2013

Axial Flux Permanent Magnet Generator

ME 495

NICK BANNON, JIMMY DAVIS & ERIN CLEMENT

UW ME | University of Washington

Executive Summary

The goal of this project was to design and manufacture a submersible generator that could be mounted to the preexisting micro power helical tidal turbine. The budget for the project was $3,000. The generator had to be capable of producing 1 kW of power with a 48 V output in order to limit the current and heat produced. To accompany this, the generator needed to be more efficient than the WindBlue generator that was previously used, which operated at around 60% efficiency. Furthermore, no external power could be used in the system. This ruled out any doubly fed designs immediately.

After considering an array of generator designs, an axial flux permanent magnet design was elected. This design was chosen because it is easier to manufacture and also potentially easier to adapt to a submerged setting. After initial electrical calculations and researching what size stock magnets could easily be acquired, neodymium magnets with and OD of 14” and an ID of 8” were elected. These were the largest percent of the overall cost, however, they provided a very strong magnetic field.

Since the efficiency of an axial flux generator is inversely proportional to the air gap to the fourth power, the goal of the assembly was to be able to achieve the smallest air gap possible. To get a small air gap, it was necessary to have very sound alignment mechanisms built into the design. As a result, a design was produced that aligned itself as it was assembled.

The assembly of the generator went smoothly and all the alignment mechanisms that were built into the design worked exactly as planned, which allowed for the air gap to be adjust from around 10 mm down to 0 mm. Because of an unexpected issue with potting the coils, however, the smallest air gap that was achieved was about 7 mm. If the coil potting had gone as planned it is likely that the desired air gap of 3 mm (1 mm of epoxy on both the coils and magnets and 1 mm free space) would have been attainable.

Initial test run on the generator concluded that, under the operating conditions it would be subject to with the turbine, the generator was capable of producing 12 V. This is less than what was hoped for, but it must be kept in mind that the air gap was 7 mm as opposed to 1 mm. Since the voltage produced is highly dependent upon the air gap it is likely that a higher voltage could be achieved with a very small air gap.

Due to time constraints it was not possible to run all of the tests necessary in order to determine the efficiency of the generator. Additional tests on voltage and current at predicted optimal resistance and various air gap settings would have been helpful in determining the true electrical performance of the machine.

Although time was short and not all of the testing required was performed, it is believed that the overall design of the generator is sound. There are a few modifications which could improve the design for future iterations. These modifications include enlarging the bulkhead design and making it removable, revising the bearing configuration and using corrosion resistant materials for a production model.

Table of Contents

Introduction/Motivation

The objective of this project was to build a generator which could supply power to underwater testing equipment in Admiralty Inlet. The key feature of this generator design was that it be submersible. Originally, the plan had been to make the system operational in seawater, however due to time constraints it was decided to build a prototype which would only need to operate in freshwater. The thought behind this was that the need to select and machine materials based on saltwater corrosive effects, and extended operating lifetimes would not need to be taken into account. The generator was constrained by the need to fit beneath the profile of the existing Sea Spider platform as well as couple to the shaft of the existing helical turbine system. The goal was to achieve efficiency at average operating water speeds that exceeded the existing air-operating generator, greater than 60%. The weight of the generator was not a major concern in this design process. The generator was designed to output 3-phase AC power. The rectification and connection to the battery bank was beyond the scope of this project.

Technical Specifications & Design

Turbine Operating Conditions

Early in the project, our team was given information regarding the water speeds at Admiralty Inlet as well as turbine specifications such as the coefficient of performance, optimal tip speed ratio, and dimensions of the turbine, as shown in Table 1

Table 1: Turbine parameters

U_{max}	2.5 m/s
Optimal TSR	1.4
C_p	16%
$D_{turbine}$	0.724 m
$H_{turbine}$	1.013 m
$A_{turbine}$	0.733 m^2

From this the peak rotational speed was calculated from the equation for tip speed ratio, with known radius and water speed,

$$TSR = \frac{R * \omega}{U_{max}}$$

where ω = 9.669 rad/s = 92.3 rpm.

Next, maximum power and torque were calculated as

$$P = \frac{1}{2}\rho U_{max}^3 A C_p = 1468\ W \text{ and}$$

$$T_{max} = \frac{P}{\omega} = 152\ N$$

where ρ = density of seawater = 1025 kg/m^3.

Using these parameters, the goal was to obtain an operating efficiency of greater than 60%, defined as the ratio of electrical power output to mechanical power input. These calculations were the basis for the electrical and efficiency calculations done throughout the project.

Generator Overview

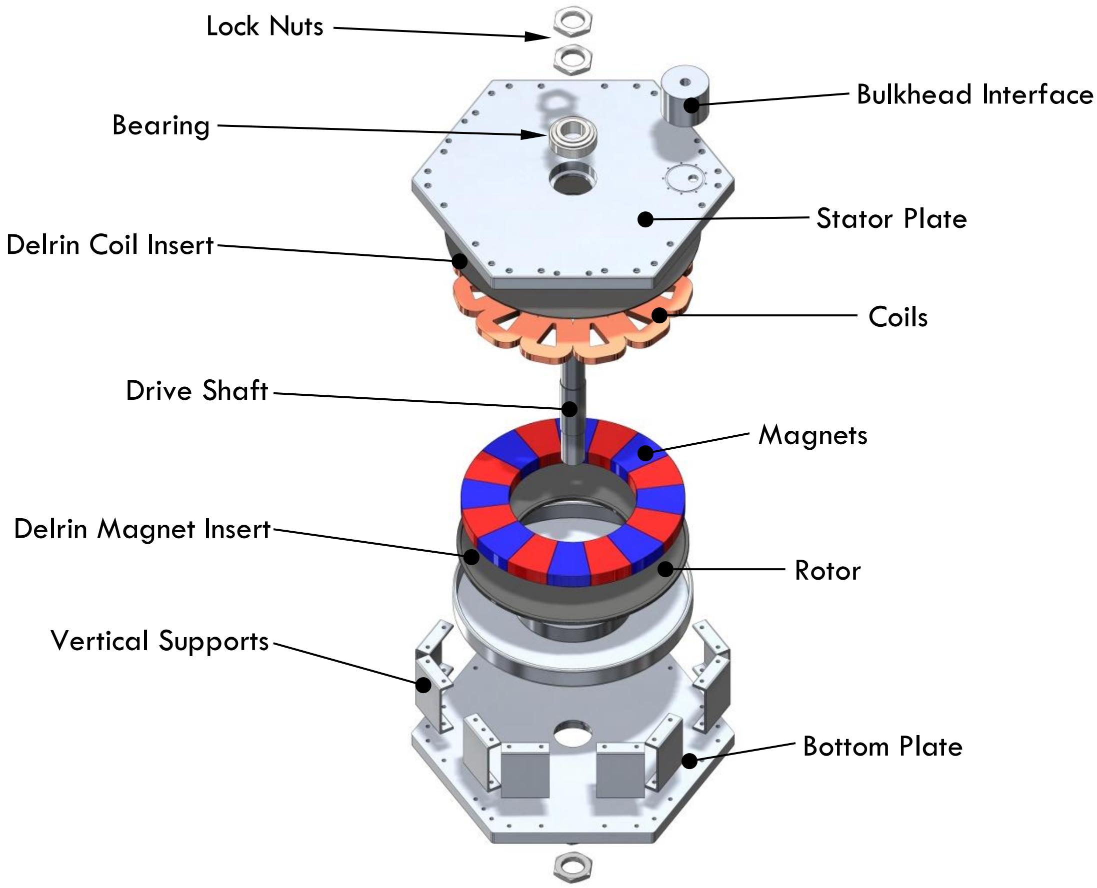

Figure 1: Exploded view of generator assembly.

The first step in the design was selecting the generator type. One of the biggest constraints was that there would be no external power source. An external power source, used to excite the motor at startup, is a key requirement for many types of generators. Without the external source, our choice of generator type was limited to a self-excited shunt generator or a permanent magnet generator (PMG). Shunt generators are more complex electrically and include both capacitors and inductors. For this reason, our team chose to move forward with the PMG. Another consideration for the generator type was whether to build a radial flux, or axial flux PMG. The radial flux would have required many concentric cylindrical parts, a cylindrical casing, cylindrical magnets, rotor etc. In an axial flux generator, also known as a pancake generator, the rotor is a flat disk of magnets which rotates on a shaft above a flat ring of stator coils. In analyzing the two design types, an axial flux PMG was chosen as our final design choice for reasons of simplicity, ease of manufacturing and cost of materials.

As described above, in an axial flux PMG, there is a rotor mounted with a ring of magnets. The rotor is connected to the generator shaft which is driven, in this case, by the helical turbine. The magnets on the rotor are arranged so that alternating north and south poles are perpendicular to the rotors flat top and bottom faces. The rotation of the rotor causes an alternating magnetic field at a given point above or below the rotor. In our design, we have the stator ring, a flat plate, with a ring of copper coils situated above the rotor. The alternating magnetic field from the rotor induces a voltage in the coils of the stator. The higher the number of turns in the coils, the higher the voltage that will be induced. Also, the closer the magnets are to the coils, the higher the voltage that will be induced. Magnetic flux density drops off with the square of the distance, so it is important to reduce the air gap between stator and rotor for better efficiency. And finally, the faster the rotor spins, the faster the magnetic fields are switched, the higher the voltage that will be induced. Voltage is a function of speed, while current is a function of torque. The higher the torque, the higher the current that is produced. In order to control the turbine connected to the generator, the resistive load can be changed. The lower the resistance, the higher the current and torque that will be produced. Efficiency is affected by the weight of the rotor and shaft, as well as the resistive losses in the copper coils, the frictional losses in the bearings and the viscous drag losses from rotating in water. These are the basics of axial flux PMG operation.

Electrical

Magnet Selection

In an early stage of the design, two types of magnet configurations were considered, a traditional array with north and south poles alternating each magnet in the ring, or a Halbach Array. The Halbach Array is a configuration of magnets that restricts most of the magnetic field to one side of the ring, which would improve the efficiency of the generator. However, it is achieved by arranging the magnets in a fashion so that the north and south poles are no longer in contact with each other, meaning there would be a lot of magnetic resistance to get the ring to remain aligned. The Halbach arrangement is more like a puzzle, since the magnets are each cut with their magnetic fields in different orientations, and the ring does not want to hold together on its own. Because of the difficulty to assemble, as well as being more challenging to source magnets to meet the needs of the design, our design utilized a traditional magnet array. Magnet selection was a very important step in the design of our generator. The magnets were the most expensive, and difficult to customize part of the design. For this reason and to address time constraints, it was desirable to source stock, rather than custom, magnets. This decision constrained the rest of the design of the generator to build around the magnets. Because of the importance of magnetic field strength, rare earth magnets, samarium-cobalt and neodymium-iron-boron, were most appropriate. However, because neodymium corrodes rapidly in salt water, we briefly considered using samarium-cobalt, even though it has a lower magnetic flux density. In the end, we chose the stronger neodymium magnets because, in our design, the magnets were coated in epoxy to protect them from corrosion or scratching, regardless of the magnet material. The magnets we chose to use were 1" thick, 14" outer diameter, 8" inner diameter magnets. The thicker the magnets, the stronger the magnetic field density would be at the coils. 1" was the thickest single magnet we could find. In ordering the magnets we found that the 1" were not available, so opted to stack ½" thick ring segments instead. As we found, the magnets are very brittle, and break easily. For example, a second pair of stacked ring segments was ordered to replace a pair that was damaged. Had we chosen to use a custom magnet, we would likely have not have had time to reorder the damaged pair.

Coils
Voltage induced is a function of the number of turns per coil, and the number of phases produced based on the 16 magnet ring configuration depends on the number of coils. These two considerations were kept in mind when deciding on the coil configuration for the stator. In order to produce 3-phases of power, which provides better efficiency than single phase, it was necessary to use 12 or 24 (or any multiple of 12) coils. With 24 coils, it would be possible to overlap three phases for every $1/8^{th}$ of a ring, but they would be too wide with the number of turns we wanted to lay one deep around the full ring. The other option would be to lay 12 coils, single depth, around the ring so that three phases covered ¼ of a ring. We chose this second configuration for ease of manufacture. The magnets and coils are arranged in a way so that the north side of every fourth magnet passes over the leading edge of every third coil. This way the 16 magnets and 12 coils produce 4 coils with each of the 3 phases. These phases are tied together into a y-configuration so that one side of each coil is tied to a neutral point at the center of the stator ring, while the other sides of each of the 4 coils containing the same phase are tied together. By having multiple coils with the same phase, the resistance due to the copper windings is reduced by combining the coil resistances in parallel. This also reduces the current in each coil, which will, in turn, reduce the heat losses. The y-configuration used to tie the coils together also provided higher voltage and lower current for the same power rating compared to a delta connection. Based on the magnetic flux density, and the desired voltage of 48 volts, the coils were wound with 150 turns. The voltage calculations can be seen in the Performance Estimates section below.

Mechanical

Materials Selection
To ensure that the generator assembly satisfied all the design constraints adequately and did not exceed the project's budget, the selection of materials was very important. Since the desired assembly was purely a prototype, it was not necessary to pay special attention to functionality in saltwater or longevity. This resulted in materials being easier to source and a reduction in cost.

For the bulk of the design, 6061 aluminum was decided upon as the material of choice. The aluminum parts consisted of the stator plate, the bottom plate, the rotor, and the vertical supports. 6061 aluminum was chosen for these parts since it is easy to machine, easy to source, nonmagnetic, and not terribly expensive. Since it is easier to machine, it allowed us to meet the desired tolerances more easily without having to have parts manufactured by a third party. Again, since the prototype was never intended to see use in saltwater, the poor corrosion resistance of 6061 aluminum was not of concern.

It was also necessary that the magnets and coils were able to be inserted and secured into the rotor and stator plate. This also required a material that was easy to work with, preferably with hand tools so that it could be modified while installed. This lead to the choice of Delrin for the inserts. Besides being easy to work with, Delrin provided insulation and good heat resistance, which would be desirable in the event that the generator short circuits.

To pot the magnets and coils, a high strength epoxy primarily utilized on boats was elected. This epoxy was a good choice since it has been proven to be effective in marine and freshwater environments and exhibits excellent adhesion to many surfaces, including aluminum alloys.

For the bearings, relatively inexpensive tapered steel roller bearings were purchased. Being steel, the bearings have extremely low resistance to corrosion in both fresh and saltwater. This was not a concern for this design though, as the main goals were to prove that the design was able to produce electricity and that the bearing alignment mechanisms were effective. A possible issue with the steel bearings, however, is that there could have been an interaction between them and the magnets. This is explained further in the Bearing Losses section.

Lastly, the material used for the fasteners had to be considered. For the fasteners it was desirable that they be able to be immersed in water for relatively short periods of time without corroding or seizing. To accomplish this, stainless hardware was used. Since stainless steel is not magnetic, this also ensured that the fasteners were not attracted to the extremely strong magnets. Corrosion between dissimilar metals was not considered for the fasteners because the prototype generator was not intended to endure long periods of time submerged.

Alignment Mechanisms

Because the efficiency is inversely proportional to the air gap between the stator and the magnets to the fourth power, it was imperative that this gap be minimized. In order to achieve this, the stator plate and the rotor had to be almost perfectly parallel. For an air gap of one millimeter, the maximum allowable angle between the two plates was less than about 0.3°. For the alignment to be this exact, the drive shaft also had to be almost perfectly perpendicular to the stator plate. To achieve such requirements, tight tolerances were necessary on many parts and sound alignment mechanisms had to be used.

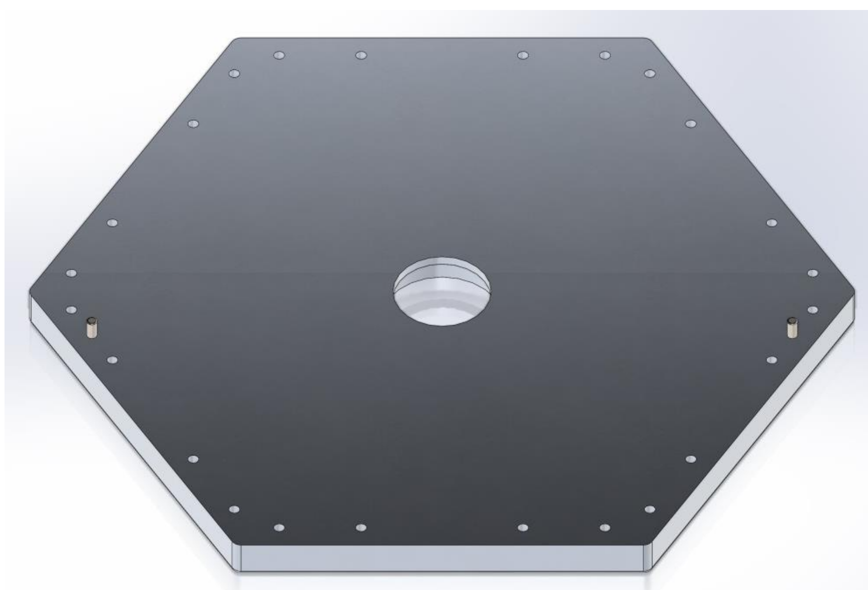

Figure 2: Bottom plate with dowels on left and right for location.

The method for aligning the two plates was pressed dowels, as shown in Figure 2: Bottom plate with dowels on left and right for location.. Dowel pins have extremely tight tolerances and since they are pressed, their positioning is guaranteed to be exactly where their holes were located. By putting two dowel pins on the stator plate and the bottom plate, it was possible to make the two bearing races almost perfectly concentric. This was done by aligning the two plates from the bearing races and then creating the dowel holes. Having the two races concentric ensured that the rotor would be perpendicular to the stator plate. This was further ensured by using tapered bearings, since, when they are loaded, they force concentricity in the design. With the drive shaft being assured to be perpendicular to the stator plate, the only remaining necessity was that the rotor be parallel to the stator plate. This was accomplished by shrink fitting the rotor to the drive shaft. Using a shrink fit made the rotor perpendicular to the drive shaft, and therefore parallel to the stator plate, and also created an interface between the rotor and the shaft that would not slip under torque.

For all of the methods previously listed to be feasible, very tight tolerances were required for certain dimensions. The dowel holes in the plates had to be a press fit, but not so tight that the dowels wouldn't press in. This required a the diameter of the holes to be accurate to about 0.001 inches, since an interference of about 0.001 inches was necessary. Then, to ensure that the stator plate and the top plate were parallel, which was necessary to make the bearing races concentric, the vertical supports all had to be extremely close in height. Similar to the dowel holes, the drive shaft and the rotor had to have around 0.001 inches of interference for the shrink fit to be effective, which meant both the drive shaft and the hole in the rotor had to be very accurately sized. Finally, the faces of the rotor and stator plate had to be flat. This tolerance was not quite as important as the others, so the factory finish on the stator plate aluminum sheet was acceptable.

Maintenance and Assembly
In both the prototype and final design, ease of maintenance is highly desirable. In the case of the prototype design, the ability to disassemble the generator and make alterations was necessary. Making the generator easy to disassemble/maintain required all bolts and nuts to be in accessible locations. Another necessity was a bulkhead power connection that was removable, which would allow the electrical portion of the design to be accessed after potting. This feature was not included in the prototype because it was not designed with longevity in mind.

Performance Estimates
Electrical Performance

Voltage
The voltage of the generator was calculated using Faraday's law as

$$V_{max} = \frac{NAB}{t}\ [V]$$

where *N* is the number of turns on the coils, *A* is the area of the coils, *B* is the magnetic flux density, and *t* is the time for a magnet to pass over the coil. The voltage in each phase is related to V_{max} as

$$V_{phase} = \frac{V_{max}}{\sqrt{2}}\ [V].$$

From these equations the voltage was predicted to be 50V at 92 rpm and optimal TSR. The calculations are included in Table 2: Maximum Voltage Calculation (Appendix A – Calculations). These calculations were repeated for various operating speeds as can be seen in Table .

Current

The current calculation was not as straight forward. Current is a function of the torque into the generator, but it is also a function of the electrical load. A number of methods were used in trying to predict current. Finally, it was decided that current was best calculated using the Torque equation on page 41 of Axial Flux Permanent Magnet Brushless Machines [1], which is as follows

$$T_d = 2\frac{p}{\pi} m_1 N_1 k_{w1} \varphi_f I_a,$$

where the variables involved in the calculation are defined as:

$T_d = torque\ developed = \frac{\frac{1}{2}\rho U_{max}^3 A C_p}{\omega}\ [N*m]$

ρ = density of seawater = 1025 kg/m^3

U = water speed

C_p= coefficient of performance = 16%

$A_{turbine}$ = swept area of turbine = 0.733 m^2

ω = rotational speed = 9.669 rad/s = 92.3 rpm

$p = number\ of\ pole\ pairs$

$m_1 = number\ of\ phases$

$N_1 = number\ of\ turns\ per\ phase$

$$k_{w1} = winding\ factor = \frac{\sin\left(\frac{\pi}{2m_1}\right)}{q_1 \sin\left(\frac{\pi}{2m_1 q_1}\right)} * \sin(\frac{\beta\pi}{2})$$

$$q_1 = number\ of\ slots\ per\ phase = \frac{s_1}{2pm_1}$$

$s_1 = number\ of\ stator\ slots$

$\beta = coil\ pitch\ to\ pole\ pitch\ ratio$

$$\varphi_f = \frac{B_{avg}\pi}{2p}(R_{out}^2 - R_{in}^2)$$

$I_a = current\ per\ phase$

These variable values can be seen in Table and calculations can be seen in Table 52. These results were fairly close to other current approximations done by approaching from the electrical side and predicting power first and backing out for current.

Power

Power was calculated by finding the mechanical power in and subtracting the predicted losses as described in Axial Flux Permanent Magnet Brushless Machines [1]. The mechanical power (P_{mech}), the ideal electrical power ($P_{e,ideal}$), and the actual electrical power (P_e) are given as

$$P_{mech} = \frac{1}{2}\rho U^3 A C_p,$$
$$P_{e,ideal} = P_{mech},$$
$$P_e = P_{e,ideal} - P_{loss}$$

where ρ is the density of the fluid the turbine is in, U is the fluid velocity, A is the turbine area, and C_p is the coefficient of performance. The losses are primarily from rotational loss (frictional losses in the bearing and viscous drag) and to a smaller degree from the resistance in the copper wires. Since our design does not utilize iron cores in the stator, magnet losses, eddy current losses and hysteresis losses were not considered. [1] gives a generic estimate for rotational losses in axial flux permanent magnetic generators as

$$P_{rot} = \frac{1}{2} c_f \rho (2\pi n)^3 \left(R_{out}^5 - R_{sh}^5\right) + 0.06 k_{fb} (m_r + m_{sh}) n$$

where the variables involved are as follows:

$c_f = coefficient\ of\ drag = \frac{3.87}{\sqrt{Re}},$

$Re = \frac{2\pi n \rho R_{out}^2}{\mu},$

μ = dynamic viscosity of salt water,

$R_{out} = outer\ radius\ of\ rotor,$

$R_{sh} = radius\ of\ shaft,$

$n = rotational\ speed\ in\ rpm,$

$m_r = mass\ of\ rotor,$

$m_{sh} = mass\ of\ shaft,$

$and\ k_{fb} = friction\ coefficient\ of\ the\ bearings.$

These calculations can be seen below in Table 63.

The other losses which played a less significant factor, but were still accounted for, were the copper losses, given by

$$P_{cu} = 3I^2R$$

where *I* is the phase current and *R* is the resistance in length of copper per coil, combined in parallel per phase. These calculations can be seen in Table 7. Subtracting the copper losses and rotational losses from the mechanical power in gives us the predicted power, out as seen in 8.

Electrical Efficiency

The electrical efficiency is the ratio of electrical power out to the mechanical power in. Based on the loss calculations described previously, the estimated efficiency ranges from 53% at turbine cut-in speed to 86% near the maximum speed. These calculations can be seen in Table and the results are shown below in Figure 33.

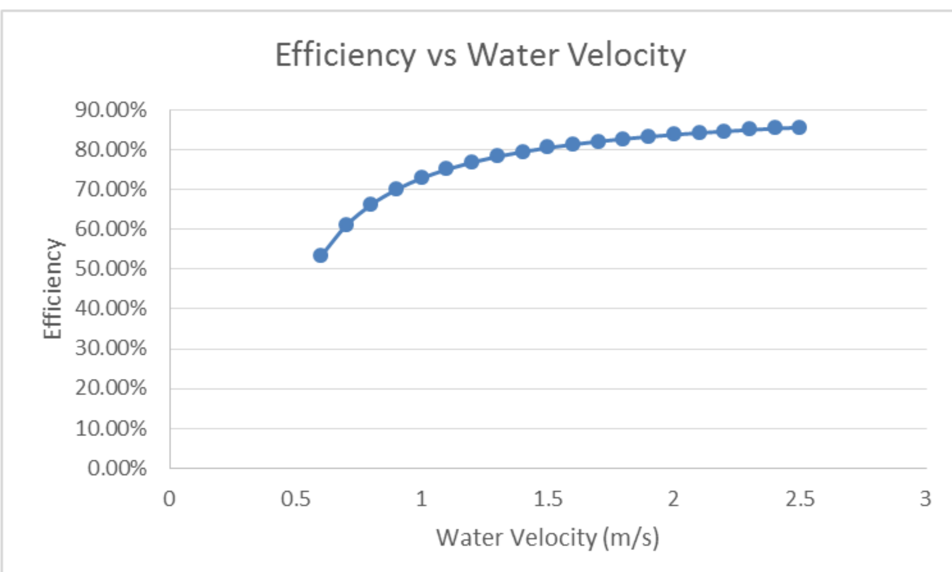

Figure 3: Efficiency as a function of RPM at optimal load

Mechanical Performance

There are two non-negligible mechanical factors that contribute to decreased efficiency. These two factors were viscous losses and bearing losses. These are included in the estimated rotational loss discussed previously, but are elaborated for the specific generator design in this section.

Bearing Losses

An estimate of the bearing losses was made using the coefficient of friction between steel and steel, such that torque from friction in the bearings was set equal to the load on the bearings multiplied by the fiction coefficient, and then multiplied by the bearing radius. For the expected rotation speeds of this generator, the losses using this estimate were approximately 0.5 W. Although bearing losses have not been quantified, turning the drive shaft by hand requires substantially more power than this. There are multiple things that may have added to this departure from the expected losses. First of all, it is probable that aluminum shavings and epoxy dust intruded into the bearings during manufacturing and assembly, making them run less smooth. Since the bearings were not particularly high quality, it is also possible that the rollers were not perfectly cylindrical or the rollers did not run solely on the races. Another possibility is that the steel bearings interacted with the magnets, increasing the load so that it was greater than the mass of the rotor. These factors would increase the friction relative to the idealized calculation.

Viscous Losses

The viscous losses were evaluated assuming the flow between the rotor and the stator plate was a simple cylindrical Couette flow. This is a very reasonable assumption since the gap between the two plates is so small. This ensures that the flow is laminar for a very large range of rotational speeds since the Reynolds number with the water gap as the critical length scale ($\mathrm{Re_d} = \frac{\rho\omega r d}{\mu}$) remains small due to the small value of d (the air gap) in the denominator. As a result, the viscous torque on the rotor can be written as

$$\mathrm{T} = \frac{2\pi\mu\omega}{\mathrm{d}}({r_2}^4 - {r_1}^4)$$

where r_2 is the outer radius of the rotor and r_1 is the radius of the drive shaft. In this equation, it can be seen that the viscous torque is proportional to r^4/d when $r_2 >> r_1$. In Figure 4, below, the relationship is plotted for varying air gap and rotor radius.

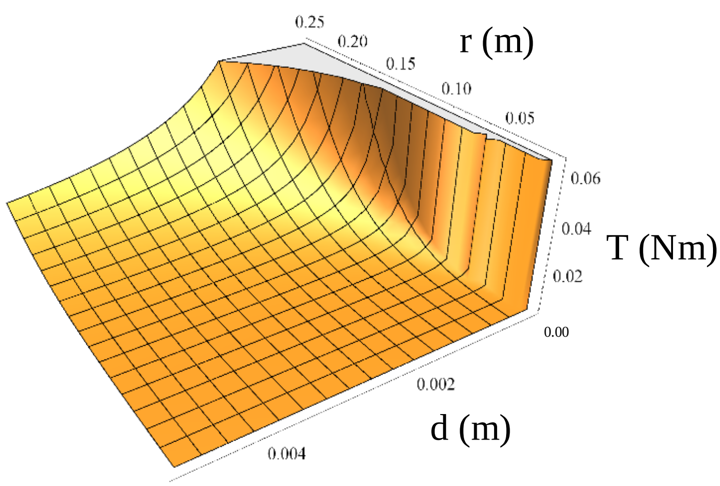

Figure 4: Plot of the viscous torque on the rotor vs. the air gap size (d) and the rotor radius (r).

This plot provides a visualization of how the viscous torque behaves depending on the two most controllable constraints for the generator. Knowing the viscous torque and the angular velocity, the viscous losses can easily be calculated as the viscous torque times the angular velocity. For the speeds the turbine operates at with the intended air gap of 1 mm, the viscous losses are on the order of less than 1 W. Since the viscous losses are so small, they can be considered negligible. This is made especially true by the fact that the generator is intended to produce around 1 kW and the fact that the efficiency is inversely proportional to the air gap to the fourth power. For a more in depth examination of the viscous torque see “Analysis of Fluid Flow in a Submerged Generator” [7].

Testing

Tolerances were a significant part of this project and were required to be exact the generator to run efficiently. Due to the high tolerances, each part had to be tested after manufacturing and prior to component assembly. Once assembled, tests were then conducted to check tolerances and possible failure modes. The primary components were the bottom plate, stator plate, rotor, driveshaft, and vertical supports. Sub components included the magnet ring, the coils, the bulkhead connector, and the Delrin inserts.

For the bottom and stator plates, the highest tolerances were placed on bearing and dowel alignment. For this reason, we first machined the bearing holes. Using the bearings and a small piece to mimic a tight-fit shaft, we then drilled the dowel holes. This process resulted in exact alignment of the two plates relative to the bearings. The remaining vertical supports were loose fits to make assembly easier.

The rotor and driveshaft were to be assembled using a shrink-fit procedure, so the tolerances had to be exact in order for the fit to happen easily and the remaining union to be completely secure. Calculations were done to estimate the change in shaft diameter when placed in dry ice, and rotor diameter when placed in the oven. They were done as follows:

> linear expansion rate of aluminum: $\alpha = 13.0$ µin/in °F
> Shaft temp in dry ice: 10 °F (measured with IR camera)
> Rotor temp in oven: 450 °F
> Room temp: 70 °F
> $D_f = D_i + \Delta D = D(1 + \alpha\,\Delta T)$

We wanted the transition of the shaft into the rotor to have 0.004” clearance during the shrink-fit procedure since we would be doing it by hand without the ability to use a mechanical press. Using this equation, we expected that an initial interference of 0.0017” would provide us with this result. Based on shrink-fit tolerance tables, an interference ranging from 0.0007”-0.0023” would give us the desired union after the shrink-fit was done. Comparing our calculations to the tables, we decided to try the shrink-fit with 0.0017” interference. The result was a tight fit that put us in danger of getting the shaft stuck halfway into the rotor. Instead of losing both parts, we aborted the shrink-fit process and machined the parts down such that the interference was 0.0007”. This was at the low end of our allowance, but it resulted in a successful union of the two parts.

Before inserting the ring of magnets, we had to be sure that the rotor spun perfectly true. Using a perfect square, we determined that the rotor was roughly perpendicular to the shaft, and symmetric all around. To confirm this more accurately, we inserted the rotor/shaft assembly into the bearings between the top and stator plates. The rotor spun true, confirming our assumptions. After the magnet ring was inserted into the rotor and potted in epoxy, the same test was performed and confirmed that the surface of the rotor was flat and did not deflect from the weight of the magnets.

The coils were a large area of concern since they would be completely inaccessible and unserviceable once potted in epoxy. Therefore, before potting the coils in epoxy, we performed a series of tests to ensure that all coils were connected properly and that there were no shorts in the circuit. The possible failure modes for the stator included a bad neutral connection, which would remove one or more coils from the circuit, scraping of the coils, which would present a short circuit, or bad connections in the bulkhead connector, which would also remove one or more coils from the circuit.

The coils were epoxied in place on the Delrin disk to maintain alignment and positioning, but the majority of the stator was left exposed, including the wire connection points. The generator was then assembled completely, but inverted such that the ring of coils wouldn't fall out of the stator. With a large air gap to prevent the rotor from scraping the surface of the coils, the rotor was spun to test the electrical output. Consistent voltage from phase to phase told us that all of the coils were connected in the circuit, and when short circuiting the phases, increased resistance was felt, which told us that the open circuit condition was not shorted. After gathering this data, we proceeded to pot the entire stator in epoxy, completing the stator assembly.

Testing of the entire system confirmed successful designs and revealed areas of improvement for future designs. It was immediately noticeable that the bearing configuration would lead to efficiency and lifecycle problems. The way the bearings are arranged currently allows for the generator to be run on any axis. The two tapered roller bearings inserted from either end transfer the load from one bearing to the other equally when the generator is inverted. Our tests have now confirmed zero deflection in the rotor from the weight of the magnets, so it would advantageous to select an orientation for the generator and use a combination of thrust bearings to hold the load of the rotor and roller bearings to align the shaft.

The question of how efficient the generator can possibly be still lingers, however. As a result of an unexpected issue with potting, the generator was not tested with the smallest air gap possible. Even with this air gap being larger, it is believed that the voltage is lower than desired. Something which was considered to be a potential reason for this lower voltage was the fact that the coils are not negligibly thick. Voltage was calculated assuming an air gap of 7mm during the initial test, however the thickness of the coils is slightly more than 10mm. If the average depth of the coil, approximately 5mm, were added to the 7mm air gap, this could partially account for the lower voltage readings. This meant the only data produced was intended as an initial test to determine whether the generator behaved as expected or not. After further tests are conducted in the future to prove the efficiency of the generator design, the next steps of the project can be considered.

The lifecycle of this generator will be limited by the life of the bulkhead connector. Due to the installation configuration of the bulkhead connector, it is unserviceable. If it does fail, it would have to be cut away from the stator to remove it, and a new connection would have to be made and sealed. As far as the other sensitive components, the coils have been designed to minimize risk of overheating and melting, the magnets have been potted in epoxy to prevent corrosion, and the steel roller bearings may corrode when tested under water, but are replaceable.

The electrical tests that were performed yielded results confirming that three phase current and voltage were produced. Unfortunately additional tests were unavailable due to time constraints and a last minute problem in setting the epoxy on the coils. The tests that were performed were variable load and variable speed with magnet and coil separation of approximately 7mm. As a result, the power produced was much lower than expected.

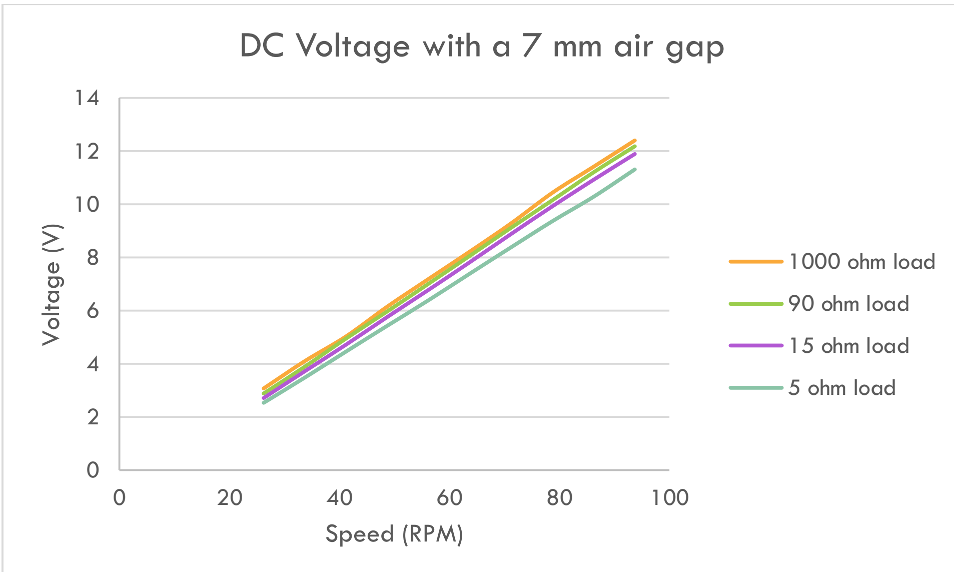

Figure 5: DC voltage as a function of RPM and load

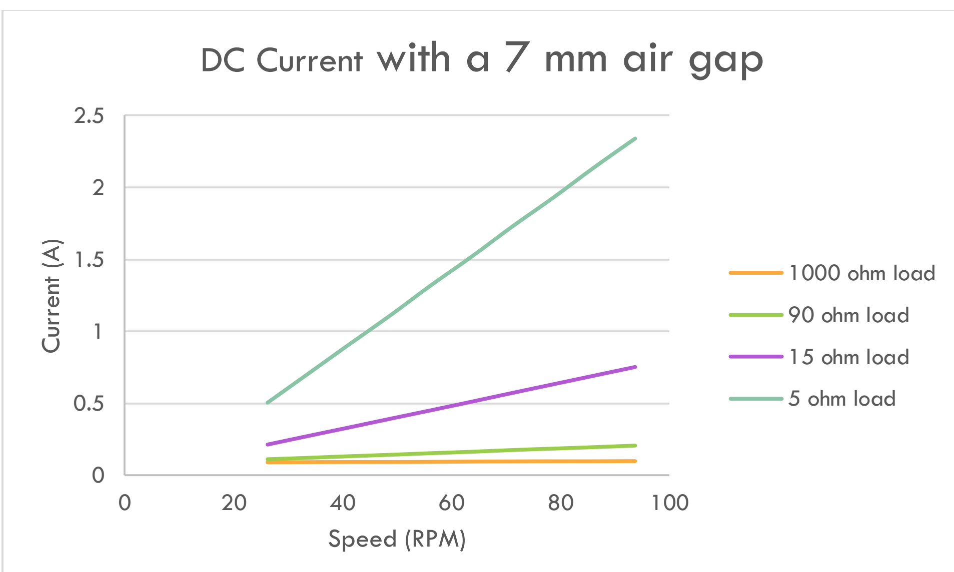

Figure 6: DC current as a function of RPM and load

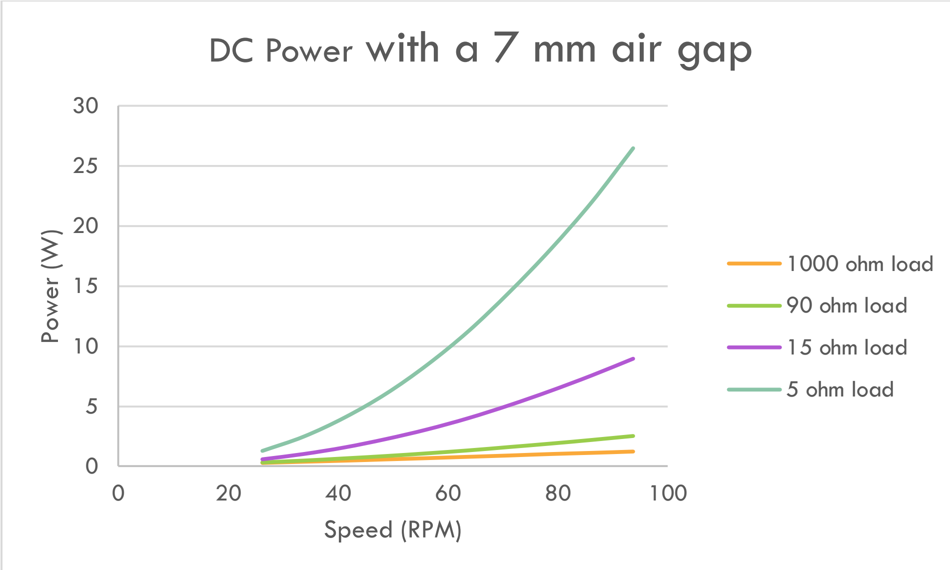

Figure 7: DC Power as a function of RPM and load

Risk & Liability

The hazards present when working with the generator involve strong magnetic flux, rotating parts and high voltages. The generator was designed with assembly in mind, which means it is easy to insert your hand within the body of the generator. If this is done while the generator is spinning, your hand will not be able to resist the inertial rotation of the rotor, and will likely be spun against the surrounding vertical supports. Injury is likely from this scenario. The rotor also contains a solid ring of neodymium 42 magnets, which are very powerful. The magnetic flux falls off quickly with distance, and is negligible at a distance of 12 inches. When working with the generator, especially when assembling and disassembling, it should be noted that anything ferrous will be drawn to the rotor with great force. Hence Stainless steel tools are recommended. Magnets will also affect cell phones, credit cards, and pacemakers, so these items must be kept away from the generator. Finally, the generator is designed to generate low current and high voltage and there are no exposed wires from the generator to present direct contact risks. Nonetheless, when spinning, the generator can produce voltage and current high enough to be possibly fatal and cause harm to sensitive equipment. Connections also must be secure, especially when testing underwater.

Ethical Issues

Sourcing Materials

The greatest ethical issues regarding this project often have environmental impacts. It is difficult to address some of these issues as separate.

Sourcing materials, especially rare earth magnets, pose both ethical and environmental concerns. The ethical concerns presented include the fact that rare earth metals are being harvested at an alarming rate, and that we may soon find ourselves in short supply. In fact, mining in the US has declined sharply as China's ability to harvest these materials for less money has grown [2]. Essentially, the US and other developed western nations are pushing the dirty and dangerous business of mining these high demand materials to areas of the world where labor is cheap, and safety of workers is not as closely monitored. Any time we purchase goods, there is an ethical implication. Where did the materials come from? How were the workers paid and treated? Are we purchasing based on the lowest cost, or taking into account where the products come from? For our project, in the R&D phase, we only purchased small quantities of materials for use in our generator. Purchasing in small batches raises the price dramatically, so cost was of the highest concern in ordering our materials. However, if this project were to be developed into a production unit to be sold on the market, a more careful consideration of magnet sourcing would be required.

Impact on Society

Advancement in Tidal Turbine Applications

The largest impact on society that the technology from this project poses is in the area of the advancement of tidal power. The generator design that was explored mitigates a few of the issues associated with typical tidal setups, such as the need for seals to protect the generator from water. By addressing these issues, the design could potentially lower the cost of energy. It would do this by increasing the efficiency of the generator and making tidal turbines easier to build and easier to install. Lowering the cost of energy could potentially help sway the energy market away from non-renewable energy sources like coal. Doing so would have a positive impact on the environment, which is closely related to society in this day and age.

Impact on the Environment

Wildlife

The obvious wildlife implication is whether fish and marine mammals could be harmed by the turbine blades, like birds and bats are harmed by wind turbines. Research conducted here at the University of Washington has shown that the speed of the blades is low enough that fish are not generally harmed by rotating blades, but rather carried through on the current [3]. Another area of concern would be the sound that is produced by the turbine and associated electrical equipment. Cetaceans in particular are very sensitive to underwater noise, and a tidal system could affect their behavior.

Carbon Reduction

Because tidal turbines are replacing conventional methods of energy generation, they do have an effect on carbon reduction. In the case of our project, the carbon reduction would be minimal, since the generator was rated for only 1 kW. If the machine were to run 1/3 of the time, it would produce less than 3,000 kWh worth of electricity over a year's time. Since we live in Seattle and over 98% of our electricity comes from hydro powered facilities, we really wouldn't be affecting carbon here. But in other areas of the country where coal is the main source of fuel, this could reduce CO_2 by as much as 6,000 lbs per year according to the EIA [5]. To put this in perspective, almost 20 lbs of CO_2 are produced per gallon of standard motor fuel. An average driver uses about 500 gallons per year, which is about 9,500 lbs of CO_2. Our system in a coal burning region would be like taking one low mileage driver off of the road each year. Of course larger scale systems will have greater impacts.

Cost & Engineering Economics

After meeting all of our design requirements, our final consideration for the design of the generator was a budget of $3,000. To achieve this, we had to minimize the amount of custom orders and maximize the amount of work that we could do ourselves in the machine shop on campus. Since our time was “free”, we wanted to make as many parts as possible. We knew that the magnets were going to be the most significant cost in the project, so the first task was determining if we could find stock magnets that would fit our design requirements. Stock magnets would not only be less expensive, but they would take less time to order and ship, and would allow us to order replacements if needed. We were successful in sourcing such magnets, and the rest of the prototype design was adjusted to fit these magnets.

Once the initial prototype was modeled, we sourced all of our material and estimated a capital cost of $4358.84, putting us significantly over budget. Plotting out the capital cost, it became easy to see the significant cost contributions in the design.

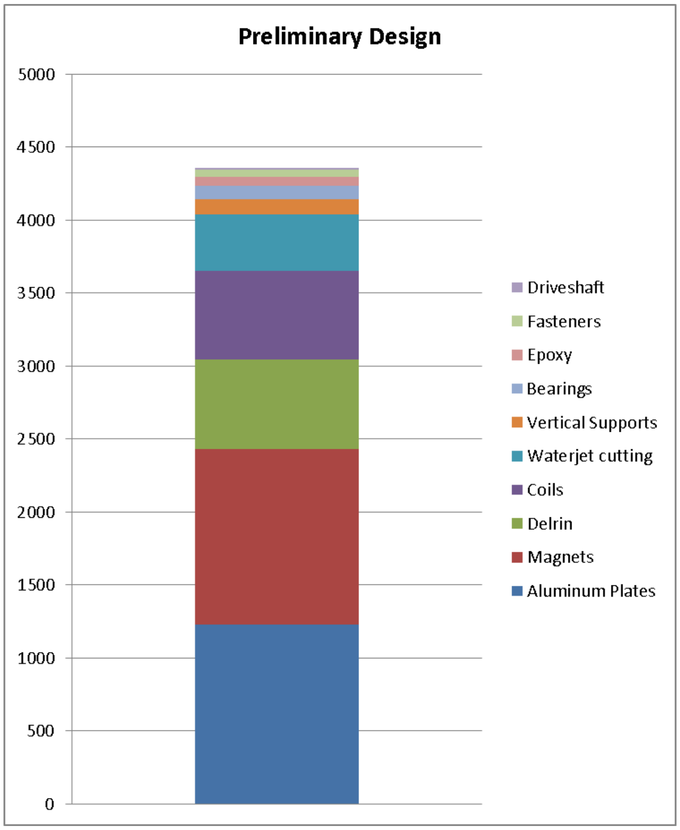

Figure 8: Preliminary design capital cost

To move the project forward, we needed to alter the design to lower cost. We had not anticipated such high cost for aluminum or Delrin, so these became obvious places to start. Reducing the size and amount of Delrin allowed us to downsize the entire generator. Also, a change in the vertical support design allowed us to utilize U-channels instead of solid blocks of aluminum. By the end of the process, we had cut costs in almost all areas, including finding a less expensive source for magnets. The following chart compares capital cost between our preliminary design, and the revised design which we manufactured. Included on the chart is the cost for water jet cutting of the aluminum plates by DaVinci’s, which became necessary due to the size constraints of the CNC mills in our shop. Excluding the water jet cost, which was a cost of machining, we were under budget by $58.50 for materials. In total, the project capital cost was $3,328.46, which was a 24% cost reduction from our preliminary design.

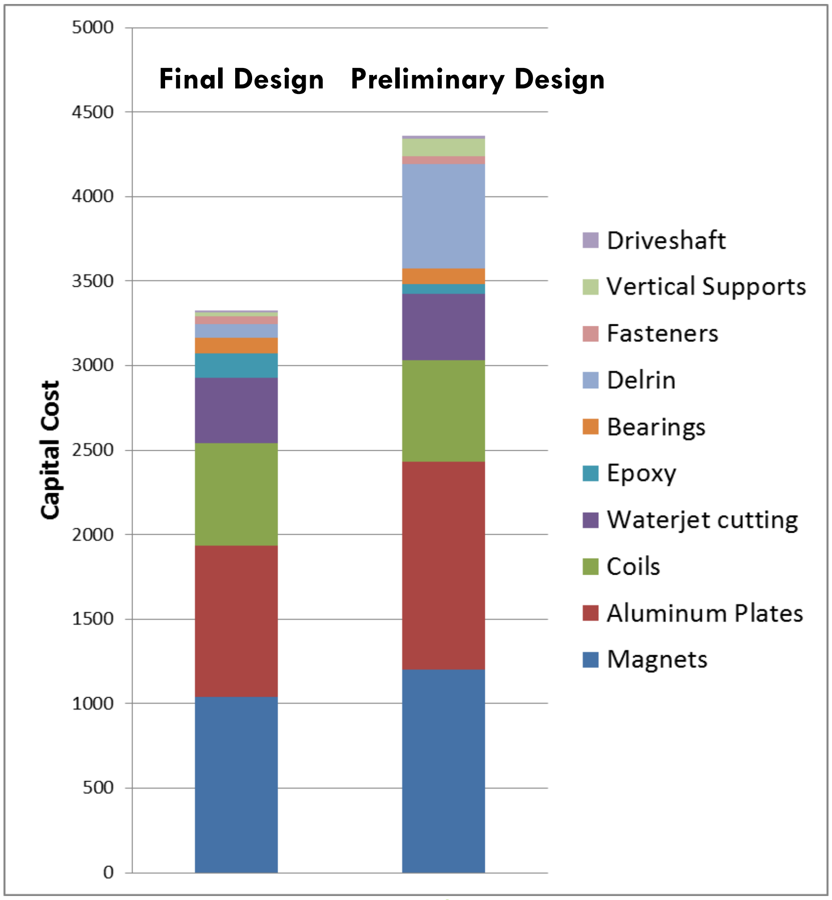

Figure 9: Capital cost comparison between final and preliminary designs

Machining costs for this project included water jet cutting of the stator and bottom plates, and coil windings. Professional staff helped with the machining of the rotor, stator plate, and driveshaft threading because of the size of the parts and need for the CNC mill and lathe to meet tolerances. Professional staff time was approximately 5 hours, in comparison to 27 hours for the design team. The team spent another 40 hours working on assembly of the components and final generator. Many more hours were spent on designing the generator, the manufacturing processes, and the assembly procedures, which would be non-recurring engineering costs. For a typical project, all of these hours would be charged and accounted for in the manufacturing costs. Using shop rates of $60/hour, this would add $4320 to the cost of this generator. However, we can also assume that future generators will take less time to produce as manufacturing and assembly methods are refined. For example, a second generator would probably require 40% less time than the initial one. In total, the cost to replicate this generator, including material and manufacturing costs comes to $5920.

Conclusions & Future Recommendations

This project demonstrated that it is possible to build a prototype submersible generator on a budget of $3,000. Most importantly, it proved that the dowel alignment method with at least one tapered bearing can effectively position the rotor above the stator with a very minimal air gap and no play in the rotor. As a result, it can be concluded that the same general alignment methods can be reused for future designs with slight modifications.

Of all the issues with the design, the bearing configuration was possibly the most problematic. Due to the bearing configuration, the entire weight of the rotor was placed on the upper bearings. This resulted in a very large amount of resistance from the bearings. After spinning the rotor, it would do a quarter rotation at most once allowed to spin freely. This causes two problems: the efficiency is decreased from excessive bearing losses and the upper bearing will wear quickly. A possible remedy for this that could be implemented in future designs is replacing the lower bearing with a pure thrust bearing accompanied by a radial bearing. The thrust bearing would reduce loads on the upper bearing, allowing the rotor to spin more freely. Loading the tapered bearing on top slightly would then ensure that the rotor was perpendicular to the stator plate.

If the generator is indeed efficient enough, then a final design that can be used with the micro power turbine can be perused. This design would make use of highly corrosion resistant materials as well as removable coils and magnets.

Appendices

Appendix A – Calculations

Phase	3
number of coils per phase	4
turns per coil	150
N - number of turns	1800
A_coils - Area (m^2)	0.005573782
rpm	92.3
B_airgap - (Tesla)	0.291
t - time (s) to rotate	0.04
V_Max	71.85978726
|V| per phase (V)	50.81254287

Table 2: Maximum Voltage Calculation

U (m/s)	rpm	Voltage (V)
0.6	22.2	12.20
0.7	25.9	14.23
0.8	29.5	16.26
0.9	33.2	18.30
1	36.9	20.33
1.1	40.6	22.36
1.2	44.3	24.40
1.3	48.0	26.43
1.4	51.7	28.46
1.5	55.4	30.50
1.6	59.1	32.53
1.7	62.8	34.56

1.8	66.5	36.60
1.9	70.2	38.63
2	73.9	40.66
2.1	77.6	42.70
2.2	81.2	44.73
2.3	84.9	46.76
2.4	88.6	48.79
2.5	92.3	50.83

Table 3: Voltage as a function of water speed

m1	3
p	8
N1	600
k_w1	2
phi_f	0.001216
B_mg	0.291
R_o	0.1778
R_i	0.1016
N	1800
A_magnet	0.005574
n	16
R_cop	0.11133
k_d1	2.309401
k_p1	0.866025
q1	0.25
s1	12
Beta	1.333333
w_c	0.009975
tau	0.007481

Table 4: Variables for Current using Torque Eq

U (m/s)	rpm	T_mechanical (N-m)	Current_pred (A)
0.6	22.2	5.60	0.23
0.7	25.9	7.62	0.31
0.8	29.5	9.95	0.40
0.9	33.2	12.59	0.51
1	36.9	15.54	0.63
1.1	40.6	18.81	0.76
1.2	44.3	22.38	0.90
1.3	48.0	26.27	1.06
1.4	51.7	30.46	1.23
1.5	55.4	34.97	1.41

1.6	59.1	39.79	1.61
1.7	62.8	44.92	1.81
1.8	66.5	50.36	2.03
1.9	70.2	56.11	2.26
2	73.9	62.17	2.51
2.1	77.6	68.54	2.77
2.2	81.2	75.22	3.04
2.3	84.9	82.22	3.32
2.4	88.6	89.52	3.61
2.5	92.3	97.14	3.92

Table 52: Current Calculations using Torque Eq

U (m/s)	rpm	P_rot (W)
0.6	22.2	6.01
0.7	25.9	7.95
0.8	29.5	10.24
0.9	33.2	12.90
1	36.9	15.95
1.1	40.6	19.42
1.2	44.3	23.33
1.3	48.0	27.69
1.4	51.7	32.52
1.5	55.4	37.85
1.6	59.1	43.68
1.7	62.8	50.04
1.8	66.5	56.94
1.9	70.2	64.40
2	73.9	72.43
2.1	77.6	81.05
2.2	81.2	90.27
2.3	84.9	100.11
2.4	88.6	110.58
2.5	92.3	121.69

Table 63: Rotational Loss Calculations

U (m/s)	rpm	Current_calc (A)	P_copper (W)
0.6	22.2	0.23	0.05
0.7	25.9	0.31	0.09
0.8	29.5	0.40	0.15
0.9	33.2	0.51	0.23
1	36.9	0.63	0.36

1.1	40.6	0.76	0.52
1.2	44.3	0.90	0.74
1.3	48.0	1.06	1.02
1.4	51.7	1.23	1.37
1.5	55.4	1.41	1.80
1.6	59.1	1.61	2.33
1.7	62.8	1.81	2.97
1.8	66.5	2.03	3.73
1.9	70.2	2.26	4.64
2	73.9	2.51	5.69
2.1	77.6	2.77	6.92
2.2	81.2	3.04	8.33
2.3	84.9	3.32	9.95
2.4	88.6	3.61	11.80
2.5	92.3	3.92	13.89

Table 7: Copper Losses

U (m/s)	rpm	P_mechanical (W)	P_rot (W)	P_copper (W)	P_electric (W)
0.6	22.2	12.98	6.01	0.05	6.92
0.7	25.9	20.62	7.95	0.09	12.58
0.8	29.5	30.77	10.24	0.15	20.39
0.9	33.2	43.82	12.90	0.23	30.68
1	36.9	60.11	15.95	0.36	43.80
1.1	40.6	80.00	19.42	0.52	60.06
1.2	44.3	103.86	23.33	0.74	79.80
1.3	48.0	132.05	27.69	1.02	103.35
1.4	51.7	164.93	32.52	1.37	131.04
1.5	55.4	202.86	37.85	1.80	163.21
1.6	59.1	246.19	43.68	2.33	200.18
1.7	62.8	295.30	50.04	2.97	242.29
1.8	66.5	350.54	56.94	3.73	289.86
1.9	70.2	412.27	64.40	4.64	343.23
2	73.9	480.85	72.43	5.69	402.72
2.1	77.6	556.64	81.05	6.92	468.67
2.2	81.2	640.01	90.27	8.33	541.40
2.3	84.9	731.31	100.11	9.95	621.24
2.4	88.6	830.91	110.58	11.80	708.52
2.5	92.3	939.16	121.69	13.89	803.57

Table 4: Predicted Power Output

U (m/s)	rpm	P_mechanical (W)	P_electric (W)	Efficiency
0.6	22.2	12.98	6.92	53.32%
0.7	25.9	20.62	12.58	61.00%
0.8	29.5	30.77	20.39	66.25%
0.9	33.2	43.82	30.68	70.02%
1	36.9	60.11	43.80	72.86%
1.1	40.6	80.00	60.06	75.07%
1.2	44.3	103.86	79.80	76.83%
1.3	48.0	132.05	103.35	78.26%
1.4	51.7	164.93	131.04	79.45%
1.5	55.4	202.86	163.21	80.46%
1.6	59.1	246.19	200.18	81.31%
1.7	62.8	295.30	242.29	82.05%
1.8	66.5	350.54	289.86	82.69%
1.9	70.2	412.27	343.23	83.25%
2	73.9	480.85	402.72	83.75%
2.1	77.6	556.64	468.67	84.20%
2.2	81.2	640.01	541.40	84.59%
2.3	84.9	731.31	621.24	84.95%
2.4	88.6	830.91	708.52	85.27%
2.5	92.3	939.16	803.57	85.56%

Table 9: Predicted Efficiency

Appendix B - References

[1] Gieras, Jacek F., Rong-Jie Wang, and Maarten J. Kamper. *Axial Flux Permanent Magnet Brushless Machines*. Dordrecht: Kluwer, 2004. Print.

[2] Bourzac, Katherine. "The Rare-Earth Crisis." *MIT Technology Review*. N.p., 19 Apr. 2011. Web. 14 Dec. 2013

[3]"Calculating Tidal Energy Turbines' Effects On Sediments and Fish." *ScienceDaily*. ScienceDaily, 02 Jan. 2011. Web. 13 Dec. 2013

[4] Whiticar, MJ. "Tidal." *EnergyBC: Tidal Power*. University of Victoria, 2012. Web. 12 Dec. 2013

[5] "How Much Carbon Dioxide (CO2) Is Produced per Kilowatt-hour When Generating Electricity with Fossil Fuels?" *EIA - US Energy Information Administration*. US Department of Energy, n.d. Web. 12 Dec. 2013

[6] El-Sharkawi, Mohamed A. *Electric Energy: An Introduction*. Boca Raton, FL: CRC, 2005. Print.

[7] Davis, James. "*Analysis of Fluid Flow in a Submerged Generator*". 2013