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Varying Capacitance Machines for Marine Energy Systems Connected to HVDC Grids

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Electrical and Computer Engineering)

at the
University of Wisconsin-Madison
2024

Date of Final Oral Exam: 12/10/2024
The dissertation is approved by the following members of the Final Oral Committee:
Daniel C. Ludois, Professor, Electrical and Computer Engineering
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Line A. Roald, Associate Professor, Electrical and Computer Engineering
Lei Zhou, Assistant Professor, Mechanical Engineering

Chapter 7

Chapter for the Public

> *Truth is ever to be found in the simplicity, and not in the multiplicity and confusion of things.*
>
> — Isaac Newton

I am including this chapter in my dissertation to communicate my research to the general public. In my opinion, making research comprehensible for people of all backgrounds is just as important as mastering the technical intricacies of any field. I would like to thank the Wisconsin Initiative for Science Literacy (WISL), including Bassam Shakhashiri, Cayce Osborne, and Elizabeth Reynolds, for providing this opportunity to communicate my work to a broader audience.

7.1 Harnessing energy from the oceans

If you've ever been on a road trip through rural areas (especially in the Midwest), you've probably seen wind turbines dotting the landscape with their white towers and sleek blades. For the past 20 years, not only have we been harnessing the power of the wind on land, but we have also been tapping into wind energy from the oceans, known as "offshore wind". In addition to being out of sight from the public eye, offshore wind turbines can generate more power than land-based turbines, since the winds are typically stronger and more consistent over the open ocean. Scientists are also working to harness other sources of energy from the oceans, including from tides, waves, and currents. While all of these sources of ocean energy are plentiful and promising for the clean energy transition, sending the electricity from the ocean to where it will be used onshore is a huge barrier to utilizing ocean energy. As such, my research is focused on developing new technologies that make it simpler and cheaper to transmit electricity for ocean energy systems.

7.2 Basics of ocean energy systems

The raw energy of the oceans is astounding. While it is difficult to pinpoint an exact number on just how much energy there is, scientists agree that ocean-derived energy could satisfy the global demand for electricity.

One of the most attractive aspects of ocean energy is its proximity to population centers. Nearly 75% of the world's population lives within 50 km of the ocean, meaning that electricity could be generated right where it is needed. Utilizing ocean energy could avoid costly upgrades to the power grid that are often necessary for integrating other sources of energy, such as solar and wind. These upgrades are not trivial, as solar and wind farms tend to be located in remote areas, necessitating extensive networks of new power lines and other grid infrastructure to be built.

Another key advantage of ocean energy is its predictability and 24-hr. availability. Because solar and wind energy are not constant, batteries and other energy storage technologies are necessary for integrating higher levels of these resources into the electric grid. In contrast, energy sources within the oceans (such as waves, tides, and currents) are not random processes and can be relied upon for consistent energy delivery.

Despite these advantages, however, harnessing ocean energy is significantly more challenging than solar or onshore wind energy. To understand why, I will provide a little background on how electricity is generated and transmitted and how it is different for ocean energy systems.

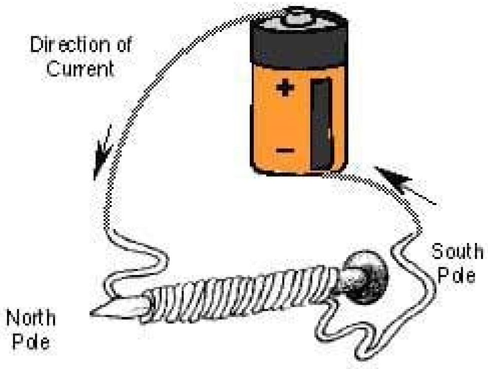

Figure 7.1: Example of an electromagnet, formed by wrapping a wire around a nail and connecting a battery to the ends of the wire. The current from the battery creates a magnetic field that allows the nail to pick up paperclips and other ferrous (iron-containing) objects.

7.2.1 Generation

Generating electricity always begins with the resource(s) supplying the raw energy, which in the case of ocean energy originates from the tides, waves, winds, or currents. From here, this raw energy must somehow be captured by a device before it can be converted into electricity. For the case of wind energy, turbine blades are the most effective way to capture the raw wind energy. For the other forms of ocean energy, scientists are still trying to figure out the best way to capture the raw energy. Many unique (and sometimes quirky) systems have been proposed, including buoys, flexible membranes, and even sea snakes! Designing these systems is typically the work of mechanical engineers, civil engineers, and naval engineers, and was not the focus of my PhD.

Regardless of how the raw energy is captured, it eventually has to find its way to an electric generator. Nearly all electricity around the world is generated in the same fundamental way (solar energy is the key exception): Kinetic energy (or energy of motion) from some raw energy source is used to spin a magnet within a coil of wire. These magnets can either be permanent magnets (think of the ones on your fridge or a bar magnet) or electromagnets (caused by running current through a coil of wire, see Fig. 7.1 for a common example).

In offshore wind, permanent magnets are the preferred choice because they offer a higher power density than electromagnets, allowing more energy to be converted into electricity. However, these gains in power density come at a price. The permanent magnets used in wind turbines (and other high-performance applications) require several rare-earth materials (such as Neodymium and Dysprosium) and advanced refining techniques. Mining these raw minerals incurs serious ecological damage to the surrounding area and is often done with forced labor and other unethical labor practices. Furthermore, only a small percentage of these magnets are mined and refined in the US, with the vast majority being sold by Chinese companies, adding to geopolitical tensions between the two countries.

In any case, the electricity generated by the interaction of these magnetic fields is not ready to be transmitted to the electric grid because a fundamental law of physics says the electricity will be at a low voltage. This fundamental law – Faraday's Law – basically says that spinning the magnet within the coil of wire produces a voltage that is proportional to two things: how fast the magnet is spun and the strength of the magnet. You can imagine that the rotational speed has a physical limit—even if we could make turbines spin faster, doing so increases the risk of damaging components from vibrations and mechanical failures. Magnet strength is also limited because magnetic materials saturate, just like how there is a limit to how much water a sponge can hold. Taken together, the physical limitations on rotational speed and magnet strength ensure that the voltage produced by electric generators is low. But why does this matter for electricity transmission?

7.2.2 Transmission

Back in the 1800s, people figured out that the most economically viable way to transmit electricity was to use high voltages. The reason for this is that raising the voltage lowered the current of the electricity that you needed to send to have the same amount of power (since Power = Voltage x Current), and lowering the current meant reducing power losses (since Losses = Current^2 x Resistance of Wire). Think of current as the flow rate of water in a pipe, voltage as the water pressure, and the wires through which the current is conducted as the pipe. Inside of the pipe, there is some amount of roughness (corresponding to resistance) causing friction with water that ultimately creates heat and wastes energy.

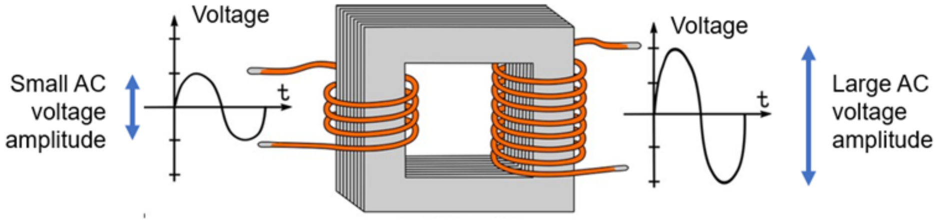

Figure 7.2: Cartoon of what transformers look like

If there is more water flowing through the pipe, there will be more energy wasted.

So, if the generators produce low-voltage electricity and high voltages are needed for transmission, how do we make the electricity high voltage? This question plagued scientists for years until the invention of the transformer in the late 1800s (yes, the same transformer on a utility pole in your neighborhood). Scientists figured out that low voltages could be stepped up to higher voltages if the electricity from the generator was run through a coil of wire with a low number of "turns" that was adjacent to another coil of wire with a high number of "turns" (see Fig. 7.2). The new voltage would be scaled by the ratio of the turns of each coil and worked best if the coils shared a common ferrous material (such as iron), since the coupling between the two coils relies on the magnetic field produced by the electricity in each coil. In fact, it is the advent of transformers that was the nail in the coffin for Thomas Edison's vision to use direct current (DC) in the power grid. When the electrons all move in one direction (DC), transformers cannot be used because the only way to create the magnetic fields that couple the two coils in the transformer is to force the electrons to wiggle (hence, alternating currents or AC). Thus, George Westinghouse (and Nikola Tesla) emerged as the clear victors in the so-called "War of the Currents" with the AC grid, since they could unlock high voltages with transformers. There's a pretty good movie with Benedict Cumberbatch portraying Thomas Edison in "The Current War" if you want a more dramatized and less technical version of this history.

The same efficiency advantages with high voltages hold true for transmitting electricity from ocean energy systems to land but with an important caveat: DC is actually better than AC! While this may seem counterintuitive since AC is used for transmitting power on

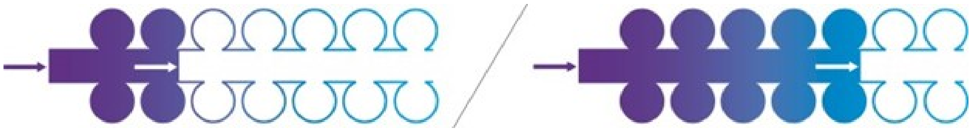

Figure 7.3: Analogy of water flowing through a pipe with "pockets" to explain charging currents in cable-based transmission, from [46]

land, a crucial difference between onshore and offshore power transmission is the medium through which the electricity is transmitted. On land, we primarily use bare overhead wires. In the ocean (and underground), we use cables. This difference may seem subtle and negligible but is actually quite significant. Because cables are essentially wires wrapped in layers of plastic and other insulating materials, some of the electric charges that would otherwise travel straight through a bare wire are trapped by the insulating layers of the cable. This phenomenon is known as "charging current" and is due to capacitive coupling within the cable. A simple way to understand this is to think of a hose with little pockets (see Fig. 7.3). In order for water to travel from one end to the other, these little pockets must first be filled with water. If these pockets must only be filled once (aka DC), it is not a big deal, but if they must be filled and emptied over and over again (aka AC), this becomes problematic. This effect is especially acute as the length of the hose increases. As a result, high voltage DC is the preferred technology choice in offshore energy systems, and AC is only feasible if the underwater transmission distance is short (usually 50 km or less).

So how do we go from AC to DC? In Thomas Edison's time, converting the generator's AC to DC for transmission was not technically feasible because semiconductors were not yet invented. Once semiconductor devices like diodes and transistors (like what you have in computers) became available in the 1950s, a new industry known as power electronics emerged. In addition to making AC to DC converters for renewable energy systems, the power electronics industry makes converters for laptop chargers, electric vehicles, and many other everyday systems. While laptop chargers fit in the palm of your hand and can be purchased for $20 on Amazon, the AC to DC converters (known as "rectifiers") used in offshore wind are around the size of an aircraft carrier and cost more than a billion

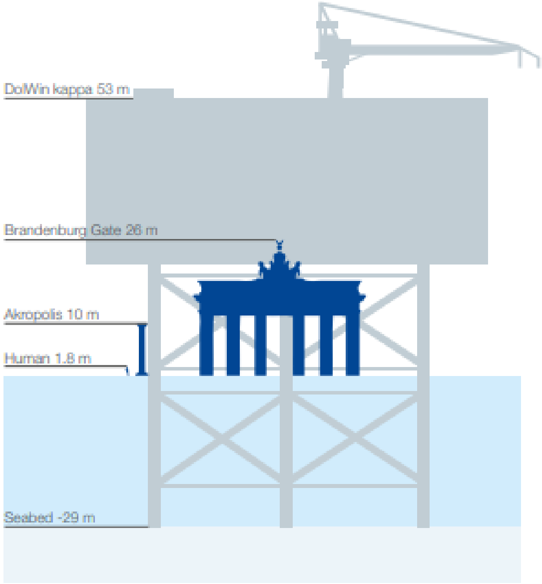

Figure 7.4: Illustration of just how large offshore converter stations are in offshore wind farms, from [43]. For those of you from Madison, the height of this structure from the sea floor to the top is almost as tall as the State Capitol from the ground to the top of Lady Wisconsin (86 m)!

dollars (see Fig. 7.4). These astronomical figures stem not only from the sheer amount of hardware needed to facilitate the AC to DC conversion but having to install everything in the open ocean makes the task significantly more challenging.

7.2.3 Layout of offshore wind systems

Now that you know how electricity is generated and transmitted, you can understand why offshore wind farms look the way they do. Fig. 7.5 shows an example of an offshore wind farm using high voltage DC transmission (HVDC), but I should mention that this layout would also apply to any other ocean energy system. Going from left to right, once electricity is generated by the turbines, it is stepped up to a higher voltage at the transformer station. While these transformer stations are not quite as large as the converter station platforms, they are still large, costly, and a pain point for offshore wind developers. From here, the electricity is converted to DC with the gargantuan converter station and sent onshore with DC cables. Finally, the converter station on land converts the electricity

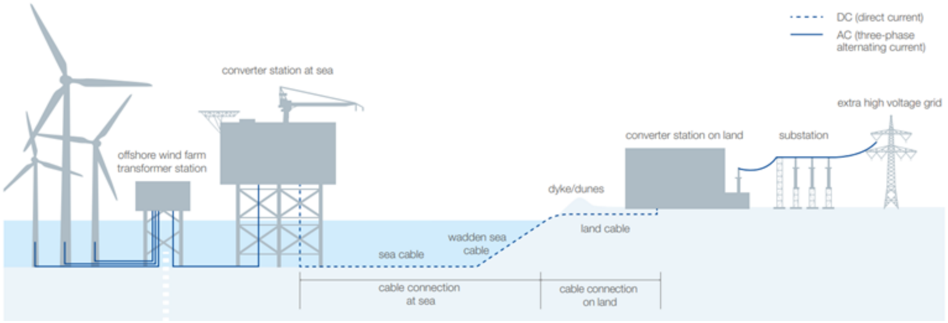

Figure 7.5: Layout of the DolWin offshore wind farm in the North Sea using HVDC transmission, from [43].

back to AC and sends it to the main grid (which uses AC).

Finding ways to simplify and reduce the infrastructure needed to connect offshore wind farms and future sources of ocean energy to the grid will allow more of these carbon-free resources to provide our electricity needs and serves as the basis of my research.

7.3 My research

Before I get into the details of my research, I'd like to start this section by mentioning that the path to my dissertation topic took many twists and turns. Research is often portrayed as a neat and tidy process where someone starts with an idea, works on it for a while, and eventually makes it work with some sweat and ingenuity, but this has not been my experience. Instead, my PhD research journey has been a reflection of my ups and downs in the lab, my own curiosity getting the better of me, and my advisor's seemingly inexhaustible supply of new (and sometimes crazy) ideas.

7.3.1 My research journey

I began my PhD with experience in power transmission engineering and an interest in all things related to the power grid and renewable energy but had very little background on the core areas of my advisor's research. My advisor is primarily interested in improving electric motors and renewable energy systems by applying electrostatics to these areas, rather than being confined to the conventional magnetic systems I described earlier. Although electrostatics is just the technical term for “static electricity” – just like when you shock yourself from touching a doorknob after rubbing your feet on the carpet – I came to learn that there is a lot more to it than that.

It turns out that there are two ways to convert kinetic energy into electricity: with magnetics and electrostatics. In the previous section, I described how spinning a magnet inside of a coil of wire produces voltages, which we call “magnetic systems” in our discipline. Another way to create electricity is to simply use kinetic energy to move electrically charged objects (such as capacitors) relative to one another. As these charged objects move, the charge distribution within the objects feels pushing and pulling from the other object’s charges, creating currents. Historically, these “electrostatic systems” have not played a major role in generating electricity because magnetic systems have satisfied our electricity needs for the past 150 years. However, as we look to expand into new domains, such as ocean energy, we may need to break from tradition and embrace electrostatic systems.

Why should we look at electrostatic systems? I came to learn that they have three key benefits over magnet systems:

1. Electrostatic systems have much lower materials requirements than magnetic systems. They do not require any rare earth materials and are primarily constructed from lightweight and abundant materials, such as plastics and aluminum. An easy way to internalize this is to think about what it takes to make magnetic forces vs. electric forces with household items: For magnetic forces, you either need a permanent magnet (could be fridge or bar magnet) or an electromagnet, like the one I showed previously in Fig. 7.1. For electric forces, you can just rub a balloon on the carpet and start attracting things like hair and pieces of paper.

2. Electrostatic systems are naturally high voltage and low current, while magnetic systems are naturally low voltage and high current. In Section 7.2.1, I discussed how the limitations in rotational speed and magnet strength ensure that the voltage

produced by magnetic systems is low. So, in order to attain higher power levels, high currents are desired, since power equals the product of current and voltage. Similarly, the rotational speed and electric field strength in electrostatic systems are limited, so the current they create will be limited, and thus high voltages are desired to boost power. One important ramification of electrostatic systems' tendency to be high voltage is that they could produce electricity that is ready for transmission without all of the infrastructure that is normally needed in magnetic systems (such as transformers).

3. Electrostatic systems tend to be more efficient at low-speed operation than magnetic systems. The reason for this is a bit nuanced but simple in principle. I mentioned in Section 7.2.2 that power losses depend on the amount of current flow, just like how more water flowing through a rough pipe will waste more energy. In magnetic systems, a large amount of current must flow and as the rotational speed decreases, a greater share of this current flow is generating heat and losses, rather than being used to generate electricity. Conversely, electrostatic systems do not rely on a large current flow to generate electricity, so even as the speed decreases, they will have negligible power losses—or so we thought (more on that later).

Bearing these advantages in mind, we thought that wave energy would be the perfect application of electrostatics because waves move incredibly slowly and previous efforts using conventional magnetic systems were largely unsuccessful due to these systems being so inefficient. On top of that, most wave energy systems reported in the literature required copious amounts of rare earth materials and were very heavy (one such system weighed 6,700 tons and only had the power capacity of a single wind turbine, which weighs less than 200 tons!!). In what turned into the first two years of my PhD, I learned that even electrostatic systems were no match for the waves, as the systems I prototyped and tested in the lab either did not work at all, led to unexpected and useless outcomes, or were less efficient and less power dense than other scientists' magnetic systems. I won't go into detail here since I want to focus on my later work, but you can read more and see pictures

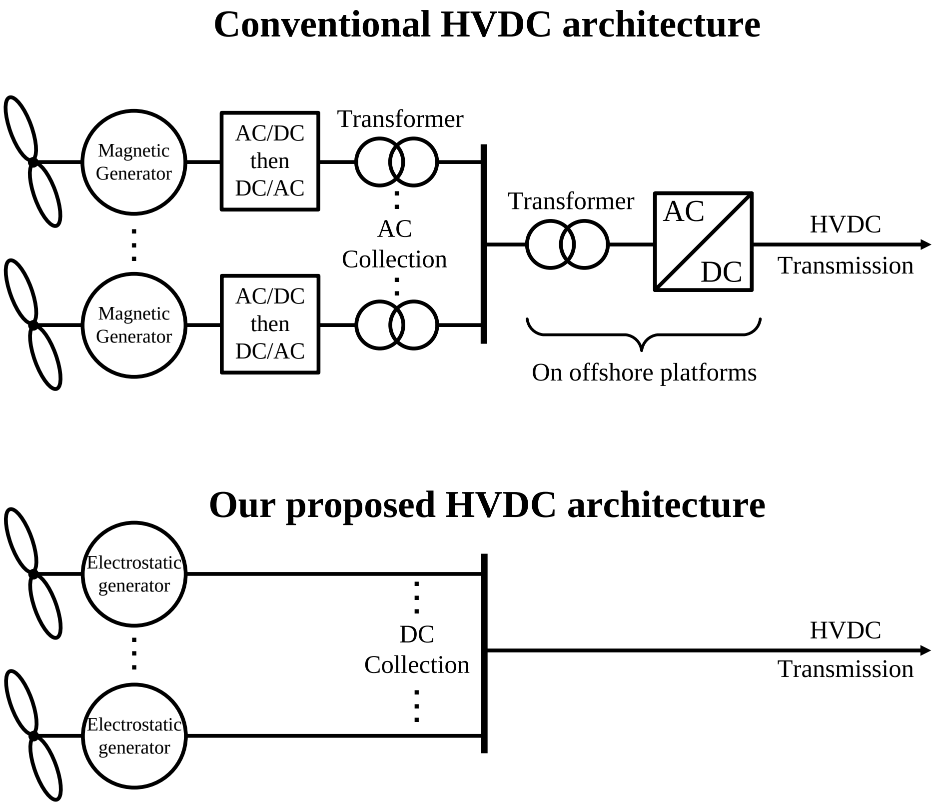

Figure 7.6: Comparison of conventional HVDC system architectures that use magnetic generators vs. our proposed HVDC architecture using electrostatic generators

of my contraptions in the Appendix.

7.3.2 My dissertation experiments

Since we did not have much luck with exploiting the efficiency of electrostatic systems at low speeds, we decided to instead explore the idea of generating electricity that was "ready" for transmission (advantage #2 that I listed above). More specifically, we wanted to develop an electrostatics-based architecture for renewable energy systems that requires HVDC transmission, which encompasses anything offshore. As I mentioned in the first few Sections, current HVDC transmission technologies are complex and costly, posing a significant hurdle to utilizing offshore energy resources. Our aim was to simplify the hardware requirements for HVDC transmission by using electrostatic generators to produce the electricity, see Fig. 7.6.

There was some existing research that helped guide us towards solutions with a greater chance of success, but we were otherwise proposing things that had never been tested before. The basic idea behind our approach was as follows:

- Use wind turbines, tidal turbines, wave buoys, or any other source of raw ocean energy to drive several electrostatic generators connected to each other with a common shaft. Each generator would operate at a high voltage and would be constructed exclusively out of aluminum and plastic.
- Use the simplest of semiconductor devices (diodes) to convert each individual generator's AC output to DC.
- Combine all of the generator's outputs so that the output voltage of the whole system equals the sum of each individual generator's output voltage. The goal is to have the output voltage of the whole system be large enough for HVDC transmission (100,000 volts or more).

To see if our proposal would work, we had to first describe it mathematically (which resulted in many hours spent deriving equations, see Chapter 3) and then run experiments on a small-scale system to see if our results matched our mathematical model. If the experimental results matched what the math predicted, we could then extrapolate our results to larger systems with confidence.

Although Chapter 4 already describes all of the experiments in detail, I want to include an abbreviated version to highlight some important things. We first contacted a local prototyping company to build us custom prototypes of our generators. Once we received the prototypes, we connected a servo motor to one of the generator's shafts and connected the shafts of each generator to each other. The servo motor simulated the raw energy that would drive our generators. I also had to construct a subsystem for providing high voltages to the generators. I won't go into the details on this (you can see pictures of it in Chapter 4), but it was able to take the 120 volts AC from the wall outlet and bring it up to 5000 volts DC for each generator! Because the generators would be spinning quickly

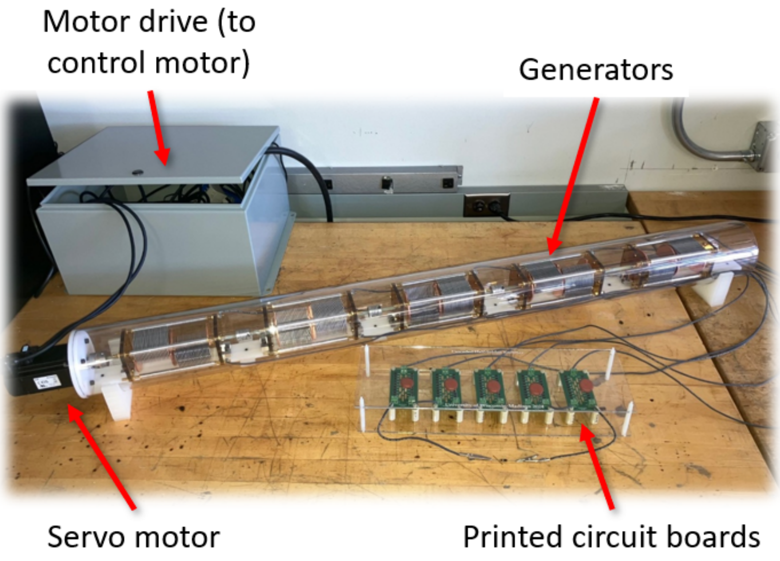

Figure 7.7: Picture of my experimental setup. On the far left is the servo motor that drives each generator contained within the plastic tube. The green printed circuit boards are the AC to DC converters, and there are five in total, since we had five generators.

and would be at a high voltage, we put them inside of a protective plastic tube. Because it was also see-through, it had the added benefit of looking cool (see Fig. 7.7). Finally, I had to build printed circuit boards (the green things in Fig. 7.7 — these are like computer chips and are found in almost every household electronic device) to house all of the diodes and other electronics that would facilitate the AC to DC transmission for each generator's output.

After running several experiments where I changed different input parameters and recorded their effect on the outputs, we concluded that our mathematical model was representative of the true physical system we tested. In light of the unsuccessful experience we had with our wave energy systems, this was a huge relief.

The next logical step was to see how we could improve our system, which meant finding ways to increase the power density. The low-hanging fruit solution was to optimize the geometry of the generator, since we knew that the original prototype was not optimal. I used a computer simulation tool to determine what the output power for different designs would look like. In order to facilitate as fair of a comparison as possible, I kept all of the physical dimensions (height, width, thickness, etc.) of the new design equal to the previous prototype's. You can see a comparison of the two designs in Fig. 4.5 and Fig. 4.18.

Over the course of six months, which spanned the initial design process of the new generators to repeating the same experiments I did with the previous generators, we were able to triple the power density with our new design! The previous power density was 26 Watts per cubic meter, and the new power density was 79 Watts per cubic meter. To put these numbers in perspective, the magnetic-based generators used in offshore wind turbines typically have a power density greater than 100,000 Watts per cubic meter. However, if you include all of the infrastructure needed to make high voltage DC electricity offshore (e.g., the transformers, the aircraft-carrier-sized platform), the power density of the magnetic generators is drastically reduced, putting it close to the power density we achieved. Nonetheless, there is still room for improvement with our electrostatic system.

7.3.3 Outcomes of my research

The main contribution of my research was identifying and characterizing a system based on electrostatics that could make it easier to integrate ocean energy with our power grid—ultimately allowing another source of carbon-free energy to be part of our electricity mix. This electrostatics-based system would require substantially less infrastructure than current ocean energy systems and is constructed from sustainable and cost-effective materials.

While the system I proposed and tested in the lab is far from being commercially viable, I plan to continue working on it as a postdoctoral researcher at UW-Madison. My team entered a marine energy competition sponsored by the Department of Energy in the summer of 2023 and have progressed through Round I and Round II. As a post-doc, I will lead our involvement in Round III, hoping to secure more funding to bring our research to the next level! Regardless of the outcome of this competition, I hope that my research can serve as a foundation for future work in this vein and can inspire others.