,.00825,.00315]*Sin[2*π*t*w*5];
//Used Function V to be able to set up a proper voltage function that produces the proper sin wave. This is now a function of Time, Also put spin rate to the outside function to be able to see how spin rate effects our project. Notice how sine wave frequency is based on rotor spin rate times half the number of magnets.

Current[t_,w_]:= $\sqrt{\frac{2*\mathrm{KE}[\mathrm{Iner},w]}{L}}$ *Sin[2*π*t*w*5-π/2];
//Did the same process for current.

Manipulate[Show[Plot[{Volt[t,w],Current[t,w],Volt[t,w]*Current[t,w],Tooltip[First[FindMaximum[Volt[t,w] Current[t,w],{t,0}]]]},{t,0,.5/w},
  PlotRange->{{0,.5/w},{-30,30}},
  PlotLegends->{"Voltage (V)","Current (A)","Power (W)","Max Power (W)"}]],{{w,1},0,30},{w,Range[30]}]

//Plotted Voltage/Current/Power/Max Power on the same plot and allowed for user to see different spin rates. Plot is labeled and also has a dynamic slider to allow for spin rate adjustment.

Appendix C - LMR64010 Boost Converter Data Sheet



TEXAS INSTRUMENTS

LMR64010

www.ti.com

SNVS736B – SEPTEMBER 2011 – REVISED APRIL 2013

LMR64010 SIMPLE SWITCHER® 40Vout, 1A Step-Up Voltage Regulator in SOT-23

Check for Samples: LMR64010

FEATURES

- Input Voltage Range of 2.7V to 14V
- Output Voltage up to 40V
- Switch Current up to 1A
- 1.6 MHz Switching Frequency
- Low Shutdown Iq, <1 µA
- Cycle-by-Cycle Current Limiting
- Internally Compensated
- SOT-23-5 Packaging (2.92 x 2.84 x 1.08mm)
- Fully Enabled for WEBENCH® Power Designer

PERFORMANCE BENEFITS

- Extremely Easy to Use
- Tiny Overall Solution Reduces System Cost

APPLICATIONS

- Boost Conversions from 3.3V, 5V, and 12V Rails
- Space Constrained Applications
- Embedded Systems
- LCD Displays
- LED Applications

DESCRIPTION

The LMR64010 switching regulators is a current-mode boost converter operating at a fixed frequency of 1.6 MHz.

The use of SOT-23 package, made possible by the minimal power loss of the internal 1A switch, and use of small inductors and capacitors result in the industry's highest power density. The 40V internal switch makes these solutions perfect for boosting to voltages of 16V or greater.

These parts have a logic-level shutdown pin that can be used to reduce quiescent current and extend battery life.

Protection is provided through cycle-by-cycle current limiting and thermal shutdown. Internal compensation simplifies design and reduces component count.

System Performance

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

All trademarks are the property of their respective owners.

PRODUCTION DATA information is current as of publication date. Products conform to specifications per the terms of the Texas Instruments standard warranty. Production processing does not necessarily include testing of all parameters.

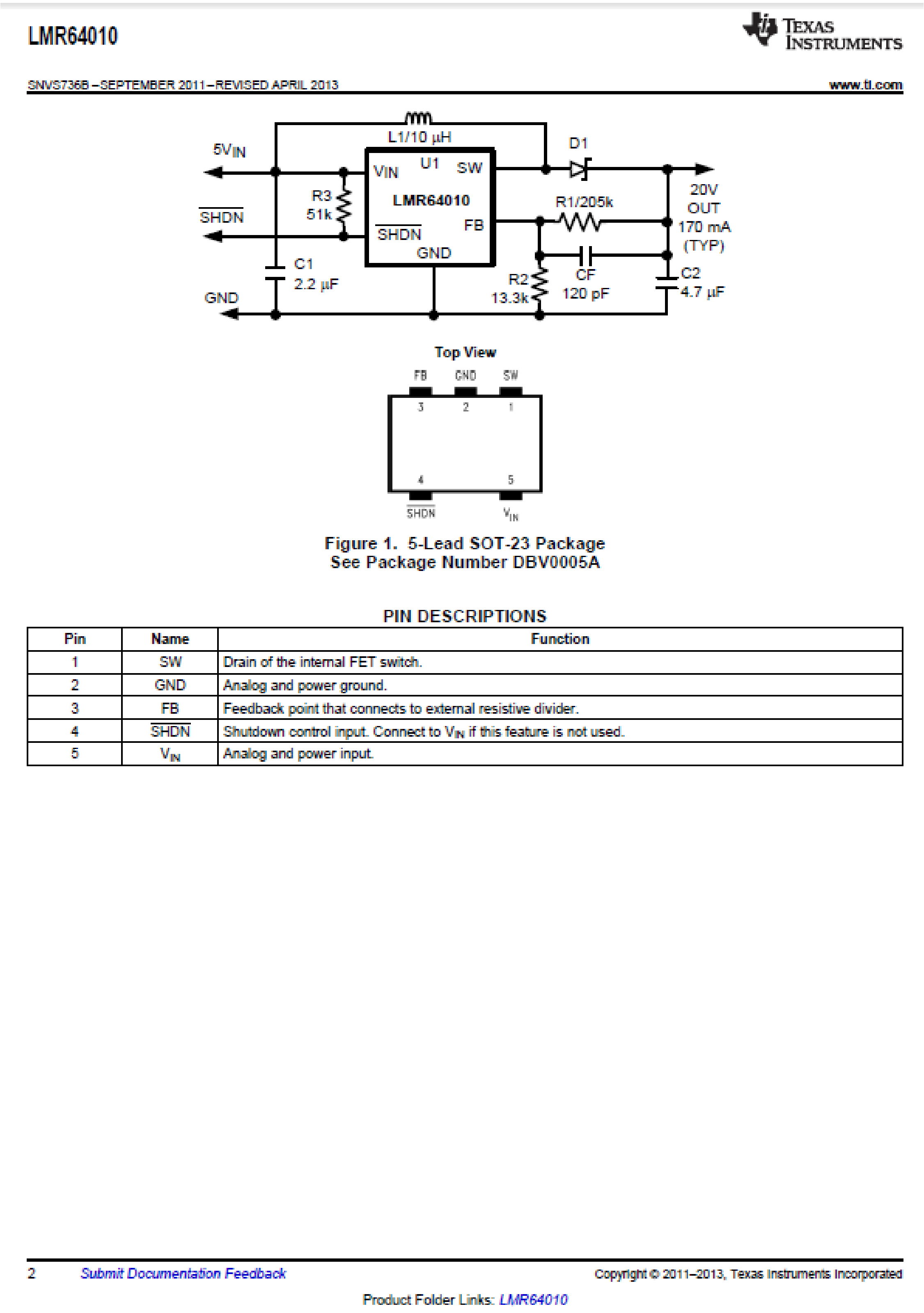
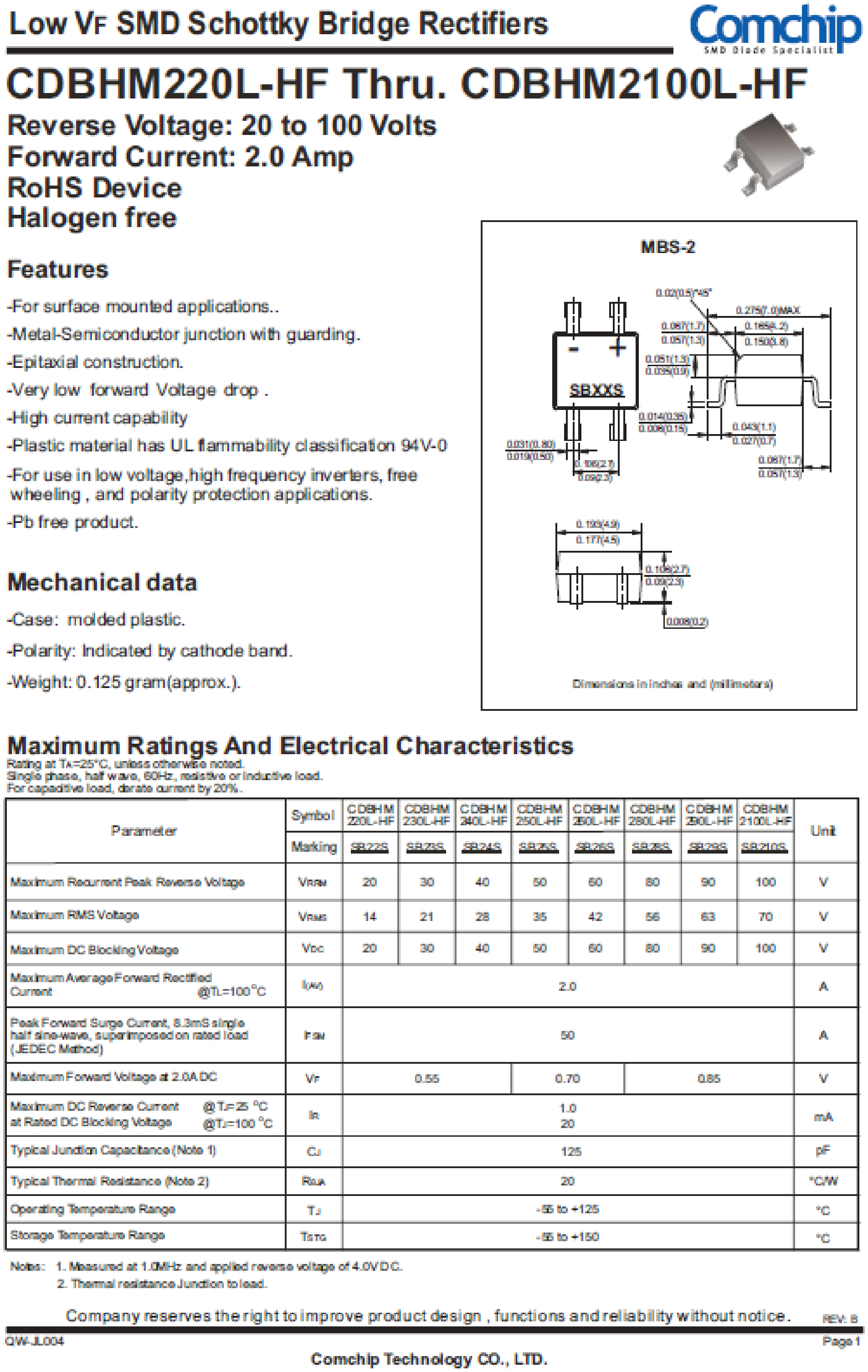


Figure 1. 5-Lead SOT-23 Package
See Package Number DBV0005A

PIN DESCRIPTIONS

Pin	Name	Function
1	SW	Drain of the internal FET switch.
2	GND	Analog and power ground.
3	FB	Feedback point that connects to external resistive divider.
4	$\overline{\text{SHDN}}$	Shutdown control input. Connect to V$_{IN}$ if this feature is not used.
5	V$_{IN}$	Analog and power input.

Appendix D - CDBHM220L-HF Full Bridge Rectifier Data Sheet



Low VF SMD Schottky Bridge Rectifiers

Comchip
SMD Diode Specialist

CDBHM220L-HF Thru. CDBHM2100L-HF

Reverse Voltage: 20 to 100 Volts
Forward Current: 2.0 Amp
RoHS Device
Halogen free

Features

- For surface mounted applications..
- Metal-Semiconductor junction with guarding.
- Epitaxial construction.
- Very low forward Voltage drop .
- High current capability
- Plastic material has UL flammability classification 94V-0
- For use in low voltage,high frequency inverters, free wheeling , and polarity protection applications.
- Pb free product.

Mechanical data

- Case: molded plastic.
- Polarity: Indicated by cathode band.
- Weight: 0.125 gram(approx.).

MBS-2

Dimensions in inches and (millimeters)

Maximum Ratings And Electrical Characteristics

Rating at T_A=25°C, unless otherwise noted.
Single phase, half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

Parameter	Symbol	CDBHM 220L-HF	CDBHM 230L-HF	CDBHM 240L-HF	CDBHM 250L-HF	CDBHM 260L-HF	CDBHM 280L-HF	CDBHM 290L-HF	CDBHM 2100L-HF	Unit
	Marking	SB22S	SB23S	SB24S	SB25S	SB26S	SB28S	SB29S	SB210S	
Maximum Recurrent Peak Reverse Voltage	V_{RRM}	20	30	40	50	60	80	90	100	V
Maximum RMS Voltage	V_{RMS}	14	21	28	35	42	56	63	70	V
Maximum DC Blocking Voltage	V_{DC}	20	30	40	50	60	80	90	100	V
Maximum Average Forward Rectified Current @T_L=100°C	$I_{(AV)}$	2.0								A
Peak Forward Surge Current, 8.3mS single half sine-wave, superimposed on rated load (JEDEC Method)	I_{FSM}	50								A
Maximum Forward Voltage at 2.0A DC	V_F	0.55			0.70		0.85			V
Maximum DC Reverse Current @T_J=25 °C at Rated DC Blocking Voltage @T_J=100 °C	I_R	1.0 20								mA
Typical Junction Capacitance (Note 1)	C_J	125								pF
Typical Thermal Resistance (Note 2)	$R_{\theta JA}$	20								°C/W
Operating Temperature Range	T_J	-55 to +125								°C
Storage Temperature Range	T_{STG}	-55 to +150								°C

Notes: 1. Measured at 1.0MHz and applied reverse voltage of 4.0VDC.
2. Thermal resistance Junction to lead.

Company reserves the right to improve product design , functions and reliability without notice. REV: B

QW-JL004 Page 1

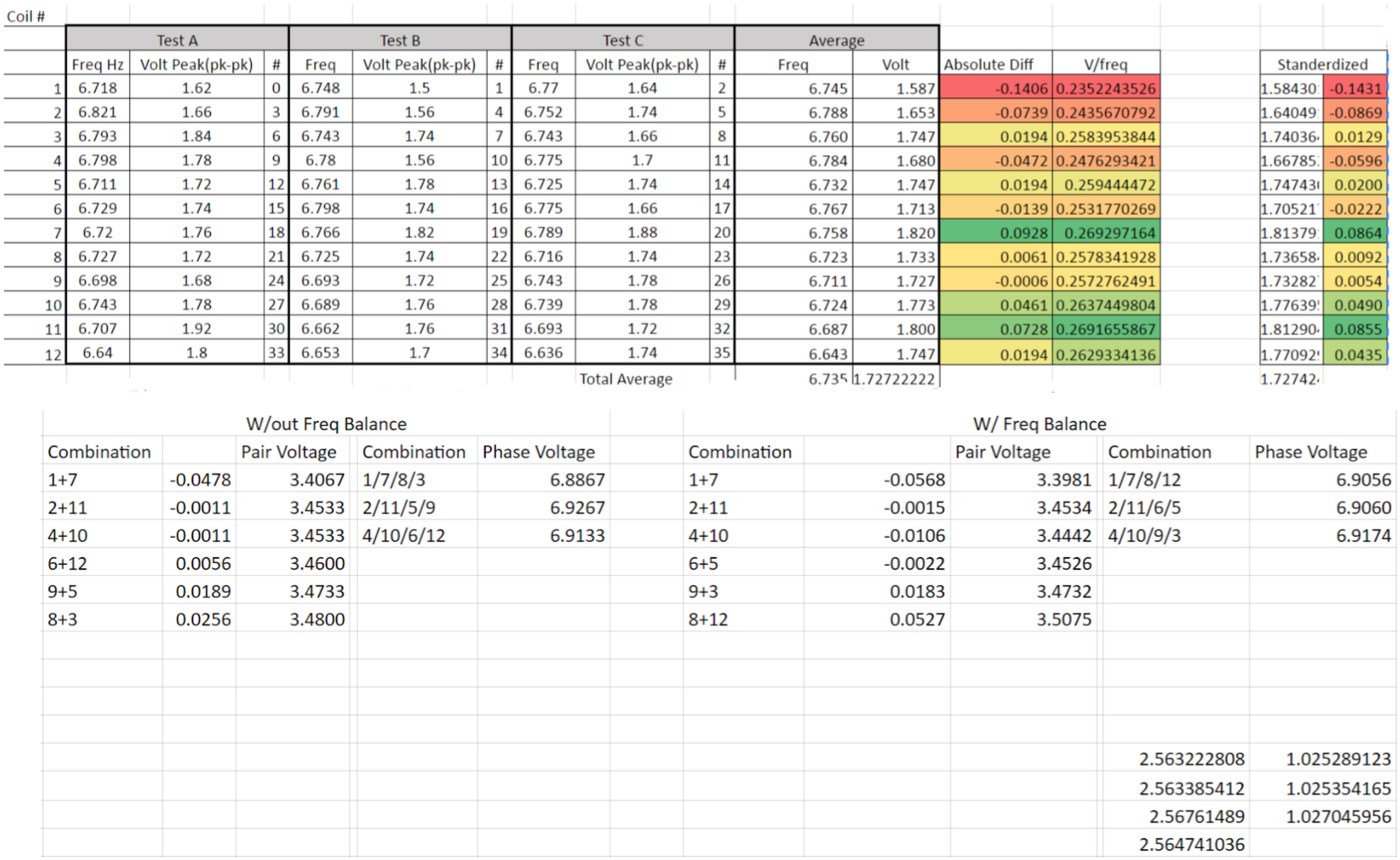
Comchip Technology CO., LTD.

Appendix E - Voltage Testing for three phases of generator

	Phase 1			Phase 2			Phase 3		
Trial	Peak V	Freq	Spin Rate	Peak V	Freq	Spin Rate	Peak V	Freq	Spin Rate
1	17.80	14.37	2.87	19.80	16.23	3.25	19.40	14.08	2.82
2	20.00	16.78	3.36	15.80	12.30	2.46	22.20	19.72	3.94
3	13.20	9.77	1.95	12.20	10.00	2.00	20.80	18.03	3.61
4	20.40	15.63	3.13	8.80	7.16	1.43	12.80	11.11	2.22
5	15.20	12.69	2.54	22.80	17.17	3.43	10.20	7.86	1.57
6	17.80	15.90	3.18	15.60	11.52	2.30	14.60	12.38	2.48
7	23.80	20.41	4.08	24.00	20.41	4.08	23.00	20.41	4.08
8	16.80	13.77	2.75	16.80	13.77	2.75	15.80	13.77	2.75
9	14.40	11.85	2.37	14.80	11.85	2.37	14.00	11.85	2.37
10	22.60	18.60	3.72	22.40	18.60	3.72	21.80	18.60	3.72
11	20.40	16.97	3.39	20.40	16.97	3.39	19.80	16.97	3.39
12	22.20	18.84	3.77	22.20	18.84	3.77	21.60	18.84	3.77
13	15.80	13.33	2.67	15.80	13.33	2.67	15.40	13.33	2.67
14	11.00	9.07	1.81	10.80	9.07	1.81	10.40	9.07	1.81
15	12.60	9.90	1.98	12.40	9.90	1.98	12.00	9.90	1.98
16	8.40	6.36	1.27	8.20	6.36	1.27	7.80	6.36	1.27
17	8.00	6.74	1.35	8.00	6.74	1.35	7.60	6.74	1.35
18	7.00	5.50	1.10	6.80	5.50	1.10	6.60	5.50	1.10
19	5.60	4.49	0.90	5.60	4.49	0.90	5.40	4.49	0.90

20	11.20	8.32	1.66	11.20	8.32	1.66	10.60	8.32	1.66
21	9.40	8.01	1.60	9.60	8.01	1.60	9.40	8.01	1.60
22	8.20	6.05	1.21	8.20	6.05	1.21	7.80	6.05	1.21
23	10.20	8.50	1.70	10.20	8.50	1.70	9.60	8.50	1.70
24	12.40	9.36	1.87	12.20	9.36	1.87	11.80	9.36	1.87
25	32.40	23.31	4.66	32.00	23.31	4.66	30.60	23.31	4.66
26	19.40	16.34	3.27	19.20	16.34	3.27	18.40	16.34	3.27
27	17.20	13.23	2.65	17.60	13.23	2.65	16.80	13.23	2.65
28	18.00	15.24	3.05	18.00	15.24	3.05	17.20	15.24	3.05
29	26.00	22.12	4.42	26.00	22.12	4.42	24.80	22.12	4.42
30	26.20	23.00	4.60	26.40	23.00	4.60	25.60	23.00	4.60
31	31.20	25.41	5.08	31.20	25.41	5.08	29.60	25.41	5.08

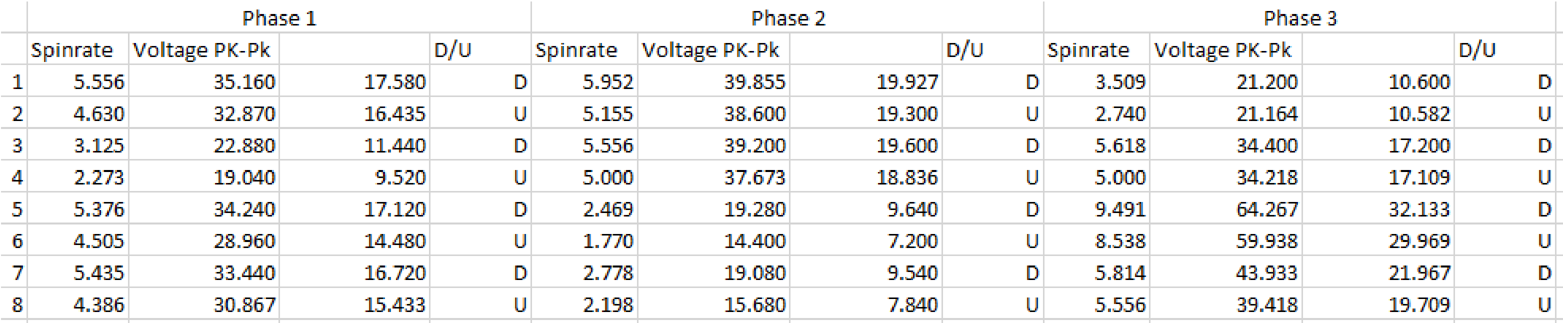
Appendix F - Individual Coil testing results



Coil #	Test A			Test B			Test C			Average					Standerdized	
	Freq Hz	Volt Peak(pk-pk)	#	Freq	Volt Peak(pk-pk)	#	Freq	Volt Peak(pk-pk)	#	Freq	Volt	Absolute Diff	V/freq			
1	6.718	1.62	0	6.748	1.5	1	6.77	1.64	2	6.745	1.587	-0.1406	0.2352243526		1.58430	-0.1431
2	6.821	1.66	3	6.791	1.56	4	6.752	1.74	5	6.788	1.653	-0.0739	0.2435670792		1.64049	-0.0869
3	6.793	1.84	6	6.743	1.74	7	6.743	1.66	8	6.760	1.747	0.0194	0.2583953844		1.74036	0.0129
4	6.798	1.78	9	6.78	1.56	10	6.775	1.7	11	6.784	1.680	-0.0472	0.2476293421		1.66785	-0.0596
5	6.711	1.72	12	6.761	1.78	13	6.725	1.74	14	6.732	1.747	0.0194	0.259444472		1.74743	0.0200
6	6.729	1.74	15	6.798	1.74	16	6.775	1.66	17	6.767	1.713	-0.0139	0.2531770269		1.70521	-0.0222
7	6.72	1.76	18	6.766	1.82	19	6.789	1.88	20	6.758	1.820	0.0928	0.269297164		1.81379	0.0864
8	6.727	1.72	21	6.725	1.74	22	6.716	1.74	23	6.723	1.733	0.0061	0.2578341928		1.73658	0.0092
9	6.698	1.68	24	6.693	1.72	25	6.743	1.78	26	6.711	1.727	-0.0006	0.2572762491		1.73282	0.0054
10	6.743	1.78	27	6.689	1.76	28	6.739	1.78	29	6.724	1.773	0.0461	0.2637449804		1.77639	0.0490
11	6.707	1.92	30	6.662	1.76	31	6.693	1.72	32	6.687	1.800	0.0728	0.2691655867		1.81290	0.0855
12	6.64	1.8	33	6.653	1.7	34	6.636	1.74	35	6.643	1.747	0.0194	0.2629334136		1.77092	0.0435
							Total Average			6.735	1.72722222				1.72742	

W/out Freq Balance						W/ Freq Balance				
Combination		Pair Voltage	Combination	Phase Voltage		Combination		Pair Voltage	Combination	Phase Voltage
1+7	-0.0478	3.4067	1/7/8/3	6.8867		1+7	-0.0568	3.3981	1/7/8/12	6.9056
2+11	-0.0011	3.4533	2/11/5/9	6.9267		2+11	-0.0015	3.4534	2/11/6/5	6.9060
4+10	-0.0011	3.4533	4/10/6/12	6.9133		4+10	-0.0106	3.4442	4/10/9/3	6.9174
6+12	0.0056	3.4600				6+5	-0.0022	3.4526		
9+5	0.0189	3.4733				9+3	0.0183	3.4732		
8+3	0.0256	3.4800				8+12	0.0527	3.5075		
									2.563222808	1.025289123
									2.563385412	1.025354165
									2.56761489	1.027045956
									2.564741036	

Appendix G - Pump Drill Data



	Phase 1				Phase 2				Phase 3			
	Spinrate	Voltage PK-Pk		D/U	Spinrate	Voltage PK-Pk		D/U	Spinrate	Voltage PK-Pk		D/U
1	5.556	35.160	17.580	D	5.952	39.855	19.927	D	3.509	21.200	10.600	D
2	4.630	32.870	16.435	U	5.155	38.600	19.300	U	2.740	21.164	10.582	U
3	3.125	22.880	11.440	D	5.556	39.200	19.600	D	5.618	34.400	17.200	D
4	2.273	19.040	9.520	U	5.000	37.673	18.836	U	5.000	34.218	17.109	U
5	5.376	34.240	17.120	D	2.469	19.280	9.640	D	9.491	64.267	32.133	D
6	4.505	28.960	14.480	U	1.770	14.400	7.200	U	8.538	59.938	29.969	U
7	5.435	33.440	16.720	D	2.778	19.080	9.540	D	5.814	43.933	21.967	D
8	4.386	30.867	15.433	U	2.198	15.680	7.840	U	5.556	39.418	19.709	U