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Designing an Accessible Wave Energy Conversion Device for Powering Ocean Sensors

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Abstract

Currently, less than 5% of our oceans are comprehensively monitored and much more ocean data is needed to facilitate understanding of ocean physics, carbon cycling, and ocean ecosystems. Today, most autonomous ocean sensors are powered by primary battery, which have both limited capacity and lifetime. The goal of this research is to design a small, accessible renewable wave energy device to power autonomous free-floating ocean sensors. By designing a cheap, accessible, and simple wave energy converter, this work hopes to make ocean sensor deployment easier and cheaper for researchers, increase the lifetime of autonomous ocean sensors, and reduce the reliance on non-renewable battery power sources. This work presents the final mechanical and electrical designs for a linear point absorber wave energy converter to power a range of ocean sensors.

Justification and Research Objective

Currently, less than five percent of the oceans are comprehensively monitored (Adler & Degnarain, 2017). And although we collected more ocean data from 2015 to 2017 than all previous ocean data combined, much more data collection is needed to facilitate understanding of ocean physics and carbon cycling (Adler & Degnarain, 2017). Today, most autonomous ocean sensors are powered by primary battery (Chao, Y., 2016). These battery power systems have limited capacities and lifetimes, with most lifetimes around 1-1.5 years and the newest battery-powered floats with predicted lifetimes of up to 5 years (Riser, S. C., Swift, D., & Drucker, R., 2018). As it is difficult and often nearly impossible to retrieve these floats once the battery dies, many autonomous sensors along with their toxic battery system are abandoned in the oceans (Riser, S. C., Swift, D., & Drucker, R., 2018). According to Weimer, Paing, and Zane (2006), power consumption is frequently cited as "the primary limiting factor in the duration and performance of autonomous sensor networks". A renewable energy power source would be a promising alternative for primary battery systems, as the system could have a much longer lifetime and prevent toxic batteries from being abandoned in the ocean.

Wave energy is a promising renewable energy form for powering autonomous ocean sensors. Wave energy is present everywhere in the oceans and is less geographically variable than, for example, solar energy. Furthermore, wave energy devices sit on the surface of the ocean and can thus easily be paired with a wide range of surface ocean sensors.

The objective of this project is to design a small, accessible, autonomous wave-energy device that can be used to power a range of ocean sensors. The designed wave energy device should be cheap and simple so that it increases accessibility to renewable power devices for researchers who would like to deploy autonomous ocean sensors. It must also be compatible with a range of different ocean sensors to encourage the collection of much-needed ocean data.

To begin, a literature review must be conducted to provide background for and inform the wave energy device design. The research questions motivating the literature review are: How are autonomous ocean sensors currently powered? What is the best type of wave energy device and power take-off system for this application?

After conducting a literature review, the goal of this project is to advance through as much of the design process as possible in the five-week project period. The design steps this project will follow are 1) sketching design and iteration, 2) for mechanical components, 3D CAD modeling iteration and for electrical components, circuit diagram program iteration, 3) physical sketch model design and iteration, and 4) final model design.

Introduction

Types of Wave Energy Devices

Click on each wave energy device figure in this section to see an animation showing the motion of the device. All figures and animations are from the Aqua-RET Project (2012), an e-learning tool funded by the EU promoting aquatic renewable technologies.

I will introduce the five most common types of wave energy devices, characterized based on their motion as per the guidelines of the Wind and Hydropower Technology Program of the US Department of Energy (Kolliatsas, Dudziak, Schaefer, & Myers, 2012).

Point absorbers harness the vertical heave motion of waves using a buoy (either on the surface or sub-surface) and a power take-off system that includes at the minimum a generator (Kolliatsas et al., 2012). Point absorbers can either be anchored to the sea floor or weighed down by a heave plate. As the buoy moves up and down with the passing waves, the generator converts the kinetic energy of the buoy into electrical energy (Figure 1, Aqua-RET Project, 2012) (Kolliatsas et al., 2012).

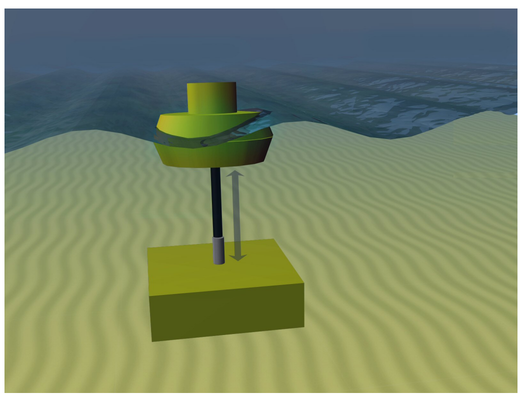

Figure 1. General point absorber wave energy converter design and motion.

Attenuators float on top of the waves and selectively restrict motion along their length to produce energy (Kolliatsas et al., 2012). Passing waves cause the hinges between the segments to flex (Figure 2, Aqua-RET Project, 2012) and hydraulic pistons at the hinges create a pressurized fluid that is pumped to a generator to produce electricity (Kolliatsas et al., 2012).

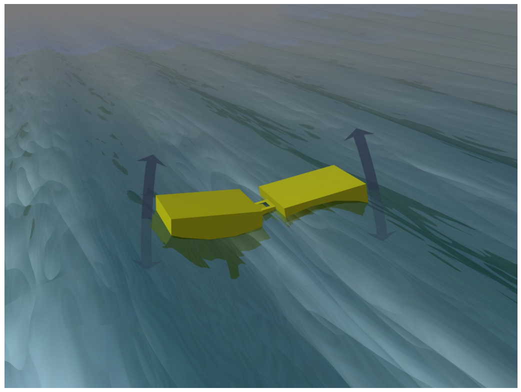

Figure 2. General attenuator wave energy converter design and motion.

Oscillating Water Columns (OWC) generate electricity from the wave-driven rise and fall of water in a chamber (Kolliatsas et al., 2012). The air in the chamber above the water level is pushed through a cylinder with an air turbine as the wave-driven water level rises and falls, generating electricity (Figure 3, Aqua-RET Project, 2012) (Kolliatsas et al., 2012). OWCs can be installed either onshore or offshore (Kolliatsas et al., 2012).

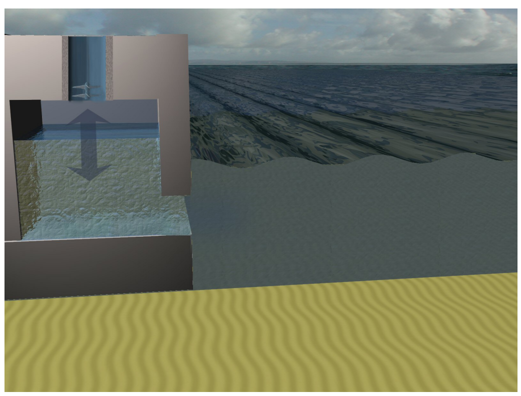

Figure 3. General oscillating water column wave energy converter design and motion.

Oscillating Wave Surge Collectors harness the predominantly horizontal water motion in shallow waters by using a paddle with one end fixed to a structure or the seabed while the other end is free to move (Figure 4, Aqua-RET Project, 2012) (Kolliatsas et al., 2012). Oscillating wave surge collectors can be installed on the shoreline or near-shore (Kolliatsas et al., 2012).

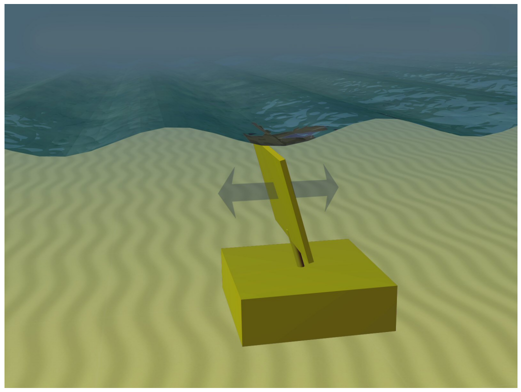

Figure 4. General oscillating wave surge collector wave energy converter design and motion.

Overtopping devices convert the kinetic energy of waves into potential energy by trapping the water at the height of the waves in an elevated reservoir (Kolliatsas et al., 2012). The water then passes through a cylindrical outlet feeding it back into the ocean and powering a hydroelectric turbine which creates electricity (Figure 5, Aqua-RET Project, 2012) (Kolliatsas et al., 2012).

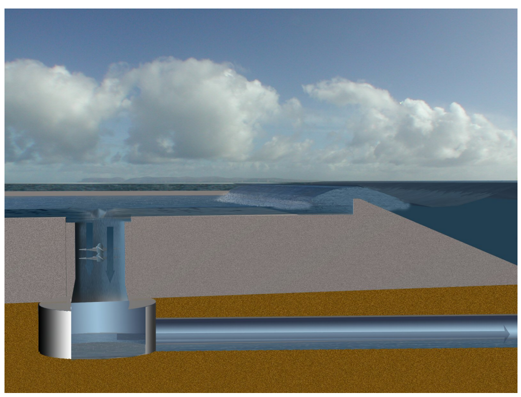

Figure 5. General overtopping wave energy converter design and motion.

Of these five types of wave energy devices, linear point absorbers are best suited for the objective of this project. Firstly, linear point absorbers can be free-floating as the point absorber system can be attached to a heave plate as a counterweight instead of the seabed. Secondly, point absorbers are a relatively simple mechanical design which is important to make the device cheap and accessible for researchers who need to fix or modify the device. The simplicity of the mechanical design also means that point absorbers can more easily be scaled down to a small size, unlike devices which require hydraulics or large reservoirs for example. Finally, linear point absorbers can harness wave energy from any direction which is extremely important in a free-floating device as the device will experience variable and unpredictable wave motion.

Types of Linear Point Absorbers

I will introduce the three most common types of linear point absorbers, categorized based on the power take-of system used. A power take-off system is the device or method used to transfer an energy source's power to another piece of equipment, usually through generation of electricity. Linear point absorbers tend to be large-scale devices (high-kW and MW systems) used for generating grid electricity, so the common power take-off systems found in the literature are best suited for large devices.

Hydraulic power take-off systems utilize a hydraulic pump which uses the linear mechanical motion of the point absorber to pressurize a liquid or gas (Fan, Y., Mu, A., & Ma, T., 2016). This highly pressurized liquid or gas is then pumped into a turbine, which generates electricity.

The linear mechanical motion of the point absorber can also be coupled with a rotational alternator. A rotational alternator is a generator that converts rotational mechanical energy into electricity. Using a rod with teeth coupled with a gear, the linear mechanical motion of the point absorber can be converted to rotational motion that can be fed into the rotational alternator.

Dielectric elastomer generators can also be used in linear point absorbers (Bortot, E., Springhetti, R., deBotton, G., & Gei, M., 2015). This type of generator consists of a dielectric elastomer sandwiched between two electrodes, essentially forming a deformable capacitor (Figure 6, Bortot, E., Springhetti, R., deBotton, G., & Gei, M., 2015). When subject to a voltage, the elastomer expands and becomes thinner, increasing its surface area. Charge then builds up on the electrodes. When the applied voltage is removed, the elastomer thickens and reduces its surface area, increasing the voltage. This boosts the dielectric elastomer from a low voltage to a high voltage reservoir and creates electricity. In linear point absorbers, the linear mechanical motion is used to physically compress and decompress the dielectric elastomer and create electric current.

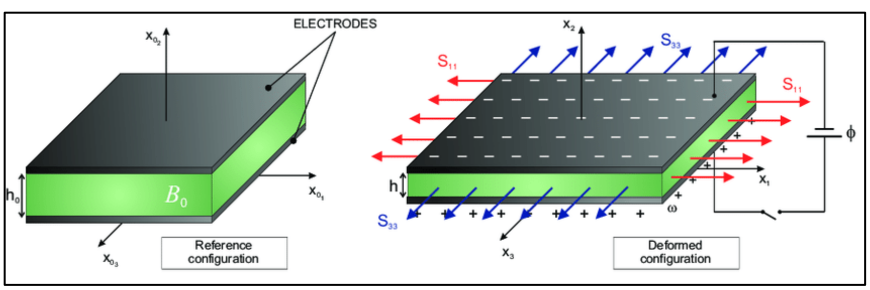

Figure 6. Applying a voltage to a dielectric elastomer generator causes it to deform into a thinner, flatter shape, allowing more charge to build up on the electrodes.

Methods

Overview of Design Methods

The goal during this five-week research project was to get as far into the design process as I possibly could, as it was initially unclear how far I would be able to get in the span of five weeks. The first step was to perform a literature review and conduct adequate background research on wave energy devices, ocean sensors, and power take-off systems. The next step was to decide on a type of wave energy device and begin the brainstorming and iterating through designs. For the mechanical components, I began with sketching design iterations, followed by simple models made in PowerPoint, and finally creating a model on the 3D CAD program Fusion360. For the electrical components, I began with sketching potential circuit designs and ultimately constructed the final circuits on an online circuit diagram maker.

Power Take-off System

Having decided that a linear point absorber system would be the best for the intended applications of this wave energy converter, I then needed to decide what power take-off system I would use to physically convert the heaving motion of the waves into electricity. There were three main options I came across in the literature: hydraulic, linear heave coupled with a rotational alternator, and dielectric elastomer generator. These power take-off systems are explained in the Introduction. These power take-off systems are used in large high kW and MW wave energy converters and are quite mechanically and materially complicated. None of these seemed feasible for a small-scale point absorber device, so I continued to do research on power take-off systems used in other devices that could potentially work for this project.

In researching electrical generators to understand how rotational alternators work, I stumbled across this diagram of a linear alternator shown in Figure 7 (De Pasquale, 2013). I had been agonizing over the best way to convert the linear heaving motion of waves into the rotational motion that rotational alternators require to generate electrical energy, so this linear alternator seemed both too good and too simple to be true. I began sketching some rough designs for a linear alternator wave energy converter – all much simpler than the large-scale power take-off systems I had been trying to scale down before. Linear alternators are hardly ever used in large-scale wave energy converters because the coil and magnet materials required to produce that much power would be far too large and expensive to be feasible (Fraunhofer Institute for Wind Energy Systems, 2013).

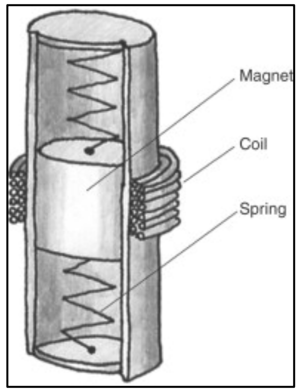

Figure 7. Linear alternator with fixed coil and oscillating magnet attached to springs.

After sketching a few linear alternator designs, I searched the literature for wave energy converter designs powered by linear alternators. Fraunhofer Institute for Wind Energy Systems present electrical linear generators (i.e. linear alternators) as a possible generator technology for wave energy devices (2013). I was unable to find other mentions of linear alternators as power take-off systems for wave energy converters. I was able to find research by Nolte, Ertekin, and Davis (2013) who built a small wave energy conversion device to power ocean sensors or charge dry cell batteries, a very similar objective to that of this project. Their wave energy device converted vertical linear heave into rotational motion to generate electrical power through a rotational alternator (Nolte, Ertekin, & Davis, 2013). Eriksson (2019) presents a simulation method for direct-drive permanent-magnet linear generators for a wave energy converter. Eriksson concludes that copper losses in the coil are inherent to large linear alternators (slower-moving machines) and that the high-efficiency provided by linear alternators must be balanced with material cost (2019). Eriksson's conclusions did not change my decision to use a linear alternator as my power take-off system as I am designing a small linear alternator, thus my design will have smaller copper losses and the material cost is relatively low because the linear alternator is not large. Due to the design simplicity, feasibility, and relative affordability of required components, the electrical linear generator emerged as the best option for this project.

Linear electrical generators (also referred to as linear alternators) are a type of electrical generator that produce alternating current (AC). Most alternators are powered by rotational motion, while linear alternators are powered by linear motion. The electromagnetic induction principle is what makes linear alternators work. Electromagnetic induction occurs when a magnet moves in relation to an electromagnetic coil (a coil of wire, for example). As the magnetic flux through the coil changes, an electrical current is induced in the coil. This phenomenon is summarized in the fundamental relationship known as Faraday's Law, which is derived from Maxwell's equations and describes how voltage can be generated by a changing magnetic environment (Nave, 2017). Faraday's Law, shown in Equation 1 below, shows that induced voltage (Emf) in a coil is equal to the negative of the number of turns in the coil (N) multiplied by the rate of change of the magnetic flux ($\frac{\Delta\Phi}{\Delta t}$). The change in the magnetic flux ($\Delta\Phi$) is equivalent to the change in the external magnetic field (B) times the area of the coil (A).

$$\mathrm{Emf} = -N\frac{\Delta(BA)}{\Delta t} = -N\frac{\Delta\Phi}{\Delta t} \quad (1)$$

The negative at the beginning of Faraday's Law comes from Lenz's Law, which states that the induced current in the coil due to the change in magnetic flux will flow in the direction that creates a magnetic field opposing the change in magnetic flux that induced it. In other words, the induced magnetic field (from the induced current) will act to keep the magnetic flux inside the coil constant. In Figure 8 below from Nave (2017), if the magnetic field is increasing, the induced magnetic field from the induced current acts in opposition. If the magnetic field is decreasing, the induced magnetic field acts in the direction of the applied magnetic field to try to keep it constant.

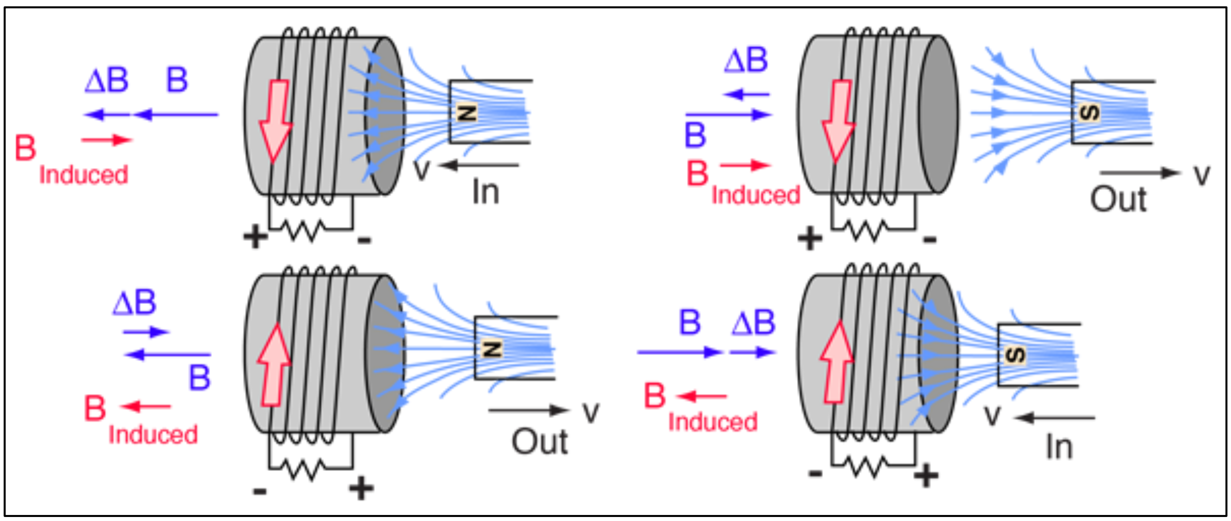

Figure 8. Faraday's Law and Lenz's Law explain how emf is generated by change in magnetic flux in a coil of wire, depending on the variables depicted in the figure.

With all that said, a linear alternator is simply a magnet and surrounding conductive wire moving in relation to one another due to linear mechanical (Figure 7, De Pasquale, 2013). This converts linear mechanical energy to electrical energy. Designs can include a stationary coil and oscillating magnet or vice versa (De Pasquale, 2013).

Therefore, the induced voltage in a linear alternator can be manipulated in four ways according to Faraday's Law. Assume a scenario in which we want to increase the induced voltage (Emf). We can either increase the number of turns in the coil (N), increase the speed of the relative motion between the coil and magnet (thus increasing the rate of change of the magnetic flux $\frac{\Delta\Phi}{\Delta t}$), increase the strength of the magnetic field (B), or increase the area of the coil (A) ("Electromagnetic Induction", 2019).

According to the Fraunhofer Institute for Wind Energy Systems, the major drawback to linear alternators is that the technology has a relatively low distribution, meaning that often linear alternators must be tailor-made to fit a machine (2013). This can result in “high investment cost and additional development risks” (Fraunhofer Institute for Wind Energy Systems, 2013). This drawback is not a large concern for this project as the objective was to build a tailor-made wave energy converter from the beginning. The high investment costs (temporal and financial) and development risks were anticipated as inherent to this design project, so they were not obstacles to choosing a linear alternator power take-off system.

Mechanical Components

Having decided that I was going to design a linear point absorber with a heave plate and linear alternator power take-off system, the scope of my design for mechanical components was quite focused. For each mechanical component, I performed a small literature review to understand how these components had been designed in the past and what design would likely be most applicable to this project. I would then perform sketch iterations integrating that mechanical component into my design and figuring out the best iteration.

To provide an example, I will walk through considerations I made in the design of my heave plate. In my literature review, I learned that I had to be considering the size and shape of the heave plate, as well as the hydrodynamic coefficient of each possible design (Brown, A., Thomson, J., & Rusch, C., 2017) (Brown, A.C., & Thomson, J., 2015). So I then considered multiple heave plate shapes and associated hydrodynamic coefficients based on the ideal characteristics for this application. I had to consider the directionality of certain heave plate designs and the free-floating nature of this model.

Electronics

While mechanical research and design was a large component of this design project, the electronic components and circuit design was also quite complicated. Designing an electrical circuit that was appropriate for such a small wave energy converter and general enough to properly power a wide range of ocean sensors proved quite challenging.

To begin, the power source (the wave energy converter) had to be characterized. As the wave energy converter is itself a linear alternator, the direct output from the wave energy converter will be variable alternating current. The output will be alternating current because the magnet reverses directions in the solenoid as the buoy and magnet component bobs up and down with the motion of the waves. This alternating current will be variable in nature because the height, wavelength, and frequency of waves will not be constant. This creates a difficult power source because devices cannot be properly powered by an inconsistent variable electric current.

To address the variability in the power source, a battery is needed that can respond to the short-term fluctuations in power on a second timescale. A battery will be able to store the additional energy created by larger waves and supply energy during low-energy generating waves. Furthermore, a battery will be able to accommodate swells, which have much longer wavelengths than normal waves, by storing the extra energy generated.

The next step was to determine what battery would be optimal to use in this design. Zhou, Benbouzid, Charpentier, Scuiller and Tang (2013) conduct a review and comparison of energy storage technologies applicable to marine current energy systems. Table 1 from Zhou et al. (2013) below provides a comprehensive summary of their battery analyses. As the objective of this project is to build an affordable and accessible wave energy converter, I chose to use a lead-acid battery. Lead-acid batteries are easily accessible and cheap, meaning that both the initial battery cost and any potential battery replacements required will not be a barrier for those who want to use this device. Furthermore, lead-acid batteries have low self-discharge, a phenomenon where chemical reactions in the battery reduce the amount of stored energy without the electrodes being connected to one another or an external circuit (Zhou et al., 2013). Lead-acid batteries do have short cycle lifetime than other battery types, however this is less of an issue for this small wave energy converter application because the battery will hardly ever be fully charged by the small wave fluctuations (Zhou et al., 2013).

Table 1. Comparisons of battery technologies applicable to marine current energy systems.

Battery type	Advantages	Disadvantages
Lead-acid	√Low cost	×Short cycle life (1200–1800 cycles)
	√Low self-discharge (2–5%per month)	×Cycle life affected by depth of charge
		×Low energy density (about 40 Wh/kg)
Nickel-based	√Can be fully charged (3000 cycles)	×High cost, 10 times of lead acid battery
	√Higher energy density (50–80 Wh/kg)	×High self-discharge (10% per month)
Lithium-ion	√High energy density (80–190 Wh/kg)	×Very high cost ($900–1300/kW h)
	√Very high efficiency 90–100%	×Life cycle severely shorten by deep discharge
	√Low self-discharge (1–3% per month)	×Require special overcharge protection circuit
Sodium	√High efficiency 85–92%	×Be heated in stand-by mode at 325 °C
Sulphur (NaS)	√High energy density (100 Wh/kg)	
	√No degradation fo deep charge	
	√No self-discharge	
Flow battery	√Independent energy and power ratings	×Medium energy density (40–70 Wh/kg)
	√Long service life (10,000 cycles)	
	√No degradation for deep charge	
	√Negligible self-discharge	

After doing extensive research on electric circuits in renewable energy technologies, from solar to wind to large-scale wave, I came across the work of Muller, Diecke, and de Doncker (2002) using a circuit called a doubly fed induction generator which is used to decouple control of active and reactive power (the power input and output) in wind turbines. A doubly fed generator allows the circuit to run at generator speeds above or below their natural speed, protecting from under/over voltage and under/over frequency (Atwa, 2019). This protects the power output from being damaged by overcurrent that could surge through the circuit when a wave produces surplus energy that the battery is not able to fully regulate (Wang, Kang, & Ren, 2016). A doubly fed induction generator consists of two AC/DC converters as well as a capacitor in between the two converters. A set of inverters can also be used to regulate over/under current and frequency, but inverters are much more costly than the components needed for the doubly fed induction generator.

That being said, AC/DC converters can still be quite costly, so I decided to build my own AC/DC converter circuit that can be assembled with simple and common circuit parts. Using my knowledge of electronics, I designed an AC/DC converter circuit.

All electrical circuits were designed first by many sketch iterations followed by final circuit diagrams created using Circuit Diagram, a free online circuit schematic builder.

Ethics

All works and information that were used in the design and writing process of this project have been correctly referenced and cited. All uncited work is my own.

Results

Mechanical Model

Figure 9 is the final mechanical design of this wave energy device. The buoy moves up and down with the heaving motion of the waves, moving the attached metal rod and magnet along with it. A spring is attached to the magnet to dampen the wave motion and prevent any internal damage in the event of a large wave. The heave plate (flat and circular in shape) remains essentially static as the buoy oscillates with the waves. The static heave plate keeps the attached casing and solenoid in place as the magnet moves within the device.

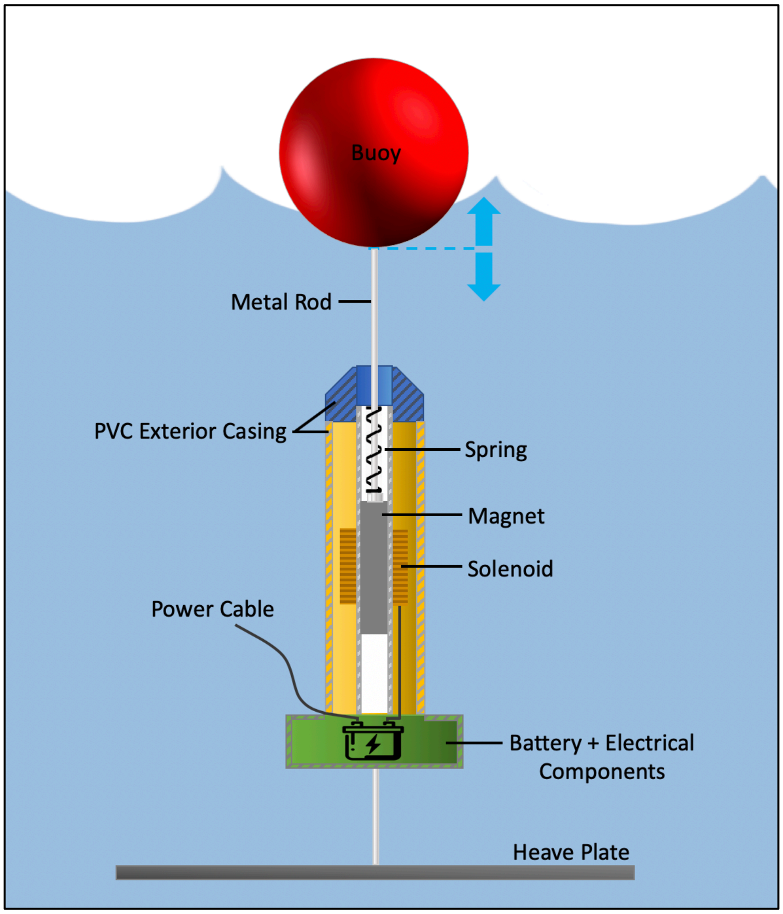

Figure 9. Final mechanical design of wave energy device.

Figure 10 demonstrates the motion of the mechanical design through one wave cycle. As the wave passes through the device, the buoy and magnet change height along with the wave heave while the rest of the device stays relatively stationary thanks to the heave plate.

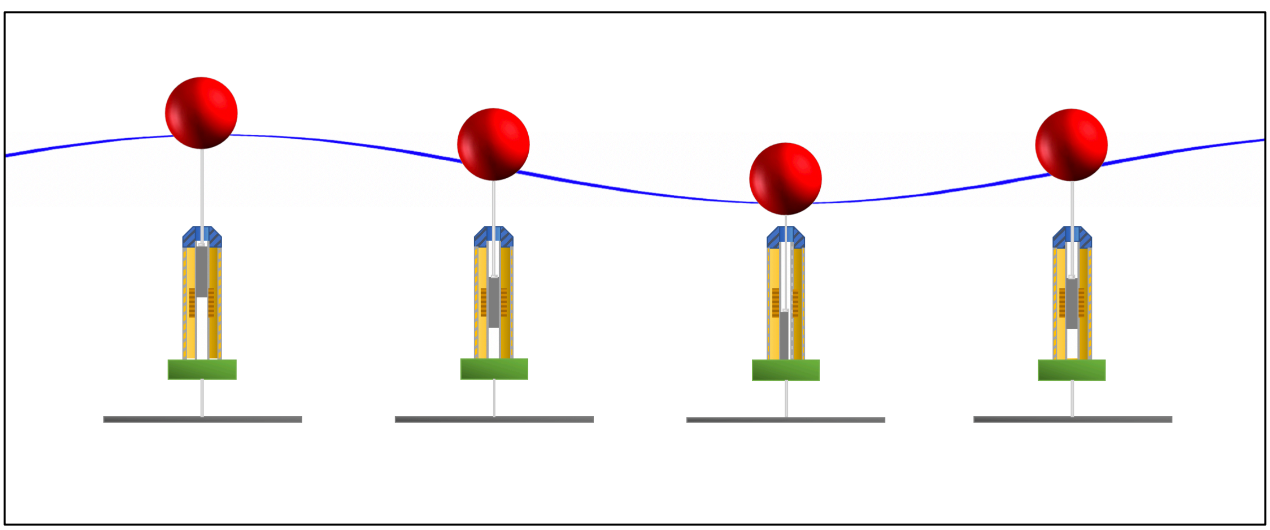

Figure 10. Motion of wave energy device through one wave cycle.

Electrical Model

Figure 11 below is a circuit diagram showing how the wave energy converter (represented by the AC power source) will be connected to the lead-acid battery using a maximum power point tracking (MPPT) charger. The MPPT charger manages the power being fed into and extracted from the battery when the AC power source is variable. The doubly fed induction generator protects the power output from overcurrent events. The capacitances of the three capacitors in the doubly fed induction generator can be varied based on the average AC input power and the desired DC output power (based on the type of ocean sensor being powered).

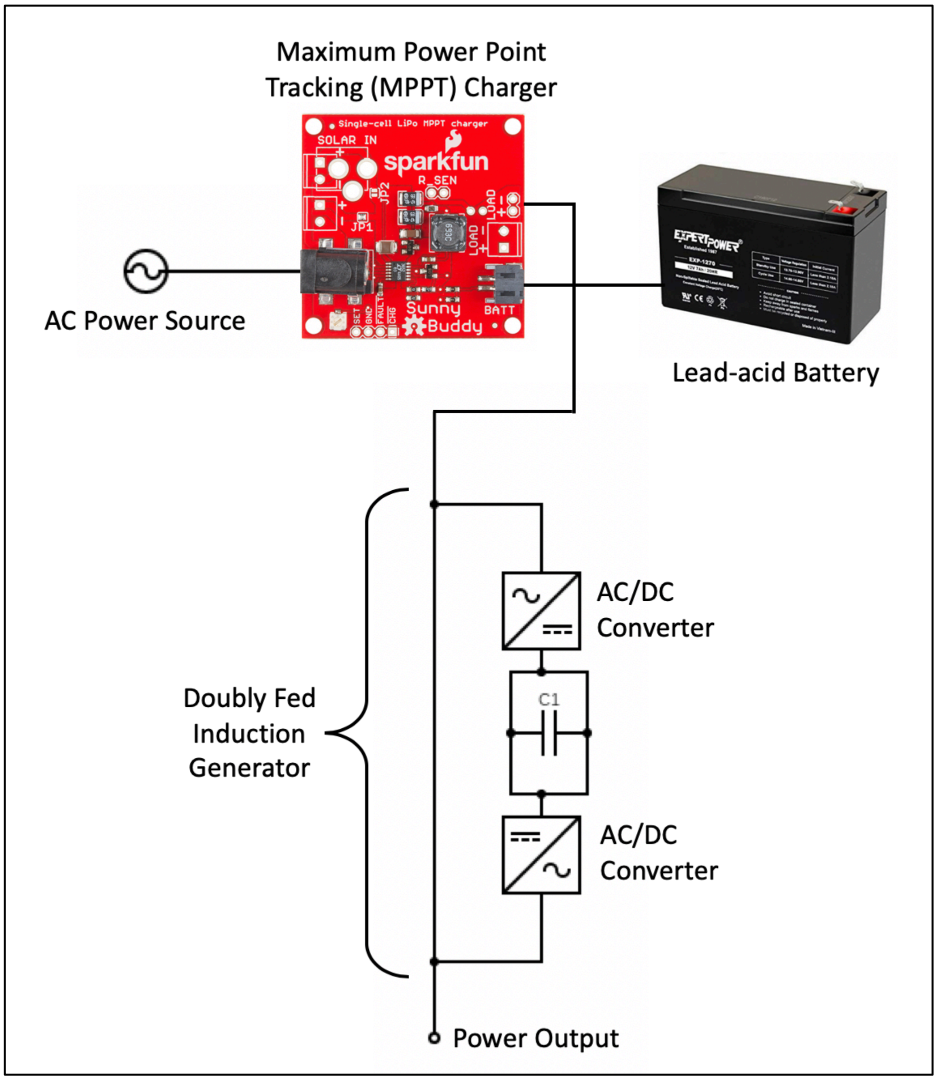

Figure 11. Overall circuit diagram of wave energy conversion device.

As AC/DC converters are quite expensive, I designed an AC/DC converter from simple, cheap electrical components (Figure 12). The AC/DC converter circuit in Figure 12 will be inserted into the overall wave energy converter circuit in Figure 11 where there are currently symbols for an AC/DC converter unit. All of the electronic components will be housed in the watertight compartment below the linear electromagnetic generator (the green compartment in Figure 9). The final power cable with the power output to be fed into an ocean sensor will exit the watertight compartment and can attached and then secured to any ocean sensor configuration (Figure 9).

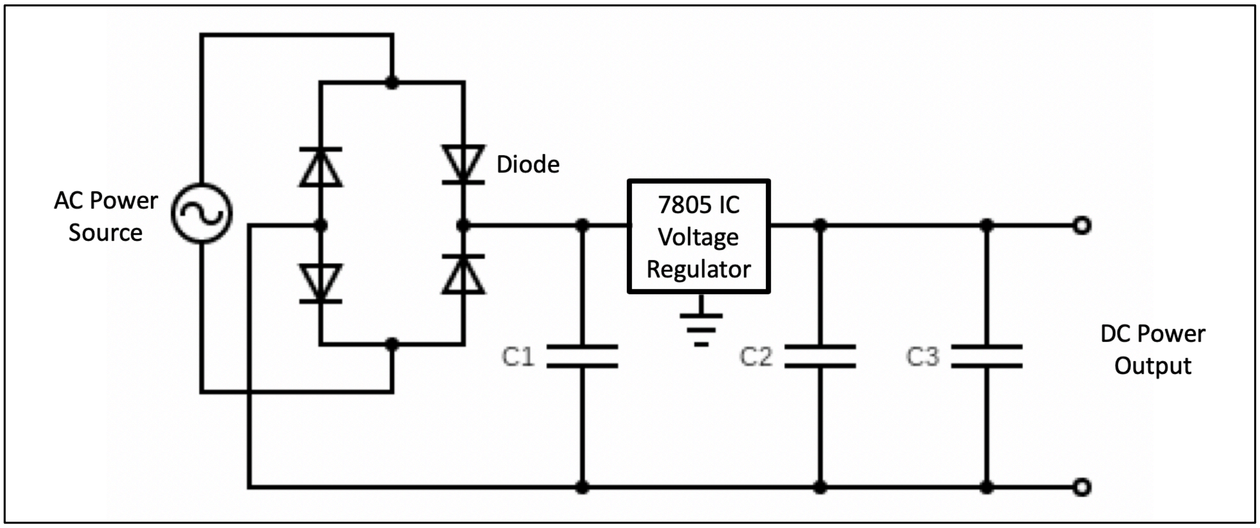

Figure 12. Circuit diagram from AC/DC converter circuit component.

Discussion

Overall, this design process took much longer than I had expected. I had expected to be able to build physical prototypes by the end of the five-week ISP period. Although this did not turn out to be feasible, I am still pleased with the final design of this wave energy converter. While I could have quickly designed a wave energy device and started prototyping for the sake of prototyping, I decided that I really wanted to be optimizing the design at every step in the design process. Having a well-researched and iterated design was more important to me than having a less thoughtfully designed physical prototype. This was difficult to decide at first, but ultimately I am pleased with the final design as it provides a very solid model for any future prototyping of this project.

As a next step, sketch models should be built of this design. Sketch models are simplified physical models made of cheap and readily available materials to test specific components or general mechanical components of a design. After multiple sketch model iterations, full prototypes with proper materials would be built to test different materials and confirm the mechanical integrity of the design beyond sketch models. The electrical circuit should be first built on a breadboard and tested with an oscilloscope, before being built in a prototype. I hope to be able to move forward with this project as it would be very interesting to see if these final models would succeed as physical prototypes.

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