Electronics II – Design Project Report

Energy Harvesting Exercise Machine

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December 4, 2016

Abstract

Despite the vast research on developments of renewable energy and the recent push by global government legislation to force corporations in to using clean energy, there has been little progress in providing renewable energy that benefits the consumer and average everyday person. This is mostly due to a lack of motivation and lack of personal benefit from a corporation standpoint. The large power companies are receiving considerable tax reliefs and funding programs for switching to renewable energy but still charge the everyday consumer the same price for power.

The project outlined in this document was created from the motivation of resolving this imbalance to allow consumers to benefit from the remarkable advancements in renewable energy. The revolutionary and incredibly innovative Energy Harvesting Exercise Machine (EHEM) looks to attack two very prominent issues in modern society while promoting healthy and active lifestyles. The first is to bring the benefits of renewable power to consumers by enabling consumers to utilize the marvel of biological mechanical energy within them to not only help the environment but also save money. The second issue this project looks to attack is the imbalance of electricity in the world. While electricity has become one of the most fundamental and important basic requirements in the modern world, over 3 billion people today still do not have access to electricity. The project put forth by the team looks to solve this by allowing users to generate their own power with nothing but their bodies, meaning that anywhere in the world a person will be able to generate clean and efficient electricity for themselves.

The proposed method was restricted to a budget of $30 and the use of mostly analog electronic components in hopes that anyone would be able to afford the solution. The solution utilizes a three phase synchronous generator, a stationary exercise bike, a 12 V battery, and a simple phase shift oscillator constructed out of common analog components to provide perhaps the most practical and promising solution to the poverty of electrical energy.

Through simulations as well as real-world prototype testing presented in this report, it is demonstrated that this unique and remarkable solution has a very real and important role in solving many modern day problems with electricity.

Collaboration and Participation

The conceptualization and development of the project was the result of dedication and creativity demonstrated by both team members. Both individuals were present during each brainstorming session, worked together to solve problems that arose, and strived to attain results while fine tuning the design during each testing session. Each team member took responsibility for the following duties:

Eric Parker

I. Defining, developing, and researching the overall goal of the project and its potential applications
II. Relevant research, design, and synthesis of the quadrature oscillator circuit
III. Synthesis of the audio amplifier circuit
IV. Synthesis of the battery charging circuit
V. Component research, choice, and acquisition of all discrete electronic components
VI. Measurement and interpretation of all circuit parameters required for proof of concept
VII. Root causing unexpected results during testing
VIII. Choosing the design that best met the goal of the project

Sean Santarossa

I. Research of theoretical principles governing circuit behaviour
II. Relevant research and design of the audio amplifier circuit
III. Relevant research and design of the battery charging circuit
IV. Design and synthesis of all mechanical systems involved in power generation
V. Component research, choice, and acquisition of all power generation components
VI. Performing LT Spice simulations
VII. Development of overall project constraints
VIII. Implementation of design improvements during testing

Together, both team members were not restricted to the activities listed above; rather each member contributed to every challenge faced in order to ensure the overall goals and constraints of the project were met.

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Introduction

From the moment the project was first introduced, it was mutually understood by both team members that the goal was to design a circuit that could solve a significant problem encountered daily by many individuals all around the world. One particular field that the team felt could face increasing problems in the future is demand for electrical power. Although power engineers in modern society are very good at solving such problems and have successfully overcome many issues resulting from increased demand for power, as the world's population continues to increase, engineers must push the limits of ingenuity in order to continue to supply reliable electrical power for the many generations to come. An increasing human population means an increasing demand for electricity that many businesses and individuals are dependent on. This means engineers must create new ways to accommodate this increased demand for power by introducing innovative ways to generate renewable electricity and reduce strain on power generation stations in order to ensure the electrical grid is capable of accommodating everyone.

One way engineers can accomplish this daunting challenge is to develop environmentally friendly solutions that reduce the demand for power from the electrical grid by decentralizing power generation; that is, develop environmentally friendly ways for consumers to generate their own electricity at home thus reducing individual demand from the power grid. As engineers, it is important to understand the power of one. That is, a single individual decreasing the quantity of a resource they use may seem extremely insignificant when compared with the demands required by the entire world, however as more individuals partake in such practices, it has the effect of multiplying the impact each person has millions or even billions of times over leading to drastic reductions in the demand for a given resource. Put simply, small changes add up… significantly. With this in mind, the team began researching simple ways in which people could decrease their demand for electrical power by just a little bit each day.

There are obvious benefits to reduced strain on electrical generation stations. Generating electricity from universally available renewable resources has clear environmental benefits. Producing electricity using renewable resources such as moving water or wind reduces the need for other forms of generation such as burning fossil fuels, thus preventing the release of harmful chemicals contributing to air pollution and global warming. Such practices are well understood, and great strides have been made in recent years in the field of power engineering to realize this. A much newer, very promising topic is the concept of energy storage. Due to overinvestments in nuclear power in Ontario [1], the province sits on a very large and inflexible power surplus. That is, since a very large percentage of Ontario's power is generated in slow-to-respond nuclear power plants, it is often cheaper to generate excess electricity and pay our neighbours (including the state of New York) to take this power when it is not needed. Such a practice is not sustainable, and leads to increased power bills for Ontario residents. The objective of our project was address said issues by leveraging both renewable power generation and energy storage in a design that is completely separated from the power grid;

thus enabling users to generate, store, and consume off-grid electrical power without increasing demand for electricity generated by power generation stations therefore significantly reducing their electricity bill.

The first task that needed to be completed in order to achieve our objective was to tailor the design to target a specific, universally available renewable resource. Although it is very common for off-grid power generation systems to feature solar or wind driven generation, the team had a drastically different, incredibly abundant resource in mind… you! That is, the design targets energy naturally expended by humans each day. Since both team members are very creative thinking individuals, we began brainstorming new ideas that could leverage clean energy already being expended each day. The final idea was formulated when our team members, both of which are frequent physical exercisers, felt as though they were wasting energy while working out. It is very physically demanding and energy intensive, and people spend most of their time in one location expending all of their energy to accomplish zero necessary work. The solution to this problem is to find a way to convert the mechanical energy exhausted by people while working out in to electrical energy that can be stored for later use.

Another objective of the project was to enable an excellent user experience to encourage users to utilize the exercise device frequently; the more the consumer uses this device, the greater their personal impact on decreasing demand for grid power. There are many ways to accomplish this, however research has consistently shown that synchronization of music with repetitive exercise leads to increased levels of work output [2]. With this in mind, the team decided to include an audio amplifier directly targeting music players such as cell phones or iPods/MP3 players that allows users to listen to music via headphones or loudspeaker.

The final step required to meet our objective was to allow users to consume this newly stored electrical energy. Since the vast majority of electric loads used by consumers are AC loads that plug in to household electrical outlets, the goal of this portion of the project was to convert the stored DC electricity into a $60\ Hz$, $120\ V_{RMS}$ sine wave to exactly mimic electrical power delivered from the electrical grid. This allows users to plug in virtually any electrical load they would normally plug in to their household electrical outlets.

The team's final design accomplishes all of the objectives outlined in this report allowing users to convert and store energy expended while exercising in the form of electricity, as well as consume this power with virtually any electrical load that plugs in to household electrical outlets, all while maintaining an excellent user experience to encourage consumers to repetitively use this product in order to reduce demand for electricity generated by power generation stations.

Design Objectives

1. Effectively and efficiently convert energy expended by users exercising in to electrical energy
2. Store the converted electrical energy for use at any time as required by the user
3. Convert the stored electrical energy into a $60\ Hz$ AC sine wave to mimic electrical power delivered from the electrical grid
4. Enable an excellent and motivating user experience to encourage users to utilize the product as often as possible

State of the Art

From the research conducted by the team, the majority of the circuits that involved the generation of electricity were either intended for powering small electrical loads, did not have any storage components for excess electricity generated, or were very expensive. Many of the designs found did not use synchronous motors but rather much smaller permanent magnet generators which (although are less expensive) provide only a fraction of the power and offer little to no control of the output voltage. These designs were more targeted towards powering light bulbs and other small loads and were more for recreational projects, but they did provide the team with useful concepts and ideas that were applicable to the problem statement the team was attempting to solve.

Other designs encountered also used alternators but did not have batteries to store the built-up current. The idea behind these circuits was that a consumer could connect the output directly to a TV and watch TV while biking. While this does have the benefit of less power conversion losses, the problem is that once the consumer stops biking the TV immediately losses power and turns off. Not only does this introduce potential safety issues due to abrupt shortages of power, but it is also not practical for powering appliances and other electrical loads for long periods of time.

The following three designs are circuits/products encountered during research that had desirable aspects and traits that the team felt could potentially be used in the team's final design. By comparing the pros and cons of each design, the team was able to extract the components and concepts that we felt would give the best experience and product to consumers.

The first design the team found useful was the K-TOR Power Box which is shown in Figure 1.

Figure 1 – K-TOR Power Box

This incredible design comes from the innovative technological company K-TOR, LLC [3] and it is their solution to the very limited battery life of portable electronics. The device works by connecting a portable electronic device to the standard 3 prong outlet on the device and then pedalling with your legs or arms in order to charge electronic devices.

The team liked the idea of pedalling to power electronic devices because it utilizes the mechanical efficiency of a pedal generator and the device was entirely self-sufficient, meaning no other external components were needed for the device to work. Although the device was also very portable and quite efficient (about 85%), it had a couple of major weaknesses. The first being that it could only charge a phone or tablet; any load that was larger than that could not be powered due to the small permanent magnet generator. The second major weakness was the fact that the energy created could not be stored meaning that in order to charge a portable electronic device, the user would have to continuously pedal and if they stopped the charging would stop very abruptly. Another minor issue with the device is that although it is self-sufficient using the device without a chair or back support would be extremely uncomfortable which would not provide consumers the high level of comfort the team wanted to achieve.

The next design the team discovered is shown in Figure 2.

Figure 2 – Pedal-A-Watt

The Pedal-A-Watt design is another product that shows some great feats of engineering [4]. The design works by connecting the permanent magnet generator to any bicycle that has a wheel diameter of 20 inches or greater and the output power generated by pedalling is supplied to the proprietary Power Pack battery provided when you buy the device.

The team liked the idea of having a battery to store the energy being created as well as the internal voltage regulator which sources current between the battery and the load simultaneously while also providing safety for the user. The weakness of this device are the small output power and the limited output functionality. The output of the device is claimed to be 125 to 300 watts depending on the rider which is higher than the K-TOR Power Box but still only powerful enough to charge smaller electronic devices. However, the main problem with the output is not its power but its versatility. The output of the device is a male cigarette lighter plug, which very little modern electronic devices can use. Thus, other electronic devices are needed in order to make use of the power of the generator. Perhaps the biggest weakness in the device despite all the extra components that are needed for its use is the fact that they cost over $900 US. At this price point the device becomes more of a luxury for consumers rather than a practical alternative way to generate the necessity of electricity.

The last design that the team felt best represented the goals of the project was the Green Wheel device [5] shown in Figure 3. This device is a concept device that utilizes the human mechanical energy of running. The consumer would run in the wheel much like a hamster in a hamster wheel in order to generate electricity. The concept is that these wheels will be implemented in public places so that joggers can generate electricity while they run and then be paid for the generated electricity when they are done.

Figure 3 – Green Wheel Concept Design

The design has some major weaknesses, the biggest being that generating energy from running is nowhere near as efficient as cycling and thus these products generate very little energy. This concept was founded on the idea that the joggers are already running anyway so why not be paid for it? The team really liked this idea that people are going to be exercising/running anyway so why not capitalize on all of the millions of watts of already regularly expended energy? This concept became one of the central themes in the advertising campaign for the product.

All three designs contain aspects that the team saw potential in and they proved to be important cornerstone models in the formulation of the design requirements of the device. The idea of pedalling to produce and harness the power of humans from the K-TOR was used in the final design as well as the idea of self-sufficiency. The Pedal-A-Watt device gave the team the idea of using a battery to store energy, the idea of using a voltage regulator to maintain a high level of safety, and the idea of powering larger electronic devices not just small electronics. Finally, the Green Wheel gave the team the idea that became a central and predicated concept in the advertising campaign.

Values and Constraints

Table 1 – Circuit Elements Used Cost

Name of Circuit Element	Amount	Cost of Circuit Element ($)
Scrap Bicycle Frame	1	20.00
Vehicle Battery (Salvaged)	1	0.00
Vehicle Alternator (Salvaged)	1	0.00
Speaker (8 Ohm)	1	0.00
3.5mm Female Connector	1	0.00
3.5mm Audio Cable	1	0.00
Op-Amp (LM324)	2	0.00
Op-Amp (LM386)	1	0.00
Resistors	6	0.00
Capacitors	10	0.00
Total	--	20.00

Constraints:

1. Time constraint
   a. 12 weeks
2. Money constraint
   a. $30 budget
3. Restricted list of digital components; Project must consist of 90% analog components
4. Limited supplies
5. Input
   a. Human user can only input limited amount of mechanical energy at a defined maximum rate
6. Energy conversion
   a. Percentage of mechanical energy converted into electrical energy is limited by efficiency of generator and rectifier/regulator circuit
7. Energy storage
   a. Electrical energy is most easily stored for long periods of time in a battery which requires DC input even though the goal is to supply AC power
8. Loads
   a. Electrical loads connected to the output of the circuit must not require an input current greater than the maximum current the battery can supply

Deliverables

1. Effectively and efficiently convert energy expended by users exercising in to electrical energy

   Through the conversion of input mechanical energy into rotation using gear ratios to rotate a synchronous generator at a high speed in order to generate a large output current ideal for charging a vehicle battery quickly

2. Store the converted electrical energy for use at any time as required by the user

   The electrical output of the synchronous generator is used to charge a large capacity deep cycle vehicle battery whose output can be used whenever desired by the user

3. Convert the stored electrical energy into a $60\ Hz$ AC sine wave to mimic electrical power delivered from the electrical grid

   The output of the battery is used as the input to a quadrature oscillator circuit with a very specific RC combination chosen to convert the battery's output DC voltage into a sine wave with a frequency of 60 Hz; The resulting AC waveform would then be sent through a step-up transformer to convert the amplitude of the waveform to the required $120\ V_{RMS}$

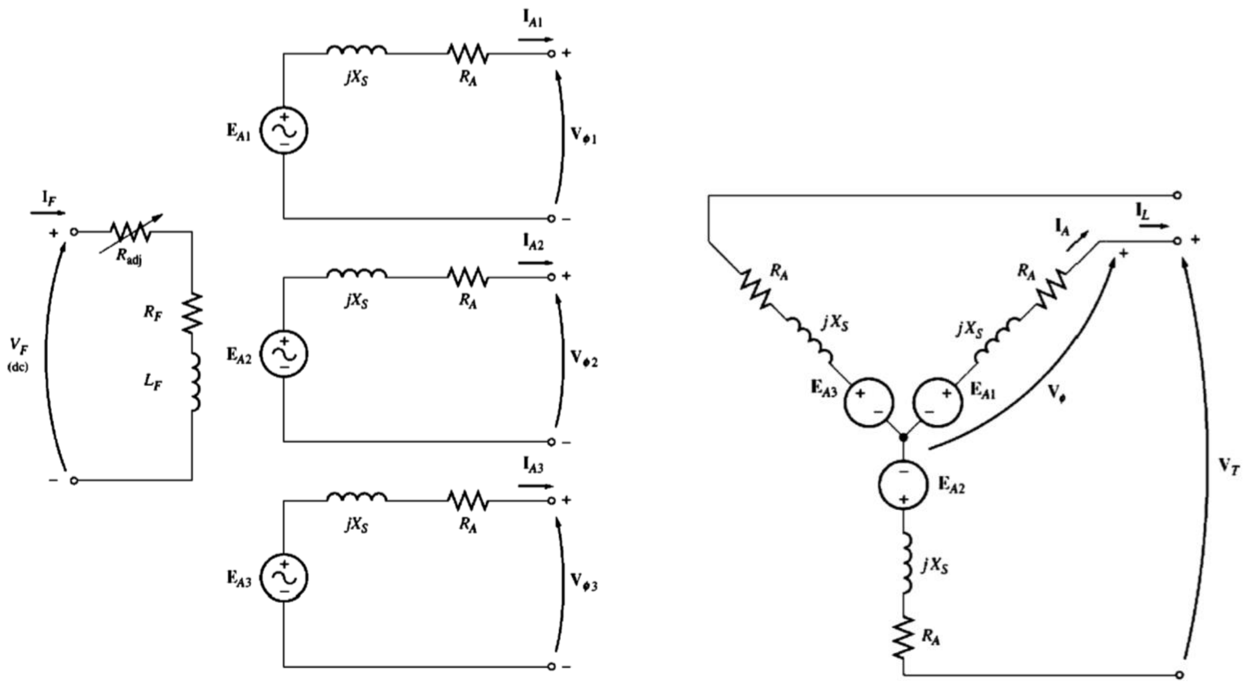
4. Enable an excellent and motivating user experience to encourage users to utilize the product as often as possible

   Provide users with an audio amplifier directly targeting music players such as cell phones or iPods/MP3 players that allows users to listen to music via headphones or loudspeaker while they use the exercise machine

Design Methodology

I. ENERGY CONVERSION

In order for the design to store energy, it must first convert mechanical energy supplied by the user into electrical energy. In order to do this, a stationary exercise bicycle is modified and combined with a synchronous electric generator to provide the rotational input necessary to generate electricity. The synchronous generator used is a used vehicle alternator, chosen primarily because of high accessibility and low price. A synchronous generator can be modelled according to the equivalent circuit diagrams shown below in Figure 4.



(a) (b)

Figure 4 – a) Equivalent circuit of a vehicle alternator (synchronous generator). b) The 3-phases of the armature circuit of the Y-connected alternator.

The field circuit is supplied with a constant DC voltage V_F via connecting the vehicle battery to the rotor winding. Since the rotor circuit is essentially a very large solenoid, the applied DC voltage produces a constant magnetic field in the rotor. When the rotation of the machine is provided via mechanical energy (i.e. the user begins pedalling the stationary bike), this causes the rotor to rotate effectively creating a rotating magnetic field. This produces a changing magnetic flux which incites an AC voltage in each of the armature windings thus producing the internal generated voltages E_{A1}, E_{A2}, and E_{A3}, which are mechanically positioned $120°$ apart from one another via the design of the generator to produce 3-phase electricity.

II. **ENERGY STORAGE**

Now that electricity has successfully been generated by the user, the energy must be stored to allow the user to utilize the electricity whenever they please. A very effective way to do this is to use a battery. Relative to many energy storage alternatives available for this application, this option provides the best long-term storage of electrical energy and allows for large quantities of energy to be stored. This effectively allows the user to power loads with significant power ratings for relatively long periods of time. However, in order to ensure proper charging of the battery, a few circuits must interface between the generator and the battery. Firstly, batteries require constant DC current as an input to the positive terminal of the battery in order to charge. As stated previously, the output of the generator is 3-phase AC electricity. Thus, a 3-phase rectifier circuit is used for the conversion of AC to DC. This is achieved using a six-pulse rectifier circuit with a smoothing capacitor (see left side of Figure 5 below). Moreover, the current supplied to the battery must remain within very specific boundary conditions to ensure that the battery is not damaged while charging. Namely, the output voltage of the generator must be limited in order to prevent charging from harming the battery. That is, if the alternator was allowed to constantly produce all of the power it could, the system voltage would rise to a damaging level, harming both the battery and the alternator. Voltage regulation is achieved through the implementation of a voltage regulator circuit which uses a L9407F voltage regulator IC to ensure that the system voltage is in the correct range [6]. For a vehicle battery, this correct range is usually between $14.0\ V$ and $14.6\ V$ [7].

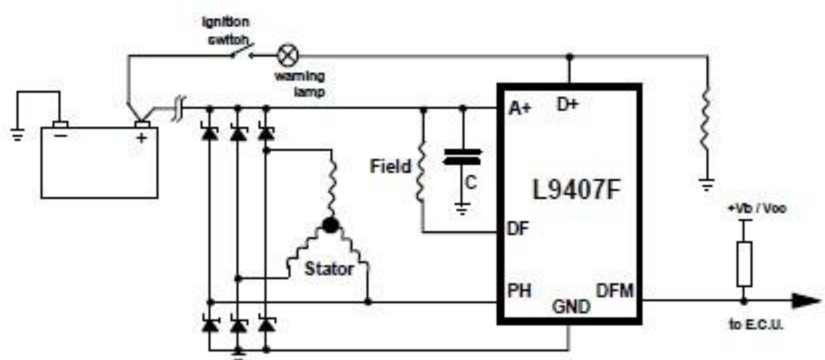


Figure 5 – Alternator Rectifier (diodes/capacitor) and Regulator (L9407F IC)

For the implementation of this circuit, the alternator chosen contains both an internal regulator and rectifier according to Figure 5 shown above. This ensures that the battery is always charging properly when the user is operating the stationary bike, thus increasing the lifetime and safety of the design.

III. ENERGY USAGE

In order to make the use of this stored electricity virtually universal, the output of the battery goes through an interface circuit specifically designed to mimic the waveform delivered in all household electrical outlets in North America. This design requirement has the added benefit of allowing the user to use virtually all consumer electronics capable of plugging in to a household electrical outlet with the power generated by the system. In order to achieve this, it is required to convert the output DC voltage of the battery to an AC wave with a frequency of $60\ Hz$. This can be done in a number of different ways, from using a 555 timer to generate and AC square wave to using LC tanks to generate repetitive oscillation. The circuit chosen to achieve this task is a quadrature oscillator circuit, which features two op-amp integrators that convert DC into an AC sine wave with parallel RC combinations that allow the user to determine the frequency of the output waveform. Note that this circuit was primarily chosen primarily because it converts DC into a sine wave (which is what is present in household electrical outlets in North America) and offers flexibility in output frequency allowing the team to choose an RC combination yielding $60\ Hz$ (the frequency of the waveform present in electrical outlets in North America). The circuit for a quadrature oscillator can be seen in Figure 6 below. Note that the resistance and capacitance values were changed in order to achieve an output frequency of $60\ Hz$, not $1.5\ kHz$ as indicated in Figure 6.

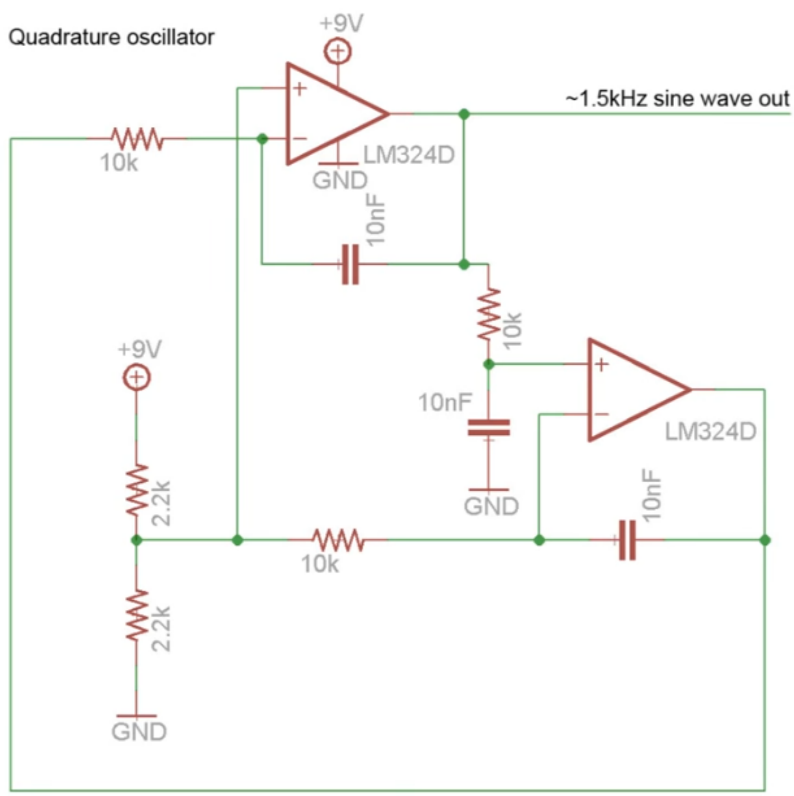


Figure 6 – Quadrature Oscillator Circuit with Output Frequency of $1.5\ kHz$

The frequency of the quadrature oscillator circuit can be controlled by changing the values of the $10\ k\Omega$ resistors and $10\ nF$ capacitors as shown in Figure 6. If all resistors and capacitors are matched, the output frequency of the oscillator circuit can be attained using the formula [8]:

$$f = \frac{1}{2\pi RC}$$

With the goal of an output sine wave with a frequency of $60\ Hz$, the RC combination chosen was $R = 10\ k\Omega$ and $C = 265\ nF$. This theoretically yields an output frequency of $60.06\ Hz$ which is very close to the desired frequency. Note that in the physical implementation, high tolerance resistors were used to ensure the best possible result. Now that a $60\ Hz$ AC sine wave has been achieved, the final step for household electrical consumption would be to put this AC waveform through a step-up transformer with a turn ratio specifically designed to convert the output waveform to a voltage value of $120\ V_{RMS}$. Since the frequency and magnitude of the final output voltage now exactly match those present within North American household electrical outlets, users can now plug in any household electronic devices of their choosing allowing very flexible and universal consumption of the power generated and stored by the device.

IV. USER EXPERIENCE

The more our users use our product, the greater their individual impact on decreasing demand for power from the electrical grid. Thus, the final objective of the project was to enable an excellent user experience to encourage the user to utilize the exercise machine as often as possible in order to have the greatest positive environmental impact and health benefits to the user. As mentioned previously, research has consistently shown that synchronization of music with repetitive exercise leads to increased levels of work output. Moreover, how music is delivered to athletes is also very important. Music intended to enhance group cohesion or inspire a group of athletes is best delivered with a portable loudspeaker audio system, whereas if there are other athletes training nearby that may be disturbed by one’s music, it should be delivered via a personal MP3 player [2]. Recognizing the importance of music on athlete motivation and performance, the team decided to include an audio amplifier circuit with the design of the exercise system. The circuit chosen features an LM386 audio amplifier IC that is specifically designed for high quality audio amplification. The design features controllable volume and increased gain versus normal MP3 speaker systems, and can be seen below in Figure 7. Note that a $474\ nF$ capacitor was added between pins 1 and 8 as indicated by the diagram to improve the voltage gain of the circuit which increases the volume of the audio above the noise level produced by friction between mechanical parts while operating the exercise machine.

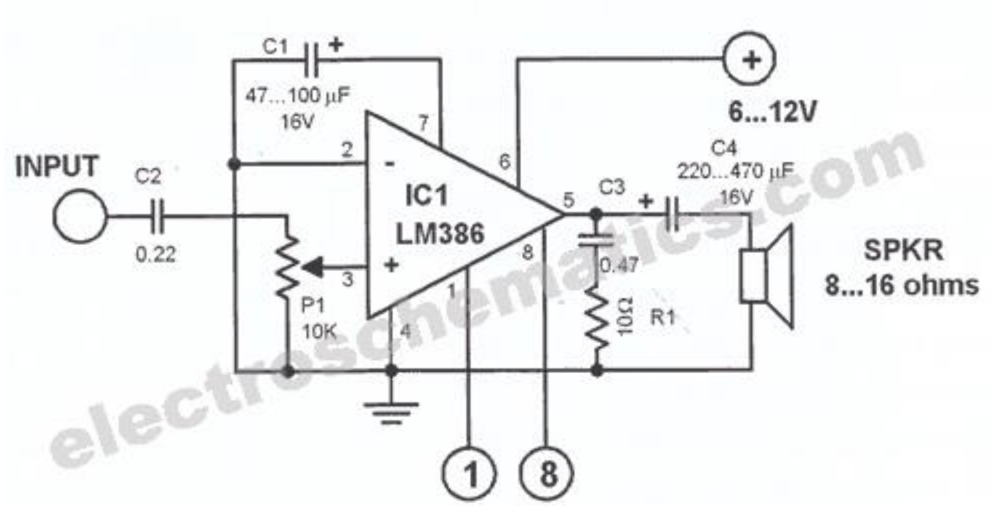


Figure 7 – High-Quality Audio Amplifier Circuit

The output of amplifier circuit is wired in parallel to an $8\ \Omega$ speaker and to a $3.5\ mm$ audio female connector, thus giving the user the option to listen to music via the loudspeaker or personal headphones depending on what is desired by the user at that time!

Physical Implementation

The physical implementation of the design was relatively straightforward as the circuit schematic shown in Figure 10, proven to be valid on a simulation level, was constructed without many difficulties. In order to ensure that the circuit was built successfully and safely, each component was tested individually first so that its functionality was familiar and predictable to the team before combining with other electronic components. Once each individual component was tested, they were then combined one at a time with the other electric components and the functionality of the two combined components was then tested to ensure that its operation correlated with the known theory and properties regarding each component. Using this incremental and recursive process, the schematic used in the simulation was constructed safety and successfully. By utilizing this construction methodology troubleshooting the circuit became easier when irregulars arouse as the team could quickly narrow down which electrical components could be causing the anomalous results.

The first electrical component tested was the alternator (synchronous generator) which was the most dangerous component in the circuit and as such was handled with extreme care while working with it. The used alternator was acquired from a scrap vehicle at a mechanic's garage and hence did not have a datasheet. Upon further inquiry, the pinout was given by the manufacturing company and is shown in Figure 8.

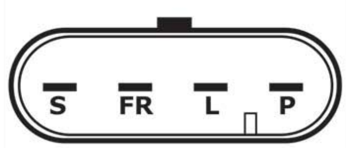


Figure 8 – Pinout for Alternator

Through research and testing of the alternator, it was found that the best results came from putting the S, FR, and L pins to the positive terminal of the battery and the P pin left as an open circuit. The S pin is the voltage sensing pin that the internal voltage regulator uses to "sense" the voltage level of the battery so that it can adjust the pulse width modulation to control the alternator's output. The FR pin is also used by the regulator and is normally used by the Engine Control Unit (ECU) of the vehicle to determine the loading on the alternator and it can increase/decrease the engine speed accordingly. Through rigorous testing the team found that without the pin the field terminals of the alternator would not become powered unless this pin was powered. The L pin is the lamp terminal pin which connects to the field of the rotor to power the electromagnet. The P pin is the stator pin and it provides square waves (which is why it is called the Pulse "P" terminal) to various electronic control modules in a vehicle to provide performance feedback of the alternator. The team found that this pin to power causes irregularities in the output of the alternator and was left open-circuited. The output terminal of the alternator which is the red wire in Figure 19 was a separate terminal on the other side of the alternator. The alternator was rated for 108 amps at around 1500 rpm which is much faster than any human could provide with the current gear ratio, so determining the output amperage was a trial and error process that required a great deal of testing and calibration.

Once this alternator was understood and its output was tested through the use of an ammeter, the team connected it to the exercise bike through a 68-inch serpentine belt. This serpentine belt was carefully chosen to ensure a high level of friction was maintained between the belt and alternator, and the belt and the exercise bike wheel. At this point the electrical generation portion of the circuit was complete, by wiring the three pins (L pin, FR pin, and S pin) to the battery, the body of the alternator to ground, and the output of the alternator to the battery, (using high amperage rated 12 gage wire) the high voltage/high current circuit of the project was finished without any hazards occurring. The team cycled on the bike for long periods of time to guarantee the performance of the alternator after prolonged use and the safety of the circuit after long periods of cycling. The output of the alternator remained constant at around 10 amps which was achieved at relatively low cycling speeds and saturated at about 18 amps under full cycling. The full performance characteristic of the alternator is shown in Appendix A. The internal voltage regulator was also tested to ensure its performance by applying various loads to the alternator and measuring the output voltage of the alternator. Once a load was applied the output voltage dipped a little and then was brought back up to its operating capacity proving that the voltage regulator was increasing the field current of the alternator during loading in order to keep the output voltage constant.

The next portion of the project was to complete the quadrature oscillator which provides the function of converting the DC voltage in the battery to an AC sine wave of 60Hz. The LM741 operational amplifiers used in the circuit were tested to confirm that their output was in coherence with the datasheet provided. Then the negative feedback loops were constructed and the output of the oscillator was tested. The output was as expected, it produced the 9V peak-to-peak 60Hz sine wave the team desired. Some adjustment was required as the frequency was a not quite 60Hz at first, the original values for the capacitor and resistors were chosen based on the values given in the schematic of the quadrature oscillator found online [9] but upon further analysis the formula to calculate the output frequency was obtained. The starting point was based on the open loop gain of the circuit shown in Figure 9:

$$A\beta = \left(\frac{1}{R_1 C_a s}\right)\left(\frac{R_3 C_3 s + 1}{R_3 C_3 s (R_2 C_2 s + 1)}\right)$$

and by setting $R_1C_1 = R_2C_2 = R_3C_3$ the loop gain reduced to:

$$A\beta = \left(\frac{1}{(RCs)^2}\right)$$

Thus since $s = j\omega$ by setting $\omega = \frac{1}{RC}$ the loop gain reduces to

$$A\beta = \frac{1}{(j)^2}$$

which reduces to

$$A\beta = 1\angle -180°$$

So by controlling the RC components in the feedback loop according to

$$\omega = \frac{1}{RC}$$

we can control the output frequency of the sine wave.

After the physical implementation of the circuit was complete the circuit was tested in order to ensure that all the circuits combined worked as expected.

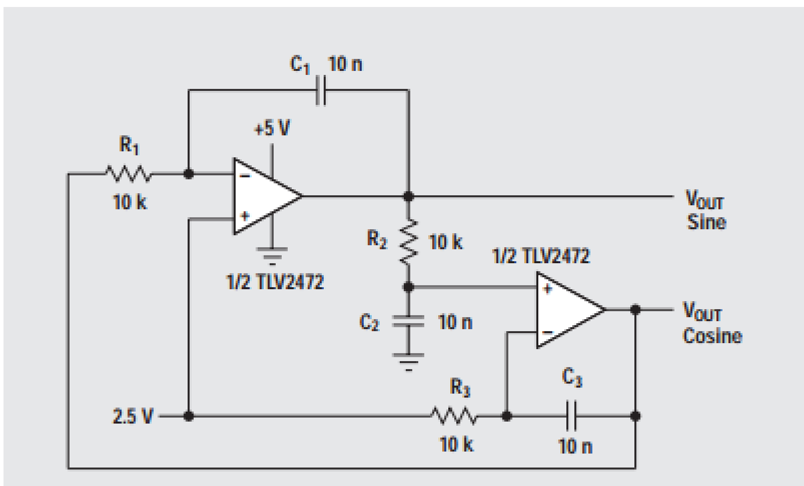


Figure 9 – Circuit Schematic for the Quadrature Oscillator

Experimental Results

Many results were obtained from the countless tests and simulations performed over the development process of the proposed design, however there are a number of results that the team feels truly characterize and highlight the progressive development of the circuit. These results and simulations are shown in the following section.

The circuit simulation for the quadrature oscillator is shown in Figure 10. This was the prototype design of the project.

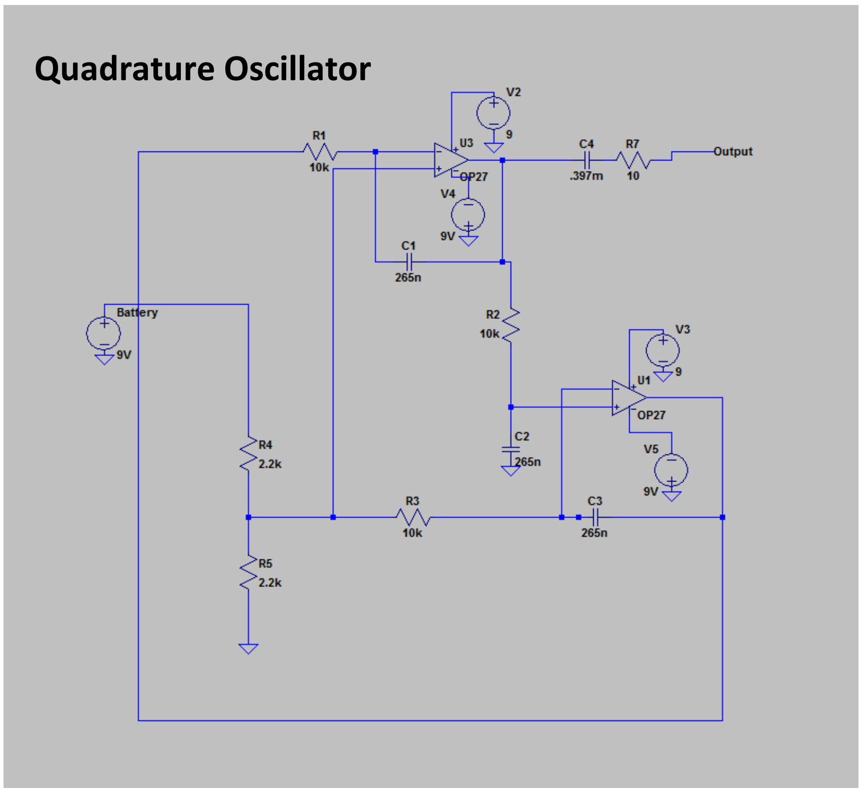


Figure 10 – LT Spice Simulation for Quadrature Oscillator

As can be seen in Figure 10, the voltage source labelled “Battery” is the representation of the car battery being charged by the generator. The output of the simulation is shown in Figure 11.

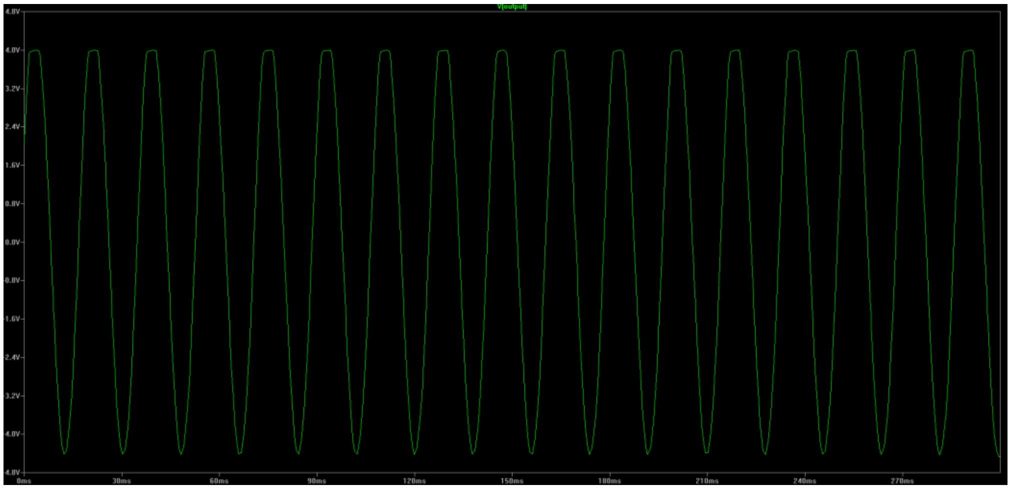


Figure 11 – Output of the Quadrature Oscillator

This output is approximately 9V peak-to-peak and has a frequency of exactly 60Hz which is exactly what the calculations of the RC feedback network gave. This output is idealized however as the team encountered some discrepancies from the simulation. The first being the frequency of the output voltage being 50Hz rather than 60Hz. To overcome this obstacle, the team used a variety of different combinations for the RC feedback values. The team emphasized the use of increasing the resistances rather than the capacitances whenever possible due to capacitors being more expensive.

The second issue the team encounter was a slight saturation of the positive cycles of the output voltage. The team increased the rails of the op amp in an attempt to solve the issue but it was still occurring. The team found that by decreasing the time constant and thus the RC values the saturation went away.

The audio amplifier simulation is shown in Figure 12.

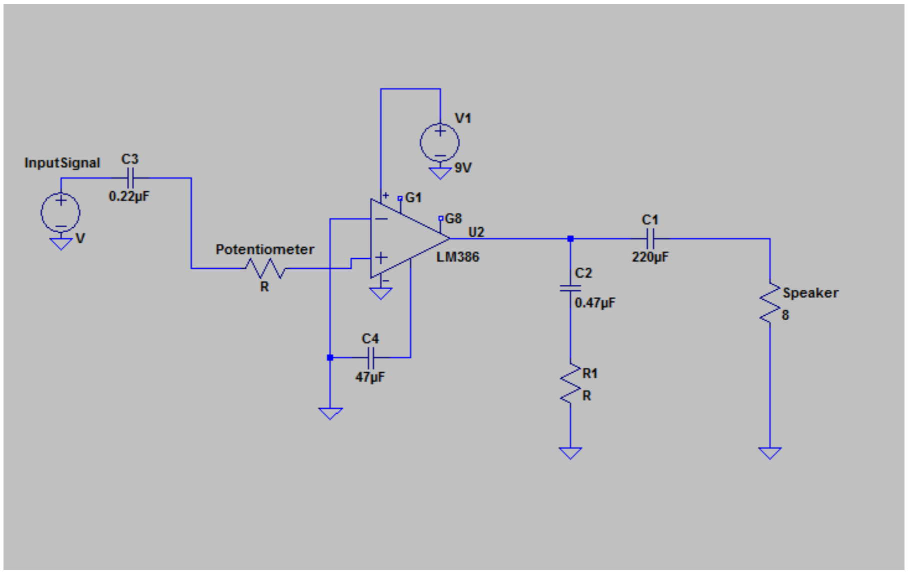


Figure 12 – LT Spice Simulation of the Audio Amplifier

As indicated in Figure 12, the circuit makes use of the widely known LM386 audio amplifier for its incredible performance as well as its versatility. By connecting various external components to pins G1 and G8, the gain of the amplifier can be greatly adjusted to provide a huge variety in performance. The volume of the amplifier can be adjusted using the potentiometer at the non-inverting terminal of the LM386 and the electronic device that is playing the music is connected to the male 3.5mm jack shown as the input signal voltage source also at the non-inverting terminal of the LM386 amplifier.

No issues were encounter while constructing this audio amplifier circuit as the output from the speaker was loud and very clear. The team tested numerous different external circuits between pins G1 and G8 in an attempt for an even louder sound and discovered later that the speaker became too loud and the speaker began to sound muffled due to the gain of the amplifier being too large. The results of the various external circuits tested by the team are further explained in the *Prototype Specifications* section of this lab.

Prototype Specifications

The prototype for the electrical generation circuit is shown in Figure 19. As discussed in the more detail in the *Physical Implementation* section of this report, the electrical generation prototype had to be adjusted in order to improve its performance. The team also had to adjust the audio amplifier prototype circuit in order to achieve a more linear and louder sound.

As can be seen in the alternator pinout wiring in Figure 13 the S, FR, and P pins of the alternator go to the battery, while the L pin goes to ground. This was the original wiring of the alternator based on the theory behind synchronous motors as well as how a general four pin alternator is connected.

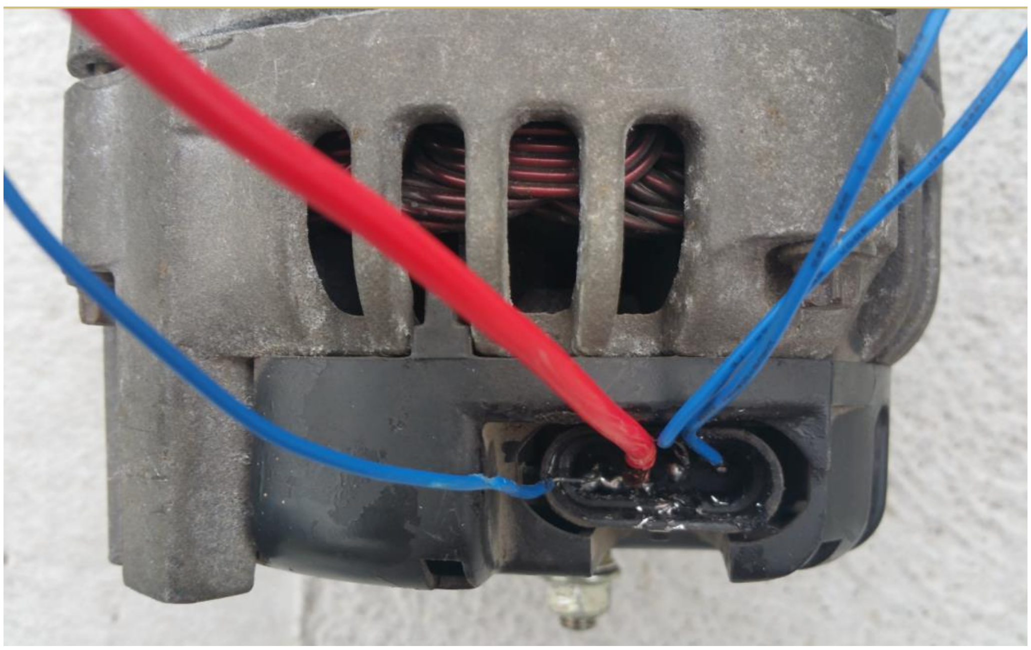


Figure 13 – Original Pinout of the Alternator

The theory was that the field current in the rotor of the alternator needed two terminals, one for power and one for ground and while this is true, the ground terminal is internal to the alternator. The team later discovered that although many alternators from the early 1990s had two external terminals for the field circuit due to the alternators having external voltage regulators, the newer internally regulated alternators only have one external field circuit terminal needed. The P pin was originally to power under the assumption that this terminal was necessary for powering the internal voltage regulator but after several tests the alternator's output was highly inconsistent and the team determined that the performance of the alternator was much more consistent without it.

The prototype for the audio amplifier shown in Figure 12 is the original prototype designed by the team and ultimately the final design of the team but there were multiple tests done to see if a better performing circuit could be obtained with minimal extra components.

Looking internally to the LM386 audio amplifier as shown in Figure 14 [10].

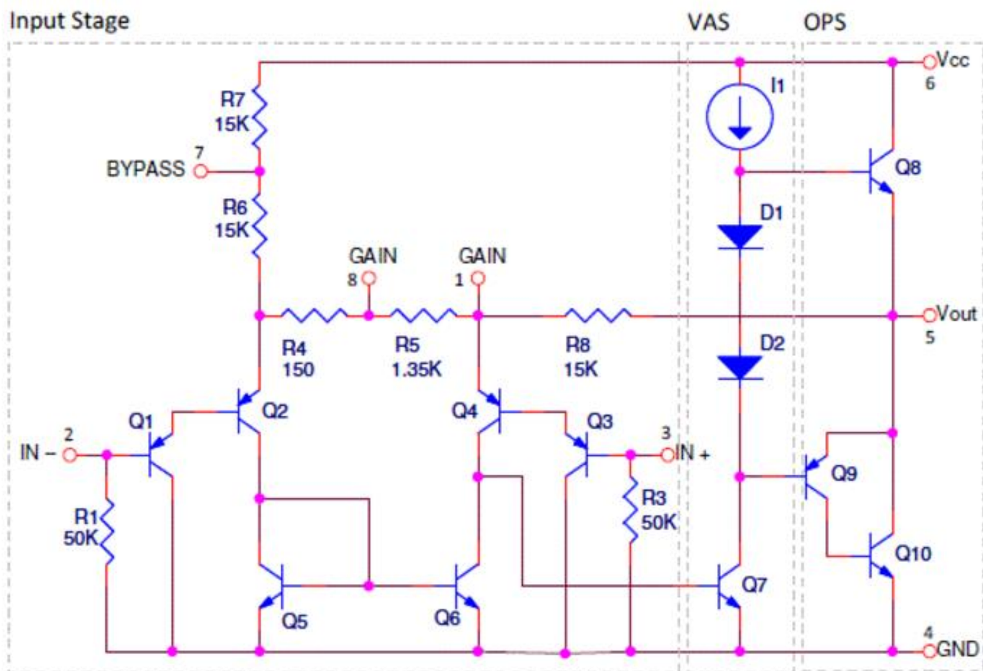


Figure 14 – Internal Circuit of the LM386

The closed loop gain was found to be:

$$G_V = \frac{2Z_{1-5}}{150 + Z_{1-8}}$$

Where Z_{1-5} is the impedance between pins 1 and 5 on the amplifier and similarly Z_{1-8} is the impedance between pins 1 and 8 of the amplifier.

Without any external components meaning $Z_{1-5} = 15k\Omega$ and $Z_{1-8} = 1.35k\Omega$, the gain of the amplifier is around 20 V/V or 26dB. By increasing and decreasing Z_{1-5} and Z_{1-8} with external components, the gain of the circuit can easily be manipulated. The first proposed test done was to connect a capacitor between pins 1 and 8 thus providing an AC short circuit for the signal; this increases the gain substantially as shown:

$$G_V = \frac{2(15k\Omega)}{150}$$

$$G_V = 200\ \frac{V}{V}$$

By adding a single capacitor, the gain was increased tenfold from 20V/V to 200 V/V or 46dB. The team quickly realized that any substantial increase in gain resulted in distortion known as audio clipping. When audio clipping occurs the speaker produces incredibly distorted sound and can even damage the loudspeaker. Upon further testing of numerous different external components the team found that given the specifications of the loudspeaker and the purpose of the speaker, the amplifier without any external components provided an adequate sound for its purpose and reduced the cost and energy consumption of the design.

Proof of Design

Final Design

The fully constructed electrical power generation system is shown below in Figure 15. The positive terminal of the battery is wired to the field winding of the alternator to provide the small amount of electricity required to induce a magnetic field in the rotor of the alternator. The rectified and regulated output of the alternator (which is safe and ideal for charging batteries) is connected directly to the positive terminal of the battery to allow the output current of the alternator to charge the battery.

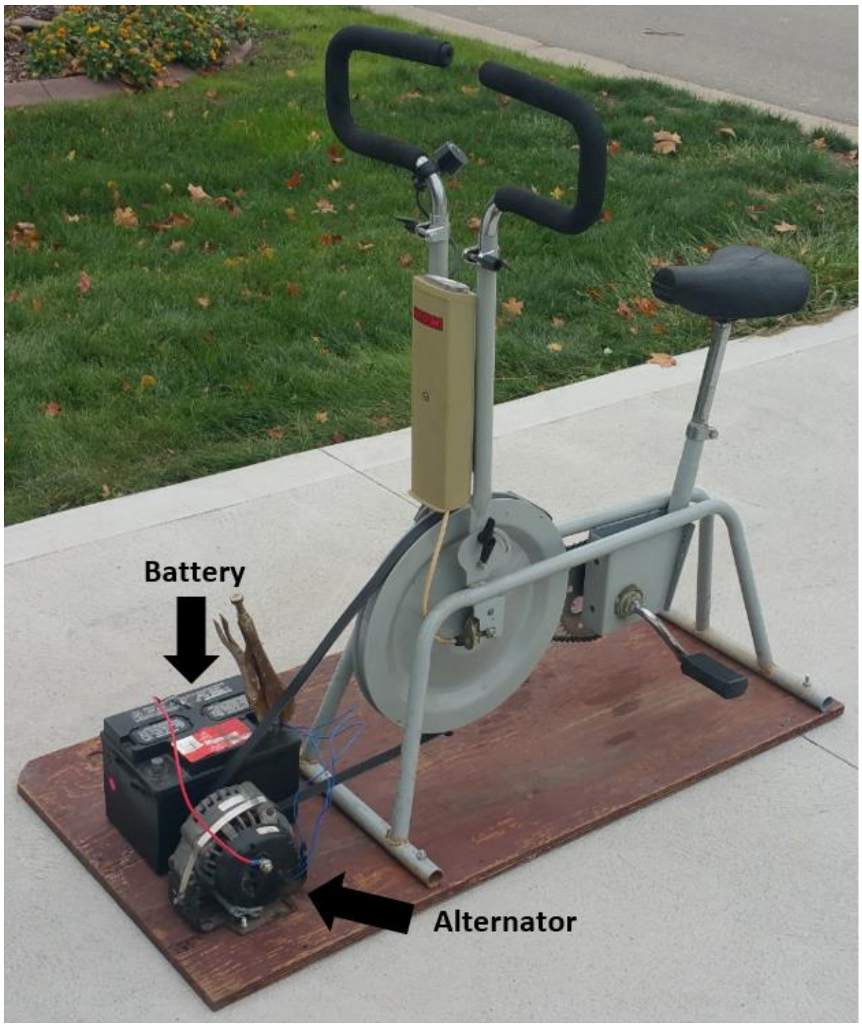


Figure 15 – Physical Model of Energy Harvesting Exercise Machine

As the user pedals the stationary bike, this causes the belt to rotate which in turn provides the rotation necessary for the alternator to generate electricity. In order to prove the battery is being charged by the alternator, an ammeter is used to measure the current flowing from the output of the alternator in to the positive terminal of the battery. This current measurement can be seen below in Figure 16.

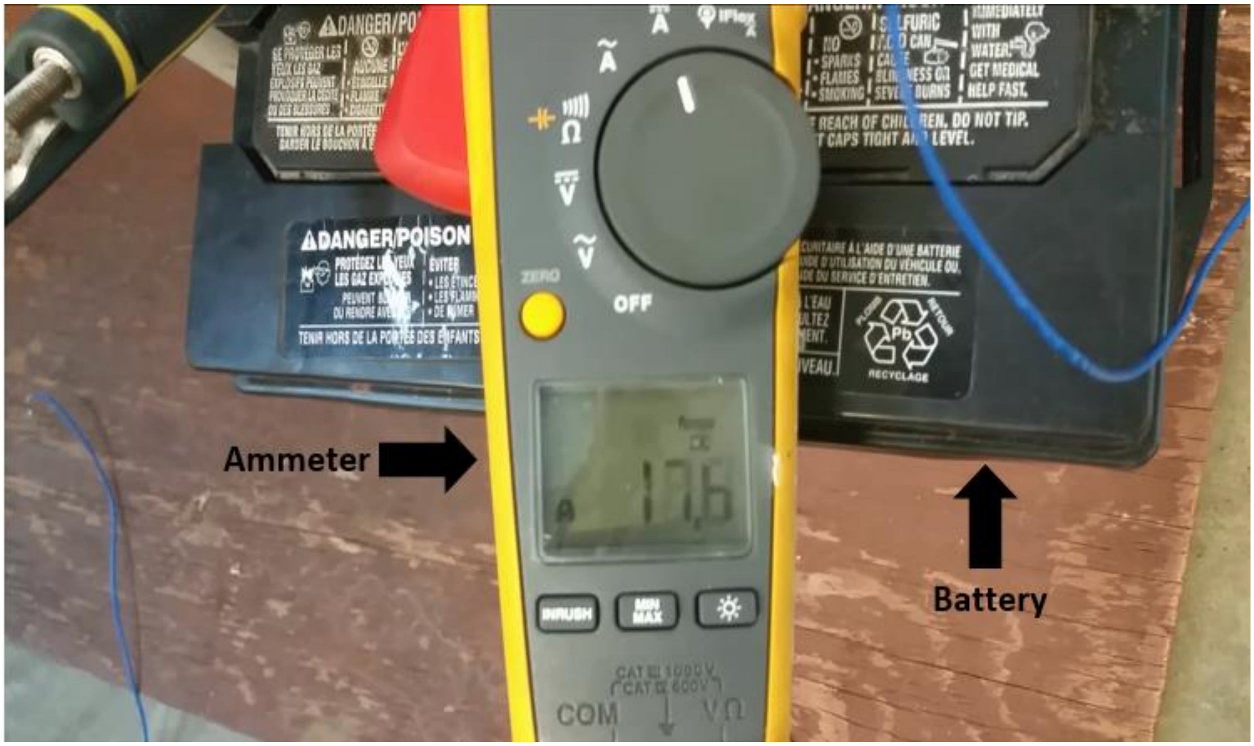


Figure 16 – Current Measurement from Output of Alternator to Positive Terminal of Battery

As seen in Figure 16, $17.6\ A$ of current is easily produced by the user that is directly being used to charge the battery. With the chosen battery having an amp-hour rating of $37.5\ A \cdot h$, it is estimated that if the user continually supplies this input current and the battery is initially completely discharged, the battery will charge fully charge in approximately two hours. Likewise, assuming that a 42 inch LED television consumes on average about $80\ W$ of power [11], that television could be powered continuously for about two hours on a fully charged battery based on the following transformer calculations. If the output waveform of the quadrature oscillator has a peak-to-peak amplitude of about $12\ V_{PP}$ (which is what was consistently during testing when the car battery was used), the input waveform to the transformer has an RMS value of $V_1 = \frac{12/2}{\sqrt{2}} \cong 4.24\ V_{RMS}$. Since the load requires $80\ W$ of continuous power and power is conserved in an ideal transformer, the input current required on the primary side of the transformer (via the quadrature oscillator) is $I_1 = \frac{80\ W}{4.24\ V} = 18.86\ A$. Since the amp-hour rating of the battery used is $37.5\ A \cdot h$, this implies that the battery can supply this current for $\frac{37.5\ A \cdot h}{18.86\ A} \cong 2\ h$. That is, the battery could power a 42 inch LED television continuously for about two hours on a full charge. Note that the charging rate of the battery could be significantly improved by increasing the speed at which the alternator rotates, which could be easily achieved by increasing the gear ratio even higher between the exercise machine and the alternator through a mechanical design, but this is outside the scope of the project.

The fully constructed physical implementation of the quadrature oscillator and audio amplifier circuits are shown in Figure 17. Note that the power supplied to both the oscillator and audio circuits is from the battery that is charged by the user when he or she uses the exercise machine.

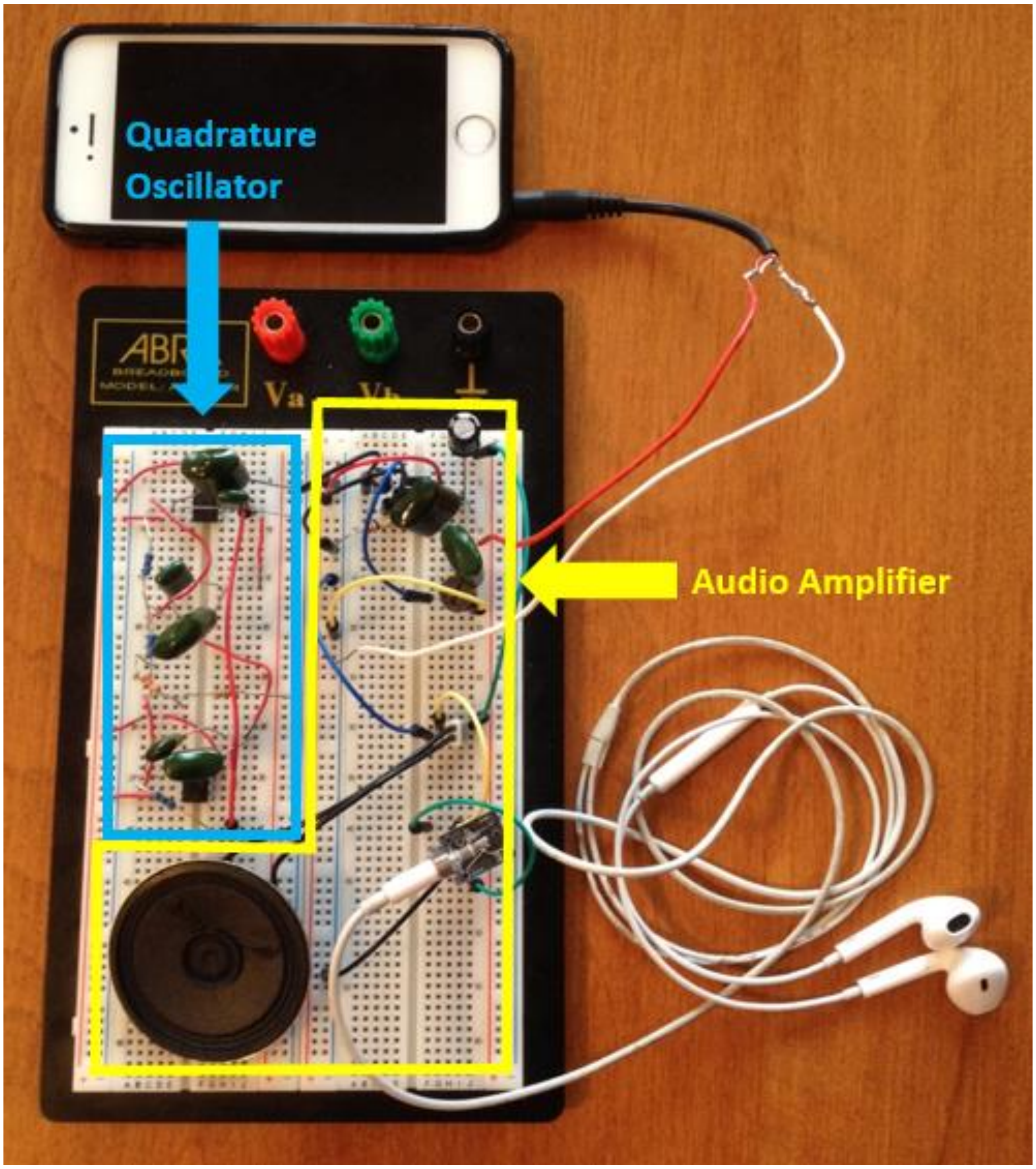


Figure 17 – Physical Model of Quadrature Oscillator and Audio Amplifier Circuits

The quadrature oscillator was specifically designed to convert the output DC voltage of the battery to a sine wave with a frequency of $60\ Hz$. The output of the quadrature oscillator circuit measured with an oscilloscope can be seen below in Figure 18.

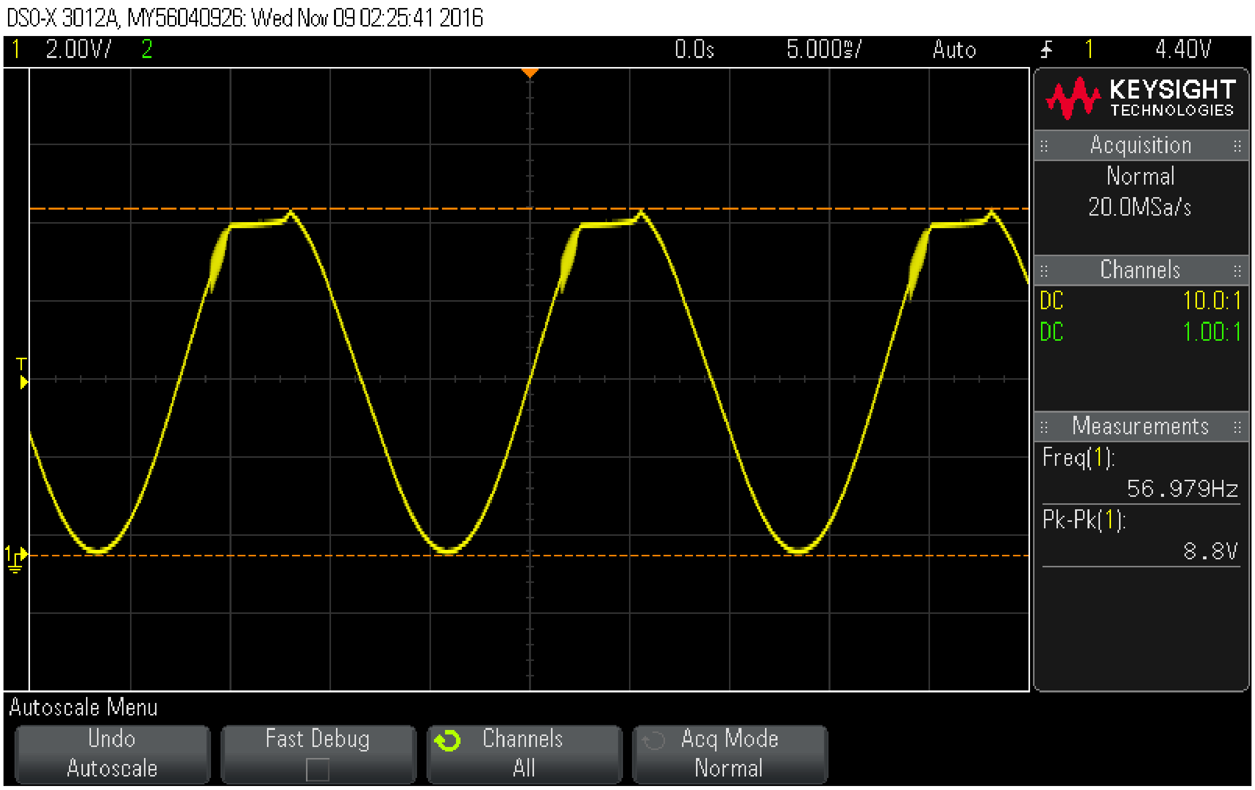


Figure 18 – Output of Quadrature Oscillator Circuit

As seen in Figure 18, the frequency of the output waveform is about 57 Hz which is very close to the desired value of 60 Hz, and the shape of the waveform is sinusoidal as required. The distortion seen on the top of the waveform is insignificant for our intended purpose of the output since it is not necessary to have a perfect sine wave for household electronics.

The output of the audio amplifier circuit is also as expected, producing audio signals that can be listened to via the built-in loudspeaker or personal headphones. The output waveform has an increased voltage gain as evidence by an increased volume at the output of the audio amplifier. The volume can be increased or decreased as desired by the user by rotating the potentiometer shown in the circuit schematic in Figure 7.

Concept Demonstration

The following section will demonstrate and sequentially describe the process the circuit takes to generate, store, and deliver power. Throughout this explanation important power conversions and other aspects will be highlighted as well as some compromises the team had to make.

Figure 19 shows the user pedalling on the exercise bike. If the user does not pedal, the battery has to supply a small amount of current in order to power the field circuit in the rotor of the alternator. This output can be seen in Figure 20. The -0.36A in Figure 20 is the current being supplied by the battery to the field circuit. Once the user begins pedaling and the alternator has generated a sufficient amount of power, the regulator starts directing the output current of the alternator into the field circuit and simultaneously switches off the current being supplied from the battery. It is important to note that the output current of the alternator is DC current since the alternator has an internal rectifying circuit that converts the generator AC power into DC.

Figure 19 – User Pedalling on the Exercise Bike

Figure 20 – Initial Output Current Being Supplied to the Alternator

Once the battery has enough charge it provides the 12V DC needed to power the quadrature oscillator and the audio amplifier. The quadrature oscillator and audio amplifier shown in Figure 17 are not yet being powered as the battery does not have enough power to meet the required loads. Figure 21 shows the output of the alternator once the consumer has reached about 45 rpm (the average speed of a normal bike ride). As can be seen in Figure 21, the output current is now approximately positive 10 amps indicating that the current is flowing into the battery and thus the battery is being charged.

Figure 21 – Output Current Being Supplied to the Battery

At this point, a small amount of current from the alternator is being redirected back into the field circuit so that the alternator is self-sufficient while the rest of the power is either being used to power the quadrature oscillator and audio amplifier or to charge the battery depending on the load of the oscillator and amplifier.

As can be seen in Figure 22, the output of the quadrature oscillator is the 9V peak to peak 60Hz sine wave that was found during the initial testing in the lab and simulation of just the oscillator itself (shown in Figure 11).

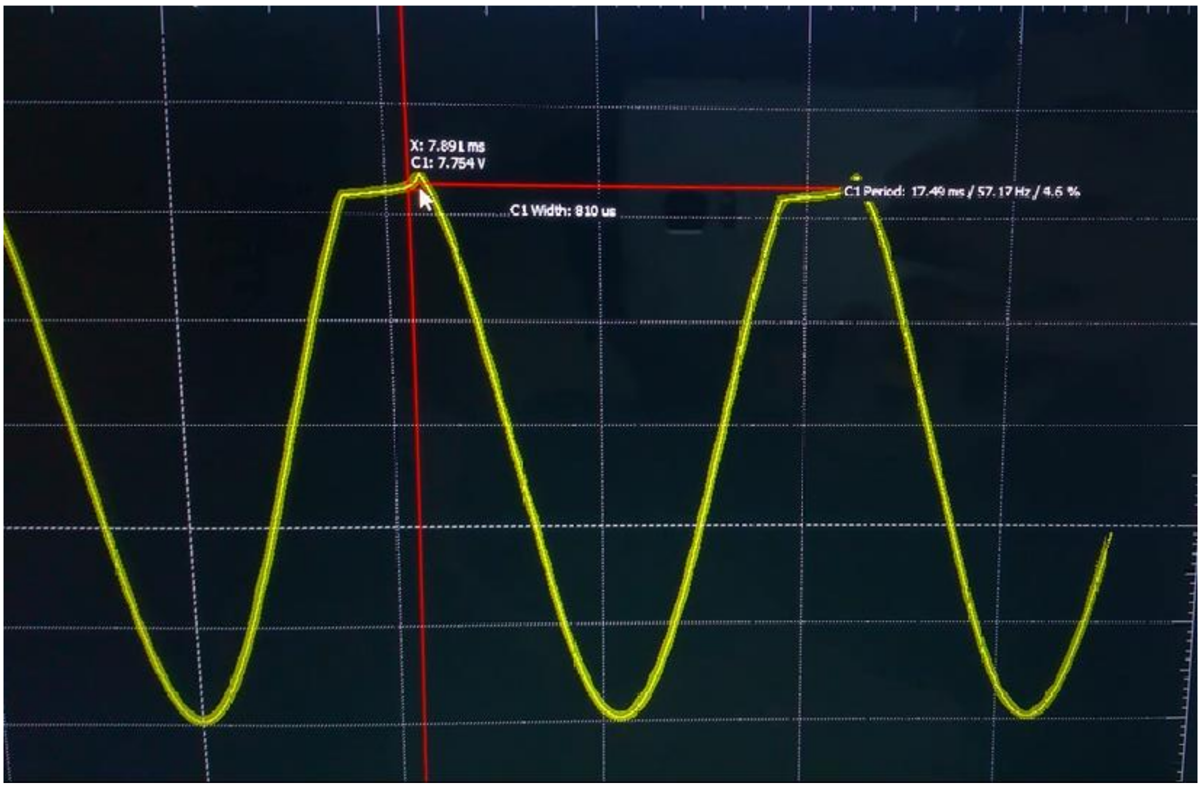


Figure 22 – Output of the Quadrature Oscillator

Initially, the main concern with the design was with the output current of the alternator at relatively low rpms compared to the speed a vehicle engine would be driving the alternator at. However, as can be seen in the graph of Appendix A (which is a graph of the output current of the alternator versus the rpms of an average bike ride), current performance is exceptionally high, peaking at about 20 amps around 90 rpm.

Conclusions

The underlying theme during all the research, physical implementation, and testing of the design was to provide modern day society a solution to electrical demands while also promoting a healthy lifestyle all in a safe and reliable manner. With this in mind the team decided to use the Engineering Design Process Guidelines that are used by professional engineers in today's industry. This highly iterative design process is used by engineers that need to come up with a solution that needs to not only solve a problem but also meet certain criteria and adhere to restrictions. There are eight steps in this methodical process with each step reflecting certain core principles regarding the underlying concepts of framework in engineering design.

The eight steps are:

- Define the Problem
- Do the Background Research
- Specify the Requirements
- Brainstorm Solutions
- Choose the Best Solution
- Do Development Work
- Build a Prototype
- Test and Redesign

The steps in this process can be repeated or referred back to as long as each step is completed and reviewed. As stated previously, this is a highly iterative process meaning that parts of the process often need to be repeated many times before another can be entered.

Define the Problem

The general restrictions and guidelines for this step were provided for the team by the project specifications in the Project Information document. The general restrictions were that the team had to construct and explore the designs of analog electronic circuits through the designing and creation of a "product" that has a set of overall objectives and minimum specifications on a budget of $30. This problem statement was then refined and pulled into a direction by the team because the team wanted to create a product that could potentially solve a serious issue in modern day society. With this underlying theme in mind the team began its research on the top modern day issues of the average person. By applying the knowledge and also harnessing the power of analog circuits, each issue brought up was critically analyzed to determine if the issue could potentially be solved using analog electronics.

Do the Background Research

This step was the step that gave the project its first true direction. By researching common everyday problems faced by consumers, the idea of electricity and renweable energy became the forefront focus of the team. By researching and learning about modern day industry solutions to the various issues associated with electrical power generation, it became apparent that there was a huge disconect between everyday consumers and renewable energy. The team took the best components from each solution to create a hypthetical design that could potentially be a practical and efficient mthod for solving an issue.

Specify Requirements

By reviewing and redefining the functions the team wanted to achieve outlined in the Background Research step, the team derived a list of the most critical functions that the design had to perform and accomplish. These must-have functions and minimum requirements became the newly refined specification requirements.

The requirments and objectives of the report are outlined in more detail in the *Design Objectives* section of this report but are elabroated on here for clarity.

- Provide efficient and clean electricity for virtually anyone in modern day society
- The design should be self-sufficient and not require the consumers to need other components for the operation of the product
- Be able to store the electricity generated by the consumer
- Promote the importance of healthy living and regular exercise
- Save everyday consumers large sums of money
- Be powerful enough to easily power large houshold products
- Maintain a high level of safety in operation throughout a wide range of environments.

Brainstorm Solutions

The team began brainstorming individual designs that targeted just one of the requirments stated in the Specify Requirements step and compared each individual design with current industry designs. After comparing with industry designs the team would repeat the analysis of the individual deisgn until it was up to industry standard and then repeat this process for the next requirement. By combining all of these indivudal designs the team developed the prototype circuit seen in the *Prototype Specification* section of this report.

Choose the Best Solution

The best solution was found though numerous simulations done in LT Spice. By testing each prototype circuit in the simulation environment, the team was able to decide upon the best prototype and determine which design sufficiently met every requirement stated in the Specify Requirments section.

In this step numerous protoypes were scrapped but documented and understood so that the team was constantly building towards a design that was aware of its limitations and restrictions. The simulations provided the nessasary information for eliminating potential designs as well as providing the team with potential issues that were not thought of in the Brainstorm Solutions step.

Do the Development Work

The development work was done by both analyzing which circuit elements could produce the best results and by actually constructing individual physical model circuits containing such elements. By observing the real world performance of each electronic component the team was able to again rule out potential designs. By observing which circuits were the most effective and which circuit operations were the most practical, the team began to develop a more specific and detailed prototype.

Build a Prototype

The prototype that was chosen was one of the few designs left after the elimination process that the team felt best captured the underlying theme of the project. The final prototype specification can be seen in the *Prototype Specification* section of this report.

Test and Redesign

This final step was the longest and most resiliant step in the Engineering Design process but perhaps the most beneficial. After countless hours of redesign and performance tweaking, the final circuit was chosen as documented in the *Proof of Design* section of this report. Each redesign and tweak were primarily based on the practicality of each function, and any component that was removed was ultimately due to the strong discrepency between the real world performance of each component and the simulation/theoretical performance.

The team stressed the importance of meeting each core requirement decided upon in the Specify Requirements section, however some non-essential goals/features had to be removed after the team reviewed and weighted the benefits and compromises of each.

By using this industry proven engineering design process, the final circuit design was finalized and documented. The final design incorporated all the functions listed in the *Design Objectives* section of this report in a very efficient and practical manner while ensuring user safety was kept the number one priority.

The final design of the solution aimed to solve the disconnect between renewable energy and the everyday consumer and the team feels that the final product accurately and realistically represents the team's theme and specified requirements. The product actively enables consumers anywhere in the world to create their own renewable electricity efficiently and inexpensively that can be stored or used to power large electronic devices all while promoting a healthy and active lifestyle. The design can effectively utilize and capture otherwise wasted energy that millions on people around the world already expend daily while exercising to create useful and clean electricity for anyone. From saving money on electricity bills in first world countries to providing electricity to the 3 billion humans without electricity, the Energy Harvesting Exercise Machine is a phenomenal solution for anyone's electricity needs.

The final product which was created through the combination of intuitive engineering, knowledge in analog and power electronics, and the iterative engineering design process reflects all of the work gone into the design of just one product. This process has taught the team members valuable lessons and concepts in the engineer design process and has made the team much more prepared for future engineering design ventures.

For future redesign and implementation of this project, the team would eventually combine this stationary bike exercise machine with other exercise machine products such as bench press machines or elliptical machines in order to potentially implement dozens of various energy harvesting exercise machines in workout facilities all over the world in order to capitalize on the billions of joules of energy expended every day in exercising, essentially creating a tapestry of renewable energy power plants around the world powered by humans.

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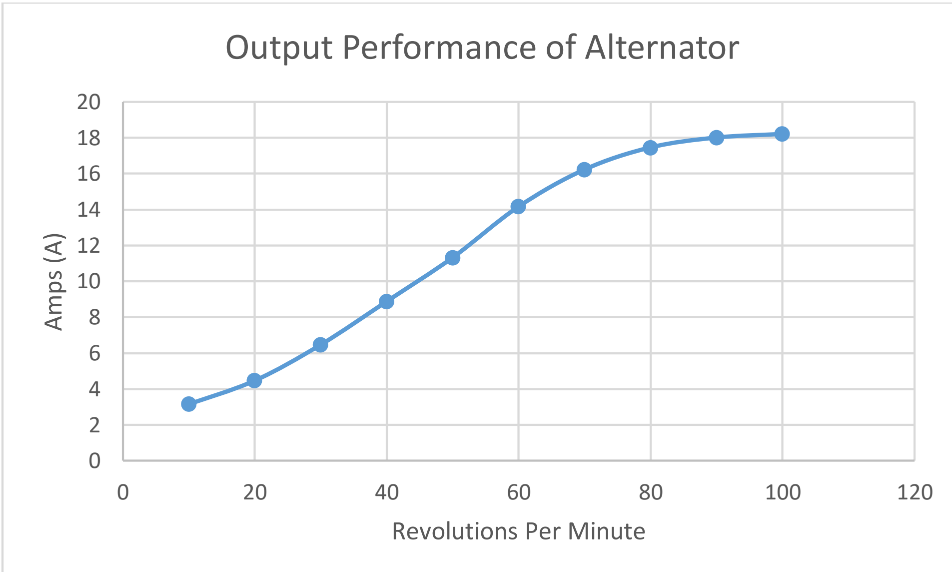
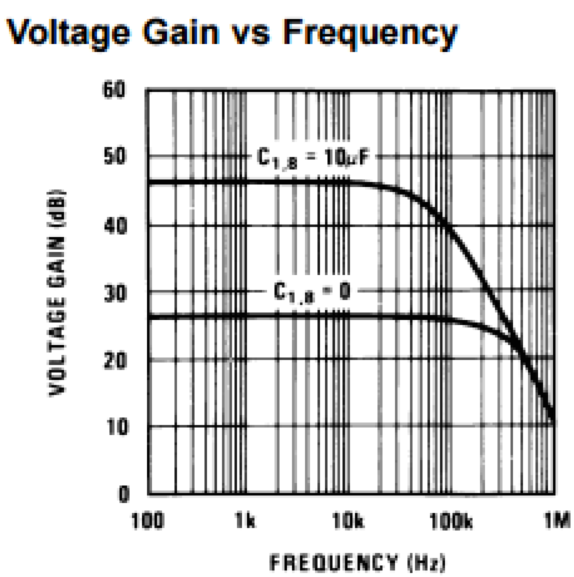
Appendix

A. Output Performance of Alternator



B. Bode Plot of LM386



C. Battery Specifications

Battery Specification Chart

BCI Group Size	Motorcraft Part Number	Cold Cranking AMPS (At 0° F)	Cranking AMPS (At 32° F)	Reserve Capacity (Minutes)	Maximum Dimensions Inches (mm)			Approx. Weight (Wet)
					Length	Width	Height	LBS. (KG)
TESTED TOUGH MAX								
12-Volt Post Terminals								
24	BXT-24	600	750	120	10.95 (278)	6.87 (174)	8.70 (221)	44 (20.0)
24F	BXT-24F	600	750	120	10.95 (278)	6.87 (174)	8.70 (221)	44 (20.0)
34	BXT-34	500	625	100	10.95 (278)	6.88 (175)	7.80 (198)	44 (20.0)
35	BXT-35	550	685	100	8.99 (228)	6.87 (174)	8.83 (224)	37 (16.8)
36R	BXT-36R	650	810	130	10.25 (260)	7.18 (182)	7.79 (198)	41 (16.1)
40R	BXT-40R	590	735	105	10.90 (277)	6.42 (174)	6.88 (175)	37 (16.9)
56	BXT-56	550	685	86	10.21 (259)	6.02 (153)	8.32 (211)	33 (15.0)
58	BXT-58	540	675	92	10.03 (255)	7.19 (183)	6.86 (174)	33 (15.0)
58R	BXT-58R	582	725	100	10.03 (255)	7.19 (183)	6.86 (174)	34 (15.4)
59	BXT-59	540	675	100	10.03 (255)	7.47 (190)	7.63 (194)	37 (16.8)
64	BXT-64	600	750	120	12.28 (312)	6.23 (158)	8.83 (224)	46 (20.9)
65	BXT-65-650	650	810	130	12.03 (306)	7.47 (190)	7.63 (194)	42 (19.1)
65	BXT-65-750	750	935	140	12.03 (306)	7.47 (190)	7.63 (194)	49 (22.2)
65	BXT-65-850	875	1090	165	12.03 (306)	7.47 (190)	7.63 (194)	52 (23.6)
66	BXT-66-650	650	810	130	12.03 (306)	7.47 (190)	7.63 (194)	44 (20.0)
66	BXT-66-750	750	935	140	12.03 (306)	7.47 (190)	7.63 (194)	49 (22.2)
96R	BXT-96R	500	625	90	8.97 (228)	6.30 (173)	6.88 (175)	32 (14.5)
12-Volt Side Terminals								
75	BXT-75	550	685	93	9.68 (246)	7.62 (194)	7.22 (183)	32 (14.5)
12-Volt Dual Terminals								
7586DT	BXT-7586	700	875	100	9.71 (246)	7.24 (184)	8.96 (228)*	37 (16.8)
3478DT	BXT-3478	800	1000	110	11.00 (279)	7.24 (184)	8.96 (228)*	42 (19.1)