Spring 2018

Understanding, Designing and Building a Hydroelectric Generator

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Senior Project Submitted to
The Division of Science, Mathematics and Computing
of Bard College

by
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Annandale-on-Hudson, New York
May 2018

Acknowledgements

A big thanks goes out to all of the following people, but especially to my advisor Matthew Deady and to Richard Murphy for all their help with my senior project.

Matt was extremely helpful when it came to understanding the complicated concepts within my project. He helped and reminded me of the physics I have learned over my four years and how to implement it in my project. He gave me explanations to the new ideas I was learning and didn't understand during my research. Had it not been for Matt, I would not have known the best ways to progress when I was stuck or to push further into concepts I was just touching the surface of. Our weekly meetings were illuminating and always left me with new information I hadn't come in with. Besides being my advisor, Matt has also been a great professor over the past four years. Matt, thank you very much for all you've taught me over the years and especially for all your help on my senior project. I really appreciate all the time you've taken to help me grow as a student and keep me working hard to always do the best I can. I'll surely miss all of our sports talks after our work was done. I think you've managed to make me a Celtics fan by now!

Richard was also extremely helpful but in a different kind of way. I met with Richard for the first time towards the end of the first semester, coming into his office with my half formed ideas and just a bit of knowledge. Guiding me with skills and experience, Richard helped me to refine my ideas into concrete designs. He taught me how to use new complex machines like the lathe and the milling machine, always providing just enough assistance for me to understand what I was doing, but making sure I was the one actually doing the work. When I had a new idea, we always talked about it, allowing me the chance to explain what I meant and what I wanted to happen. This not only helped in completely forming basic designs but also my explanations of them when I got down to writing my project. So often in today's society, why we do each little step gets overlooked, but understanding all of our actions is important in building new technology as well as just in life. Thank you for teaching me that. When it finally came down to testing, Richard was my second pair of hands with lifting and setting up at the Creek as well as providing me with the tools and devices I needed to collect my data. Richard, thank you very much for all your energy and interest into my project, your passion helped to fuel my own even when things didn't work out, you always seem to have another angle to view things. Your help on my project as well as your optimism are greatly appreciated and something I hope to be able to hold onto in my life too.

Additionally, I couldn't get to where I am today without the help of my parents and sister who have supported me throughout my whole Bard experience. Through the thick and thin of life, I know I can always count on your love and support in everything I do. Thank you.

Finally, you can't go through life without friends and I have made some of the best here at Bard. Avalon thank you for always being there for me when I need it. Emily and Elena, you two are both great friends with so much love and wisdom to share with the world. I hope the four of us remain as close for the rest of our lives. I've met too many great friends at Bard to mention them all, but each one has shaped me in their own way and I thank you all for that. I can't wait to see where we all end up in the future.

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Introduction to Hydropower

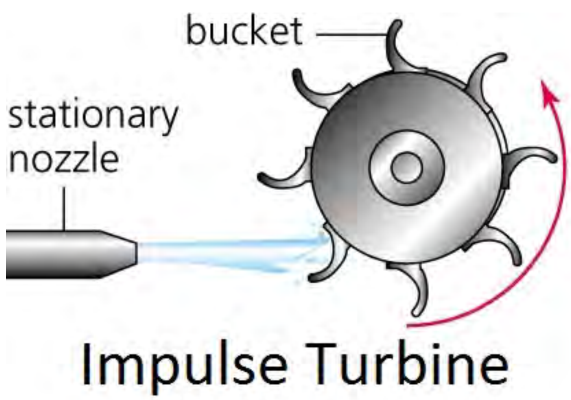
Hydropower or hydroelectric power is the process of producing electricity utilizing the power of water. Water can move fast or slow, there can be a lot of it or a small amount. Utilizing waterpower to create a maximum amount of electricity differs depending on your system. In terms of a hydroelectric generator this means, figuring out a location for a generator and seeing how the water in that location could best generate energy.

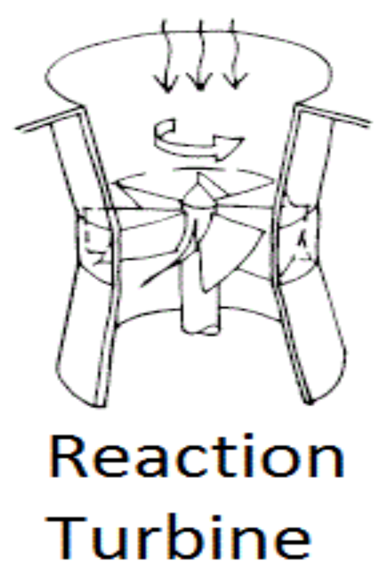
To determine these types of things in a system it is often efficient to make use of the terms flow or flow rate and head. Flow is how much water passes through a location given a period of time (volume over a given time). With greater amounts of water, like in rivers and oceans, the movement of the water over time is much greater since there is so much more water in general. Streams and creeks often have much less water traveling through them and while it can be moving at high or low speeds, the general amount of water (given a specific location and over a time period) is less. The other important factor in a water source is called head. Head essentially is the water levels over a certain distance or the height that the water travels. In a river the heads are generally very low, as the water level doesn't drop much over a distance. Places with high heads are waterfalls or dams, where water is falling a significant distance over a short amount of time. High heads correspond to high distances, just as large amounts of fast moving water correspond to high flow rates. These two factors influence the different types of water turbines that are made to produce electricity and they are two ideas I needed to understand in order to make the decision about what turbine I should use for my generator.

I began looking into hydro turbines to discover what might be the best system to implement in my situation. That also meant that I had to come to the conclusion of what my situation was, or in other words where was I going to place my hydroelectric generator.

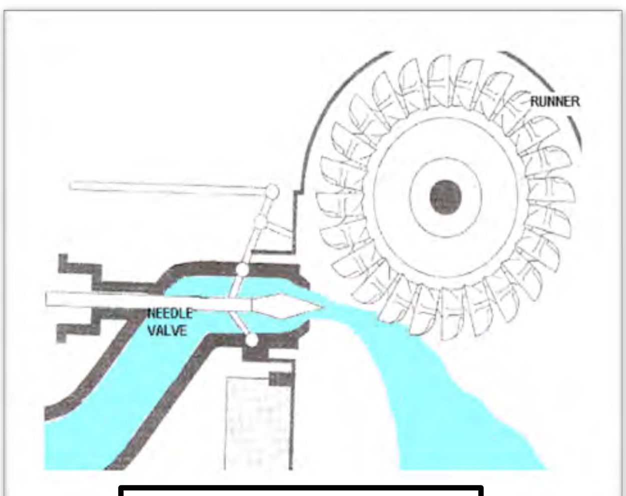
Hydro-Turbines:

A hydro or water turbine is a rotary device that takes the potential and kinetic energies of running water and converts it in mechanical work. There are two main types of hydro turbines, impulse and reaction. An impulse turbine is a system that channels water and directs it into a blade, bucket or runner, moving the runner by a collision with the water. Impulse turbines are made for high head situations, where water travels far distances and gains potential energy. It then is channeled into a nozzle which converts the potential energy into kinetic. The nozzle sprays the water at a blade, runner or bucket on the turbine. The collision between the runner and the water, transfers the kinetic energy of the water to the blades causing the mechanism to spin and generate energy in the form of mechanical work. Depending upon the set up of a generator the spinning of the turbine will drive the rotation of magnets around coils which will create the electricity as a result of the water. On the other hand, a reaction turbine is a system that relies on a combination of pressure and moving water. Here, the turbine is placed directly in the body of water so that instead of hitting each runner individually, the water flows over all the runners at once. The differences in water pressure between the front and the back of the runners allow them to move and convert kinetic energy into mechanical work.

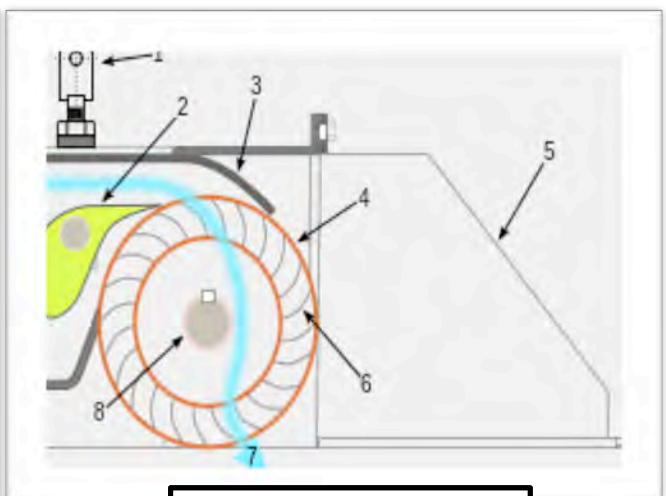




For all impulse turbines, the goal is to implement them in a location, which has some type of head, or distance that the water falls before it enters the turbine. Knowing that, I'll assume that the water's energy has already been turned from potential into kinetic before it goes through the turbines. There then are two main types of impulse turbines, the pelton wheel and the cross-flow turbine. The pelton wheel turbine is the most common impulse turbine and is where water gets jetted through speed vets into buckets on a wheel. The process transfers the kinetic energy of the water into kinetic energy that spins the wheel after a collision with the water. This process then consequently generates work. In the cross-flow turbine, water is jetted through at a much slower speed so that the water passes through the top of the turbine and then flows through the middle of the turbine, passing through the blades again at the bottom. The water flows first outwards to inwards and then inwards back out on the second pass. Cross-flow turbines were developed to accommodate water that has a higher flow rate or moves more water faster than that of a situation for a pelton turbine. Impulse turbines in general, are well suited for high head situations, where water can collect a large amount of potential energy in the distance it falls that way the kinetic energy that gets transferred to the turbines is as high as possible.



Pelton Wheel Turbine

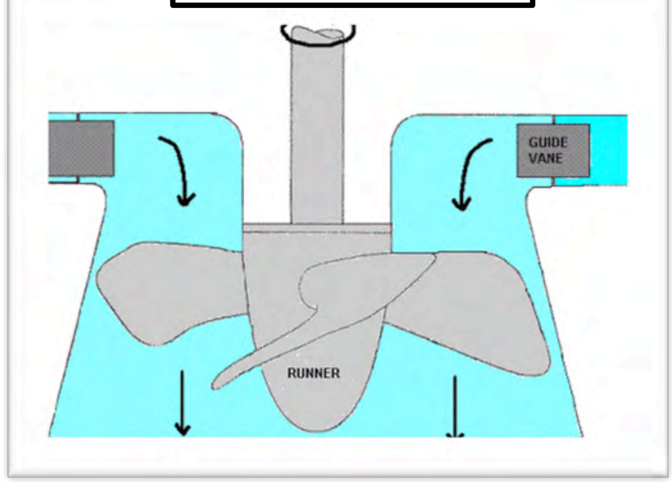


Cross-Flow Turbine

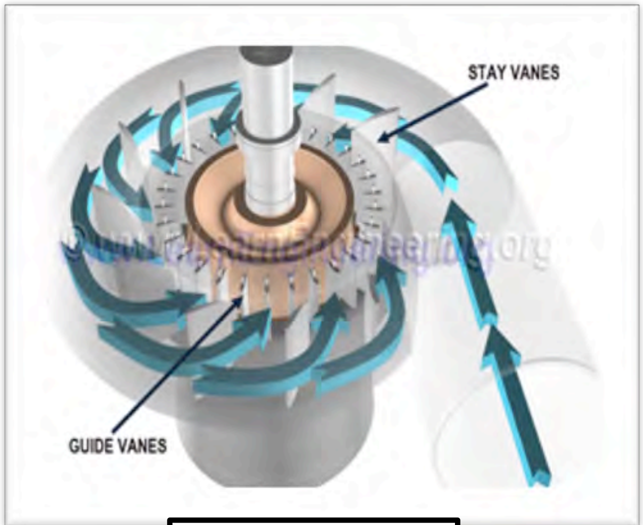
Reaction turbines on the other hand, are quite opposite of impulse turbines. They are nearly all meant for high flow rates and either little or no head so that there is no potential energy added to the kinetic, but instead the kinetic energy from the flow is higher. There are three main types of reaction turbines, a propeller turbine, the Francis turbine and the kinetic turbine.

A propeller turbine is a turbine that has anywhere from three to six blades which are all in constant contact with water. A propeller turbine is essentially like the propeller of a boat but put upright inside of a pipe with a constant flow of water. The propeller is always emerged in water so that the pressure inside the pipe is constant. The propeller moves just like any other reaction turbine; by the differences in pressure on the upper and lower sides of the blades. The top having greater pressure causes the propeller to get pushed and spin. The greater the water flow, the greater the pressure and the faster the turbine can spin.

Propeller Turbine

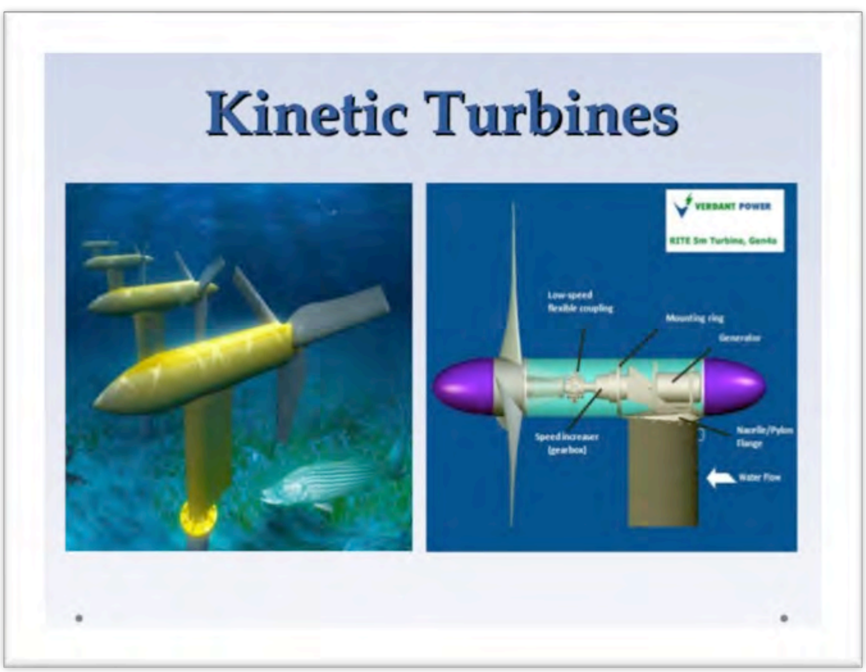


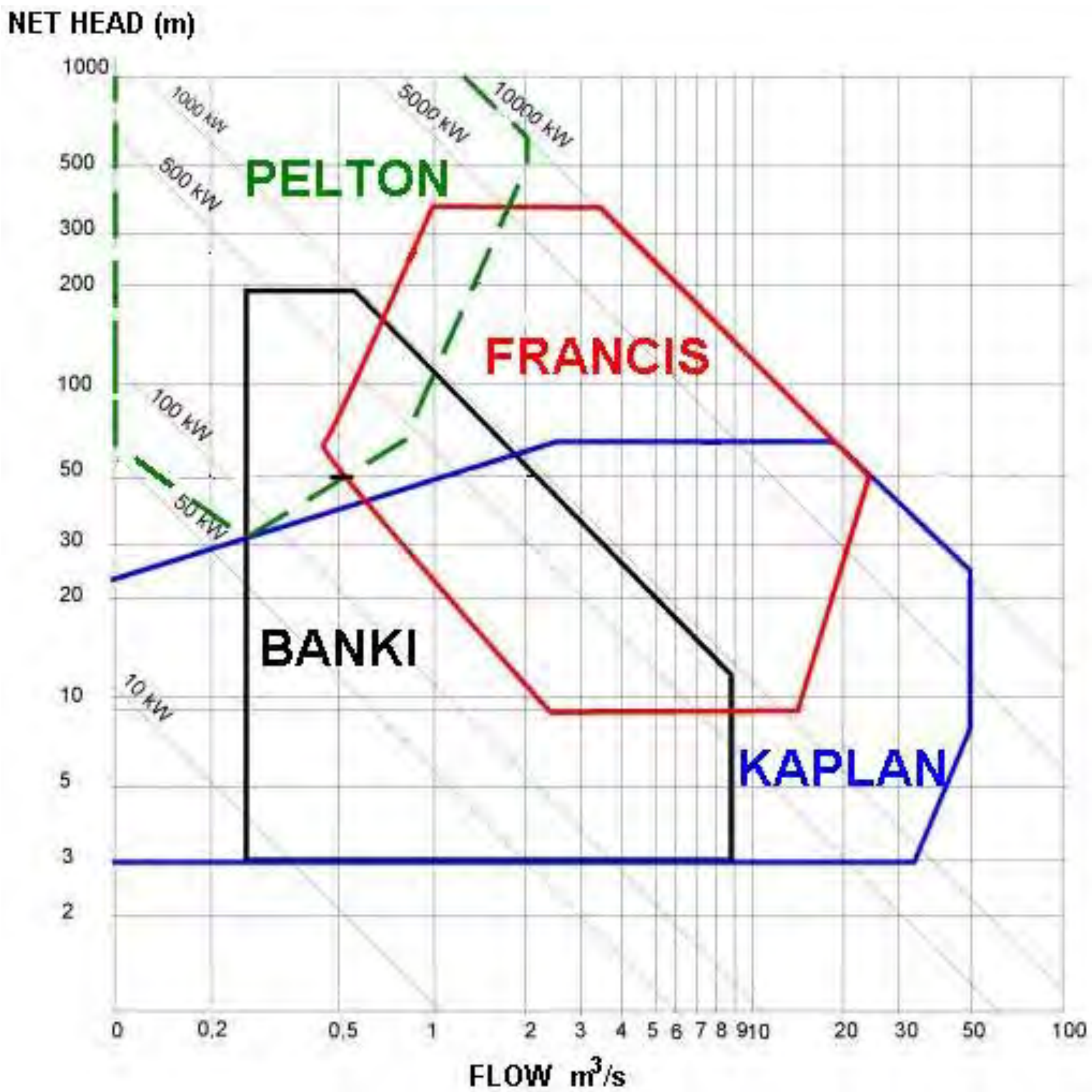
The second type of reaction turbine is the Francis turbine. This turbine has stationary buckets or vanes that are attached to the runner. The water flows in a large pipe around the vanes and forces the runner to spin. Again this is through differences in pressure. There are larger and smaller sets of vanes that are either meant to guide the water or propel the runner to spin. The spinning generates the kinetic energy that gets converted to work.



Francis Turbine

Finally, the last reaction turbine is a kinetic turbine, which basically resembles an underwater windmill. It looks exactly like a windmill, but goes underneath the water's surface in rivers, large streams or other man made water sources and sometimes even oceans. The kinetic turbine uses the flow of the natural water source to turn blades of the turbine (again based on differences in pressure) and change the kinetic energy of the water into work.





Pictured here is a comparison graph of flow rate vs. head, which shows the best ranges of each turbine. The Banki turbine is just another name for the cross-flow turbine, while the Kaplan is just the most common propeller turbine. From the graph, you can see how the flow and head rates are exactly what I've detailed out. The Pelton wheel and cross-flow (Banki) turbines in general are better for greater head and less flow, while the Francis and propeller (Kaplan) turbines are generally better with more flow and less head.

Location:

After discovering the different types of hydro turbines and what situations they work best in, I had to examine the different locations at Bard in which to apply my generator and then decide which turbine is best to use in my situation.

I knew that, I would need to implement my generator in the Sawkill Creek that is located next to Bard. The creek itself does not have a large amount of water in order to implement a reaction turbine, so I was left with choosing an impulse turbine and one of the two waterfalls to implement it.

Each of the two waterfalls was good in their own way. One is larger meaning that it has a greater head, but the other has a greater flow rate and is still decent sized. The ultimate decision in choosing one over the other was access. The smaller of the two falls was much more accessible and easier to implement piping alongside the falls and down to the generator. The bigger of the falls was much more difficult to get to and not as feasible to implement the generator so ultimately I had to go with the smaller one.

After measuring the falls, I determined the head to be approximately 15 feet or 5 meters. This is considered a low head situation and not ideal for an impulse turbine, but given that implementing a reaction turbine isn't doable, I have to make it work. Furthermore, deciding between the two impulse turbines the flow rate was higher and the head was lower making it more ideal for a cross-flow turbine. However, given these factors, it was more interesting to build a pelton wheel turbine and see how the lower head and higher flow rate impacted the energy outputs. Mainly the basic question I was looking to answer was given a set up that is not ideal for a pelton turbine, how much electricity am I still able to produce.

Designing the Generator

After beginning to understand hydropower and hydro turbines, it was time to turn to my own design of a generator. The next steps were to decide what aspects I wanted and needed in my design to produce power in my generator keeping in mine of course, that I'm using an impulse turbine in an improper setup. The two big focuses then became the electric part of the generator and a way to connect that part with my impulse turbine.

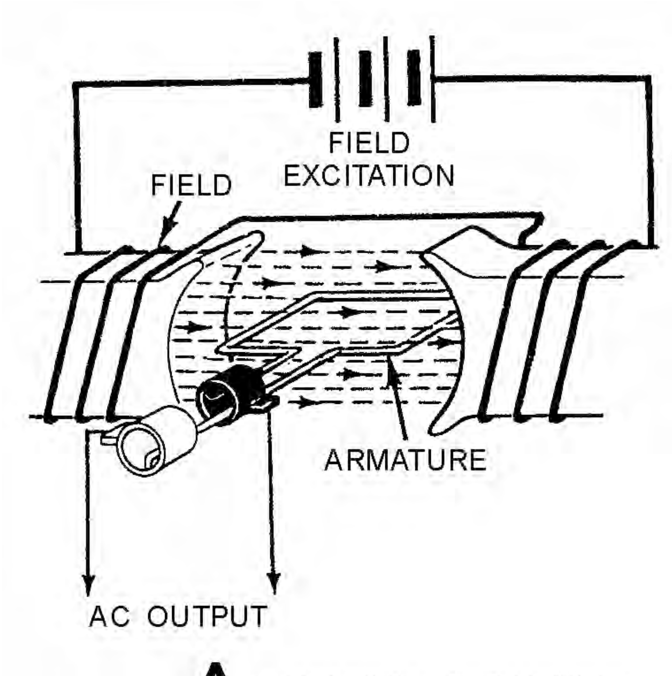
Electricity:

In order to create power in a generator you need to understand how a voltage and current are formed. This is illustrated by using Faradays Law which says: $\varepsilon = -N\frac{d\Phi_{\boldsymbol{B}}}{dt}$. In other words, the electromotive force (ε), which is another way of saying the voltage that is generated, is equal to the number of turns in a coil (N) multiplied by the change in magnetic flux ($\frac{d\Phi_{\boldsymbol{B}}}{dt}$). The change in magnetic flux is equal to the strength of the magnetic field multiplied by the area of the coil ($d\Phi_{\boldsymbol{B}} = \Delta\,(BA)$). So overall, this means to generate a voltage, you need a changing magnetic field over a period of time. The coils in a generator are used to capture that voltage and depending upon how the coils get connected will vary how much total voltage and total power you're able to produce.

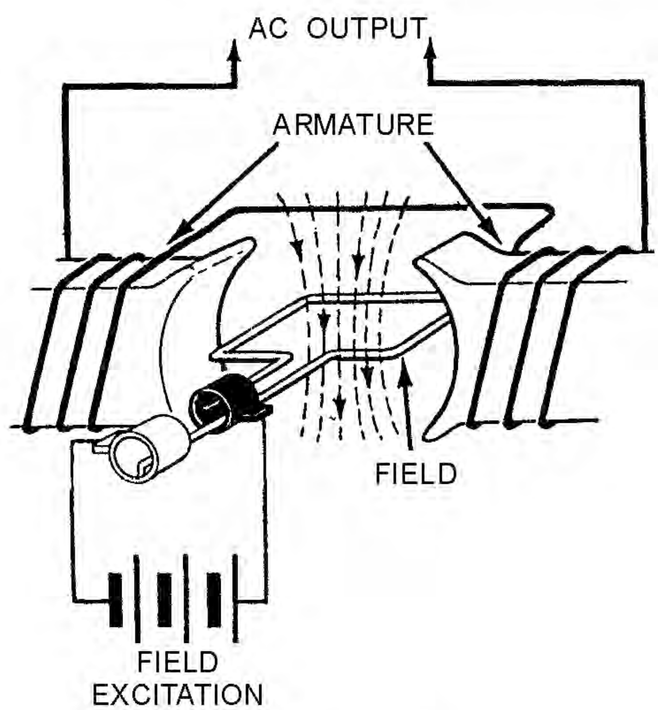
Now understanding how voltage is generated, there are two broad categories of generators, AC (alternating current) generators and DC (direct current) generators. The main difference in these two categories is the direction of the current that is created by the generators. For DC generators, the current flows in one direction only, whereas with AC generators the current constantly changes in direction; it alternates. Because of the alternating current, AC generators use a device called a commutator, which will allow the current to mimic a DC generator and have it travel in one direction also. There are two types of AC generators to explore, rotating-armature alternators and rotating-field alternators. As for DC generators, there is the shunt generator, the series generator and the compound generator. I'll explore each of these as possible ideas for my own generator design.

First up is the rotating-armature generator (**A**). This generator design consists of a rotating armature (a coil of wire in a loop shape) that rotates between two magnets. In this situation, the magnetic field that is generated by the fixed magnetics is constant. In addition, the area of the loop of coil is also constant. What causes the current to be generated is the change in orientation of the loop of wire over time. This generates an electromagnetic force (EMF) that is then fed through slip rings and brushes to what I am powering, often referred to as the lead. In addition this type of generator is easily transferrable to direct current if a commutator was to be connected to the armature.

The second generator is the rotating-field generator (**B**). In this design, the armature is stationary with the loop of wire fixed. This stationary armature is often referred to as a stator. The magnets then rotate around the stator creating a changing magnetic field that generates the EMF. Another difference between the rotating armature and this design is that here you do not need slip rings or brushes, you can just transfer current right into the lead. As with the rotating-armature generator, the rotating-field generator is easily transferrable to direct current if a commutator was to be connected.



A ROTATING ARMATURE ALTERNATOR



B ROTATING FIELD ALTERNATOR

Next there are also the DC generators, beginning first with the shunt generator. This generator does not consist of magnets but instead has an energized field winding that is connected in parallel with the armature to generator current. The coil that is used in a shunt generator has a large number of turns but a small cross-sectional area. It generates direct current and doesn't require any commutator.

The series generator is quite similar to a shunt generator, but with a small difference. This generator also has an energized field winding but it is connected with the armature in series. The coils in a series generator have a small number of turns but a large cross-sectional area. The voltage generated for a series generator is small but it gradually increases until it reaches terminal voltage.

The compound generator is the last DC generator and is a combination of the two just mentioned. It has two separate field coils that are wound over field poles, one being a shunt field coil and one being a series field coil. Overall this is the best DC generator as it encompasses both generating current in parallel and voltage in series.

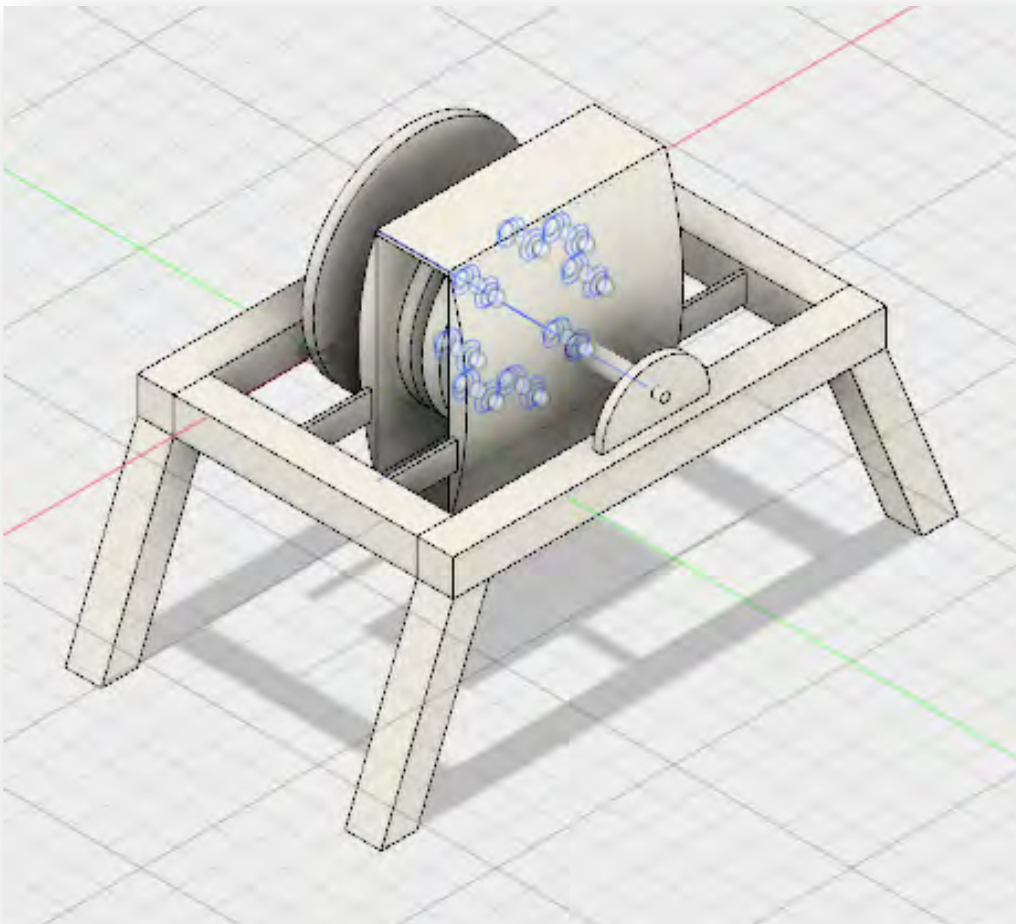
After looking into each of these various different ideas, I have come to the decision to choose one of the AC generator designs, either the rotating armature or the rotating field generators. The DC generators are often not used in smaller scale projects but are more common in big factory settings, so none of them are really optimal for what I am looking to do. Given all this, it really seemed that there was not much difference between the two AC generator designs; I noticed that a lot of designs did center around rotating magnets instead of coils. This seemed to occur because rotating smaller disk magnets is easier than large bulky coils, but regardless of the reason, I decided to go with what I observed primarily and use the rotating field generator.

Design:

Once I had the knowledge to combine the hydro and electrical parts of my generator, I began designing by drawing my ideas using the computer programs AutoCAD and Autodesk Fusion 360. Both programs allowed me to get high quality and accurate layouts of what I wanted before moving to physical materials. In addition, I also looked online for specific pelton turbines, since the specifications to replicate one is something that I could not produce with the access I had. I found only a few pelton turbines available for purchase and of them only the one made by a company called *PowerSpout* was the right shape and size for my design.

Pelton Wheel Turbine from *PowerSpout*

I also examined other projects to see what types of designs had been chosen in "do it yourself" (DIY) types of situations. Ultimately, I came up with the following design that I drew in AutoCAD as a simple general version of what I envisioned.

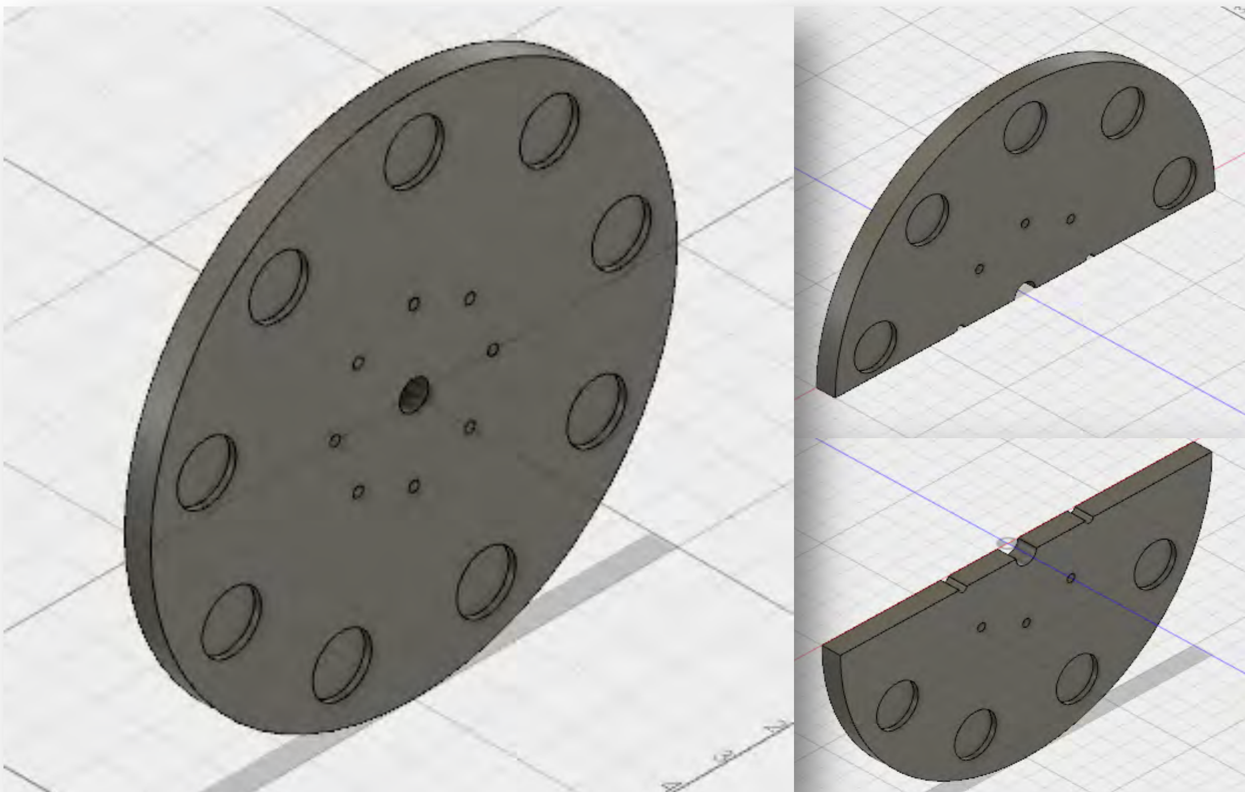


The design included a stand to hold the turbine, coils and magnets. It had the axle that would allow the turbine and magnetic plate to rotate as it did. I also had envisioned a shield to protect the electric part of the generator from any flying water. Overall, this was mainly used to get my ideas down on paper and then be able to recreate them from there.

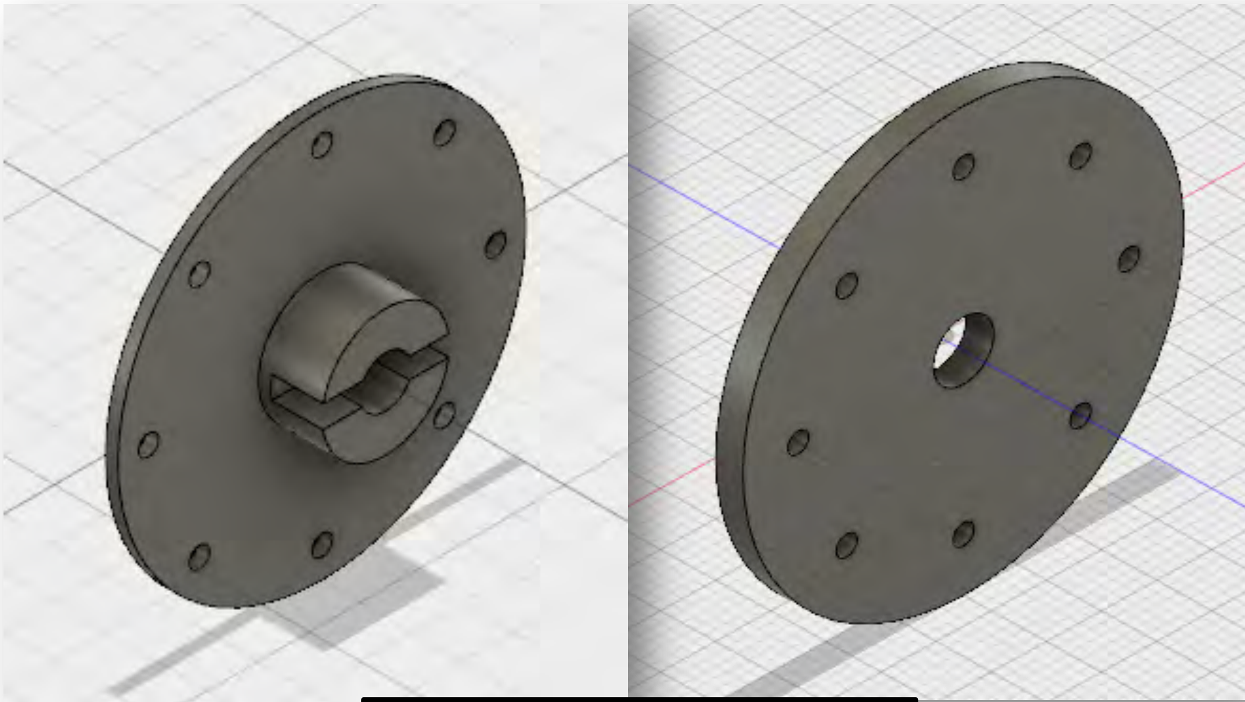
After creating this sketch, I went directly into designing the specific parts of the generator individually. I knew I wanted both magnets and coils on separate places, with the coils being stationary and the magnets able to rotate. I envisioned the turbine to be attached to an axle that would spin as the turbine did. From there I planned to attach the axle to a plate full of magnets so that when the turbine spun it caused the axle to spin which then spun the magnetic plate. The plan morphed into building a double-sided magnetic plate so that I could then place two stationary plates on either side of the magnetic plate and use more coils in the hope of generating more voltage.

I first found what size magnets I wanted to use, choosing powerful neodymium magnets that were an inch in diameter so that I could optimize the electricity generated with a strong magnetic field. Knowing the size of the magnets I was able to draft a design for the magnetic plates, with spots for the magnets to sit in. Initially, I had implemented a design with eight magnets per side, however after determining that I would switch to three-phase power I needed a multiple of three for my amount of magnets and thus chose nine. I chose the thickness of both plates to be half an inch so that it would take time to print one plate and would still be thick enough to withstand spinning at high speeds. The diameter of the full plate was chosen to be ten inches so that it resembled the size of the turbine.

Unfortunately, when I went to print this plate I realized that the maximum size to 3D print anything was 6 inches. I then decided to print the plates in halves and designed a smaller aluminum plate to hold the two halves together while holding the plate itself to the axle. I used the milling machine to carve out two sets of aluminum plates, one to connect the rotor (magnetic plate) to the axle and the other to connect the turbine to the axle. The aluminum mounting plates had holes for screws to go through them and then through each half of the magnetic plate and then through another plate on the other side, this way it would sandwich together the halves of the magnetic plate. One of the aluminum plates also had a screw drilled into it to secure it to the axle. The design for the aluminum mounting plates and the magnetic plate are pictured below.

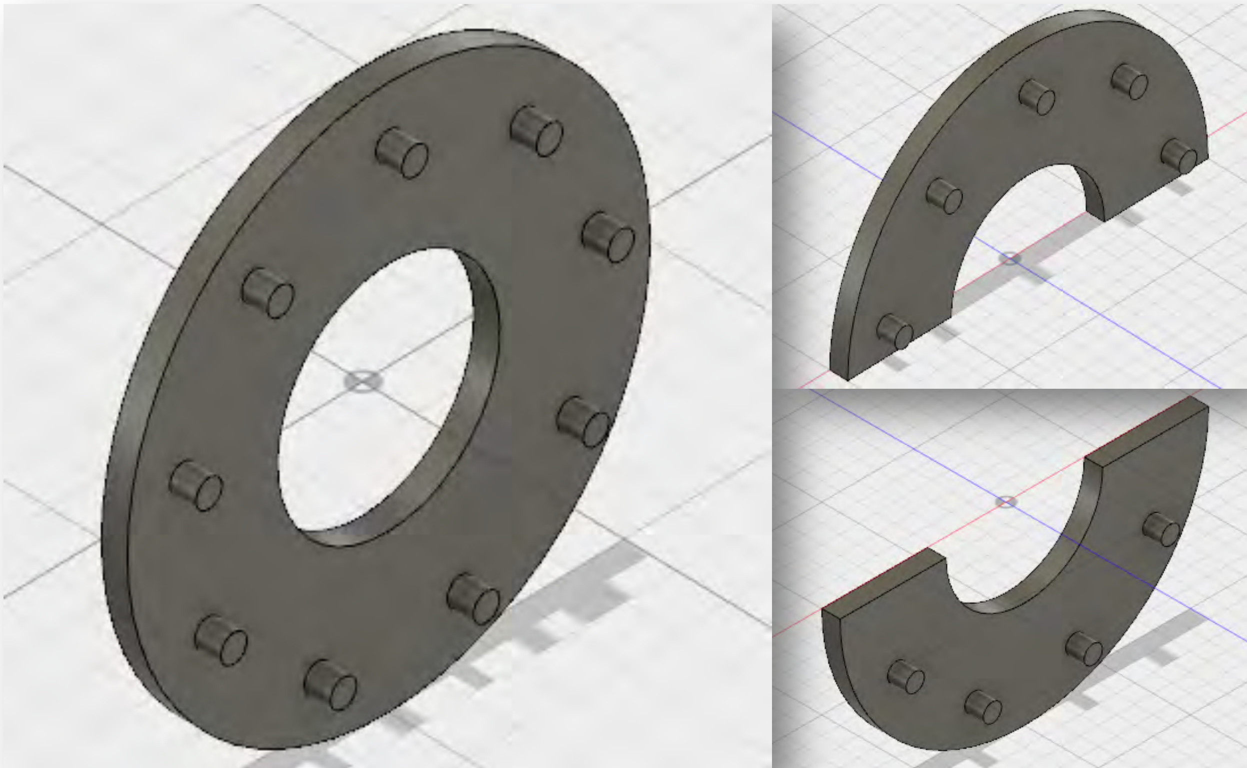


Magnetic Plate

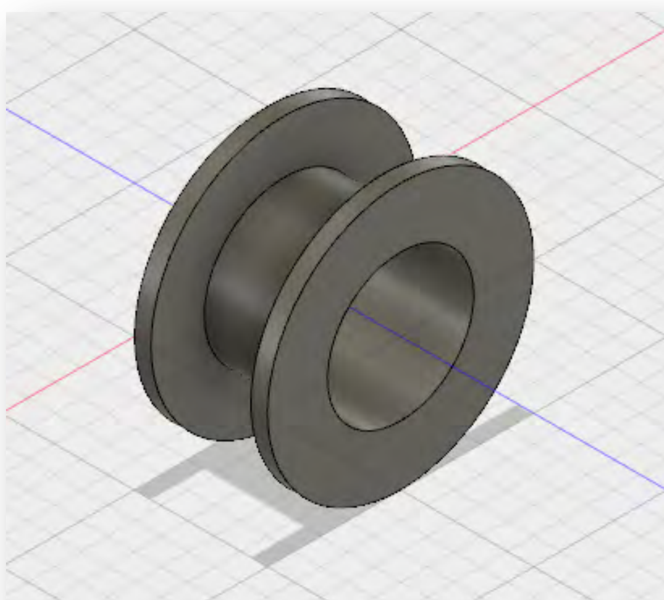


Mounting Plates

The coil plates were the next step of the process. Since I had to make the plates reciprocal in size to the magnetic plates, the only thing I had to decide was how big the coils would be. I designed a bobbin that would hold each coil and which could easily be attached to the coil plates. I then selected between a thicker and a thinner magnetic wire to wind the bobbins. I chose the thicker of the two wires as it could fit the desired number of turns on the bobbin that I wanted (200), plus the thicker wire is able hold more amps of currents than the thinner wire. The bobbin as a whole was designed initially and then I wrapped wire around it to find if the number of turns would fit, and whether I would need to change anything. The sizing worked out so that the coil plates and bobbin looked like the following.

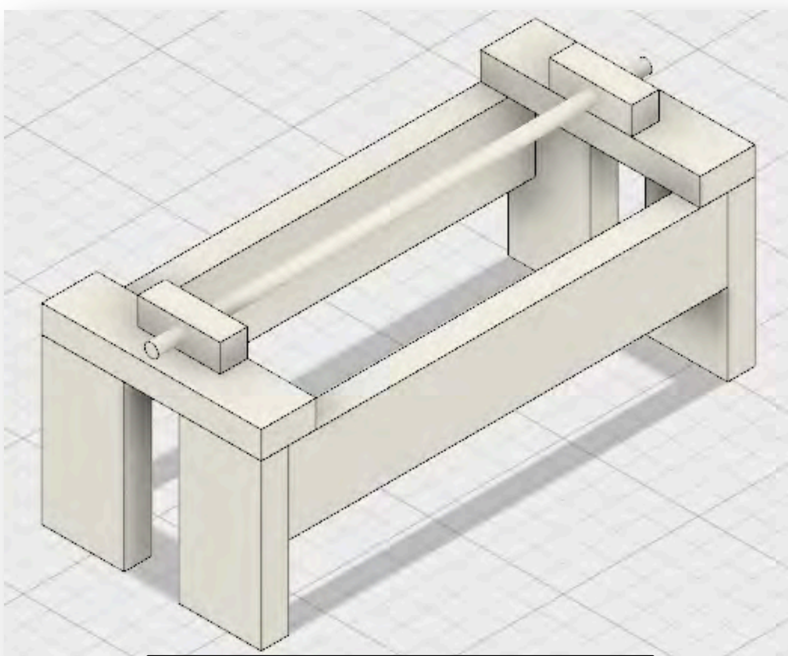


Coil Plate



Bobbin

Finally the last step before beginning to build was to create a design of a stand that would hold the turbine and the generator together. We had already purchased a steel rod so I changed my original stand sketch to center around the rod. The stand would be made entirely of wood to support the generator and have an outer sealant on it to protect it against water damage. The only part that isn't pictured in the design below, is two rectangular pieces of plywood, which I planned to drill each half of the coil plates to. The plywood would hold both halves of the plates together as well as be a protection shield from splashing water. The sheets of plywood holding the coils are pictured in the final real version but not in the stand design below. Everything was drawn in AutoCAD to scale after measuring the sizes of the plates and estimating good values so that the turbine, coils and magnets were all at a good height and distance from each other to operate properly.

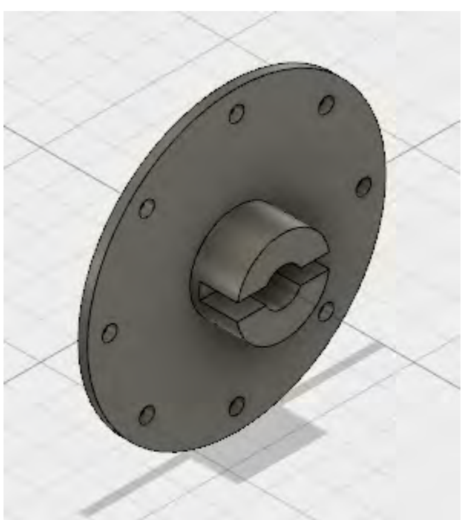


Stand

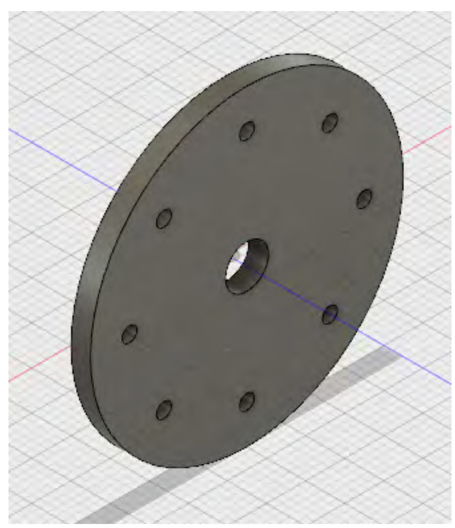
Building the Generator

Once the designs were finalized the building process was able to commence. The easiest parts to build were the magnetic and coil plates. Each of these plates had already been designed in AutoCAD so they simply got plugged into the 3D printer and printed. The downside of this was they had to be printed in half (as I explained earlier), so I had 6 halves of each plate that needed to be put together. This process, I actually started before designing my stand so that I could use the actual measurements of the plates and the turbine to design the stand.

When it came down to conjoining the two halves of the magnetic plate, I already had designed the mounting plate but it had to be stronger than the 3D printed material to be able to attach and stay on the axle of the generator. Knowing this, I learned how to use the milling machine and was able to mill two mounting plates out of aluminum, one to hold the magnetic plate and the other to hold the turbine. The back of the mounting plate would just serve as a plate to screw into and this was made with the 3D printer as well.



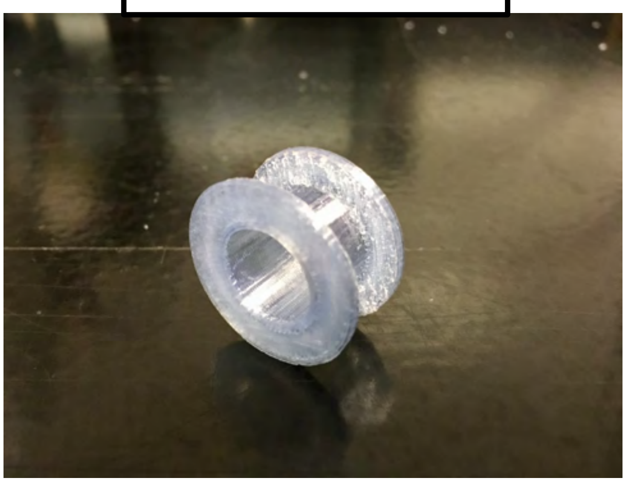
Made out of aluminum with the milling machine.

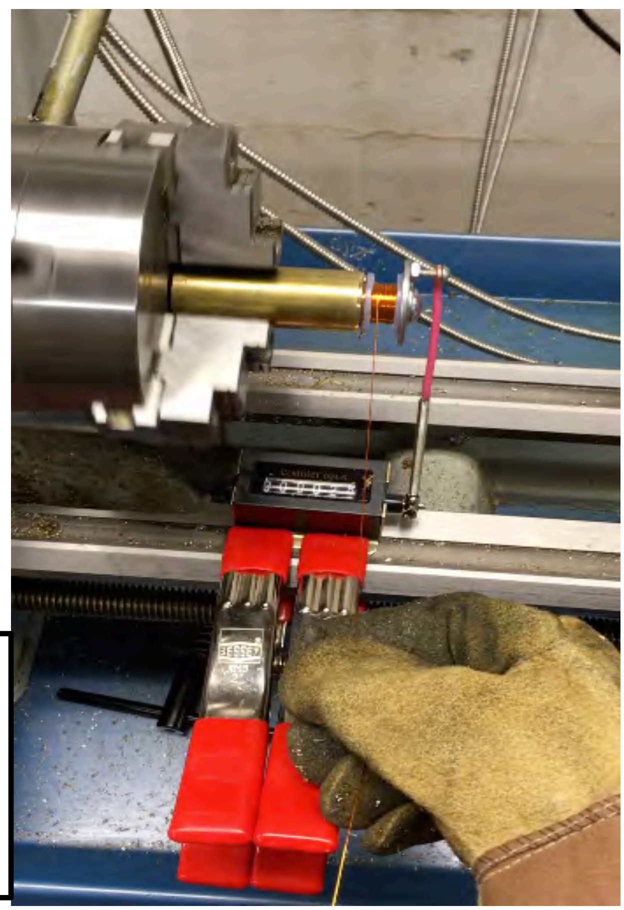


3D printed back of the mounting plate was used to just sandwich turbine or magnetic plate together.

The last things to get printed out were the bobbins. I had 18 bobbins, to create 9 coils on each coil plate. Once I had the bobbins, I set up a contraption on the lathe and set the spin speed to be low. As I mentioned, I chose between two sets of wire, one was thicker and one thinner. Thicker wire can hold more current in it and in general thicker wire has less resistance, but thinner wire can be wrapped more times so I had to chose between the two wire sizes. I came to the arbitrary decision that I would like at least 200 turns in each coil. I then set up a contraption to count each revolution as the lathe spun the wire a full turn. That way I could be as accurate as possible with how many turns each of my coils had. Knowing that the thicker wire would hold more current, I decided to just go ahead and see how many turns the bobbins would hold of the thicker wire. It turned out that two hundred turns was about the perfect amount of turns for the bobbins that I had created which were 0.60 inches in diameter and half an inch long.

3D printed bobbin





Here I used the spinning of the lather to turn the bobbin. The black device connected to the coil and clicked once every revolution. I guided the wire back and forth as evenly as I possible could.

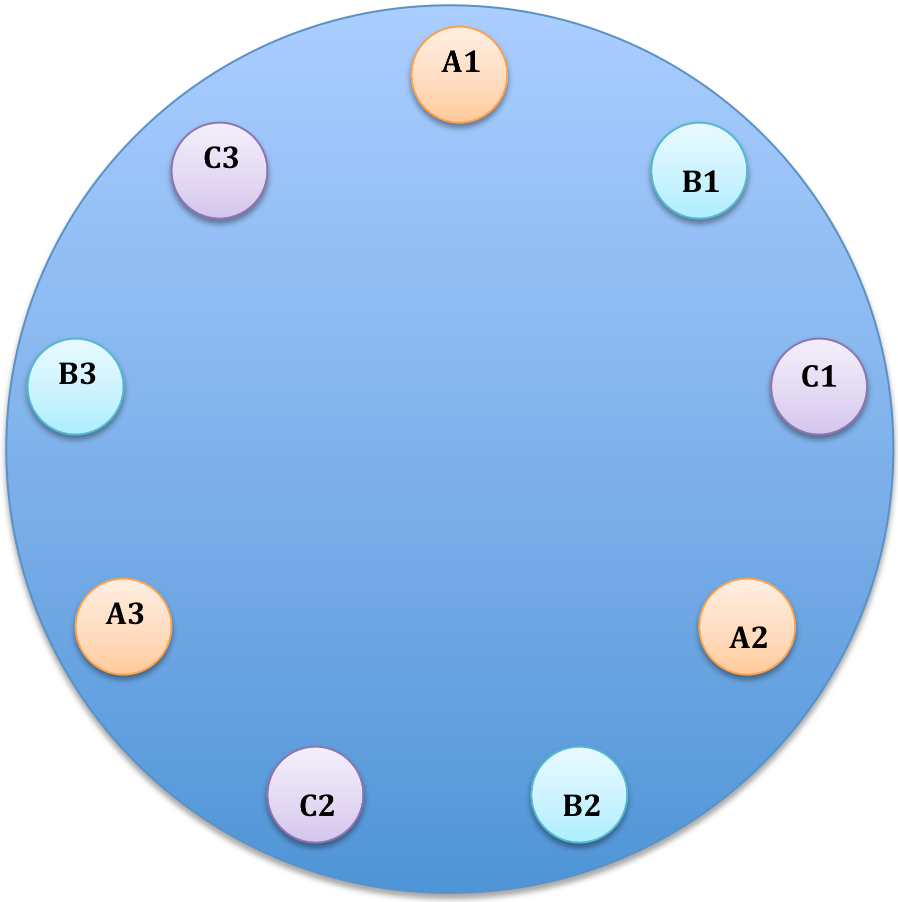
The final part to build before I began connecting everything was the stand. Here I followed the design I created to make the stand, using just wood. I cut and screwed together the pieces to make a sturdy base to hold my generator. The pieces not pictured below are the axle, the turbine, and the magnetic and coil plates.

Three-Phase Power:

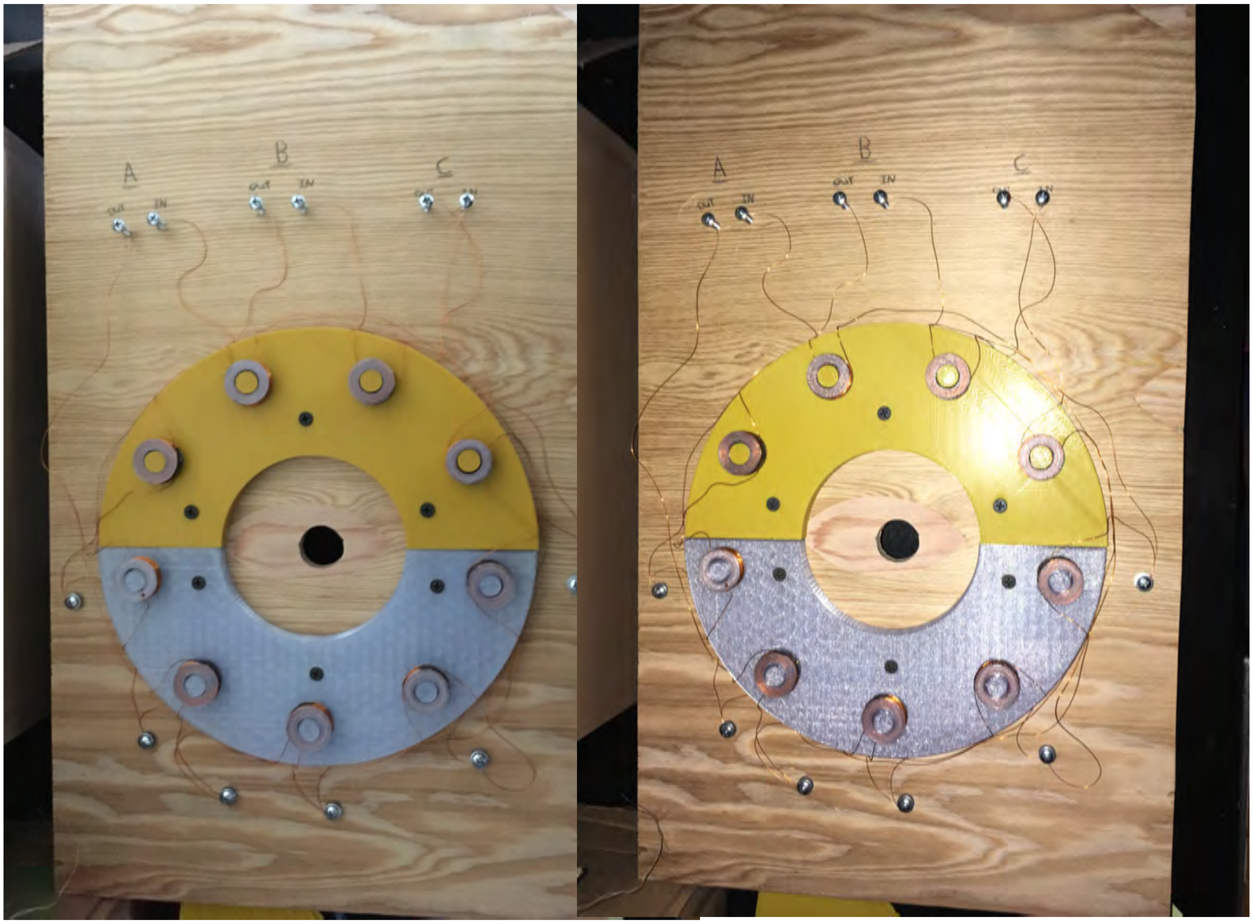
Once I had all of the 3D printed objects built, I actually decided with the help of my professors to make my generator into a three-phase generator. Luckily it was something that we had already thought about a little and had made each plate with 9 coils and 9 magnets so that I could implement three-phase power if I wanted to. One of the basic ideas for three-phase power is that you need your coils to be a multiple of three, meaning you can use either 3, 6, 9, 12… amounts of coils. Before I had considered doing three-phase power I had 8 coils but it was an easy switch to nine so I did that during the design process.

Three-phase power is the most common way of transmitting AC power in today's society. In simple terms, when transmitting power in single phase system there are two wires, one that serves as the main conductor to carry current and voltage to your source, this is the main supply of power. The other wire is the neutral and connects back to the source and often to the ground; this is not only the return source for the circuit but is also a much safer wire. A live wire or hot wire is dangerous to touch but the neutral wire in a single-phase system is safe. For a three-phase system, you can bring the same amount of current and voltage capacity in one phase as a single-phase system, but it does it in three phases. This means you can generate 3 times the power since P (power) = I (current) x V (voltage). In a three-phase system you need 3 wires, one for each phase but no neutral, so you generate 3 times the power with only 1.5 times the wire, which is very beneficial. This reason is why three-phase is so common in today's power companies.

In terms of my generator, to create three-phase power means I needed to connect three coils into one phase and have three of those different phases. In order to do this I have a circular plate that is 360° so to break it up in three-phases, each phase needs to be 120° apart. That means that my coils which are connected need to be 120° apart as well. Given that I have 9 coils I then needed to wire up 3 coils for one phase and make each of these coils 120° apart. My setup for each plate looked like this:

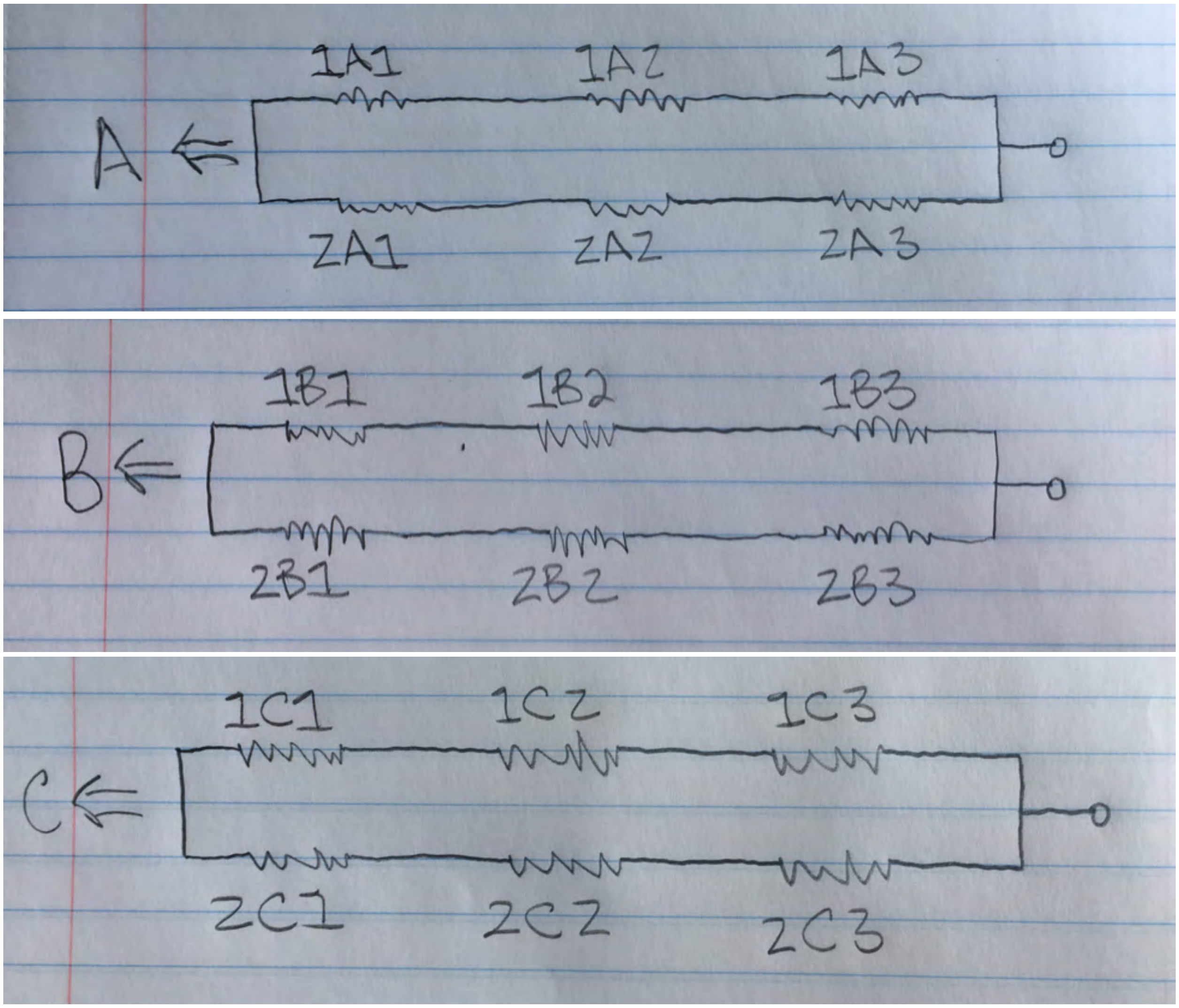


Again here each phase, A, B and C are connected in series (meaning the voltages all add together and the current remains the same). So the A1 coil has its voltage added to A2 and to A3, that way the total voltage for phase $A_{total} = A_1 + A_2 + A_3$. The same is true for phase B and C. Each plate is set up so that when they are put next to each other the same coils are facing each other, i.e. in parallel. Each coil plate when wired up is pictured below. There is an in for each phase and an out for each phase, meaning that it goes into A1, then out, then in to A2 then out and all the way through until you have an in and an out around the whole phase.



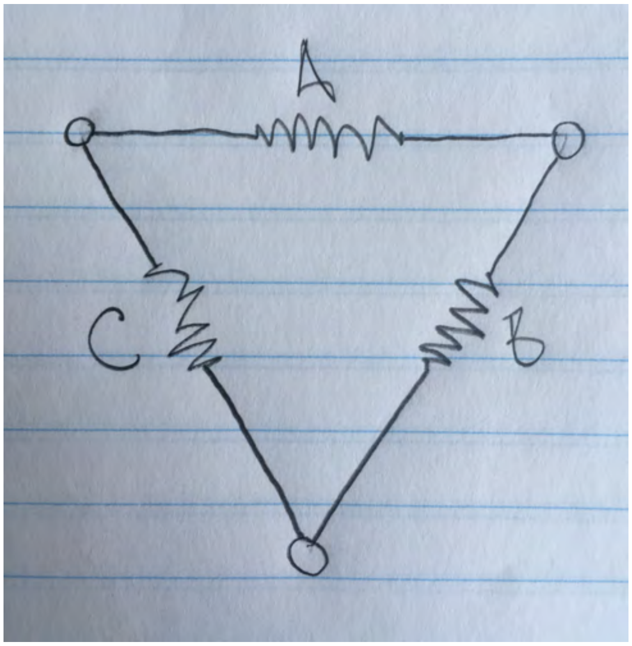
The crucial part of generating the three-phase power is the 120° difference for each phase. If the phases are not correctly 120° apart, then you will have them add in a way that cancels out your power and it will give you less than what a single phase would give you.

As a note here, the three-phase power does not need two plates; it can be done with one. The extra plate here is to generate more current capacity for my generator. The voltages as I mentioned are supposed to be the same for each phase. Adding another plate with the same set up then allows you to connect each plate in parallel as I end up doing. When connecting anything in parallel the voltage remains the same, but the current capacity adds so with two plates each phase is able to produce twice the amount of current that one plate would. The sample circuit diagram for my set up thus far looks like the following.

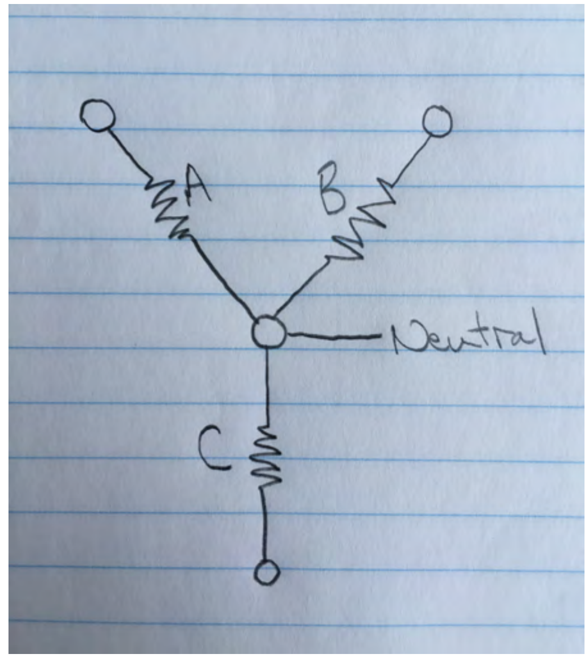


Here, the first number (1 or 2) represents the plate or stator number. The letter (A, B or C) represents the phase. The second number (1, 2 or 3) represents the coil number of that specific phase.

As you can see here again, each plate has three coils in series. Then those three coils are connected in parallel with the three coils in series of the other plate. Each of these additions I'll call A, B and C in order to explain how the connection of three-phase works. There are two set ups for three-phase, the delta and the WYE ("Y") set ups.



Delta set up



WYE set up

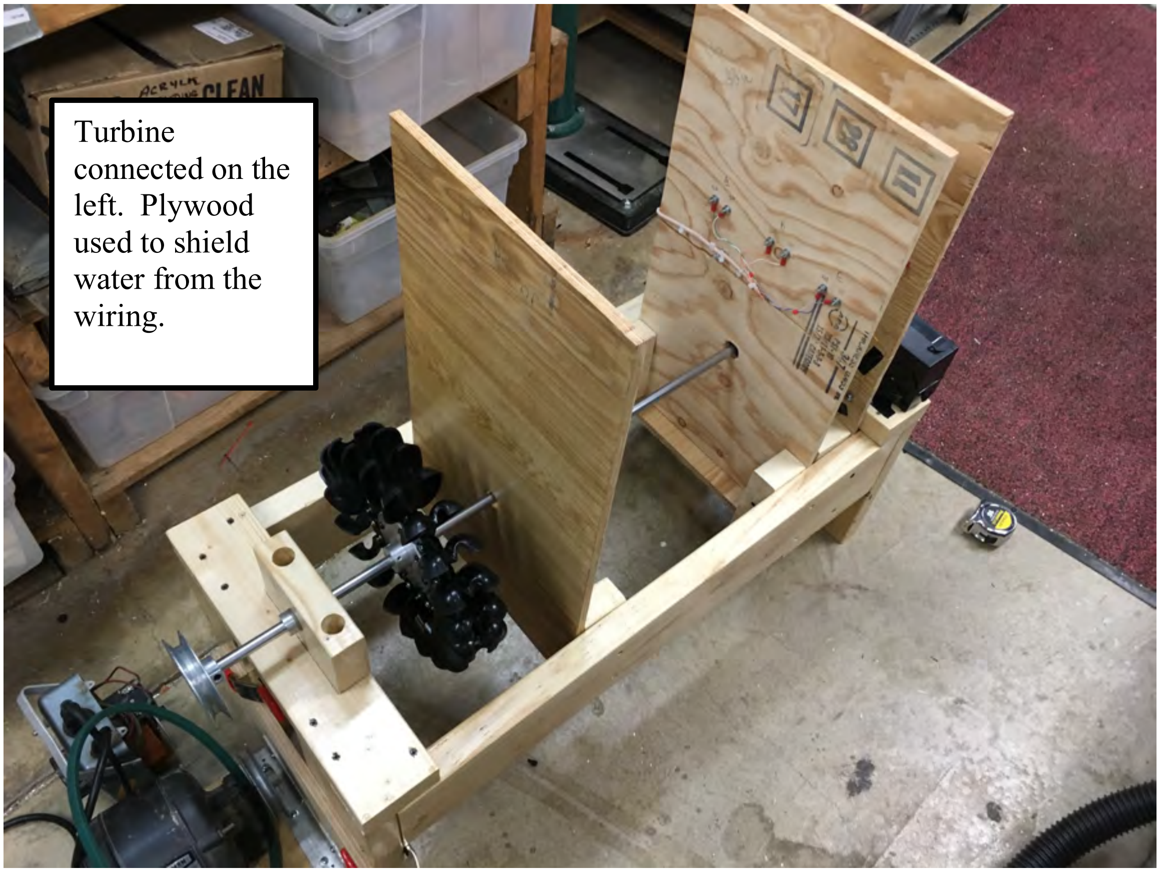
To begin, we'll look at the WYE set up. Here there are four wires, 3 connected in series and one that is a neutral. In the WYE set up, there is the phase voltage and the phase current, which merely means the voltages and currents that each phase (A, B or C) produces. Then the line voltage and line current are the addition of any two phase voltages or currents depending where you measure. So for example line voltage AB is the voltage measured by the addition of A and B voltages together, and same if it were the current. For the WYE set up, the total line voltage is equal to the total phase voltage multiplied by the square root of three, $V_{line} = \sqrt{3}\,V_{phase}$. The phase voltage and line voltage are equal so, $I_{line} = I_{phase}$.

For the Delta set up, it is opposite the WYE set up. The definitions of line and phase voltages and currents are the same, but for the Delta the line voltage is equal to the phase voltage, $V_{line} = V_{phase}$. And the line current is equal to the phase current times the square root of three, $I_{line} = \sqrt{3}\, I_{phase}$.

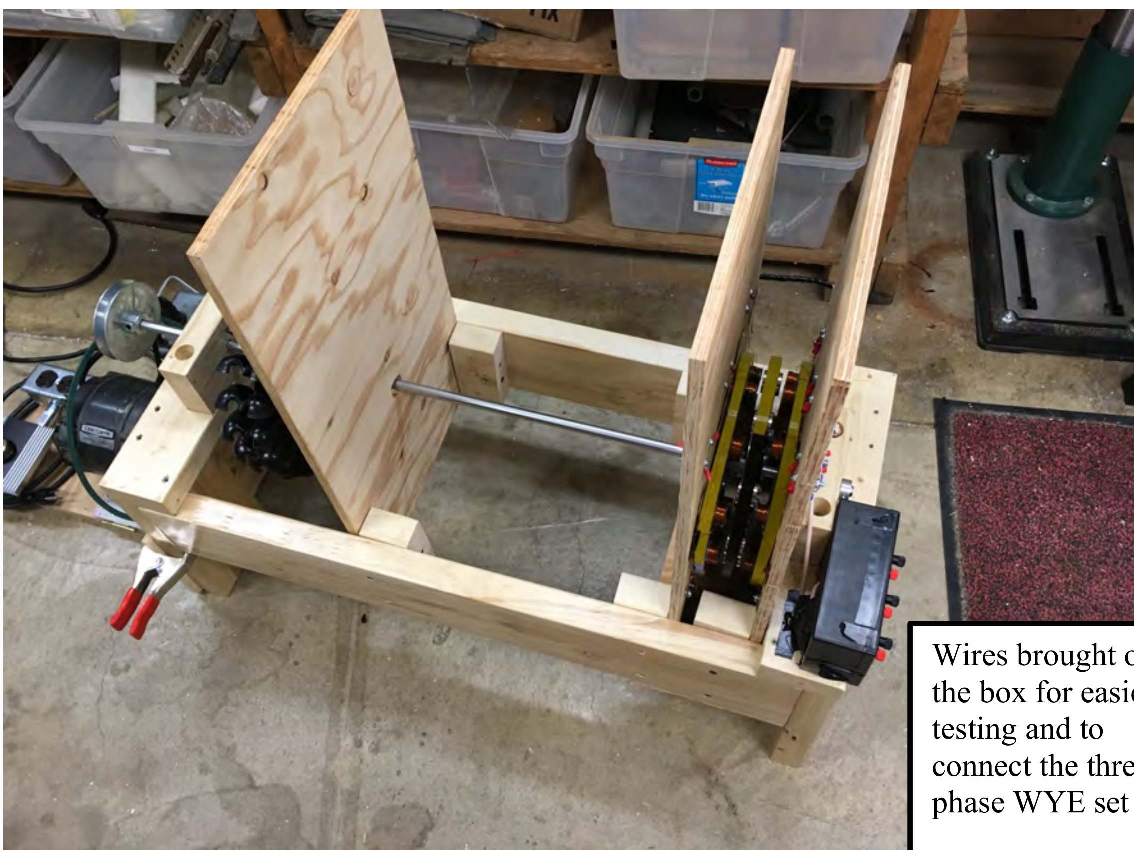
The real difference between using a Delta and a WYE set up then is how much voltage or current you're looking to produce. The Delta will give you more current and the WYE will give you more voltage. For my generator, these set ups were made as the last connection. The plates were wired up and then connected in parallel before I brought out each of the wires to a black box. At the box, I could set up either connection simply and then use a voltmeter to measure between phases to see whether or not I had an increase in voltage (if I chose the WYE set up). Ultimately, since I expected that my system wouldn't generate too much voltage within each phase, the WYE set up made the most sense, that way I could maximize the voltage I was getting since the phase voltage gets multiplied by the square root of three, thus giving me more.

Putting it all together:

Once I had each part of the generator built and my understanding of how each part went together close to complete, I merely had to do it. The coil plates were mounted on pieces of plywood, which were cut just wide enough to be able to force them into place and remain standing up by the pressure on them. I then set up the magnetic plate in between and moved the plates as close as possible while still allowing the magnetic plate the ability to rotate. Once I had them in their positions, I screwed the plywood into place and tightened the magnetic plate on the axle to make sure nothing could move. After connecting all the wires to the box I had my finished product ready to test.



Turbine connected on the left. Plywood used to shield water from the wiring.



Wires brought out to the box for easier testing and to connect the three-phase WYE set up

The last thing I completed before testing was to create a Lucite encasement to go around the electric side of my generator. Lucite, similar to Plexiglas, is a clear plastic that can be easily cut and screwed together. I wanted to make sure that water and electricity didn't touch during the testing process, plus I wanted to look through and make sure everything was working properly so Lucite was the obvious choice.

Testing it out

Indoors:

To start out with testing the generator, we set up a motor and spun the generator at a few different RPM values in order to see how different speeds would impact how much voltage the generator would produce. In addition, throughout the whole process, we measured the voltages on an RMS (root-mean-square) voltmeter so the values are less than what it would be for a peak set up. The RMS is the square root of the mean of the voltage, where as the peak voltage is the highest that the voltage will ever reach. In order to find the peak voltage you can divide the RMS voltage by 0.707. I will list both for my calculations.

	RMS (Volts)			Peak (Volts)		
RPM	V1 (Green, A)	V2 (Orange, B)	V3 (Blue, C)	V1 (Green, A)	V2 (Orange, B)	V3 (Blue, C)
300 Approx.	4.60	4.59	4.63	6.51	6.49	6.55
400 Approx.	6.00	5.98	6.10	8.49	8.46	8.63
600 Approx.	8.63	8.56	8.65	12.21	12.11	12.23

It's important to note that these values should be greater for this inside testing with a motor as opposed to outside at the falls where circumstances are different and constant speeds and measurements are more difficult to have. The letters are the phases (A, B and C) and the colors are wire colors that correspond to the phase.

After the tests with the motor, I knew the general rates with which I could generate certain voltages. These numbers will be good to compare to once I have actual numbers using the turbine outside. Then next step then was to get the generator ready for water and set it up down at creek. This meant attaching a nozzle to the top of the generator and getting the piping set up along the side of the creek.

Outdoors:

I had already measured the waterfall (to the best of my ability) and it was about 5 meters high, so we had purchased 50 feet of piping in order to make absolutely sure that the pipe would be able to get dunked under the water at the top of the waterfall and run all the way down to the bottom to wear I would put the generator. There were five 10-feet sections of piping which I had to glue a special attachment to so that each section would be able to screw together. The last step then, was to attach the ball valve that we had purchased to the generator. The problem with this was that the piping is 1.5 inches in diameter and the ball valve and nozzle are 1-inch in diameter. To fix the issue, we got a 1.5-inch connector and duct taped the 1-inch pipe until it was also 1.5 inches in diameter at the connection point. Next, I put another piece of plywood on the turbine side of the generator and a piece on top of the turbine to allow the ball valve to sit on top the turbine. I then drilled a hole in the plywood and angled another pipe (nozzle) towards the turbine to channel the water right into the cups of the pelton wheel. At the end of the angled pipe I screwed on a cap with a small hole in it to channel the water more powerfully into the turbine. I experimented with three different caps each with different hole sizes. One was a ¼ inch hole, one was a ½ an inch hole and the third was a ¾ of an inch hole. With each hole we measured the RPM that the turbine would spin at and ultimately the ½ an inch cap gave the highest RPM so we used that cap when taking any electrical measurements. That way we could maximize the output voltage and power generated by evaluating the generator at the highest amount of RPMs we could produce.

Here is the generator flowing actual water. You can see the plywood connection over the turbine and how the piping was able to connect to the generator and get angled downwards to push the water right into the turbine.

Another view of the generator in it's spot along the side the waterfall. Here, the ball valve is clearly visible on the top of the generator. This was before the piping was connected; you can see the gray at the end of the pipe, which is where the connector connected the valve to the 50 feet of piping.

Close ups of the turbine and the different plates together while the generator is in use.

The light bulbs that were lit by each different phase of the generator during testing.

At the top of the waterfall, the piping was buried in a pool of water, barely visible.

The piping traveled up the waterfall. We used rope to tie it to trees along the side so that when the tubes were full of water, they didn't swing into the middle of the creek.

Besides setting up and taking pictures and videos, I did also record data of our testing. The first thing that we did after setting up was to see how fast the flow rate of the water was. In order to do this, I dropped a piece of duct tape into the top of the piping and started a timer. When the duct tape came out the bottom, the timer was stopped. There was 50 feet of piping that was 1.5 inches in diameter plus an extra two feet between the ball valve and the nozzle that was an inch in diameter. Totaling this volume and having the time that it takes for the piece of duct tape to appear at the end, we then knew the amount of time it takes for the volume of water to pass through all the piping and out to the turbine, which is the flow rate of the water.

$$50\ ft = 15.24\ m \qquad 2\ ft = 0.6096\ m$$

$$area\ of\ circle = \pi r^2 = \pi(0.75\ inch)^2 = 1.767\ in^2 = 1.14\ x\ 10^{-3}\ m^2$$

$$area\ of\ circle = \pi r^2 = \pi(0.50\ inch)^2 = 0.785\ in^2 = 5.06\ x\ 10^{-4}\ m^2$$

$$Volume\ 1 = 15.24\ m\ x\ 1.14\ x\ 10^{-3}\ m^2 = 1.74\ x\ 10^{-2}\ m^3$$

$$Volume\ 2 = 0.6096\ m\ x\ 5.06\ x\ 10^{-4}\ m^2 = 3.08\ x\ 10^{-4}\ m^3$$

$$Volume\ Total = Volume\ 1 + Volume\ 2 = 1.77\ x\ 10^{-2}\ m^3$$

Time = 8.90 seconds

$$\text{Flow rate} = \text{Volume Total/Time} = \frac{1.77\ x\ 10^{-2}\ m^3}{8.90\ secs} = 1.99\ x\ 10^{-3}\ m^3/s$$

After recording the flow rate, I measured the RPM that the turbine was able to rotate at with the waterpower, which was about 420 RPMs. It was approximate because the values fluctuate on the tachometer, but 420 was about the median value. After measuring the RPMs, I got out the voltmeter and measured the voltages of each phase.

Phase	A (Green)	B (Orange)	C (Blue)
Voltage (RMS)	2.20 V	2.10 V	2.12 V
Voltage (Peak)	3.11 V	2.97 V	3.00 V

These voltages were much lower than the tests that we had done inside with the motor. With the motor at around 400 RPM, the voltages were around 6 V (RMS) and 8.5 V (Peak). So, not only was the RPM a bit higher outside than the 400 we measured inside, but also we were getting less than half of the voltage we got inside. There are a few possible explanations for this.

First is that moving the whole generator into the car, into a cart, rolling it down to the creek and carrying it all about, gives a great possibility of things shifting around. Wires can become less tight as can the turbine and magnetic plate. This likely happened in some capacity to give slightly less voltage.

Next, the axle hole was a little bit larger than the axle in order to have it spin freely and avoid extra friction. However, because the hole was a little too big, at high RPMs the axle jumped a little big up and down causing unexpected voltage drops that didn't occur with the motor. The way that the motor was set up inside, the weight of the motor kept the axle down and locked into place so we didn't notice the movement in our inside tests.

Finally the main issue all over was the closeness and accuracy with which the plates were built and aligned. Given that the only 3D printer available could print the plates in half, I did my best to make it work, however there were problems. Even though I needed only 6 halves, 2 for the magnetic plate and 4 for the coil plates, I printed around 10-12 of them because of problems with the printer. The final versions of the plates were by no means perfectly symmetric and while the ways in which we assembled them into full plates worked well, they also were not perfect. In a situation like this, the closeness that you can get between the magnets and coils is very important. The closer everything is to each other, the more voltage you can produce. Discrepancies in distant were apparent because the plates were made in two halves. At certain points, a group of magnets would be closer to one coil plate and farther from another, generating both more and less voltage at the same time.

These problems in combination with each other are some of the most likely reasons that the voltages are so different outside from the results measured using the motor inside.

Finally, the last step in calculating voltages was to set up the WYE circuit and measure what voltage would get produced in the three-phase (keeping in mind that if it worked correctly it should be the voltage I measured multiplied by the square root of three). When I took the measurement, the voltage dropped to around 1.5 V (RMS) for each phase. This meant that instead of adding properly either the wiring, the building discrepancies and alignment or some combination of both caused the three-phase to turn into a resistor to the whole system. Given this, it was time to pack up and rethink.

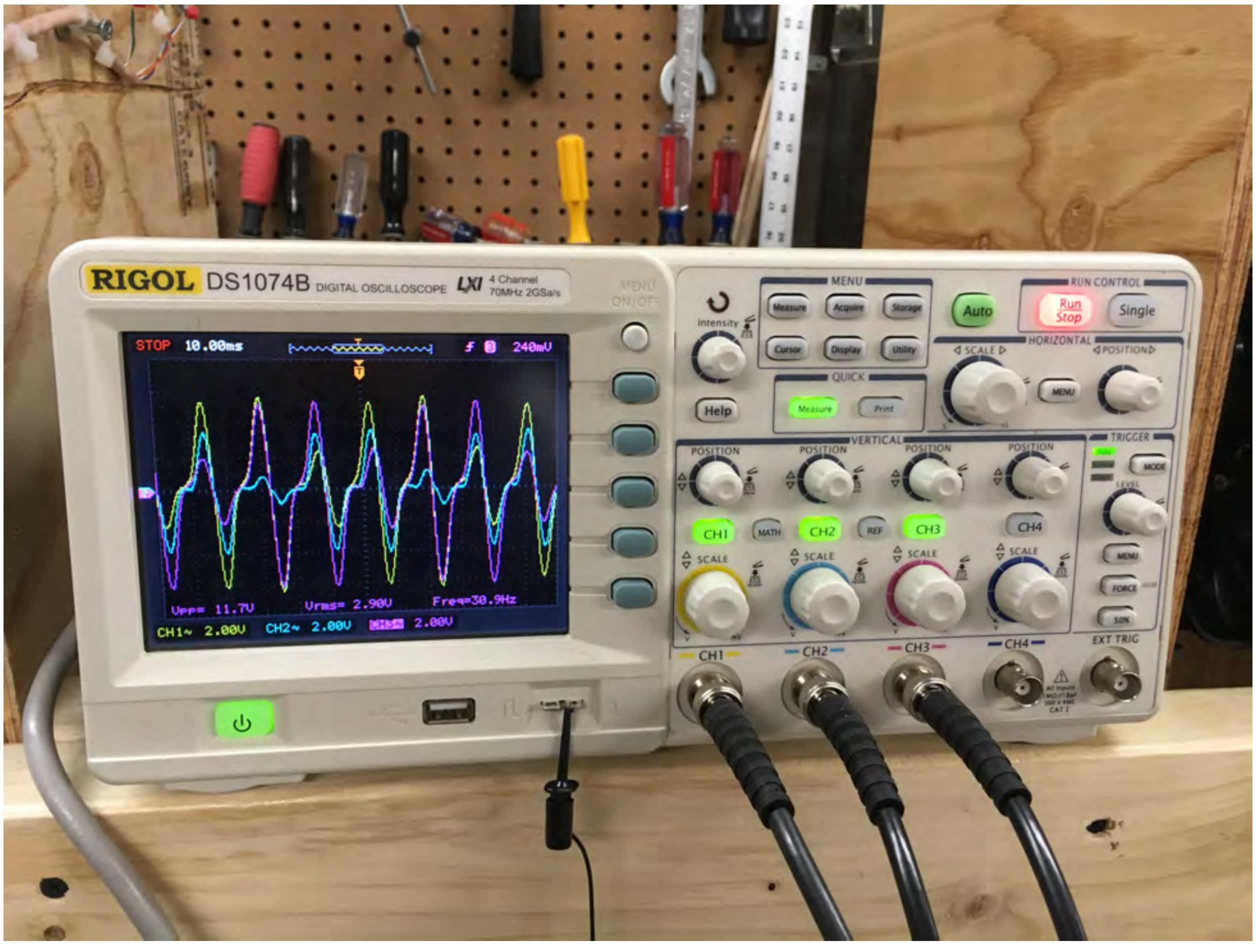
Before I left, I measured the current, the voltage when connected to a lead and the frequency. The current was 0.25 amps for each of the three phases and the voltage was 0.1 V (RMS) unanimously for each phase. This meant that the wiring was definitely not great, since when you had a source drawing power it drew virtually all the voltage available. The frequency measured was 55.0 Hz.

The calculations of power generated are below (again P = IV).

Phase	Power (RMS)	Power (Peak)
A (Green)	0.55 W	0.78 W
B (Orange)	0.53 W	0.74 W
C (Blue)	0.53 W	0.75 W

Corrections:

So now I it was back to the drawing board. I took the generator back to the shop and connected it to an oscilloscope to see if it would help me figure out some of the problems and potentially a way to fix them. When the oscilloscope was connected it gave me the following image.

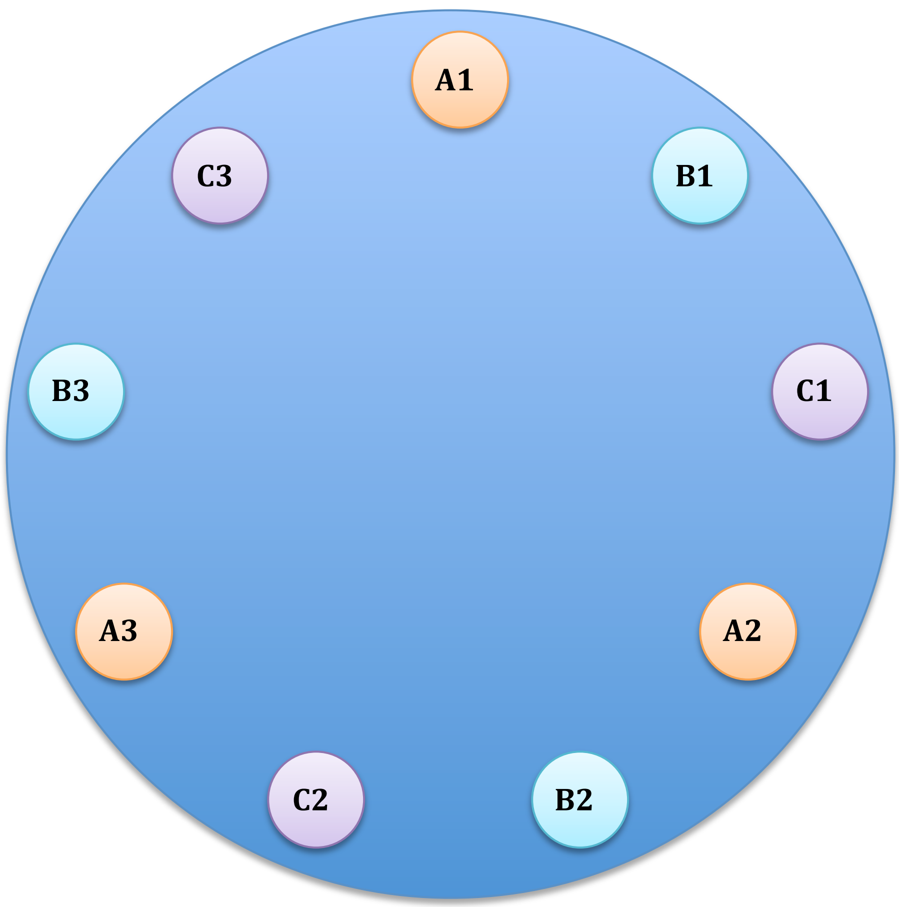


Here, I connected the oscilloscope to the generator. The yellow sine wave corresponds to channel 1 and phase A. Blue is channel 2 and phase B. Purple is channel 3 and phase C.

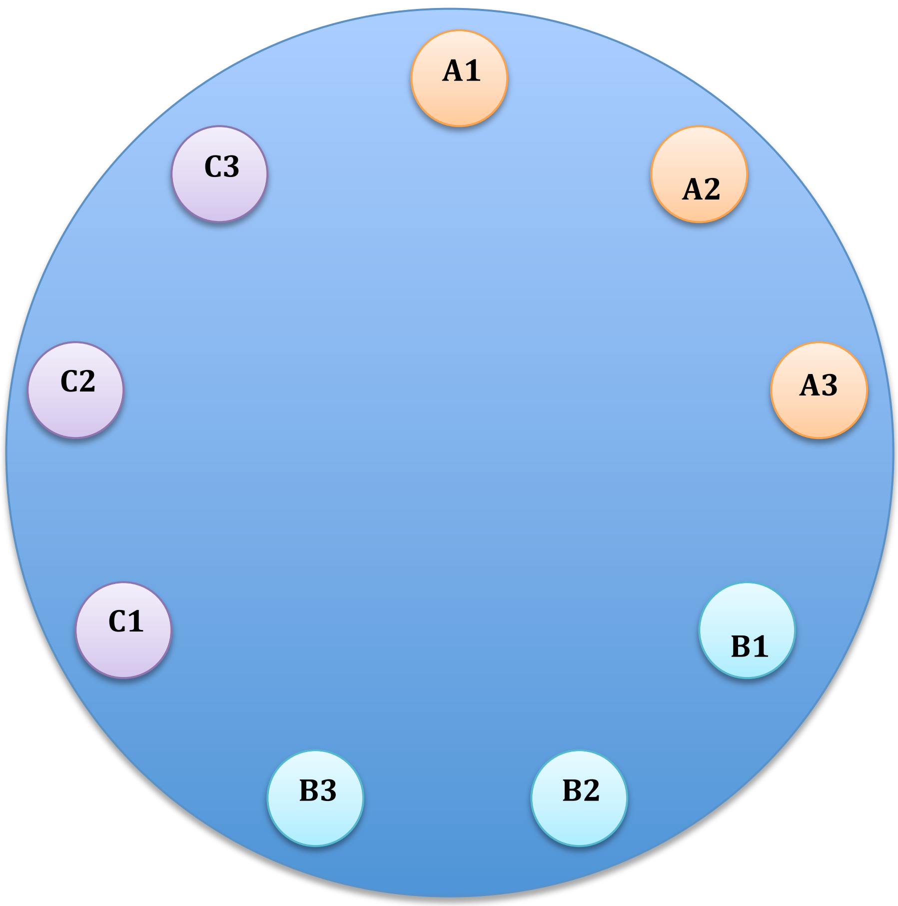
There are two main points to take away from this graphic on the oscilloscope. The first and most obvious is that the Blue channel (2), phase B, is lower than both phase A and phase C.

This isn't surprising since it showed the lowest voltages in the outdoor tests as well. That means that likely there are some poor connections occurring in the B phase of the generator. However, the more pressing problem is that if the set up was correct than instead of the three sine waves being on top of each other, they would be separated by 120°. This is crucial for three-phase power and it is not happening in this set up.

To try and correct my mistake I went back to my circuit diagram and looked more closely at the 120° separation. My original coil plate was again wired in this set up.

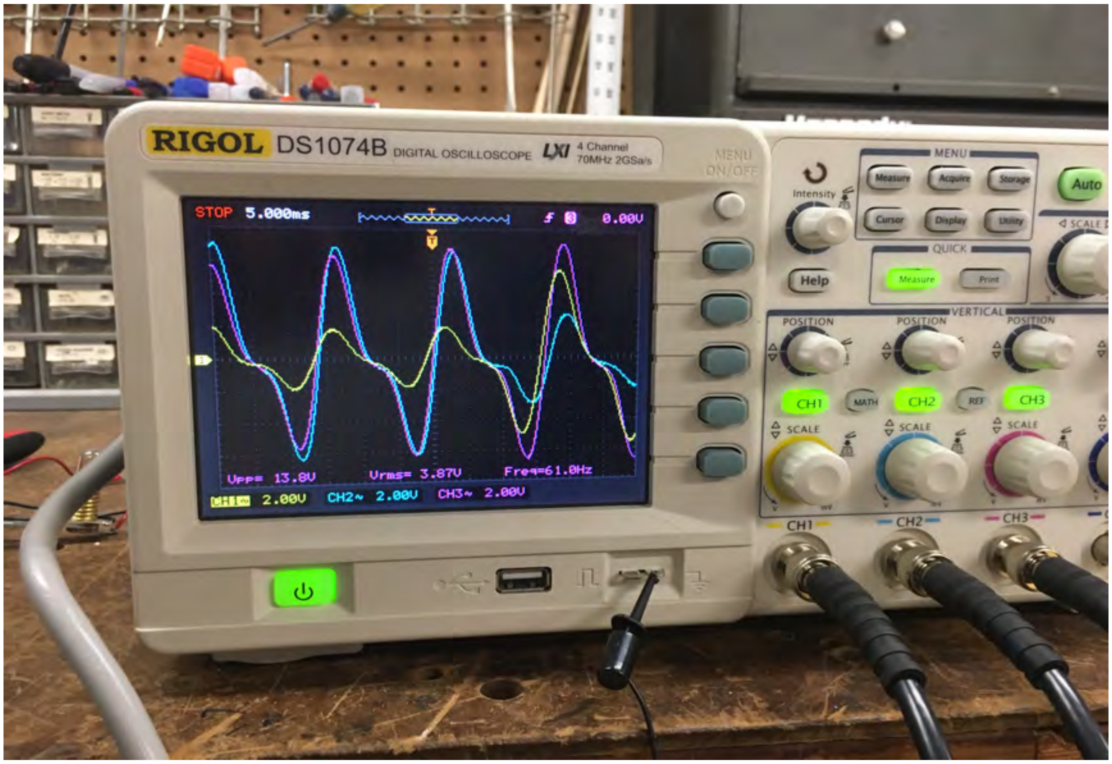


In this set up each coil in their respective phases are 120° apart, but it does not have each phase itself actually 120° apart. A, B and C are really only 40° apart since they're sitting next to each other around the circle. So in order to fix this I took apart my generator and rewired just one of the plates. I disconnected the other, since it is much easier to troubleshoot using just one coil plate to produce voltage and power. During my rewiring process not only did I move around the placement of the coil connections but I also made the connections between each coil stronger by using crimp plugs instead of just wrapping the wires around a screw. With my new set up, I fully expected the three-phase to work.



Here you can really realize where I initially went wrong. A1, B1 and C1 are clearly 120° apart in this set up as are the 2's and 3's of each letter. This set up should allow for the three-phase power to work.

Now, instead of taking the generator right back outside. I first tested the three-phase again on the oscilloscope. What I got was quite puzzling.



Here again there are two main things to notice. The first is that if this was live you could see that every three periods of the sine wave, a new phase (alternating between A, B and C) becomes the wave with the smallest amplitude. This means that there is a set of 3 magnets that are farther away from the coils than the other six, which is why the amplitude (which is the voltage) goes significantly down for three periods. The second important aspect is that while the three phases are not on top of each other anymore, they are not by any means separated by 120°. This is extremely odd. This second set up should garner a result where the phases are displaced 120° from each other but it is not happening.

The main and only reason that I can think this is happening has to be the discrepancies when building the plates. The simple fact that the plates are not whole and this creates major alignment issues between the coils and the magnets, so much so that given the plates I have built, it is likely that three-phase power might not be feasible. It would be possible that the wiring of the coils was wrong but having taken it apart and put it back together again, I didn't find any issues either time. The connections could be poor but they wouldn't cause separation problems. However, I was not going to give up here. I didn't know how else to connect the three-phase power and get it to work for the reasons I have listed, but I did want to test out if rewiring and the strengthening of the connections made a difference.

We took the generator back out to the creek and tested it again with just one coil plate connected in the new set up. Here again power was calculated using P =IV. These were the results.

Phase	Voltage (RMS)	Voltage (Peak)	Frequencies (Hz)	Current (Amps)	Voltage w/ lead (RMS)	Voltage w/ lead (Peak)
A (Green)	3.10 V	4.38 V	70.40	0.27	1.50 V	2.12 V
B (Orange)	3.05 V	4.31 V	70.30	0.50	1.30 V	1.84 V
C (Blue)	3.15 V	4.46 V	70.40	0.65	1.20 V	1.70 V

Phase	Power (RMS)	Power (Peak)
A (Green)	0.84 W	1.18 W
B (Orange)	1.53 W	2.16 W
C (Blue)	2.05 W	2.90 W

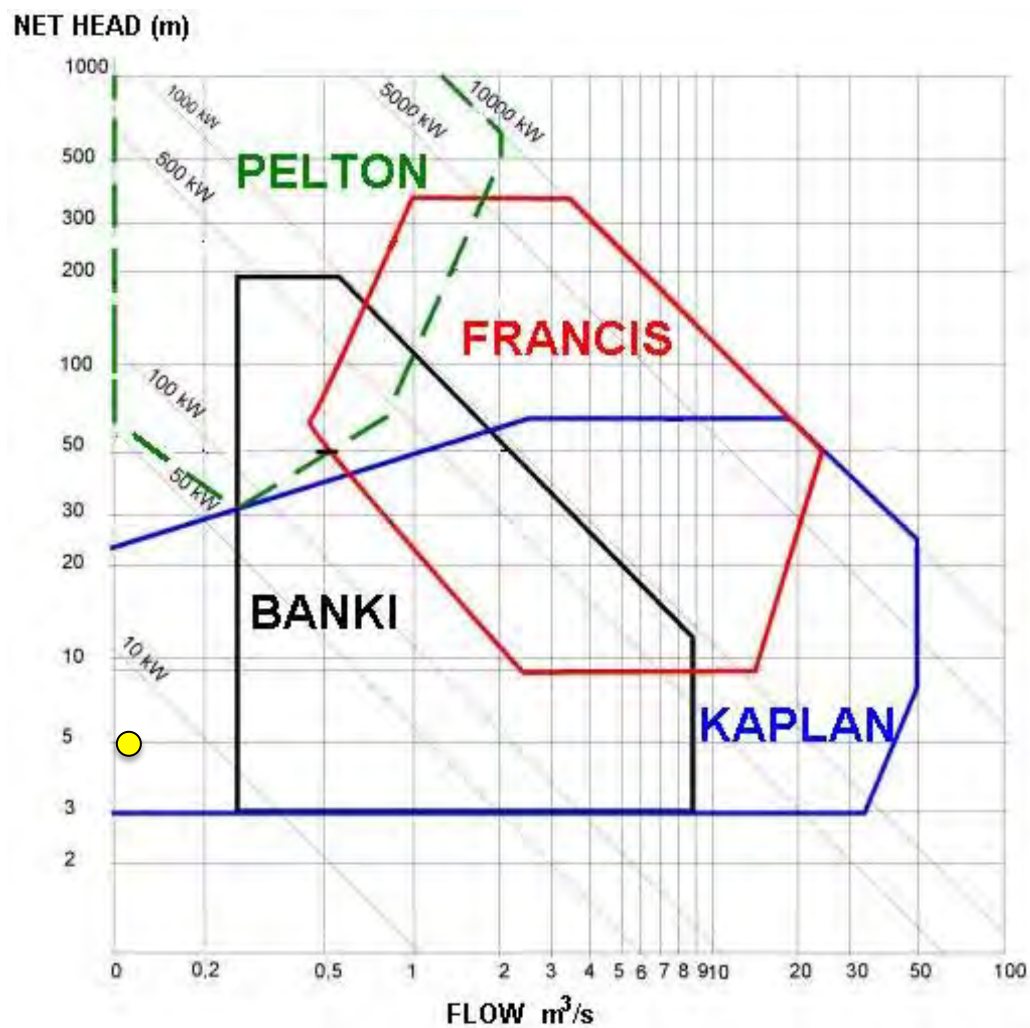
The important notes here are the comparisons in voltage and power generated compared to the first test. The voltage increased by about a whole one volt and the power increased in turn with that. It seems clear that stronger wiring was clearly an issue causing the first test data to be low. Too the frequency was higher here by almost 15 Hz. The likelihood is that is the second phase of testing the pipe was dipped lower into the water and therefore able to fully fill with more water and generate more energy to turn the turbine. This was confirmed when measuring the RPM as it jumped from 420 on the first test to 460 on the second. For the second test, I actually was able to situate the piping down under the water weighing it down with rocks. The first test must have had the pipe bobbing a bit at the surface and caused it to fill some with air as opposed to fully with water. In addition too, for the second test when the lead was applied to the generator, the voltage that was left to use was much greater than the first test, going from about 0.1 V (or virtually all the voltage) to approximately 1.3 V.

Finally, another interesting aspect of comparison is that the current in the first test was unanimously about 0.27 amps. For the second test however, it was about the same for phase A (0.25 amps) but there was more current in phase B and phase C (0.5 amps and 0.65 amps respectively). This is intriguing since adding the second plate in the first test should increase the current capabilities, but they were stronger in the second test. Again this shows how strengthening the connections can make a big difference, but it could also indicate problems with the second coil plate. Since I didn't rewire the second coil plate, but just tested the first one separately for the second set of tests, it is possible that all the issues were in this plate. I did examine the wiring on this plate though and again I was unable to see the problems besides potentially having poor connections. The fact that the three-phase power did not work is still quite puzzling from that respect.

Overall, I still haven't found any reasons why the second set up didn't allow the three-phase power to work, but it was good to at least do a second set of testing. The alignment and building discrepancies of the plates seem to clearly cause a large amount of issues and could be the cause of all the problems. Wiring can always be improved, but the more I think about it, the less it seems possible that it could have been the underlying cause of the issues.

Conclusion and Looking Further

After completing the designing, building and testing of my generator, I focused much more on what I did to create my project and what I could have done or could do in the future to maximize the power outputs. There are a large amount of reasons to which my generator didn't produce tons of power but of course the first is the kind of turbine that I used in this set up. Again the head at the location I implemented was 5 meters and the flow rate was $1.99\ x\ 10^{-3}\ m^3/s$. Looking back at the earlier graphic, the ideal generator to choose is not the pelton wheel turbine.



Notice the yellow dot in the bottom left corner of the graph. This dot represents the approximate value of the head and flow rate for my generator (given where I placed it). In this case, the optimal generator for the situation would be a Kaplan or a propeller turbine not a Pelton wheel turbine. This makes sense since the head really isn't high enough to be ideal for the Pelton wheel turbine. The flow rate is low as well, although if I had larger piping the flow rate would be higher, since the radius of the pipe would be larger. If I were going to implement a reaction turbine like the propeller turbine, I would have used larger tubing to gain that flow rate. However given my location, rocks and fallen trees prevented me from putting my generator anywhere submerged in the creek.

Now that I was able to generate power electrically through my generator, it makes sense to look at how efficient my generator actually was. To do this I need to compare the power that I generated electrically to the water power. To calculate the water power I did the following:

$$Power = \frac{Energy}{Time}$$

$$Energy = \frac{potential\ energy}{time} = \frac{mgh}{\Delta t} = \rho\left(\frac{V}{\Delta t}\right)gh$$

$$\frac{V}{\Delta t} = Flow\ rate\ (Q) \qquad h = head$$

$$Water\ Power\ = \ \rho Qgh = \left(997\frac{kg}{m^3}\right)\left(1.99\ x\ 10^{-3}\frac{m^3}{s}\right)(9.8\frac{m}{s^2})(5\ m)$$

$$Water\ Power\ = 97.22\frac{kg \cdot m^2}{s^3} = 97.22\frac{J}{s} = 97.22\ W$$

With the water power and the electrical power then, I can calculate the efficiency of my generator using: $\eta = \frac{P_{electric}}{P_{water}} = \frac{2.90\ W\ (Highest\ Peak\ Power)}{97.22\ W} = 0.0298\ or\ 2.98\ \%$ efficiency

Most well built generators operate around 85% efficiency but can reach 90 or even 95% efficiency under optimal circumstances. Noting that, the efficiency of my generator is definitely low. Of course, that is not unexpected given the design and turbine that I used to build it. The pelton wheel turbine alone is not optimal for electrical power output and this causes a big impact since regardless of the generator, the power of the water won't change in this set up. Given the problems with my own generator, the overall efficiency is not that surprising and there is a decent number of ways to increase the electrical power and overall efficiency of this generator.

Besides the turbine, the easiest ways to increase electrical power begins with making each of the half plates into full plates and aligned perfectly together. As I mentioned before, the inconsistencies of the plates and having to put two halves together creates a huge problem. If we had a bigger 3D printer then the plates should be much easier to align with each other and I could probably get them a lot closer. The closer that the magnetic field is to the coil, the more electricity can be produced. The problem too is making sure that everything is symmetrical, the coil plates need to be completely symmetrical and mirror each other and the magnetic plate in between needs to be aligned directly across from the coils. If the magnets were perfect and quite close to the coils that this should allow for an increase in electrical power.

Correcting these issues then allows for new ideas to bring the generator to new heights. One of the top ways to increase the voltage further is increasing the rotating speed. Since the water's velocity won't get changed the best way of going about this is to add some sort of gears. Gears can connect the turbine and the axle so that one revolution of the turbine can be equal to 2, 4, 8 or any number of spins of the axle and consequently the magnetic plate (depending upon the number and size of the gears). Adding gears and increasing speed will generate much more voltage.

Finally there are always improvements that can be made electrically in the wiring and connections. Using bigger wire sizes and making larger coils can increase the voltage and current tremendously. More turns in the coils will give you more voltage as will getting stronger magnets and increasing the size of the coils (all following Faraday's Law). The larger wire size has less resistance and higher capacities for current, so applying all these corrections will always provide you with more electrical power in a generator.

Given all these potential improvements it is still great to have been able to produce any electrical power at all. Through designing and building my generator I have learned so much about multiple different topics. I broaden any limited knowledge of fluids that I had, increased my understanding in engineering and design skills, learned how to use a variety of new and complex machines in the building process of my generator and was able to use much of my physics knowledge all along the way in a real application. This all came together in the culmination of being able to generate electricity even using a turbine that was not ideal for my situation. I produced at least 3 volts and almost 3 watts of power during my second set of testing. Even though I was not able to understand and fix the problems with the three-phase power, if I was able to start fresh with my second coil set up and better wirings I'm confident that eventually the problem would emerge and a solution along with it. Even still, comprehending the complex electrical processes that take place within three-phase power was intriguing and fun to try out. The journey that I took to the completion of this project was a satisfying and enjoyable one that helped to solidify my knowledge of physics and all the skills I've learned during my time at Bard.

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