Tidal Power Generation in the Piscataqua River

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Abstract

With the ongoing energy habits of today's world, the global climate is being increasingly affected by contaminants and byproducts created by traditional energy generation methods. Furthermore, an inevitable energy crisis can be foreseen in the near future, with oil prices constantly rising and many researchers predicting that the world's oil supply will peak within this century. Tidal energy addresses both the problems of climate change and energy shortage. Tidal energy is a completely clean and renewable energy source. It creates no byproducts, and has little to no impact on the environment. Unlike wind and solar power, which are dependent on unpredictable weather patterns, and hydrocarbon fuels, which are a limited energy source altogether, tidal power is a continuous, predictable source of energy.

The Tidal Power Team at the University of New Hampshire has made it its goal to create a tidal power generation system to address the energy problems of today's world, and lay the groundwork for a technology that could potentially lead the way in alternative energy production in the near future.

Introduction

Background

Tides are created by the gravitational forces created by the sun and the moon on the Earth's oceans. The noticeable effect of the tides is the change in height of the water throughout the day. There are two tidal cycles per day, and the change of water height causes strong currents particularly in constricted tidal rivers. The energy in these currents can be converted into environmentally friendly, useable power which can be predicted centuries in advance.

The idea of using energy generated from tides is not a new one. The earliest method of harnessing this energy was to dam the water at the high tide level, and release it in a controlled manner through a waterwheel. This provided a small amount of mechanical power for a short part of each tidal cycle (two per day). This system is the basis of the world's best known large scale power plant: The La Rance Tidal Barrage seen in Fig. 1. Located in Brittany, France, this plant produces 240 Megawatts of power and has been in operation for 20 years without a mechanical breakdown, making it one of the longest and largest running tidal operations. Despite its obvious advantages, the barrage has changed the ecosystem of the river and the environmental effect of this installation is still being debated.

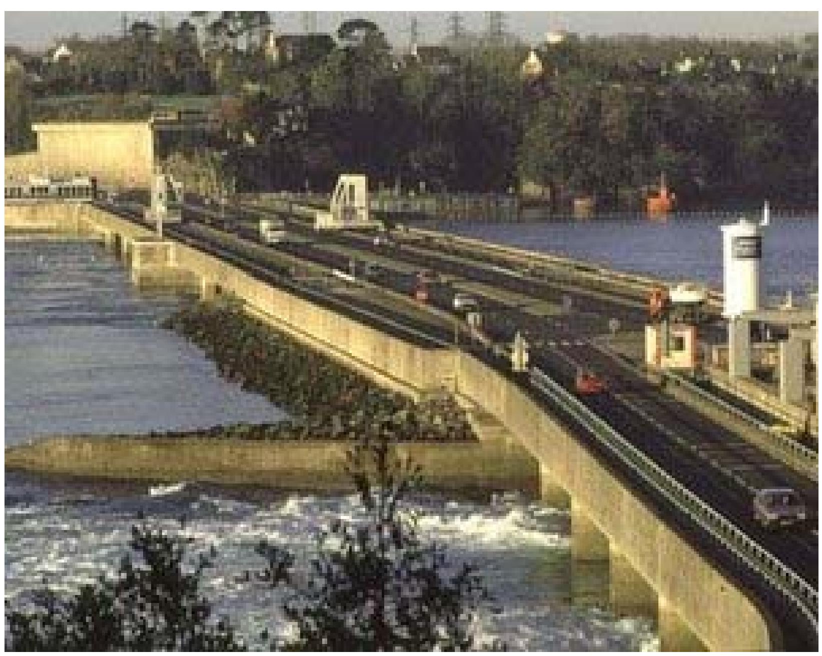

Figure 1: La Rance Tidal Barrage

Recent developments in tidal energy have shifted focus toward using the kinetic energy of the moving tides to generate power through current driven turbines. This allows power to be generated during both tidal directions, and avoids the negative effects of a blocked estuary or tidal lagoon. These designs range from those based on preexisting wind turbine technology to those developed specifically for tidal current applications.

Goals

The goal of this project is to develop the first stage of a tidal power generation system for the Piscataqua River located in Newington, NH. This project will act as a starting point for the state's tidal energy work. Ideally it will generate public interest in the field which will allow for both the continuation of the project as well as further, site specific work. Rather than attempting to create new technology, the purpose of this project is to create an interoperable system that is composed of the most efficient components from various fields. The goal is to design, implement, and test a system that will capture the energy of tidal currents and convert the harnessed mechanical energy into electrical power. The objective system is one that can generate enough energy to illuminate a 250 Watt lighting system and charge a small battery bank using a solid state charge controller.

Approach

The Tidal Energy Group at the University of New Hampshire, which consists of six mechanical engineering and two electrical engineering students, has broken the project into four major categories: turbine and gearing design, mooring and housing design, electrical systems design, and site location. The team worked throughout the academic year to develop a system that could efficiently and effectively combine each of the aforementioned subcategories into one final product. When the project first began, the team knew little about tidal power or the techniques employed to capture tidal energy. The first steps involved research into existing applications of tidal power generation to give the team a better understanding of the problems associated with the project, and of possible improvements that could be made. The design process that followed was an extremely iterative procedure, as design selections for each subgroup greatly impacted the design limitations for the remaining subgroups.

Design

The size of the initial project was based off of a design with a maximum rotor diameter of one meter. In order to create the best possible system, the team looked into many different types of rotor designs. The criteria for this choice will be discussed in detail in a later section of the report. The electrical components of the system needed to be designed based on the expected output power and torque from the chosen rotor.

Design Criteria

Site

- Location with high tidal currents, preferably over 4 knots
- Previously installed structure on which to moor the system, to avoid additional costs
- Easily accessed by land and sea

Mechanical Components

Turbine

- Relatively high efficiency, preferably above 20%
- Ability to generate power on both ebb and flood tides
- Easily fabricated or donated to lower cost
- Safe for estuarine wildlife

Deployment System

- Ability to lift 1200 lbs, with a factor of safety of 2
- Good braking system, ability to suspend 1200 lbs
- Easily assembled
- Hydrodynamic cage design
- Simplicity of lifting mechanism (requires one or two people)
- Provides for deployment and recovery of a turbine from a fixed position to a depth of one meter
- Derrick structure supports the turbine and cage horizontally and axially
- Provides a way for the turbine's weight to be loaded evenly across the bow of the flotation device

Mounting Platform

- Ability to withstand the maximum tipping moment of the larger turbine
- Ability to deploy the turbine, either through the middle or over the stern
- Hydrodynamic design
- Deck must be rigid enough to withstand torsional forces
- Deck must provide a barrier between water and instrumentation mounted on the platform

Gearing

- Ability to increase the angular velocity of the rotor, to the speed required by the generator
- No transmission
- Ability to be engaged when the turbine hits the water and starts to spin, without human interaction
- Less than $250

Electrical Components

- Convert up to 0.5-kW of mechanical energy to electrical energy
- Use a VDC (Voltage by Direct Current) to charge a 12-V battery bank
- Create and charge a small battery bank efficiently by avoiding rapid charge and discharge cycles
- Control the power seen by the battery bank as generator output varies throughout tidal cycle
- Design and test a lighting sign to display capable output power of small scale tidal energy source
- Create a load controller to match the load of the battery bank for power diverted from the charge controller
- Design and test a display driver/controller to sequence five 50 Watt quartz halogen bulbs as a response to the AC (Alternating Current) flow via power output from generator
- Accommodate all of the above electronics into one portable, easy to use box

Design Alternatives

Site

Prospective sites for the project have moved between a few possibilities based upon current velocities and over all feasibility. Initial sites investigated include a span beneath the General Sullivan Bridge in the Great Bay Estuary, a site off of Adam's Point, and a site off of Newcastle Pier. These locations are all part of the Piscataqua River estuary system and the environmental considerations for this location can be found in Appendix L. Original mooring plans included a mooring to the seafloor, and because of the fact that a rigid mooring to a bridge was deemed more practical, the Adam's Point site was ruled out. Newcastle Pier was investigated as a possible site, but was later disregarded when it was found that current velocities which average 0.2-m/s on the floating dock side of the pier were not nearly high enough to produce a sufficient amount of power with the proposed system. The General Sullivan Bridge became the prospective site for the project when it was determined to have both the necessary current velocities and water depths. Additionally, the bridge is no longer in service, making it an optimal structure for a mooring deployment. Current velocities at this location were determined to be sufficient for the project[30].Interpretation of the data suggests that the average velocity of the water can be approximated as 4 knots (2-m/s), which is ideal for efficient power generation.

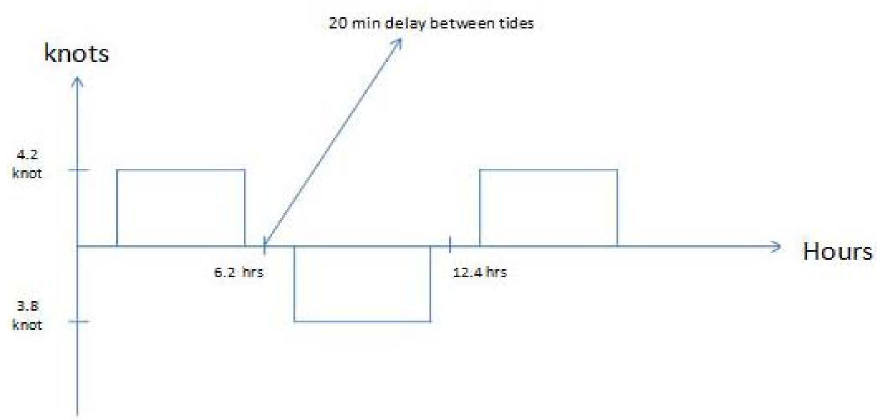

Figure 2: Approximation of Tidal Current Cycle in the Piscataqua River

Mechanical Components

Classes of Turbines Considered

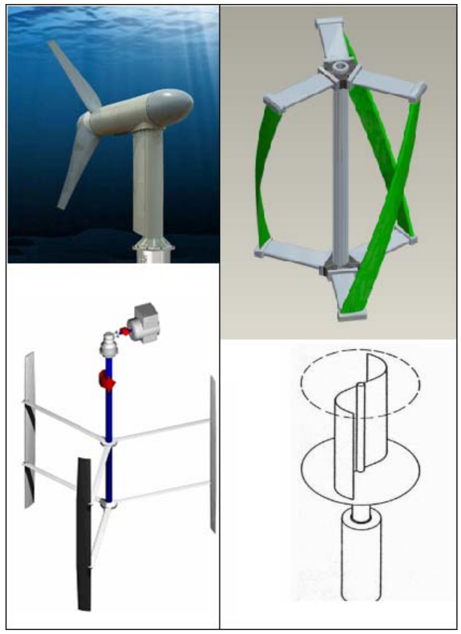

Figure 3: Clockwise from top left corner: Horizontal Axis Turbine[13], Helical Cross Axis Turbine, Savonius Rotor, Vertical Cross Axis Turbine[13]

The first step of the turbine choice process was the decision of which types of turbines would be most suitable for this application. There are several very prevalent basic designs which are well publicized and have been tested extensively. However there are also many types of turbines that are publicized with outrageous claims, as well as those which provide almost no information on crucial points of the design. For this reason the project really only considered using three of the more general types that exist.

The first general design considered was the horizontal axis propeller. The horizontal axis propeller comes in different types. The free standing types are generally two or three bladed, and the water applications of these look very similar to modern horizontal axis windmills. Kaplan and bulb turbines are commonly used in high head hydropower applications, including the La Rance tidal barrage.

Cross axis turbines have also been extensively used in wind power, which has sparked the tidal industry's interest. Various Darrieus designs use airfoils arranged around an axis to create a lift driven device which will rotate in only one direction in any cross axis flow direction. A newer modification on these types is the Gorlov Helical turbine, which arranges the airfoils around the center into a helix. This was designed in order to reduce damaging vibrations while spinning.

The third and final type of turbine that was considered was a drag based design. These are generally Savonius type rotors. Due to the fact that these turbines are designed to move from the difference in drag force between the sides facing the current, they are inherently limited to the difference in drag force which can be obtained between the two sides. However, they are very cheap and have proved very successful in low cost and low power wind generation projects.

Although they were generally not even considered in this project, it should be noted that there are several other designs in various stages of development, made specifically for tidal power. These include rotors which are surrounded by a generator rather than having a central hub, and "cyclo" turbines which have many, variable pitch blades arranged in a shape similar to the Darrieus design. Many current technologies also utilize ducts in order to accelerate incoming flow, but for simplicity it was decided early on that this would not be used in the project.

Reasoning for Final Choice

As it can be seen from above, there was a large decision to be made which would strongly affect every other portion of the project. Each type of turbine had its own flaws as well as distinct advantages. Every one of these had to be considered and weighed to make the final choice. A description of the determining factors for these turbines can be seen in Appendix K.

Table 1: Criteria weight of different turbine designs

	Criteria Weight	Horizontal Axis Propeller	Cross Axis Turbine (Helical)	Cross Axis Turbine (Davis)	Drag Designs
Efficiency	5	3.5	3.5	2	1
Capacity Factor	2	1	3	3	3
Ease of Manufacturing	1	1	2	3	4
Ease of system integration	4	1	3	3	3
Monetary Cost	3	2	1	3	4
Total		30.5	40.5	40	39

Deployment System

The first question that comes to attention when determining a deployment system is the desired location of the turbine with respect to the length of the raft to which it is mounted . The two different possibilities addressed in this case were either a turbine mounted through an opening in the center of the raft, or a turbine mounted on the back of the raft in relation to the directional flow of the water. Original cage designs began with simplistic box shaped cages for center or stern deployment, and developed into truss shapes for stern deployment as well. These designs had to be further refined in order to create a cage which could not only support the weight and forces created by the turbine, but also be deployed and removed as safely and easily as possible.

When the stern based deployment idea was addressed, the original idea was to use a box shaped cage which would slide vertically and could be deployed and recovered by a pulley system and a hoist. This idea was later replaced by one which put the turbine in a truss shaped structure and deployed it into the water using a cantilever beam type system. The structure would originally be laying flat on the deck, and then would be released slowly, pivoting around a pin at its center until it had rotated ninety degrees into the water. This idea can be seen in Fig. 4, below.

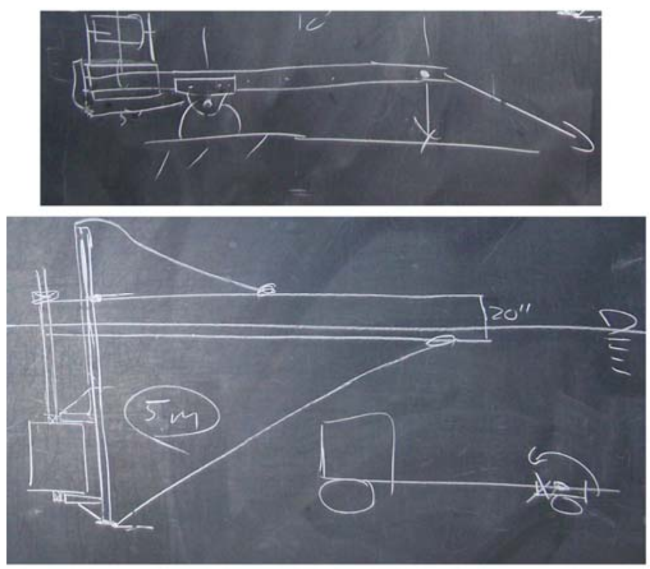

Figure 4: Options for Stern Placed Deployment Systems

The decision between the two aforementioned deployment schemes did not become clear until a derrick type structure was acquired which could easily be used to mount the turbine in the center of the raft. Once this structure was acquired, the obvious deployment system became a box shaped structure supported axially by the derrick, with a system to move the turbine vertically. Creating a drive for this system became a problem because a stationary pulley for the generator would be difficult to connect to a turbine once the turbine had been lowered into the water and began rotating. The solution was to create a rigid cage structure that incorporated the whole system (turbine and generator) into one structure, and could then move vertically on sliders while supported axially by the derrick.

The use of speed rail, which has many benefits, was considered as a possibility for the final assembly of the cage. Speed rail allows for the manufacture of the cage easily and quickly. At this stage of the project the speed rail design was deemed too expensive because of the amount of material needed. One benefit of speed rail would have been that the entire cage could be built using setscrews to mock it up and verify the design. However, the rails are made out of steel and the connection pieces cast iron, and these two materials cannot be welded together.

The budget constraint and the welding issue led to the cage being built with L channels. Because of its shape, and the interlocking capabilities of its angles, the L channel design has many different possibilities of construction. The only drawback to using L channels is that it is labor intensive, as there is a significant amount of preparation prior to having it professionally welded. The steel calculations of different size diameters using two beams with a maximum moment of 12,500 N-m is shown in Appendix G.

Hoisting Mechanism

With the turbine deployment method selected the next consideration was how to move the frame within the structure for deployment and retraction. The mechanism to do this requires a more advanced method of achieving mechanical advantage, as a simple pulley and manual pulling would not be a safe process.

The general solution considered the two basic methods of employing the lifting mechanism: either suspended above the derrick or on the deck of the boat, as seen in Figs. 5 and 6. Note that certain configurations of the lifting mechanism may require that the mechanism be located even further above the derrick, as needed by the design.

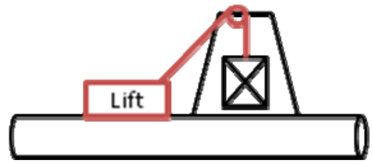

Figure 5: Lifting Mechanism Located on Boat Deck

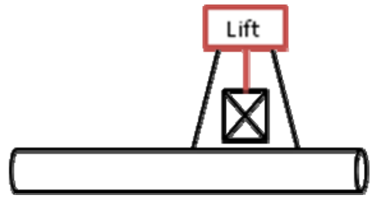

Figure 6: Lifting Mechanism Located Atop Derrick

The choice of lifting mechanism was not as simple as it may appear to be. The first option considered was a simple hand winch, as could be found on a boat trailer. This was considered for the low price and ease of attainment for the project.

The electric hoists available to lift the required weight cost between $300 and $400. They also are generally plugged into an electrical socket, which supplies AC power. The current electrical system can only supply DC power from the battery. A simple A/D converter can solve this problem, but this would be an additional cost. Additionally the power required for the hoisting could very easily require more power than the 12-V battery of the electrical system could handle.

Hand hoists are available in multiple forms, but the most appropriate for this deployment system is the chain fall type hoist. This is because the Ocean Engineering Department at UNH has many of these, an example of which can be seen in Fig. 7.

Figure 7: Chain Fall Hand Hoist [4]

No matter the type of hoisting mechanism, another important consideration is the attachment locations for the system. The two main areas of consideration are as seen below in Fig.8. The circles indicate one set of attachment points, and the hexagons represent another location of attachment points. The upper location would allow for the lifting chain to be out of the flow of the water. The turbine may be more stable if the circled portion of the cage is above the top of the derrick. This would be a problem if trying to lift using the method seen in Fig. 8.

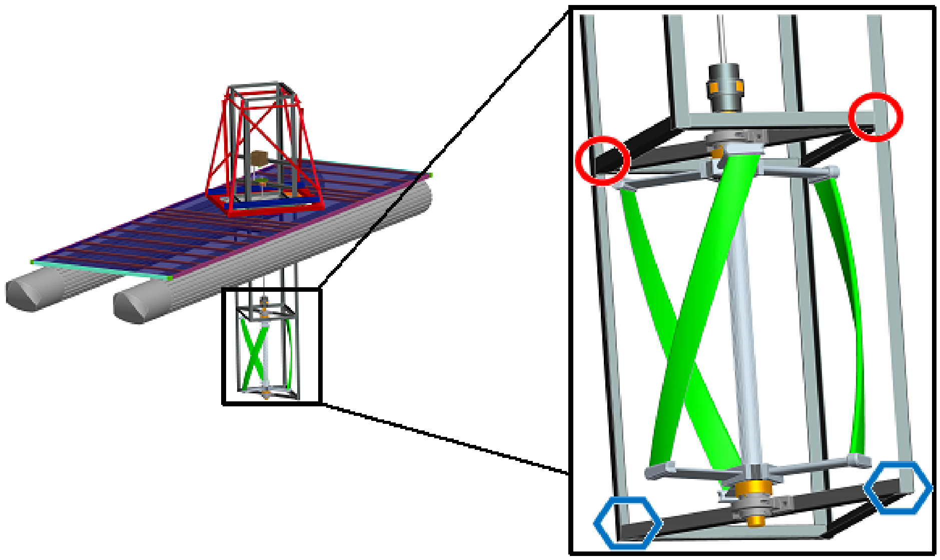

Figure 8: Hoisting Attachment Locations

Gearing

The following design alternatives have the advantage that they can be completely incorporated into the system, without the necessity of disengaging parts. This is important because once the turbine enters the water it will start spinning, which could cause problems if the system requires further connections to stationary parts. Various designs were considered to allow for the spinning gear train to be linked to the unmoving generator. These ideas included a dog clutch and a sliding pulley. There are many disadvantages with this type of system, but most notably it is unsafe. Figure 9 shows the basic idea of these sliding devices.

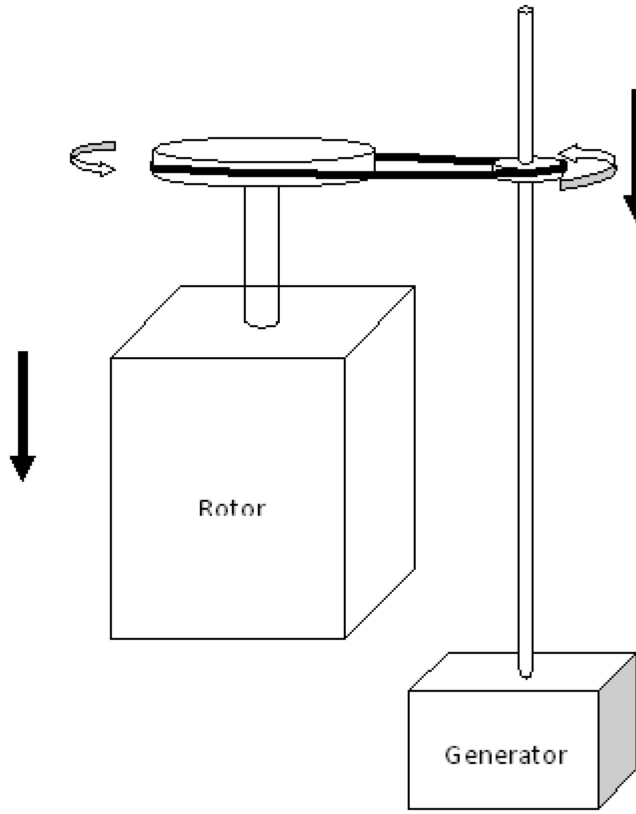

Figure 9: Sliding Pulley System

An internal gearbox increases the rotational speed from the rotor to a predetermined speed for the generator. Figure 10 shows the general idea of the internal gearbox. It is important to note that inexpensive internal gearboxes have one permanent gearing ratio and can be quite heavy. The benefits of this system are in the fact that it is one unit, it would have a known gearing ratio, and it would be very efficient. The drawback to an internal gearbox is that the gear ratio is fixed and they are often quite heavy.

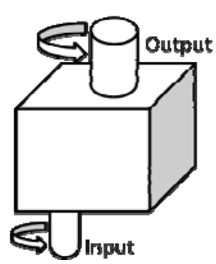

Figure 10: Generic Internal Gearbox

In belt transmission applications, the belts tend to slip, which creates a low efficiency for power transmission, but is beneficial for safety reasons.

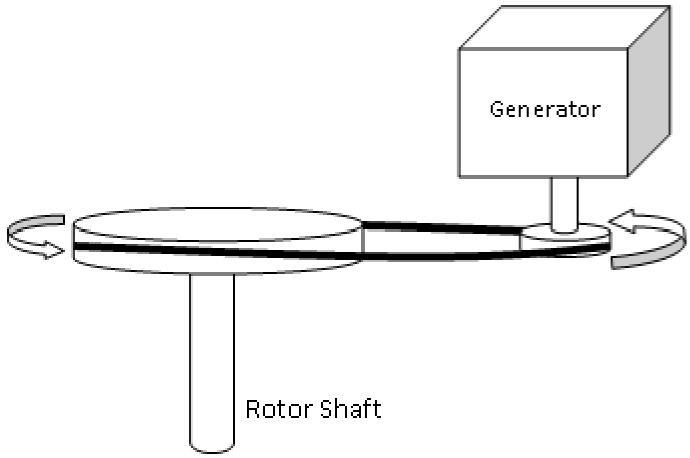

Figure 11: Single Step Belted Gearing

The first of the belt and pulley alternatives is the single staged gearing; a schematic of this can be seen in Fig. 11. A large pulley would be connected to the rotor shaft, along with a smaller pulley connected to the generator, which would be connected using a belt. To properly increase the speed of the generator pulley, using only one other pulley would require a large diameter as seen in Fig. 12. The benefit of this system is that it requires a reduced number of parts, as opposed to the compound system seen below. The major disadvantage is that the pulley is quite large, and therefore uncommon and harder to manufacture. This larger pulley system is also difficult to fit into a tight system. Additionally, this system's gear ratio is also fixed, like the internal gearbox.

Figure 12: Single Stage Belted Gearing System, used on a Gorlov helical turbine in the Amazon River [29]

An alternative concept to the single stage belted gearing system is the use of pulleys in a compound gear set, which would allow for the pulleys to be smaller, as seen in Fig. 13. The schematic shows only four pulleys as this is the fewest number of gears required for this design. The cost of this system is approximately $200, with additional gears costing approximately $20, for V-belt pulleys. This design consists of more moving parts than the others, which is undesirable, but the fact that it does not have a fixed gear ratio gives it an advantage over other options.

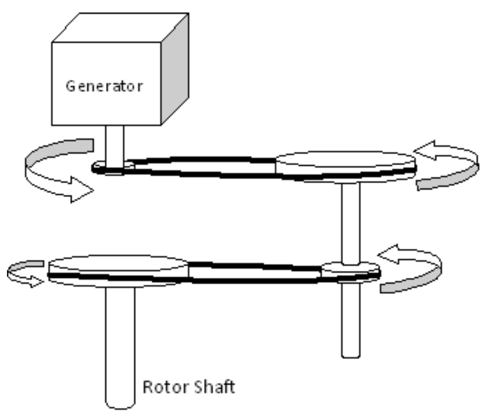

Figure 13: Compound Belted Gearing System

Flotation Platform

There are many different possible solutions for the floating platform. The initial design went through many changes as the needs for the project changed. Ideas ranged from the general idea of a large diving platform to the use of the small pontoon style boat owned by the Ocean Engineering Department.

The original solution was a type of diving-style platform, as seen in Fig. 14. These are made using simple pontoons, barrels or plastic floating pieces that interlock. The scale of the larger turbine made the use of this impractical, as a large, expensive structure would be needed. A similar effort by the team included the design of a raft system using 2x4's and plastic barrels. The idea was to create a platform that would integrate simple plastic barrels into its structure for flotation. This structure would be made out of wood and planked with plywood, and the whole structure would be treated with marine paint to prevent it from absorbing water once deployed. This idea was unfortunately rejected because it would take more assembly time than other possible structures, and concerns were raised about the structural integrity of the platform.

Figure 14:2x4 Barrel Raft (top) and Diving Platforms [6]and[7]

More complex designs were also investigated, as seen in Fig. 15. The basis of these designs was to have pontoon-like structures to counteract the tipping moment on the structure caused by the drag force in the water, with a smaller center section where the electrical equipment could be housed. The goal was to have a hydrodynamic, multi-hull design, primarily consisting of fiberglass and an internal framework of wooden bulkheads. Additionally, antifouling coating would be applied on all exterior surfaces to prevent build up of biological material. The rotor and shaft would be supported by two bearings- one in the floating superstructure and one submerged at the base of the unit.

Figure 15: Complex Housing Designs

Although these complex housing designs may have worked well with the project, the focus shifted to a pontoon type boat, as it would be the simplest premade floating platform to procure. A simple pontoon boat structure would require little manufacturing and could be easily transported on a trailer.

The first attempt at using a pontoon boat resulted in the discovery of a 12x7.6 foot pontoon boat that had been used in the past by other Tech797 projects. This would be free to use and there would be no problems altering the structure, as it was no longer in use. Further investigation was done on this design, using change in freeboard and approximating the angle of tipping due to the drag force, detailed in Appendix O. Although the boat would be able to withstand the weight of the turbine and equipment, it would not have a large enough righting moment to counter the tipping caused by the drag force on the turbine. It was approximated that a vessel two times larger would be more appropriate, and thus the search for a pontoon boat type structure larger than 30 feet began.

Hoping to find a used pontoon boat that was larger than 30 feet, thirty-five marinas within a 50 mile radius were contacted multiple times and an internet search was conducted. From these investigations, the general consensus was that to obtain any pontoon boat over 24-ft would cost more than $11,000. Through the search only one boat came up that seemed promising.

The structure turned out to be a pair of 20-ft 5-in length steel pontoons that would be loaned the University. Decking and cross members were not included, but the pontoons would be accompanied by a trailer for the short-term loan. Although these pontoons did not meet the required length determined in the analysis, the possibility of adding counter buoyant booms arose, as seen in Fig. 16. These could simply be large barrels similar to those used in the previous diving platform concept.

Figure 16: Pontoon Boat with Counter Buoyancy Extensions

Though the 20-ft 5-in length steel pontoons were a viable solution in an ideal world, the pontoons needed extensive repairs because of rust, as seen in Fig. 17.The extent of the rusting was not visible on-site, making these pontoons a risky investment for the team. The time and money needed to repair the pontoons did not balance the benefit of having them. These costs were especially large since extensions would have to be added to the platform for stability.

Figure 17: Used Pontoons Showing Rust Damage

A 16 foot aluminum pontoon boat was found, the owner of which was willing to let the team borrow it for some time. Although in excellent condition, this boat would have restrictions placed on permanent alterations. This meant that the turbine would have to be deployed over the stern of the boat, with limited modifications done to the existing deck. The counter buoyancy extensions would also have to be quite large, as the boat was only 16 feet long.

The option of purchasing a pontoon boat kit, whose size could be specified, was also investigated. It was found that a 35 foot length, 10 foot beam pontoon boat could be purchased for $9535 plus shipping. The company, Pith Products LLC, offered a 10% discount since the project was for student use. This brought the cost of the kit to $8581.50 plus the cost of shipping. A 10 foot beam is required because center deployment through the standard 8foot beam would leave less than one inch of clearance on the sides of the turbine. The kit includes the pontoons and cross-members required to build the boat. Though expensive, this option allows for the acquisition of a facility for the University, which would be beneficial for future projects. The kit does not include decking; for this project the team would most likely select wood decking as it is the most cost effective solution.

Many testing platforms used in known tidal research projects were large barges, often modified from construction platforms. Figure 18 shows an example of this. Renting a barge was a solution investigated, and it would cost $3,000 per day to do this. With an estimated three days of testing and setup, this would consume three times the team's budget, without acquiring an item to be used for future testing. Furthermore, the companies contacted to rent the barge were unenthusiastic about the prospect of mooring their barge to the unused General Sullivan Bridge.

Figure 18: Barge Platform [7]

Another option considered was the use of the 50 foot 'Gulf Challenger' boat, owned by UNH, to test the turbine by deploying it off the stern. This would not be a permanent solution, but it would allow the team to get the turbine into the water. The Gulf Challenger has a large crane on it, which would be helpful during deployment and recovery. Although the Gulf Challenger meets the stability requirements for the project, the same problem that the 16foot boat posed is present: not many alterations could be done to the boat for the implementation of the deployment system.

Mooring

The relatively low budget of the project, along with the large forces encountered in its deployment gave way to certain criteria for the mooring system. The suitability of different mooring configurations with respect to these criteria is defined in Table 2.

Table 2: Possible Mooring Configurations and Suitability

Mooring Configuration	Suitability
Spread Moorings	
Catenary Mooring	Medium
Multi-Catenary Mooring	Low
Taut Spread Mooring	High
Single Point Moorings	
Turret Mooring	High
Catenary Anchor Leg	Medium
Single Anchor Leg Mooring	Medium
Articulated Loading Column	High
Single Point Mooring and Reservoir	High
Fixed Tower Mooring	Low
Dynamic Positioning	
Active Mooring	Low
Propulsion	Low

During operational conditions, waves can create large forces upon the platform from any direction. This means that the platform must be able to have some degree of rotation with respect to its original orientation. If a spread mooring system was chosen the housing would ideally have been positioned such that the structure would be able to turn in 90 degrees relative to its original orientation. This would result in the lowest possible loading on the structure and thus allow for lower strength materials for a less expensive mooring system. A complete description of all moorings and anchor systems considered, as well as a cost caparison, is included in Appendix G.

After receiving the loaned Gorlov turbine, the original mooring design needed to be reworked. The previous design was based on a turbine that was 1 meter by 1 meter in size, considerably smaller than the 2.5 meter by 1 meter Gorlov unit. The additional 200 pound weight of the new turbine required a more robust mounting system.

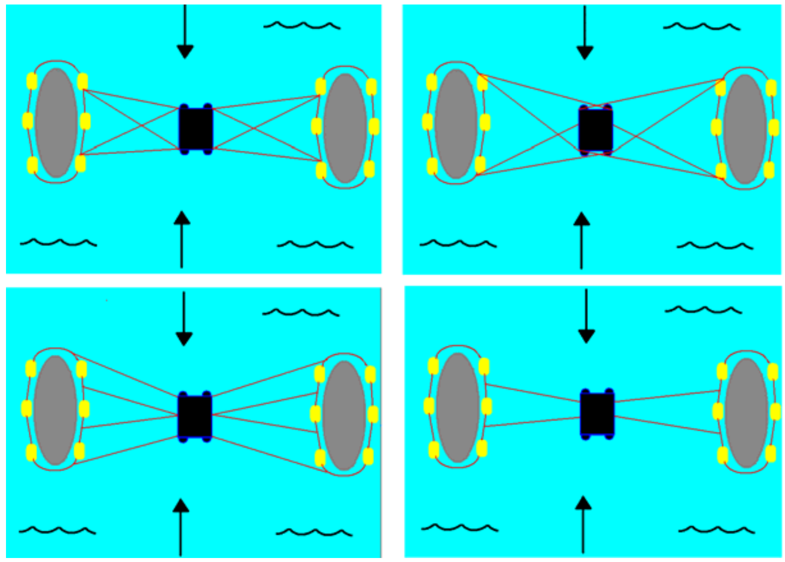

Figure 19: Several Proposed Mooring Attachments to Sliding System

The challenge in mooring a thirty-five foot pontoon boat between the bridge pilings is the seven to eight foot change in water level. The first design to compensate for the tide change involved a system that wrapped around the circumference of the pilings. Cable or chain would loosely loop around each of the two pilings, allowing vertical movement with the water. As seen in Figs. 19 and 20 the chains would have integrated flotation devices to keep them at the water surface. The floating platform would be attached to the chains on each piling with a configuration of lines from the boat.

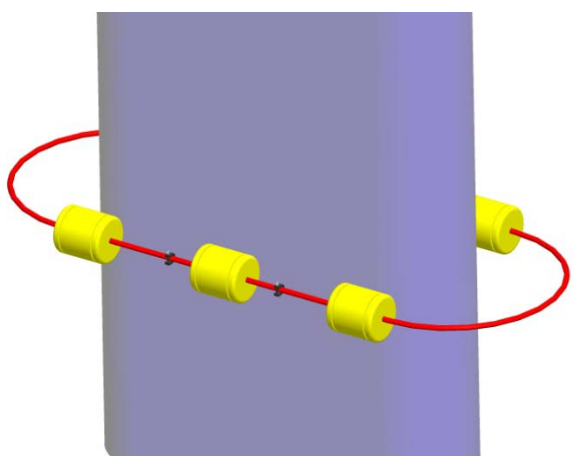

Figure 20: Pro/Engineer Model of the Loose Floating Cable Concept. Cable is shown in red, buoys in yellow, and attachment shackles in black.

A larger problem in this system was that the system may not have been able to glide vertically when in tension. When the boat was not at slack tide there would be tension on the lines due to the force of the current. The tension would cause the chain flotation system to pull tightly against the piling. This would stop the system from moving vertically. Since the currents in the proposed site are very strong in the horizontal direction, this design was discarded.

The second design concept was to use a sliding bar system. This system consisted of a set of bars with collars which slide up and down with the tide, shown in Fig. 21. The lines are then directly attached to the collars with marine fastenings, which eliminate slack in the lines and allow the pontoon boat to rise and fall with the water level. This type of system has been used for mega yachts up to 140 feet in length, which demonstrates that it is strong enough to withstand large forces. The distributor of the units has customer testimonials praising the system during use in hurricanes.

The only challenge for this design is the attaching of the sliding bar system to the pilings. The sliders are typically attached to wooden piers and docks with bolts. Because this is a temporary mooring system, it is not possible to drill into the pilings of the bridge. This led to the requirement of a removable system that could be placed around the pilings. It would be possible to construct a wooden frame to mount the slides to, but this would be more complicated than necessary and a simpler solution was developed.

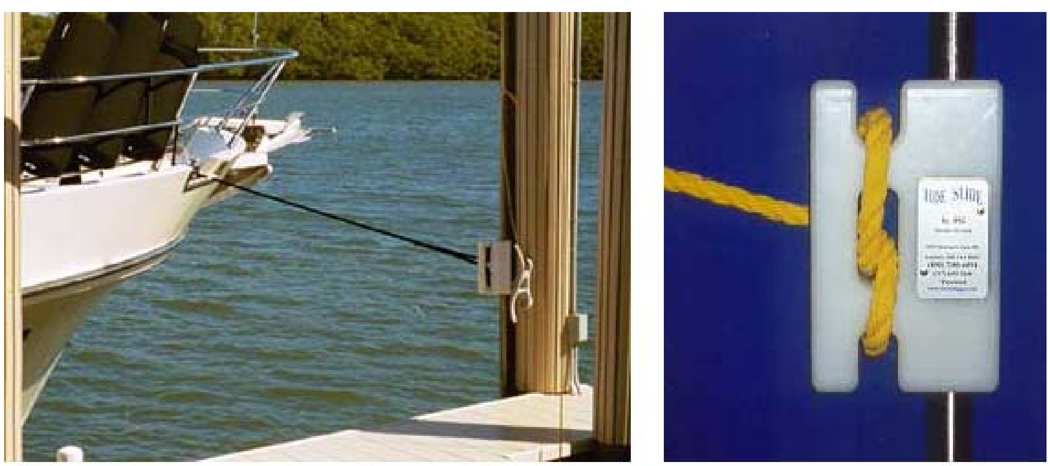

Figure 21: Tide Slide ™ [10]

The mooring system also moved from a system that would moor the pontoon boat directly between the two bridge pilings to one where the mooring lines would arrive at about 45 degrees to the pilings. Instead of being deployed for an extended period of time, the mooring would allow the platform to drift out under the bridge, in order to do deployment testing for the span of either the ebb or the flow (6 hour intervals), before disconnecting the system. This allowed for the simplification of the mooring system, and for a more stable testing environment.

Electrical Components

Generator Selection

Various electrical designs were explored to accommodate the system's mechanical design. Since the electrical load controls the torque induced by the generator, it was important to pick a design specific possible output of the turbine.

The generator was needed for the foremost design criteria since it would determine how much power could be produced from the mechanical design and how much needed to be diverted and used to charge the battery to accommodate the future lighting system. The types of generators shown in Table 3 were considered based on their load curves vs. RPM and cost.

Table 3: Comparison of various generator and alternator possibilities

Permanent Magnet Generator DC	Permanent Magnet Generator AC	Car/Truck Alternator	Permanent Magnet Alternator(PMA)
Only 10 Amp continuous Duty	Needs constant 3600RPM with 5% accuracy	Option of 12 VDC and 24 DVC to be purchased	Widely used in the industry of home brew renewable energy
Price $489	Price around $300	Needs 0.6 VDC to start	moderate gear ratio needed
Can only output a maximum of 500 W at 48 VDC load	Option of 12 VDC Battery charger	Could output the 2.2 kW desired	Could output the 2.2 kW desired
Available in Vermont	Battery needed	Battery needed	Battery needed
Efficiency of about 80 %	Charge controller needed	Charge controller needed	Charge controller needed
Battery needed	Efficiency of about 80 %	Efficiency of about 40 %	Efficiency of about 60 %
Charge controller needed	Could output the 2.2 kW desired	Rectifier needed	Ready for belt drive system
	Available in Italy	Ready for belt drive system	High gear ratio needed
		High gear ratio needed	Price around $300
		Price around $200	Available in California
		Available everywhere	

Charge Controller

The charge controller is a solid state device that prevents overcharging the batteries and may have a low-voltage disconnect to prevent the load from completely discharging the batteries. The charge controller must be carefully matched to the batteries to prevent overcharge or too much discharge. The batteries are usually of lead-acid or gel configuration and are treated the same as any stationary battery used for utility purposes.

A charge controller was utilized to control the flow of electricity between the module, battery, and the loads. It prevents battery damage by ensuring that the battery is operating within its normal charge levels. If the charge level in the battery falls below a certain level, a Low Voltage Disconnect (LVD) will cut the current to the load to prevent further discharge. Likewise, it will also cut the current from the module in cases of overcharging. Indicator lights on the controller display the relative state of charge of the battery

Since a large amount of power will be stored in a 12-V or 24-V system, a specific charge controller is necessary to charge the battery bank correctly. Using a Savonius rotor at 60 RPM for a 12-V subsystem would require about 20 Amps. Table 4 shows the only charge controllers that are capable of such current.

Table 4: Comparison of charge and load divert controllers

Model	NCHC	C60	MX60	SEA-50
Description	Highest amperage rating, contains a divert load can be used turbines and solar panels at the same time capable of more than 1 battery bank	Basic to start, but also can be attached with displays to relay relevant information	Does everything	Waterproof
List Price	$478.00	$199.00	$1,320.00	$114.95
Efficiency	99%	Not Given	98%	93%
Voltage Capability (Volts)	12, 24, 36, 48	12, 24	12v - 60	12,13,48
Current Capability (Amps)	100	60	60	50
Divert Load (Amps)	60		400	
Manufacturer	FlexCharge	Xantrex	Outback	Thermo Dyne Systems

Divert Load

Using a charge controller a divert load would be necessary so that the excess battery voltage would be leaked into a specific load instead of overcharging the battery. After the battery was completely charged the power would be leaked into a very powerful sign that could handle excess energy. The initial design of the sign was to use a large amount of bulbs behind a letter style cutout to display the name of the team.

Battery Bank

There were a number of limitations associated with the battery bank, the first of which was the cost associated with the size of the batteries. Ideally marine batteries are most suitable due to the amount of Amp/hours available. The cost was directly proportional to the amount of energy that could be stored into the battery. Pollution was another issue that the team was consistently aware of. Gel and AGM (Absorbent Glass Mat) battery types are spill proof and therefore can be placed in any direction and perform equally as well. AGM style batteries not leak acid when overcharged or misused, thus eliminating the possibility of pollution.

For this reason an AGM style marine battery was chosen for the preliminary design. A number of manufacturers produce this type of battery, but they are relatively expensive and thus only 1 or 2 batteries were considered for use in a bank.

Final Design

Site

The final location for the project was determined to be beneath the Old General Sullivan Bridge, and a site visit was conducted with Dave Shay on the ‘Galen Jones’, where depth measurements were taken, which showed that the depths in the proposed location are even higher than expected and relatively constant across the entire deployment span. These measurements concluded that there will be plenty of clearance between the turbine and the river floor. Piling dimensions and separation distances were measured, and pictures were taken of the proposed mooring location in order to provide information for mooring system design and aide in future presentations. A presentation depicting the location of the work and the general specifications that have been developed thus far has been created and sent to NHDOT contacts for approval.

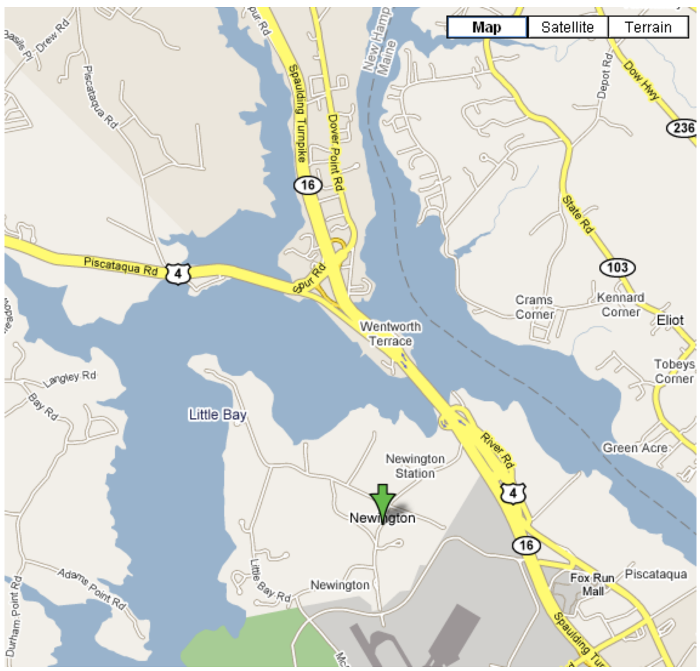

Figure 22: Geographical location of proposed system placement [22]

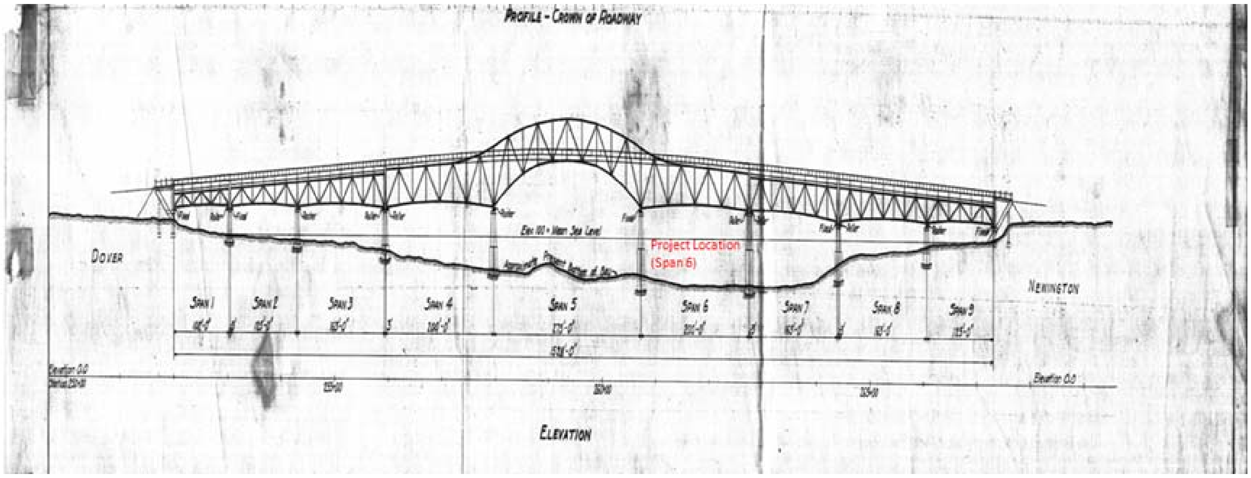

Figure 23: Project Location Within Bridge Structure [26]

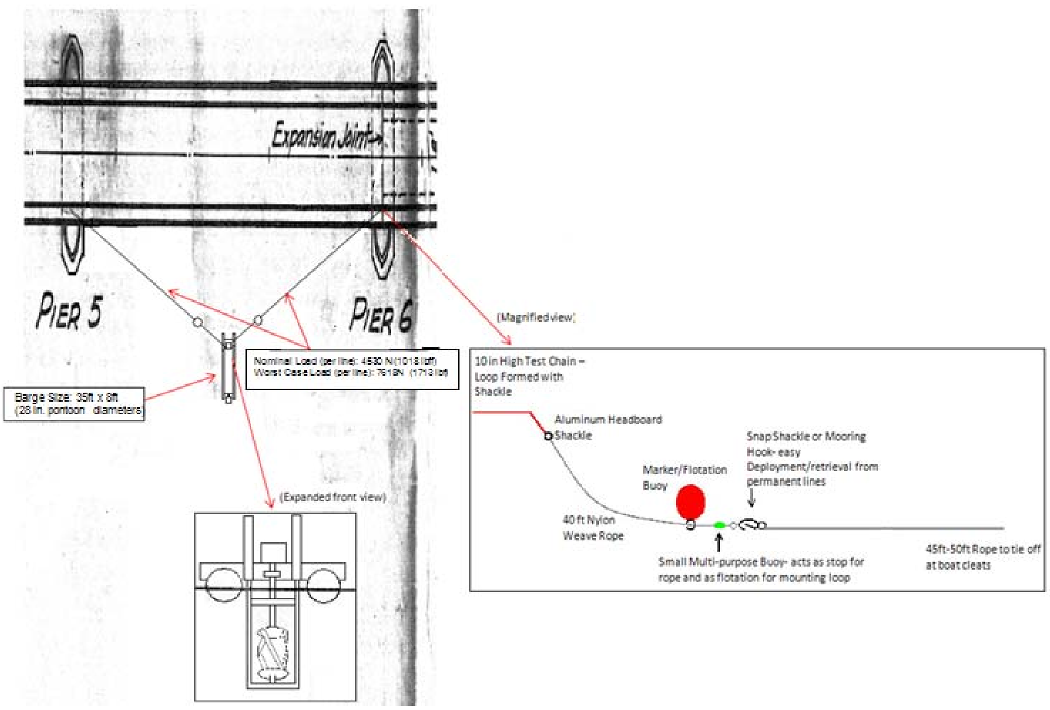

Figure 24: Scale Drawing of System Schematic, in place underneath the old General Sullivan Bridge [26]

Turbine

Based on the design criteria and weight in Table 1 the group finally chose to utilize a helical turbine design. In a situation where ease of manufacturing was more important, the Davis type turbine would have been a superior choice, but as the group had decided not to fabricate the turbine rotor themselves, this pushed the decision to the helical design. During the process of securing permission to use the specific design of the Gorlov Helical turbine, the group received a turbine on loan which was much larger than the originally planned size, which changed the scale of the project dramatically.

It is worth noting that the turbine has some flaws, particularly seen during the assembly process. The turbine was assembled using aluminum components fastened together with steel bolts. If these turbines will need to be serviced and possibly disassembled, the steel bolts will undoubtedly be so corroded from the salt water that this disassembly will most likely be difficult. The steel bolts also have a tendency to strip the threading on the aluminum components, requiring replacement parts even while assembling the turbine for the first time.

Flotation Platform

Financial factors played a major role in the selection of the platform to use in the final design. The choice was made to use the pontoon boat kit, from Pith Products LLC. This cost less than renting a barge for three or four days and provided the University with a new facility.

The pontoon boat that the team chose to purchase is made out of type 5052 H32 aluminum. This is an aluminum magnesium alloy which is highly resistant to corrosion in fresh and salt water. Each aluminum pontoon is 0.081 inches thick, has solid welded chambers every five feet, a full length under keel, and side keel for added protection. The exploded view of the pontoon can be seen in Fig. 25.

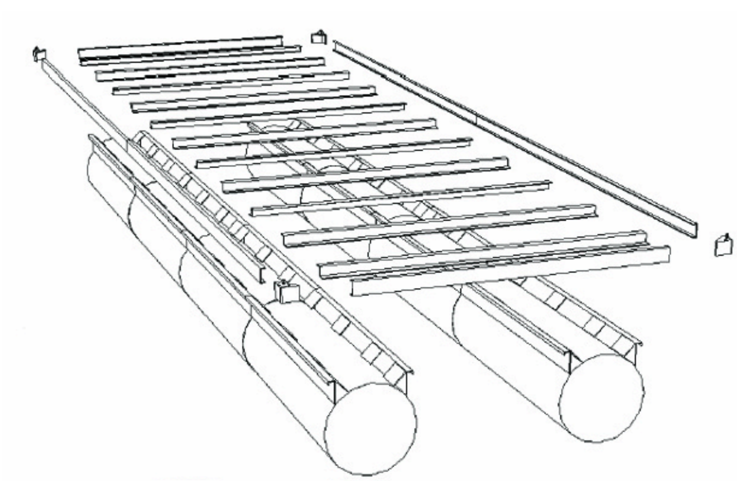

Figure 25: Exploded View of Pontoon Boat [23]

Deployment System

The final turbine support assembly is constructed of steel L-channel arranged in an elongated box shape. The bottom section of the frame has one leg removed to provide an unobstructed flow path. The turbine bearings mount to L-channel cross-members mounted across the diagonal of the frame. The stub shaft of the turbine is attached to a LoveJoy L276 coupling, which connects the system to a one inch diameter driveshaft. This driveshaft passes through an intermediate bearing mounted four feet above the level of the turbine. This bearing is mounted to a 2x2x1/8 inch square steel tube, with a steel spacer to align the shafts. Three feet above the intermediate bearing is the start of the gear train. The same steel cross-members make up the base of this assembly. The entire gear-train is rigidly mounted within the framework, so no removable belts or clutches are needed. The entire gearing and electrical system remains above the water level when the turbine is deployed. When the frame is in the lowered position, outward facing L-channels mesh together which forms a mechanical stop. Pins are inserted into the sides of the channels to lock the unit in place.

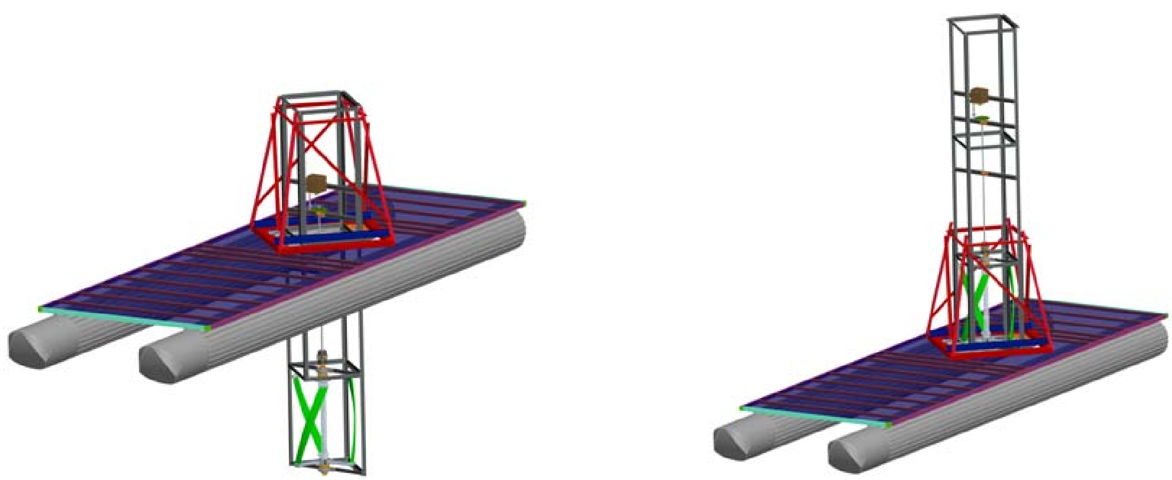

Figure 26: Final Design of Deployment System, in Position (L) and Raised (R)

Mooring System

The final mooring system consists of chain wrapped around the top of the piling, where the metal girder of the bridge meets the concrete of the piling. The use of chain will provide a sturdy anchor point and will also prevent abrasion against the rough concrete of the piling. The links of the chain will be connected using 3/8 inch marine shackles. From the chain, 60 feet of one half inch diameter poly-braid rope leads to a green plastic marker buoy. The rope feeds through the eye of the buoy and through a float. This float prevents the line from passing through the eye of the large buoy and also keeps the tag end of the line visible. These components make up the semi-permanent part of the mooring system. They will be deployed for the duration of testing, regardless of whether the boat is attached. Figure 27 shows a concept sketch of the system.

The 60-foot sections of permanent mooring lines will be connected to each other by a tag line when not in use. This will prevent the buoys from drifting into undesirable areas, particularly into the navigable channel. Deployment remains relatively simple when the time comes to attach the boat. An additional 70 feet of line for each side will be kept on the boat. A loop on one end will be tied to the floating line with a 3/8 inch shackle. The other end will be tied to cleats on the deck of the boat. This way, lines can be shortened or lengthened to accommodate for the angle of the oncoming current. Figure 28 shows a diagram of the entire system components.

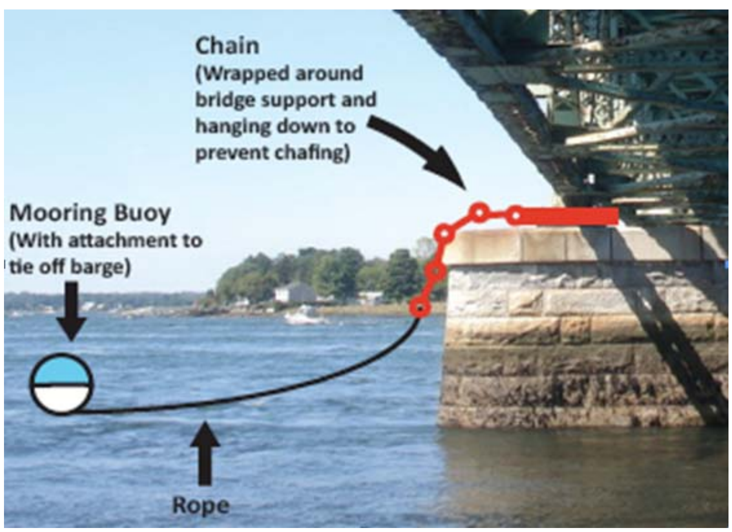

Figure 27: Concept Sketch of the Mooring System

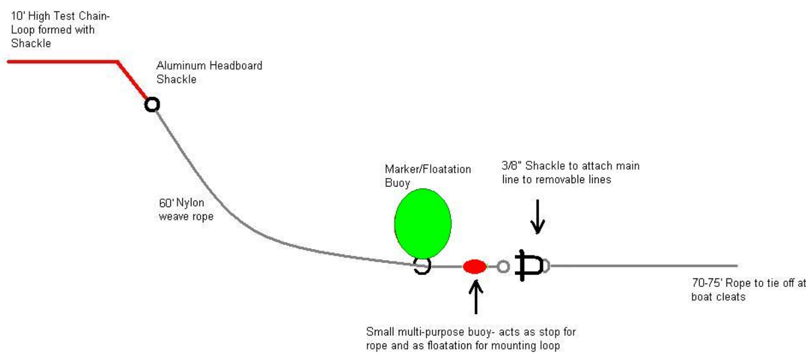

Figure 28: Final Mooring Setup Schematic. Red chain on left attaches to bridge piling.

Coupling and Gearing

A flexible shaft coupling is required to join the stub shaft of the turbine to the 1 inch diameter steel driveshaft of the system. As suggested by Lucid Energy Technologies LLC, a LoveJoy L276 jaw type coupling is proposed for use in the designed system. The coupling consists of two metal shaft collars with interlocking teeth. The collars are joined with an elastomer spacer, as shown in Fig. 29, so that there is no metal-to-metal contact.

Figure 29: LoveJoy l276 Couplings[4]

These couplings are offered in a large variety of stock bore/keyway combinations. They require no lubrication and provide highly reliable service for light, medium, and heavy-duty applications. They are also resistant to oil, dirt, sand, moisture and grease, making them suitable for a submerged application. The chosen coupling has a 2.875 inch input bore (LoveJoy part #12607) to attach to the turbine and a 1inch output bore (LoveJoy part #12586) for the driveshaft. There are two options for the spider material, SOX(NBR)Rubber or Bronze. Nitrile Butadiene (Buna N) Rubber (LoveJoy part #12612) is a flexible elastomer material that is oil resistant and resembles natural rubber in resilience and elasticity. Bronze (LoveJoy part #25767) is a rigid, porous oil-impregnated metal insert exclusively for slow speed applications requiring high torque capabilities. Bronze spiders are also not affected by extreme temperatures, water, oil, or dirt. This would be beneficial to the underwater application, as it would not be affected by water or corrosion as the rubber would be.

Although an internal gearbox has been suggested, this was not selected because it was the most expensive gearing option. When the optimal gearing ratio is determined, it may be appropriate to use an internal gearbox .

Verdant has also suggested using toothed belts, which do not allow slippage, and thus are more efficient. For this step of the project, V-belts will be used as an alternative to toothed belts. This is because toothed belts and the corresponding pulleys are much more expensive than V-belt types. Additionally the V-belt slippage can be helpful, especially since the exact reaction of the system is unknown.

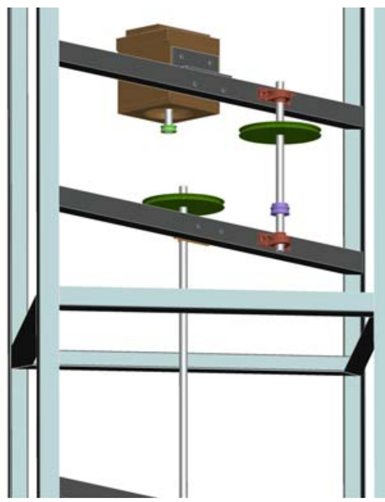

Figure 30: Final Design of Two Step V-belt Pulley System

The compound pulley gearing system with V-belts seen in Fig.30 was selected from the other design alternatives. This was mostly because it was the least expensive way to change the gearing ratio to increase RPM. This system can be easily incorporated into the cage for lifting, which allows for it to travel with the turbine and avoid disengaging from the system. It may be slightly less efficient than the other options, but at the time of the choice cost was a more pressing factor than system optimization.

Generator

Based on the power output expected from the turbine a new generator was selected. After thorough research based on the information provided by Lucid Energy Technologies LLC, the group decided to select a generator capable of a wider range of power output. The SC12, which is a permanent magnet alternator, was selected because it can output constant 275 Amps with 18,000 RPM input. If future teams find an improved method of tying their system to the grid or storing power in an appropriately sized battery bank there will be no need for a generator upgrade. Current-voltage curves from this generator are available in Appendix B. More information regarding the testing of the device under a wide variety of loads will be discussed later.

Figure 31: SC12-PMA, with fan assembly and pulley [27]

Charge Controller

The NCHC charge controller was selected for a 12-V system as it can accommodate the wide range of power provided by the new turbine and PMA. Using a divert contactor, the controller will be able to divert the load and charge the battery in one complete compact system. The system only consumes 2 Watts for 25 Amps of current that runs through it,as shown below.

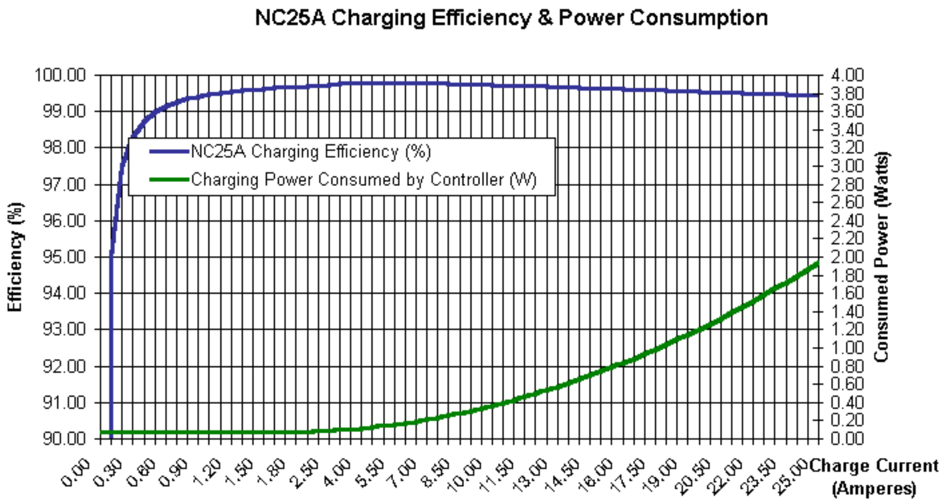

Figure 32: Charging Efficiency of 25 Amp model of NCHC Charge Controller[9]

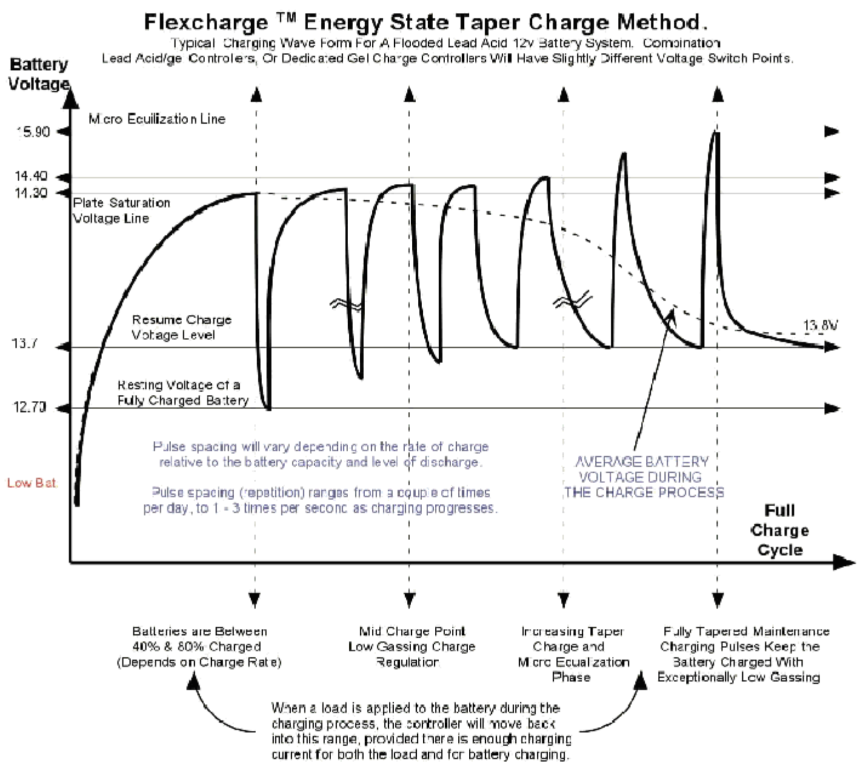

Figure 33: Charging Algorithm of Charge Controllers [9]

The controller costs more than the preliminary design but has more flexibility and much lower power consumption due to the mercury contactors provided and shown in the figure below. Specific calculations and the specification of the charge controller are provided in Appendix C.

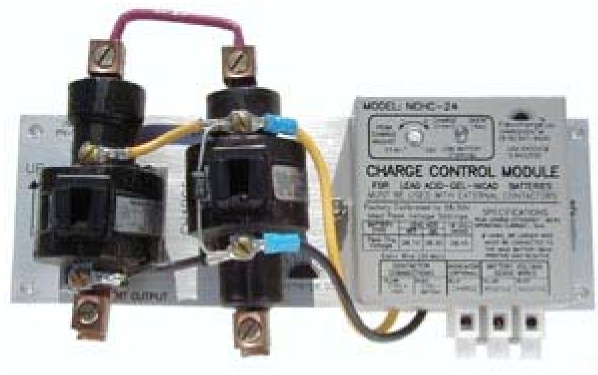

Figure 34: NCHC Efficient Charge Controller, shown with a charging and divert contactor [9]

Divert Load

The divert load was changed from the preliminary design to accommodate the charge controller and the new sign. The manual provided by the charge controller determined that the divert load needed to match the load of the battery bank, so that when the controller monitored the output of the generator it saw the same voltage as when the load was diverted. For example, if the battery were charging at 14-V and the current increased in the water such that 16-V was output from the PMA, the charge controller would divert the load. If the load drops the voltage of the alternator, increasing its torque, the voltage could drop enough so that the controller sees the batteries desired voltage range and begins to try to charge the battery again.

In order to accommodate a wide range of batteries in a battery bank, a controllable diverse load was needed. Brayton Energy, located in Hampton, NH had designed a controller comprised of 8 - 300 Watt power resistors and 2 – 300 Watt rheostats on a complete stand with switches to model various battery banks as shown in Fig. 35.

Figure 35: Load Controller, using 3.1 Ohm, 300 Watt Power Resistors

All of the resistors were placed in parallel so that the voltage remained constant but the amount of current drawn would increase. The system was loaned to the team for final testing purposes. After preliminary testing with the turbine the amount of resistors needed is determined by measuring the RPM of the alternator and the amount of batteries used in the bank.

Battery Bank

The cost of the upgraded mooring necessary for the new, larger turbine left a lack of funding for the battery bank. The system only incorporates one 12 Volt lead acid battery donated by the UNH Ocean Engineering department. This battery is capable of 50 Amp/hours, and based on its datasheet can handle the newly designed lighting system for approximately 3 hours, as shown in Fig. 37. This is a sufficient amount of time for the battery to recharge.

Figure 36: UB12500 50ah Lead Acid 12-Volt Battery[8]

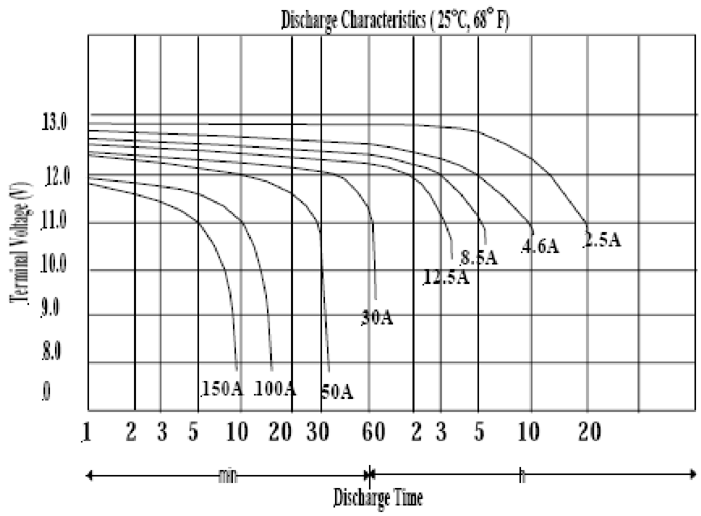

Figure 37: Discharge characteristics of the UB12500 [8]

The battery chosen is very basic, but the rest of the system allows for additional batteries to be added in the future. The focus of this year's team is to create a functional and safe system with room for improvement by future project groups.

Lighting System

The lighting system was selected such that it lights up cumulatively as the tidal current changes, representing the change in power being generated. The lighting system consists of 5 QH-7CC quarts halogen bulbs which are sequenced by the display driver and controller.

Figure 38: QC-7CC Halogen light bulbs [8]

The bulbs output 50-Watts each. Since 5 lights are being used, a total of 250 Watts will be consumed by the battery at 5 knots of tidal current. The lights are controlled in such a fashion that as the current flow increases the voltage seen from the alternator by the display driver/controller will increase linearly and thus switch each light on accordingly. The complete design of the controller is discussed further in the following section.

Analysis

Force analysis calculations were done for the flotation system, which showed that assuming the raft to have double the estimated displacement, and using approximately twice the estimated drag coefficient, there would be a force of 7618N (1713 lbf) on each line. This first estimate is a worst case scenario estimate. A closer estimate shows forces of approximately 4530 N (1018 lbf) on each line. Additional analysis was done on the various components within the cage and gearing system to be sure that they could withstand the forces applied onto them. These calculations can be found in Appendices G and J. The calculations done to analyze the boat can be found in Appendix O.

As discussed in the section above and after making the decisions necessary regarding the equipment to pick for the experiment testing, analysis of each electrical component was performed. First, the generator was tested by itself while using the load controller as a variable load to represent the charging process of the battery. The experiment is described further in the testing section as well as the final results.

The display driver/controller was designed in such a fashion that it accommodates the wide range of currents available in the Piscataqua River. Each light turns on in equal intervals from the voltage range of 3-V to 15-V outputted from the alternator. The LM3914 was used to compare the voltages using 10 comparators and was biased accordingly to drive 10 LEDs (light emitting diodes) that could serve as a possible voltage monitor. Each LED represents 1.2-V from 3 to 15. Each other LED is used to drive a TRIAC (TRIode for Alternating Current) system that consists of an inverting logic level MOSFET IRFZ10 and a 12-V SPST (Single Pole, Single throw) relay. A block diagram for the LM399 is available in Appendix D.

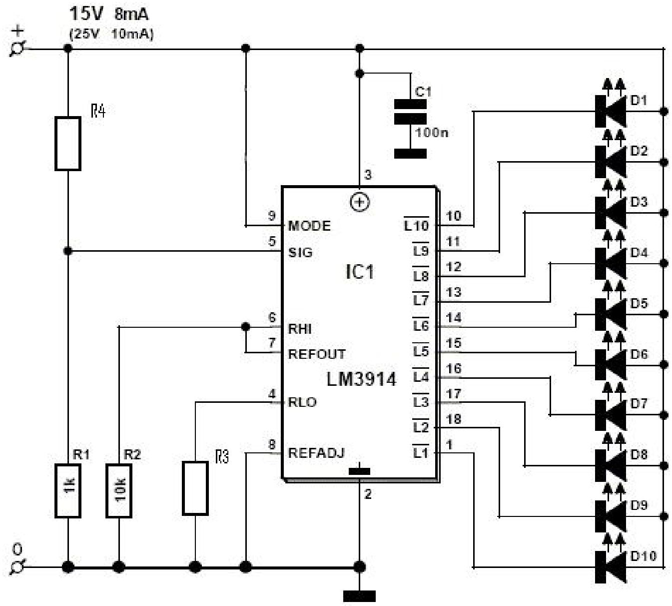

Figure 39: Typical application of LM3914 using ten diodes

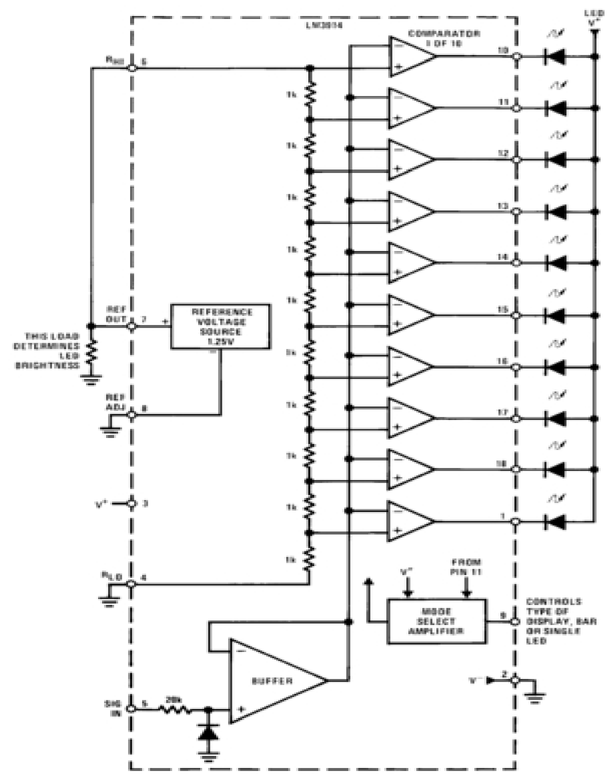

Figure 40: Block Diagram of the internal circuitry of LM3914

Resistors R4 and R3 were altered to change the voltage range at which the LEDs will light up as controlled by the comparators. Resistors were added in series with the LEDs to bias the current appropriately and to allow for very low voltage back into the chip. By allowing for low voltage back into the chip the gates of the IRZ10 MOSFETS would be controlled appropriately so that when the LED lights the FET turns off an open circuit through drain and pull up resistor to 12 volts. When the LED is off the FET was shorted to ground as well as the light. The TRIAC system is exemplified in the figure shown below. The circuit was implemented and tested by itself, as is shown later.

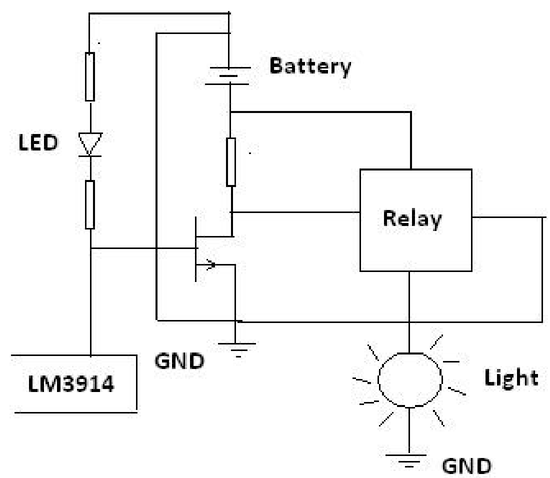

Figure 41: TRIAC System, to complement sequential lighting

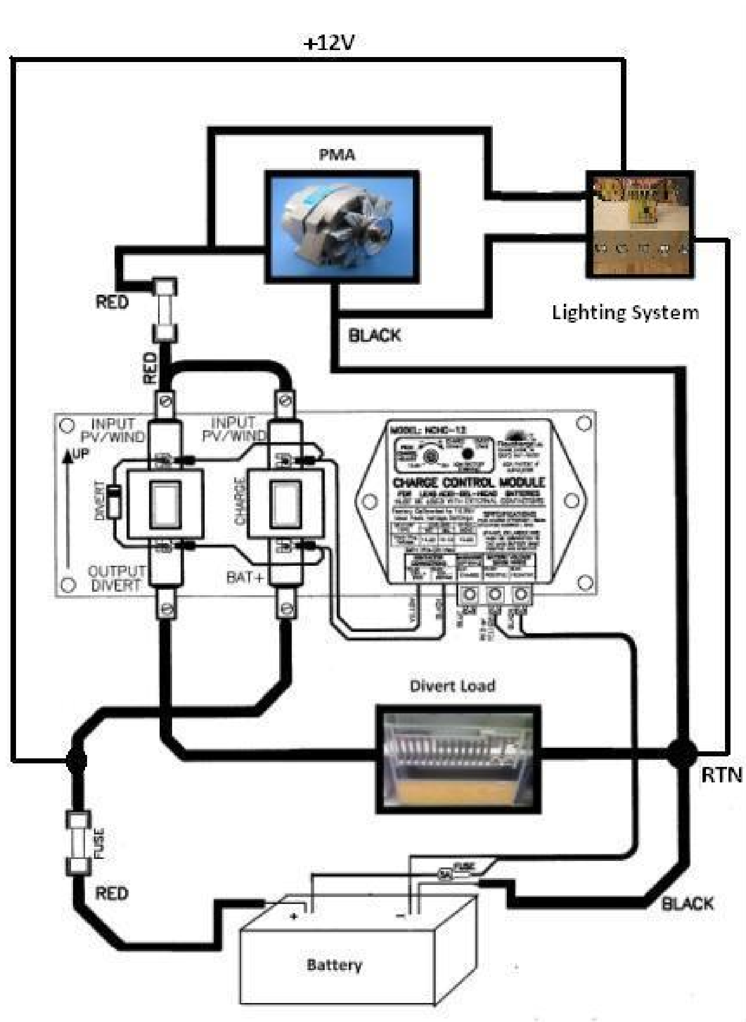

Figure 42: Block Diagram of Complete Electrical Subsystem

Testing

PMA TEST #1

Since the generator was the most important factor in the electrical design and the second most important for the mechanical design it was tested first. Since the mechanical design was not fully implemented the generator was tested using a Bridgeport provided by the UNH Mechanical Engineering department. A box was built to support the generator in a vise while cables were connected to the load controller. The Bridgeport was tied to the generator using a 1:1 pulley system. The Bridgeport's RPM was altered from 71 to 2136. The Bridgeport's speed was monitored using a TENMA 72-6633 digital optical tachometer shown in Fig. 43.

Figure 43: Tenma 72-6633 Digital Tachometer, provided by the UNH Mechanical Engineering department

The voltage was measured using a generic fluke multi-meter. Resistors were previously measured and the respective resistances noted. All data was entered into an Excel spreadsheet with preliminary calculations already programmed for real time plotting capability. Figure 44 shows the complete setup of the first test run.

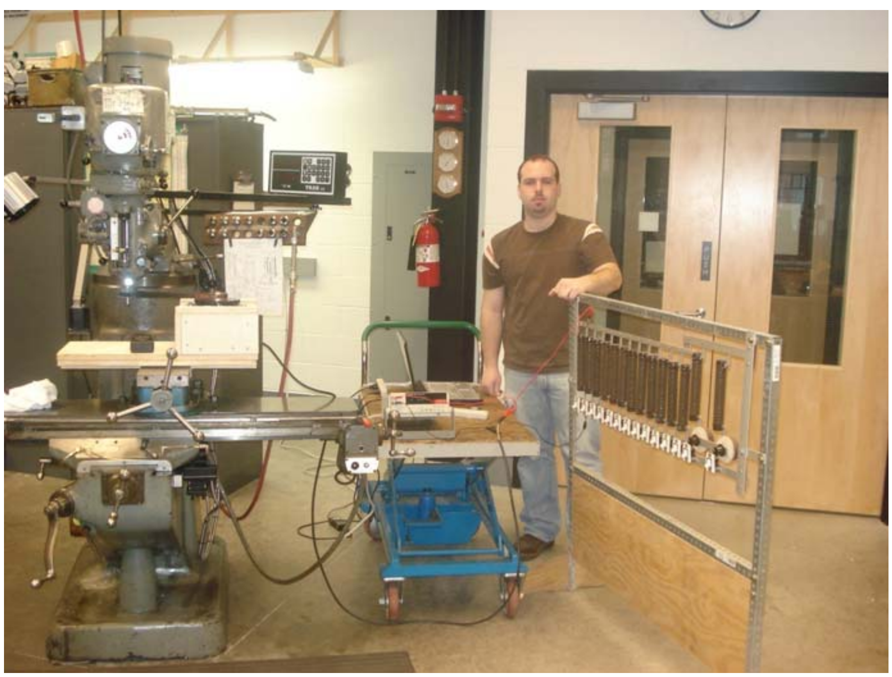

Figure 44: Complete Testing Setup, RPM provided by a drill press (left)

Figure 45 and the first table in Appendix F show the measurements and calculations made for the desired range of power and RPM for the first dry run using only the load controller and no charge controller or battery. The graph was simplified to specifically accommodate the desired voltage and power. All other RPM tests provided a voltage that was out of the range needed to charge the battery.

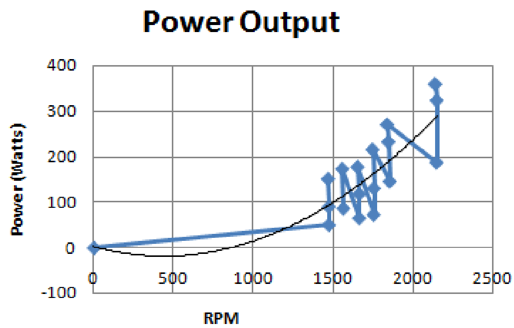

Figure 45: Power Output as Function of RPM Under Various Loads

This preliminary test of the PMA was very critical in the design of the system. It provided the mechanical team with a rough idea of what the gearing ratio should be. Previous assumptions were based on the power curve provided by the PMA's website which was later determined to be an open load curve shown below. This is the power that the alternator would output if nothing was connected to its output; an unrealistic ideal situation.

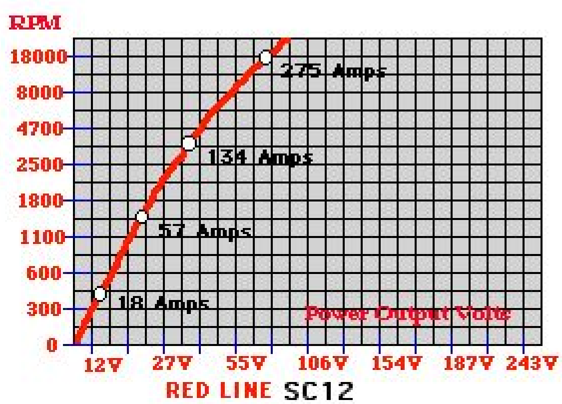

Figure 46: Power Output With Open Circuit Voltage[26]

From the ideal graph given in Fig. 46 an rotational speed of 300 RPM should produce 12 – 14 Volts. From the previous graph it is clear that for a typical battery an rotational speed of roughly 1640 RPM would be required to charge the battery and produce around 100 Watts of power.

PMA TEST #2

After receiving the charge controller and battery a complete electrical test was needed to simulate the final implementation of the system. The Bridgeport was used again in conjunction with the charge controller and battery. The battery was only charged 80% so that the charge controller would attempt to charge the battery. Fans were added to the PMA and were powered using the generator and not the battery. After connecting all components including the battery together, it was noted that the fans were spinning even though the alternator was not, which indicated that voltage was leaking from the battery back into the alternator. A blocking diode was implemented in between the devices to protect the alternator from the leaking voltage and to prevent the battery from draining itself. Since the batteries impedance changes with its charge the load was matched to 80% so that the voltage did not decrease when diverted by the charge controller. The following figure and second table in Appendix F are results of the test using two 3.1 Ohm power resistors in parallel to match the impedance of the battery when diverted.

Table 5: Averaged Power Outputs From Table in Appendix F

Current Velocity (m/s)	Expected Average Power (Watts)
0	0
1	48.87348387
1.5	92.25724194
2	153.9010753

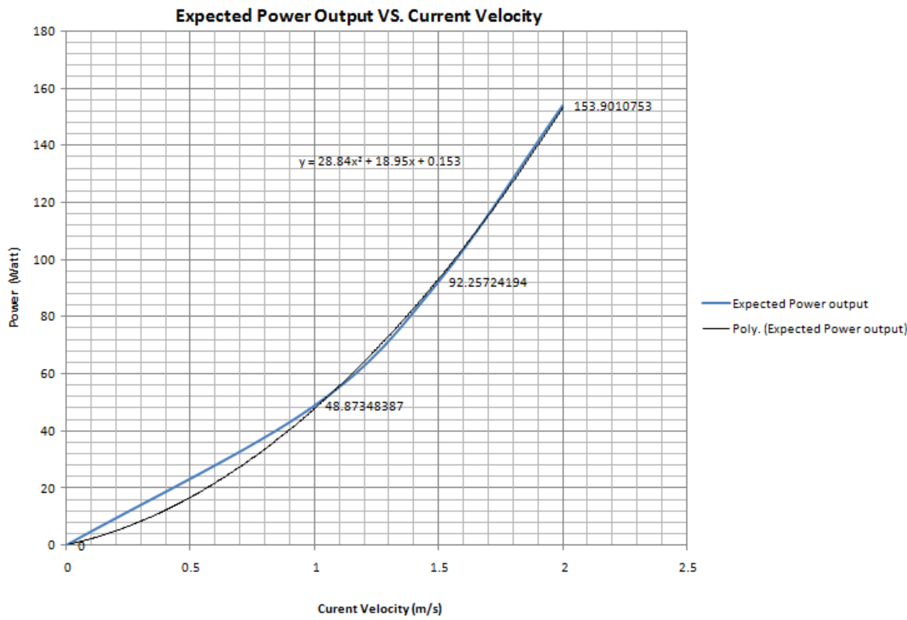

Figure 47: Expected Power Output vs. Water Velocity (m/s)

From the data a gearing ratio of approximately 25:1 was chosen to accommodate the maximum output of the alternator for the specific load of one 12 Volt battery.

Conclusions

This first year of the tidal energy project is a test of the general system. The setup is not intended as the final design, merely as a testing platform, to get the turbine in the water and produce energy. This system is the University's first step into tidal energy and has the characteristics of such a venture.

The electrical system works as predicted but has not been tested with the turbine. While testing with the Bridgeport vertical axis mill is the best possible alternative, it does not provide any information about the torque induced by the turbine. When the charge controller diverted the power during testing to a load that was much larger than the battery it was possible to hear the gearing change in the Bridgeport. The rotational velocity did not change however, because the Bridgeport compensates for large amounts of torque. In a true situation, it is very possible that the torque created by a large load could cause the turbine to stall or slow down.

The mechanical system design is nearly complete for this project, and has been designed for optimal performance given the expected conditions. The delay in building is due to the fact that the team spent a great deal of time designing and redesigning ideas without purchasing items, as the criteria for each design changed throughout the project. A great deal of time was also spent finding the least expensive options, particularly when searching for the flotation platform. Due to the scale of tidal power, the components quickly become quite large and expensive, especially since this project is the first of its kind at the University. The University was eventually willing to support the increase in budget thus resolving the budget issue.

It is difficult to draw technical conclusions about this project as a whole. At the current point, the project is still at such an early stage of fabrication that there is minimal data about how the entire system will perform. The electrical tests were based solely on a very small amount of information provided by the manufacturers of the PMA and charge controller. Overall, the system needs rigorous testing and further analysis before any actual conclusions about large scale feasibility or production scaled to an individual consumer can be made.

Future Work

The project has passed through the design stages, but still has room for a large amount of future work. First and foremost, the cage must be built and integrated with the platform, derrick, turbine, and electrical system. The entire system then needs to be tested for power output. This would first need to be done by towing the platform behind another boat, in order to have control over any problems that may arise. This testing would be done as a safety precaution for all parts of the system, as well as those responsible for testing.

Next, if permission can be secured for testing on the General Sullivan Bridge, the entire system could be tested in the actual location for one half of a tidal cycle. An optical tachometer and data acquisition system for the electrical components, while they would be helpful in the initial tow test, would be necessary for this secondary testing.

The combination of these two tests would hopefully give more of an insight into future work needed in all components of the system. They may also be indicative of whether a system of this sort actually has the potential to be a viable source of power in the Piscataqua River.

A complete electrical system with charge and load controlling has been implemented which will save future researchers time and money. With a few months work the system could be perfected for maximum efficiency. Batteries could be added to create one or more battery banks, which would allow for a more powerful sign. The system could also be implemented to tie into a grid for homeowner use or to be sold back to the power companies. The ideal design would be fitted to a complete, compact system that requires little or no effort to connect to the mechanical system. A microcontroller could also be added for real-time data acquisition without the need of a laptop for analysis. There should also be more tests performed with the turbine and the rest of the mooring system.

The mooring system will also need an almost complete overhaul for future long term testing. The current system is designed only for testing during one half of a tidal cycle. The future design will need to work in either tidal direction. Failing to consider just one component of the mooring could result in the loss of the vessel or catastrophic damage. It will take an excellent analysis of the forces within the mooring system to ensure that the system is secure. Also, the flow beneath the bridge is not straight under during the flood tide, this curvature of the current must be investigated to ensure the proper orientation of the flotation platform.

Extensive testing of the specific turbine to find the actual range in which it will operate at this location is crucial. This will allow for the optimization of a gearbox or belt drive, and increase the efficiency of the entire system. Future work includes the addition of an idler pulley. This would be a way to not only increase the efficiency of the system, but it also could be a safety component. If the idler were easily disengaged, this would allow the tensioning of the belts to go slack; the turbine could spin freely without damaging the gear train or the generator. Without the idler pulley the tension in the belts would be provided upon construction with the belts being stretched to fit the system.

If this project were to continue well into the future, it may be useful to incorporate a duct into the system. This would accelerate the flow entering the turbine, which would result in a higher power output. If more than one turbine were to be tested next to one another, the ducts would also serve as barriers that would minimize flow disturbance from those turbines situated on either side. This design could be investigated to be implemented into a permanent structure, for a more permanent solution to tidal power generation.

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Appendix A: Power Calculations

Power in the area swept by a rotor:

$$P = Cp \times 0.5 \times \rho \times A \times V^3 \times \eta_g \times \eta_b$$

- Cp= Turbine coefficient of performance
- ρ = Density of the water (seawater is 1025 kg/m³)
- A = the sweep area of the turbine (m²)
- V = water velocity(m/s)
- η_g = generator efficiency
- η_b = gearbox/bearings efficiency

Assuming

$r = \frac{1}{2} meter$

$C_p = 0.15$

$\rho = 1025 \frac{m^3}{kg}$

Ng=90%

Nb=95%

$v_{avg} = 1.958 \frac{m}{s}$

$P_{avg} = 386\ Watts$

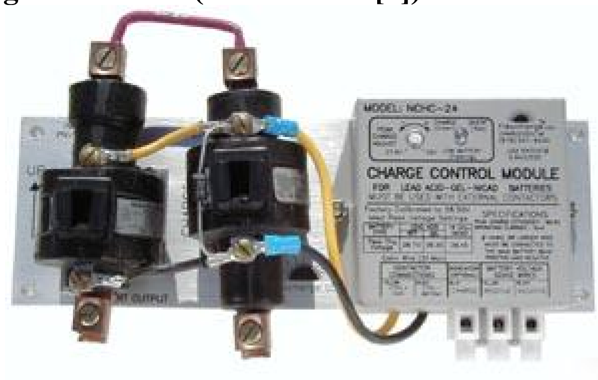
Appendix B: Permanent Magnet Alternator Specifications

SC 12 Permanent Magnet Alternator (Taken from [27])

- Capable of generating well over 12,000 Watts at speeds over 18,000 RPM.
- Great for charging large battery banks that are drained.
- Great for heavy Amp loads! The higher the Amp load the harder they work.
- Perfect for building simple, inexpensive and dependable wind or water turbines.
- A put-up and forget design! Expect decades of dependable service life.
- Bi-rotational. Makes power when turned in either direction.
- All weather rated. Rain, ice and weather proof electronics.
- Light weight aluminum body.
- 17MM hardened shaft.
- D.C. output. Includes built in rectifier.
- 2.33 phase magnetic field spread for maximum efficiency +low cogging!
- Heavy Duty coils and diodes.
- Bearings rated for 115,000 hours +
- 14 powerful #42H Neodymium magnets.

Appendix C: Charge Controller Specifications

NCHC-12-60 12V Charge Controller (Taken from [9])



NHCH from Flexcharge

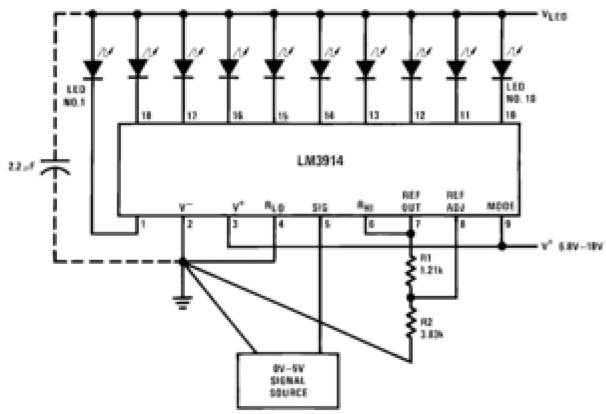
The NCHC line of controllers are series type regulators for use on flooded lead acid, gel, or flooded NiCad battery technologies. The regulation voltage is adjustable through a wide range. Available as an option with this controller is CHARGE DIVERT which allows one to use the excess unregulated energy from the charging source for other electrical jobs. The NC25A Regulates charging inputs from PV, Permanent Magnet Wind and Towed Water Generators, or any other current limited DC charging source. Standard unit is for 12V systems. Special order for 24V, 36V or 48V systems. (1000A max charging current in this configuration). Multiple battery banks can be charged with the use of a standard battery charging isolators.

- Unbeatable 99.5% charging efficiency
- Charges batteries from 0 (Zero) Volts with full uninterrupted power.
- High Ampere charging capacity. Use up to 4ea 100A contactors to regulate 400 Amperes. With a Special driver circuit, one can expand the NCHC to regulate as much as 2000 Amperes.
- Charge divert feature is available (Optional)
- Stable Charge Divert circuitry prevents divert drop-outs even if charge source voltage varies.
- Diverts only when voltage and current are at useable levels. Perfect for motor type divert loads(Fans, Pumps, etc..)
- Adjustable peak regulation voltage.
- Charges accurately through battery isolators, and works perfectly with battery combiners.
- The NCHC circuitry uses only 4mA (0.004A) while charging and at night (only 2mA when the charge indicator is not used).

- Charges batteries at full power, below the plate saturation point. This charges batteries quickly while reducing the electrolyte depletion (water loss) by up to 90% over conventional constant
- Voltage methods such as “PWM” & “High Frequency” charge regulators.
- Batteries start charging at only 0.005A of charging current.
- Controller can withstand open circuit input voltages spikes of 1000V without damage.
- Reverse polarity and transient voltage protection at on the battery sense wires.
- No power wasting sample periods.
- Voltage Sensing Wires allow greater freedom for mount the controller further from the battery bank.
- Stainless Steel, Nickel, Brass Material used for Connector and contactor terminals
- U/L 94V-O Rated Enclosure
- Electronics are completely sealed and potted for use in 100% humidity environments.
- Custom systems are available in capacities up to 2000 Amperes, also with unbeatable operating efficiencies.

Appendix D: Bar Display Driver Specifications

LM 3914 (Taken from [9])



Typical use of a LM 3914

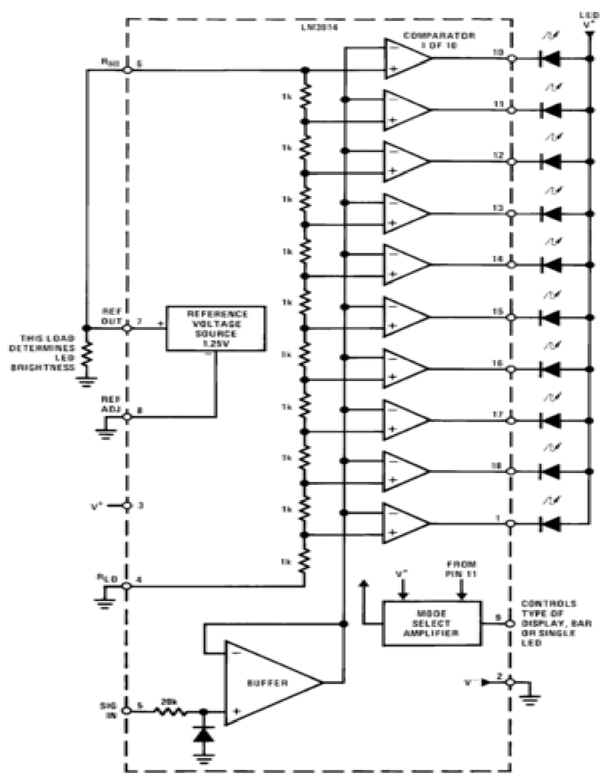


Figure2: Block diagram for the LM3914

Features

- Drives LEDs, LCDs or vacuum fluorescents
- Bar or dot display mode externally selectable by user
- Expandable to displays of 100 steps
- Internal voltage reference from 1.2V to 12V
- Operates with single supply of less than 3V
- Inputs operate down to ground
- Output current programmable from 2 mA to 30 mA
- No multiplex switching or interaction between outputs
- Input withstands ±35V without damage or false outputs
- LED driver outputs are current regulated, open-collectors
- Outputs can interface with TTL or CMOS logic
- The internal 10-step divider is floating and can be referenced to a wide range of voltages

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Power Dissipation (Note 6)	
Molded DIP (N)	1365 mW
Supply Voltage	25V
Voltage on Output Drivers	25V
Input Signal Overvoltage (Note 4)	±35V
Divider Voltage	−100 mV to V+
Reference Load Current	10 mA
Storage Temperature Range	−55°C to +150°C
Soldering Information	
Dual-In-Line Package	
Soldering (10 seconds)	260°C
Plastic Chip Carrier Package	
Vapor Phase (60 seconds)	215°C
Infrared (15 seconds)	220°C

See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering surface mount devices.

Appendix E: Light and Battery Specifications

Lights (Taken from[8])

- 55Watts, brighter than conventional bulbs
- Compact
- Die-cast housing and clear glass lenses. 2 lights, brackets, complete wiring harness and on/off switch included.

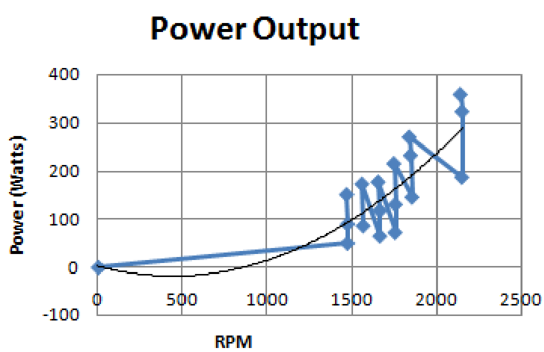
Battery (Taken from[8])

Specifications & Characteristics

Type		UB12500		
Nominal Voltage		12V		
Rated Capacity		50 Ah		
Dimensions	Length	198 ± 1 mm (7.79 ± 0.04 in)		
	Width	166 ± 1 mm (6.54 ± 0.04 in)		
	Container height	171 ± 1 mm (6.73 ± 0.04 in)		
	Height	171 ± 1 mm (6.73 ± 0.04 in)		
Weight		Approx. 14.787 kg (32.53 lbs)		
Capacity 20ºC (68ºF)	0.05 CA	2.55 A	20 HR	50 Ah
	0.1 CA	5 A	10 HR	50 Ah
	0.17 CA	8.5 A	5 HR	42.5 Ah
	0.2 CA	10 A	4 HR	10 Ah
	0.6 CA	30 A	1 HR	30 Ah
	1 CA	50 A	27 MIN	22.5 Ah
	3 CA	150 A	7 MIN	18 Ah
Internal resistance		Approx. 5 mΩ		
Max. Charging Current		15 A		
Charging Voltage 20ºC (68ºF)	Standby Use	13.5 to 13.8 V (-20mV ºC)		
	Cycle Use	14.4 to 15.0 V (-30mV ºC)		

Appendix F: Testing Data

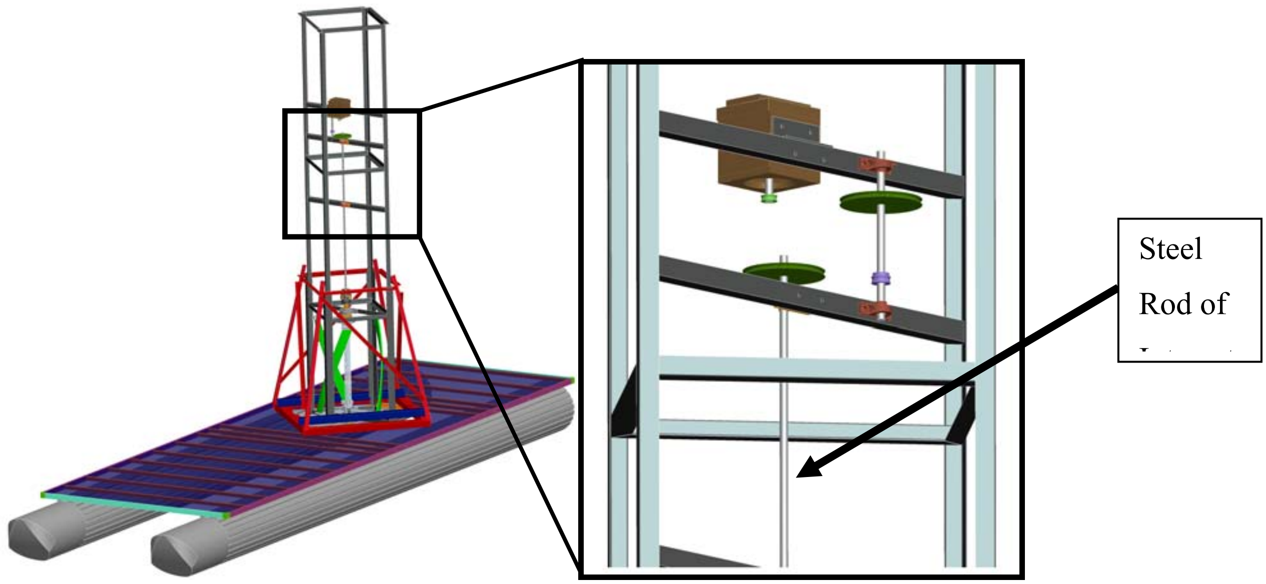
	ω (RPM) Optical Tach	ω (RPM) Bridge Port	Voltage (V)	# of 3.1 Ω Resistors	Resistance (Ω)	Current (Amps)	Power (Watts)	Power (HP)	Braking Torque (lb-ft)
14	1471	1300	12.45	1	3.1000	4.0161	50.0008	0.0671	0.2396
	1471		11.8	2	1.5500	7.6129	89.8323	0.1206	0.4305
	1466		10.8	4	0.7750	13.9355	150.5032	0.2020	0.7237
15		1400	13.29	1	3.1000	4.2871	56.9755	0.0765	#DIV/0!
	1562		11.57	2	1.5500	7.4645	86.3645	0.1159	0.3898
	1555		11.56	4	0.7750	14.9161	172.4305	0.2315	0.7817
16	1661	1500	14.2	1	3.1000	4.5806	65.0452	0.0873	0.2761
	1661		13.5	2	1.5500	8.7097	117.5806	0.1578	0.4990
	1651		11.7	4	0.7750	15.0968	176.6323	0.2371	0.7542
17	1752	1600	15	1	3.1000	4.8387	72.5806	0.0974	0.2920
	1753		14.2	2	1.5500	9.1613	130.0903	0.1746	0.5232
	1744		12.9	4	0.7750	16.6452	214.7226	0.2882	0.8680
18	1852	1700	15	2	1.5500	9.6774	145.1613	0.1948	0.5526
	1843		13.4	4	0.7750	17.2903	231.6903	0.3110	0.8862
	1836		11.8	6	0.5167	22.8387	269.4968	0.3617	1.0348
21	2145	2000	17	2	1.5500	10.9677	186.4516	0.2503	0.6128
	2146		15.8	4	0.7750	20.3871	322.1161	0.4324	1.0582
	2136		13.6	6	0.5167	26.3226	357.9871	0.4805	1.1815



Expected Electrical Current, Power and Average RPM		
Current Velocity (m/s)	Power (Watts)	Average RPM
1.00	34.00	996.1915866
1.00	43.80	996.1915866
1.00	53.43	996.1915866
1.00	64.26	996.1915866
1.50	75.25	1469.839335
1.50	89.83	1469.839335
1.50	86.36	1469.839335
1.50	117.58	1469.839335
2.00	130.09	1927.188387
2.00	145.16	1927.188387
2.00	186.45	1927.188387

Appendix G: Shaft Torsion Calculations

To calculate maximum twist of the 1inch steel rod connecting the turbine to the gear train requires simple calculations using known material properties for the rod, seen in the figure below.



The worst case scenario of this situation is assuming that one end is fixed while the maximum torque given by the 1.25-m x 1-m diameter turbine in the expected maximum current speeds is applied at the opposite end. This would be like if the gear train stopped and the turbine continued to spin. The details of this simple analysis cannot be included in this document as it would violate the non-disclosure agreement. The summary of this is that a 2.5-m long steel rod will have a maximum rotation of less than 20 degrees, which is deemed reasonable for this testing. Additionally, the maximum shear stress is well within a safe range for the material of interest, as it can be converted to tensile yield strength and has a factor of safety of two.

Appendix H: Mooring Parts List

Mooring Parts List				
Part Number	**Part**	**Quantity**	**Cost [West Marine]**	
	Buoy, Green	2	$99.99	
	Shackle, 5/8ths	6	$10.57	
	Zip Ties	6	$.89-$3.99	
	Multipurpose Buoy, Orange	6	$5.49	
	Line, Double Braided	376 ft	$1.49 per foot	
	Chain, 1/2" diameter	2 X 10'	$643 for 200ft	

Appendix I: Mooring Alternatives

When the issue of mooring was addressed, three different categories of mooring system came into focus: spread moorings, single point moorings, and dynamic positioning moorings.

Spread moorings include catenary moorings, multi catenary moorings, and taut spread moorings. With a catenary mooring, the mooring lines arrive horizontal to the seabed so that the anchor point is only subject to horizontal forces, and the restoring forces are mainly generated by the weight of the mooring lines returning the system to equilibrium. With multi catenary moorings, the mooring lines incorporate weights and buoys to form S or Wave type configurations. Steep and lazy touchdown points are possible. In a taut spread mooring, the mooring lines typically arrive at an angle to the seabed with the anchor point capable of resisting horizontal and vertical forces. The restoring forces are mainly generated by the elasticity of the mooring line. These various mooring systems are evaluated in the table below for their suitability towards the tidal energy turbine under the General Sullivan Bridges.

Single point moorings contain turret moorings, catenary anchor legs, single anchor leg moorings, articulated loading columns, single point moorings and reservoirs, and fixed tower moorings. In a turret mooring, an internal or external catenary moored turret attached to a floating structure allows it to weathervane around the turret. In a catenary anchor leg, the floating structure is moored to a catenary moored buoy and is able to weathervane around the moored buoy. With a Single Anchor Leg Mooring, the floating structure is moored to a single anchored taut buoy and is able to weathervane around the moored buoy. In an Articulated Loading Column, a moored floating structure can weathervane around a bottom hinged column, which has a swivel above the water line. With a Single Point Mooring and Reservoir, a catenary anchored SPAR buoy allows the storage of a medium (oil, hydrogen) and a floating structure to weathervane around a mooring point. With a fixed tower mooring, a fixed tower anchored into the seabed allows the moored floating structure to weathervane around the mooring point.

The final mooring system that was considered was a dynamic positioning mooring. Dynamic positioning moorings come in two different categories: Active moorings, and propulsion moorings. Active moorings consist of mooring lines that are spread around the floating structure, where the inboard end of each mooring line is held by a servo controlled winch. A central computer tensions or loosens the mooring lines in order to keep a fixed seabed position. Propulsion moorings involve positioning a floating structure above a fixed seabed point by the use of propellers or thrusters which are controlled from a central computer.

Due to the nature of the project, relatively strong currents and therefore large forces are encountered by the flotation platform. The relatively low budget of the project, along with the large forces encountered in its deployment gave way to certain criteria for the mooring system. The suitability of different mooring configurations with respect to these criteria is well defined in the table below.

Mooring Configuration	**Suitability**
Spread Moorings	
Catenary Mooring	Medium
Multi-Catenary Mooring	Low
Taut Spread Mooring	High
Single Point Moorings	
Turret Mooring	High
Catenary Anchor Leg	Medium
Single Anchor Leg Mooring	Medium
Articulated Loading Column	High
Single Point Mooring and Reservoir	High
Fixed Tower Mooring	Low
Dynamic Positioning	
Active Mooring	Low
Propulsion	Low

During operational conditions, waves can create large forces upon the platform from any direction. This means that the platform must be able to have some degree of rotation with respect to its original orientation. If a spread mooring system is chosen, the housing should ideally be positioned so that the structure is able to turn in 90 degrees relative to its original orientation, to insure that the drag on the housing does not break the mooring system lines. This will result in the lowest possible loading on the structure and thus allow for a lower strength, and therefore less expensive mooring system.

Primary mooring components are anchors and lines. These are used along with other items such as connecting elements, floats, etc. These components must be chosen with consideration of the mooring configuration, location and the requirements of a short term mooring.

In the earlier stages of the project, the site for the project had not yet been determined and the option of an anchored mooring system was still in place. Mooring anchors that were researched in this project include gravity anchors, drag embedment anchors, driven pile/suction anchors, vertical load anchors, and drilled and grouted anchors.

With gravity anchors, the horizontal holding capacity is generated by dead weight providing friction between seabed and anchor. Drag embedment anchors on the other hand create a horizontal holding capacity that is generated in the main installment direction by the embedment of the anchor in the ground. With a driven pile / suction anchor, horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction along the pile and the ground. With vertical Load Anchors, horizontal and vertical holding capacity is generated due to a specific embedment anchor allowing loads not only in the main installment direction. Lastly, with drilled and grouted anchors, horizontal and vertical holding capacity is generated by grouting a pile in a rock with a pre-drilled hole.

These methods are evaluated in the table below to their cost towards the system. It should be observed that although driven pile systems were rated at this point as high cost systems, it was later realized that structures were available where driven piles were already in place, and thus drastically decreased the cost of the mooring.

Mooring Components	**Cost**
Mooring Line	
Chain	Medium
Wire Rope	Low
Synthetic Rope	High
Connectors	
Shackles	Medium
Connecting Link Kenter Type	Medium
Connecting Link Pear Shaped	Medium
Connecting Link C Type	High
Swivels	Medium
Anchor	
Gravity Anchor	Medium
Drag Embedment Anchor	Medium
Driven Pile / Suction Anchor	High
Vertical Load Anchor	High
Drilled and Grouted Anchor	High

In the application of mooring lines, chain, wire ropes, and synthetic ropes were considered. Chain has an advantage over other lines because of its characteristic catenary stiffness, and its low abrasion and bending properties. Wire ropes have a lower weight than chain, and higher elasticity for the same tensile strength. One disadvantage of wire rope is that it is more prone to damage and corrosion than chain is. Synthetic rope has also been considered for certain sections of the mooring system. Categories of synthetic rope include polyester, aramid, HMPE, and nylon. An advantage of rope can be that it is often neutrally buoyant or buoyant, making it ideal for very deep water applications. A disadvantage in rope is that considerable change in axial stiffness after installation in ropes requires re-tensioning.

Along with the decision of mooring lines came the question of what types of connectors should be used between lines as well as the interface between lines and the anchor point, and the flotation system. Various shackles were considered for the connection of chain at the anchor point as well as at the mooring point. Kenter type and C type connecting links were researched as a way to connect two pieces of chain whose dimensions were the same. Although these do not have as long of a fatigue life as chain, they were thought of as a good link for a temporary system. Pear shaped connecting links were also considered as a method of connecting two pieces of mooring line with terminations of different dimensions. Along with these connection devices, swivels were considered to relieve twist and torque that would build up in the mooring lines. Swivels are usually placed a few links from the anchor point, but can also be placed at the interface between a section of chain and rope. Although high friction inside of the turning mechanisms of swivels often causes them to function poorly under load, newer technology has yielded swivels with special bearing surfaces that enable them to function under load.

Appendix J: Cage Design Calculations

The steel calculations of different size diameters using two beams with a maximum moment of 12,500 Nm is shown below:

Bending Moment	Diameter	Inner Diameter	Outer Diameter	R_2=y	Moment of Inertia	Sigma	MPa
M_{max}/pole		R_1	R_2	y	Ix	N/m^2	
Sold Speed Rail Cylinder							
12500	3 inch	0	0.038 m	0.038	1.638e-06	290047644	290.1
12500	2 inch	0	0.0254 m	0.0254	3.269e-07	971223052	971.2
12500	1 inch	0	0.0127 m	0.0127	2.043e-08	7769784415	7769.8
12500	4 inch	0	0.0508 m	0.0508	5.231e-06	121402882	121.4
Pipe Speed Rail Cylinder							
12500	3.5 inch/4 inch	0.0445 m	0.0508 m	0.0508	2.165e-06	210563263	293.4
12500	2 inch/2.5 inch	0.0254 m	0.0318 m	0.0318	4.712e-07	291674241	842.3

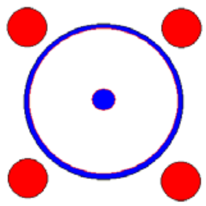
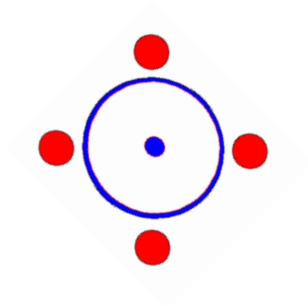
Using the table above the group determined that the cage design with two columns or beams to hold the turbine in place would not be strong enough because the breaking point for steel is 400 MPa. The group decided to change the design to using a four column or pole apparatus.

The steel calculations of different size diameters using four beams with a maximum moment of 12,500 N-m is shown below:

Bending Moment	Diameter	Inner Diameter	Outer Diameter	R_2=y	Moment of Inertia	Sigma	Mpa
M_{max}/pole		R_1	R_2	y	Ix	N/m^2	
Pipe Speed Rail Cylinder							
12500	2 inch/2.5 inch	0.0254 m	0.0318 m	0.0318	4.71e-07	290047644	290.1
12500	2 inch/2-3/8 inch	0.0254 m	0.03016 m	0.0302	3.23e-07	971223052	971.2

Frame Designs

Four poles: the steel calculations of four beams holding the turbine in place yielded a very stable system that would be capable of supporting a tension cable to the front of the raft for force distribution. Although this set up would provide good structural integrity, the orientation of the poles would create disturbances in the flow of the water around the turbine.

One way to prevent water restrictions is to remove one pole from the configuration, as seen below. However, the three-pole design is not logical when it is considered in conjunction of the mooring system. In order to fully unitize the three-pole design, the cage would need to be turned so that the flow would always be entering the open front side of the cage. Unfortunately, this adds another unnecessary degree of complication to the system.

Appendix K: Detailed Turbine Descriptions

Horizontal axis Propeller:

These turbines have been used more extensively in tidal applications than any other type, with varying degrees of success. The bulb and Kaplan type really are not appropriate for a free flow application; they require a highly accelerated flow in order to be efficient. The longer, more slender bladed type operates at various efficiencies, ranging from 12 to close to 40 percent. This means that if the correct design were used, it could have an efficiency which is very competitive with other designs.

The inherent requirement of more moving parts in order to make it operable in multidirectional flows made this turbine impractical. The other very limiting feature of this type of turbine is the fact that, as stated by its name, it rotates on a horizontal axis. This means that it would either need the electrical system to be contained on the same axis underwater, or have a gearing system transferring rotation to a vertical shaft. Both would require underwater gears and consequently sealed bearings, which could be avoided by a different rotor choice.

Horizontal axis propellers require complex blade geometry stemming from the geometric differences required along the blade. This complexity adds to the manufacturing cost, and means that manufacturing the entire rotor is quite difficult. These turbine blades can rotate at high velocities, which many people fear will kill fish and other wildlife. These negative effects on the ecosystem, as well as other environmental concerns are detailed in Appendix L.

Cross axis rotors:

The Darrieus turbine has been altered in countless ways for use in tidal power applications. Most of these are either enclosed in some sort of duct or are modifications of the Davis type, as seen in the bottom left of Fig.3. They can be oriented in any direction perpendicular to the flow, which means that if placed vertically, the entire mechanical to electrical interface can be contained above the water. Additionally, they work in any flow direction, eliminating the need for their positioning system to orient the turbine in the proper direction.

The most radical change to the cross axis rotor is the development of the helical design in the Gorlov turbine. These turbines are claimed to be very efficient, reaching into the 35% range, and have all of the other advantages listed above. They also reportedly have less vibration problems than their straight-bladed counterparts, putting less unnecessary stress on the entire system.

The non helical versions of this type could be manufactured with relative ease. However, adding the twist for the helical type designs adds complexity to the process. Many of these designs are also patented, requiring permission to encroach upon their designs.

Drag (Savonius) designs:

The major advantage of a Savonius type rotor compared to the previously mentioned types is the ease and low price of manufacturing. These designs can be made as simple or as complex as the user desires This means that they can be made out of almost any material at extremely low cost and with minimal difficulty for a basic design. These also have a few of the same advantage as the cross axis designs. They can be oriented in any direction, and will generate power in any direction of flow.

The extreme drawback of these designs is that they operate at incredibly low efficiencies. Due to this characteristic they are rarely used in water applications.

Appendix L: Environmental Concerns

When extracting energy from the environment, such as a river, there have been no conclusive studies done about how much energy can be extracted before there are detrimental effects. Currently, the maximum amount of energy suggested to be extracted from the total amount of tidal energy is fifteen percent [11]. Any more will likely have adverse effects, such as reducing the amount of water entering and leaving the tidal zone.

A tidal energy system has different environmental concerns than that of other conventional hydropower systems. The main discriminating factor is that a dam is not needed for the installation of a tidal energy system. A hydropower system has heated water leaving its turbines, which along with the dam slowing down the river, causes the water to become stratified, which means that the river will be warmer on top and colder on the bottom. As the cold water is not exposed to the surface, its oxygen content is lowered and becomes uninhabitable for fish [18]. Fortunately tidal energy systems are generally not large enough to change the water temperature.

An in-current tidal energy system is thought to be minimally intrusive to the environment. Since a dam is not necessary, it will not affect the movement of fish and other aquatic creatures in rivers or estuaries. A dam on a river will prevent fish from migrating unless there are fish ladders or an equivalent. In recent years, this has become a pressing concern for dam owners and environmentalists alike. The tidal energy system could be adapted to a fit a river application and avoid many of the existing concerns of hydropower.

With a large tidal energy system, turbidity becomes an issue. Turbidity is the amount of matter that is suspended in the water. If the tidal energy system is large enough to effect the flow of water between the estuary system and the ocean, the turbidity will decrease, causing there to be less matter in the water. When there is less matter in the water, sunlight reaches a deeper level in the water, interfering with the growth of phytoplankton.

Phytoplankton is considered the "grass" of aquatic habitats and is consumed by zooplankton, insects, fish, and other animals. It forms the basis of aquatic food chains with higher plants. In combination with algae and plants, they are the source of most of Earth's oxygen. In order to avoid reducing phytoplankton growth, the tidal energy system should not be large enough to interfere with flow of water in and out of the estuary system. [19]

The salinity varies in the estuary due to the time of year, fresh water flowing into the estuary, location, and daily tides. The salinity levels are highest at the mouth of the river where it meets the ocean. Also, in the spring the salinity typically decreases due to snowmelt and additional rain entering the estuary. In the summer, the evaporation rate increases, leaving the estuary with a higher salinity. The salinity can be detrimentally affected by lack of flow between the estuary and the ocean. This will cause salinity levels to decrease in the estuary. Aquatic life in the estuary can only tolerate certain salinity changes. Bottom dwelling animals, such as crabs and oysters, endure a certain amount of change in the salinity. However if the salinity changes too much this will adversely affect their growth, reproduction, and ultimately their survival. [20]

Salinity also directly corresponds to the amount of dissolved oxygen in the estuary water. Water with a high salinity level has a low solubility of oxygen [20]. If the exchange of water between the estuary and ocean is decreased, this results in a lower salinity level and higher oxygen levels. This could create an ecological imbalance, as the water would be more fertile for living organisms which may not have previously inhabited the estuary. Testing would be needed on salinity changes in the estuary if a permanent tidal energy system were to be installed.

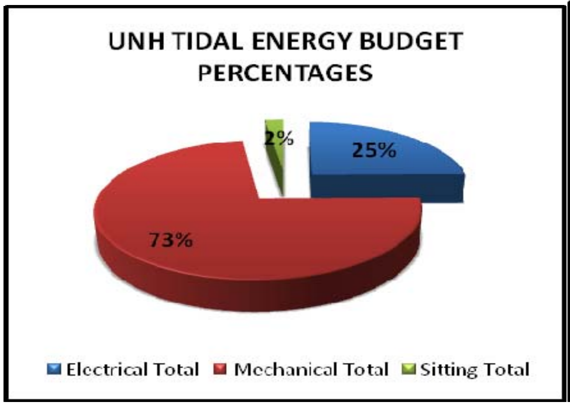
The blades themselves may also kill or de-scale the fish trying to pass through them. Fish death due to impacts with blades is uncommon; however it does occur in older turbines installed in hydroelectric dams. There are currently environmentally friendly turbines for hydropower dams in the proof of concept phase to reduce fish mortality [21]. However, the Gorlov Helical turbine has low RPM and a significant amount of free space, meaning that fish strike the blades is not a large concern. This was studied in the Amesbury Tidal Energy Project, and the results showed no fish strikes, or even fish swimming through the rotating turbine. [12]

Cavitation is also responsible for fish deaths. Cavitation is a phenomenon caused by localized regions of extremely low pressure on the trailing edges of the turbine blades, causing the water there to turn into water vapor. Bubbles then form when the hydrostatic pressure decreases to the vapor pressure of water. These large bubbles travel downstream to areas of higher pressure where they collapse forcefully, causing large shock waves that are strong enough to pit metal turbine blades. If fish are near these areas, they may be hurt or killed [18].However because the Gorlov turbine rotates at very low speeds, cavitation is not an immediate concern.

A major concern with using the Gorlov turbine is plant matter becoming entangled in the rotor. As there is a massive amount of seaweed and eelgrass in the Great Bay Estuary this is a valid concern of the present project. At certain times during the year, a large amount of both plants drift in the water column with the tides. Despite the fact that eelgrass does not grow around the chosen site, the tides that make this area superior for power generation also move a lot of debris through the estuary [17]. A protective cage can be designed and manufactured to protect the turbine while it is in use. In order to design the cage for the correct conditions, a study of the actual amount of debris suspended in the water column would be necessary.

Appendix M: Budget

The group was given a budget of $3,000 to complete the project by the end of April. The expenses throughout the project were closely monitered. The original plan was to allow the electrical team to use one third of the budget with the rest used for materials and construction of the turbine-deployment system. The budget was fully used and the percentages can be seen in Figs. 48 and 49.



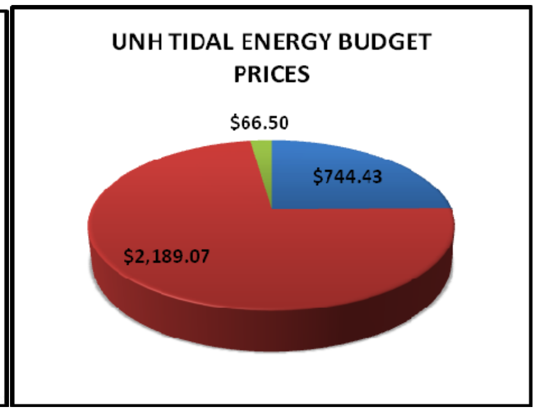
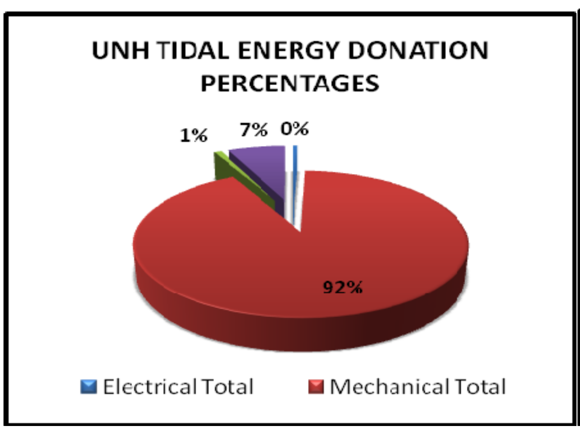


Figure 48: UNH Tidal Energy Budget Prices **Figure 49: UNH Tidal Energy Budget Percentages**

With the donation from Lucid Energy Technologies LLC of the helical turbines and aid from the OE department to purchase a pontoon boat, the group was able to turn the once small scale project into a much larger one. The total amount of donations was calculated to be about $19,500.



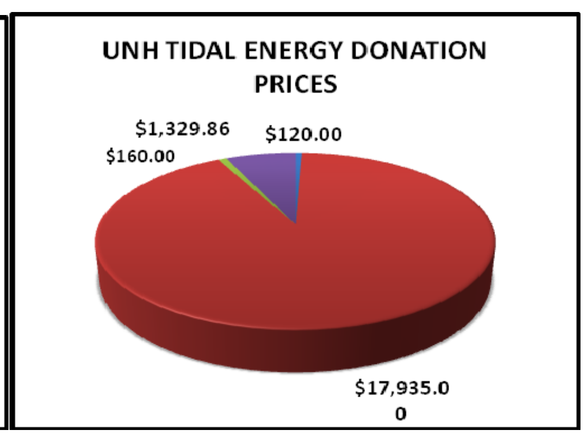
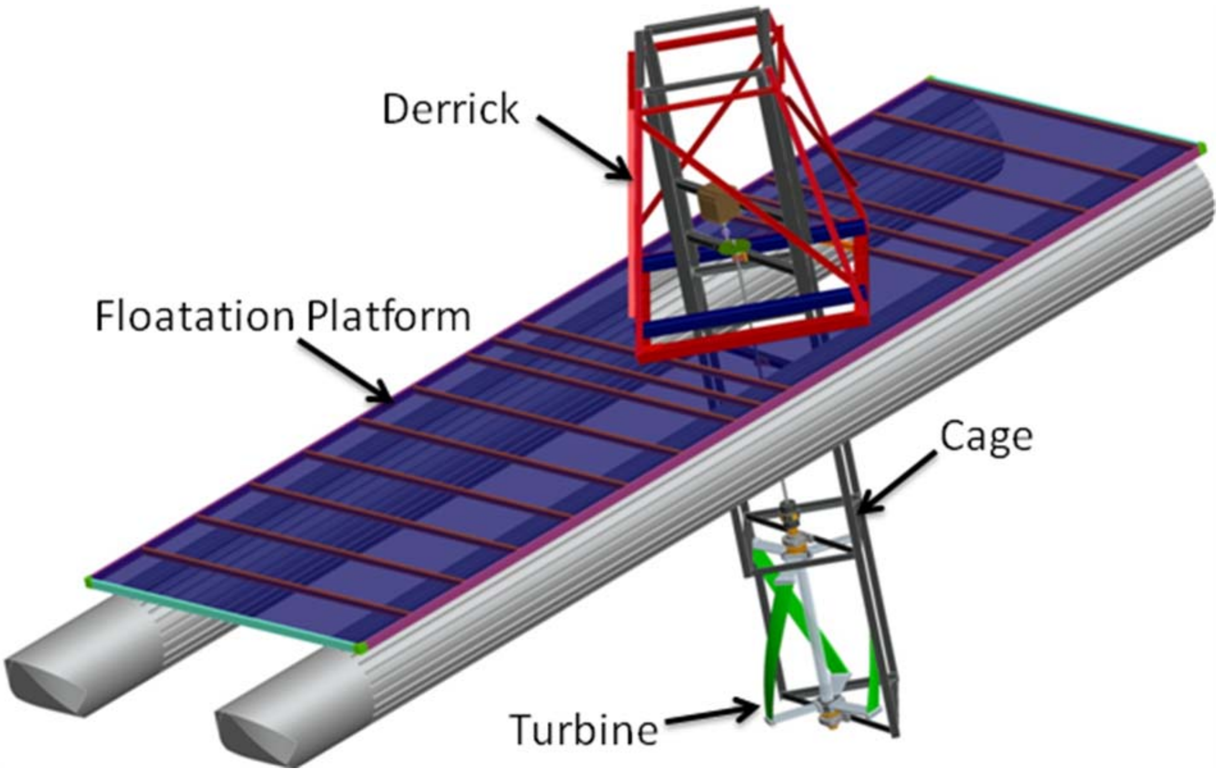


Figure 50: UNH Tidal Energy Donation Prices **Figure 51: Donation Percentages**

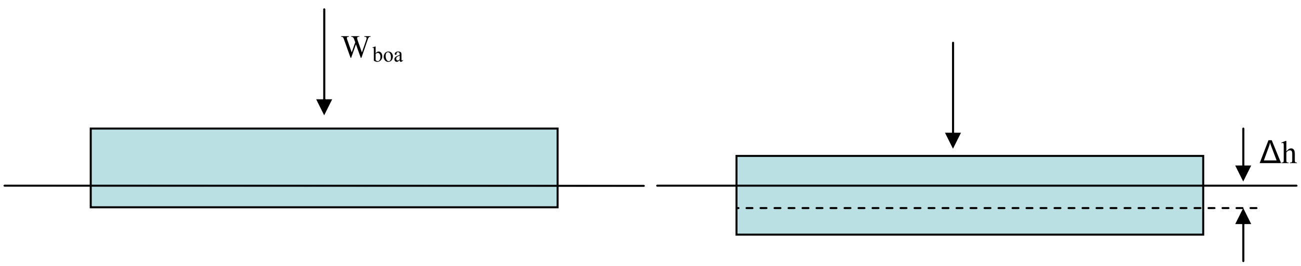
Appendix N: Definition of Terms



Appendix O: Boat Calculations

The following analysis was done to determine the change in freeboard and tipping moment using the small pontoon boat and the large turbine. It is noted that the tipping moment excluded the drag on the pontoons in the water.

Freeboard Analysis



Change in freeboard:

$$W_{equipment} = \gamma \cdot \Delta V$$

Where:

$W_{equipment}$: Weight of additional equipment = 450lb

γ: Specific weight = 64 lb/m^3

ΔV = Change in volume from addition of equipment weight

$$\Delta V = A_P \cdot \Delta h$$

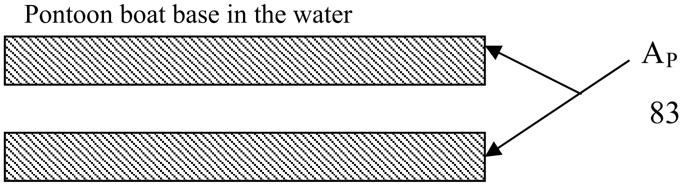
Where:

A_P: Plane area, as seen below

Δh = Change in depth in freeboard height

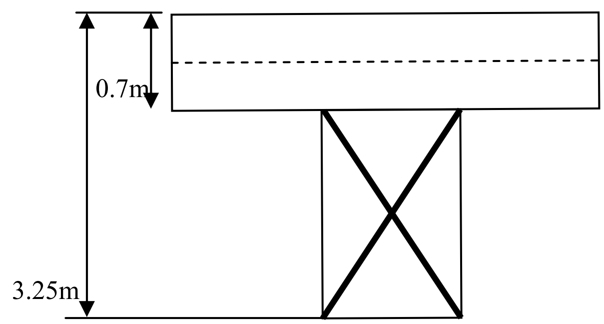
$$\Delta h = \frac{W_{equipment}}{\gamma \cdot A_P}$$

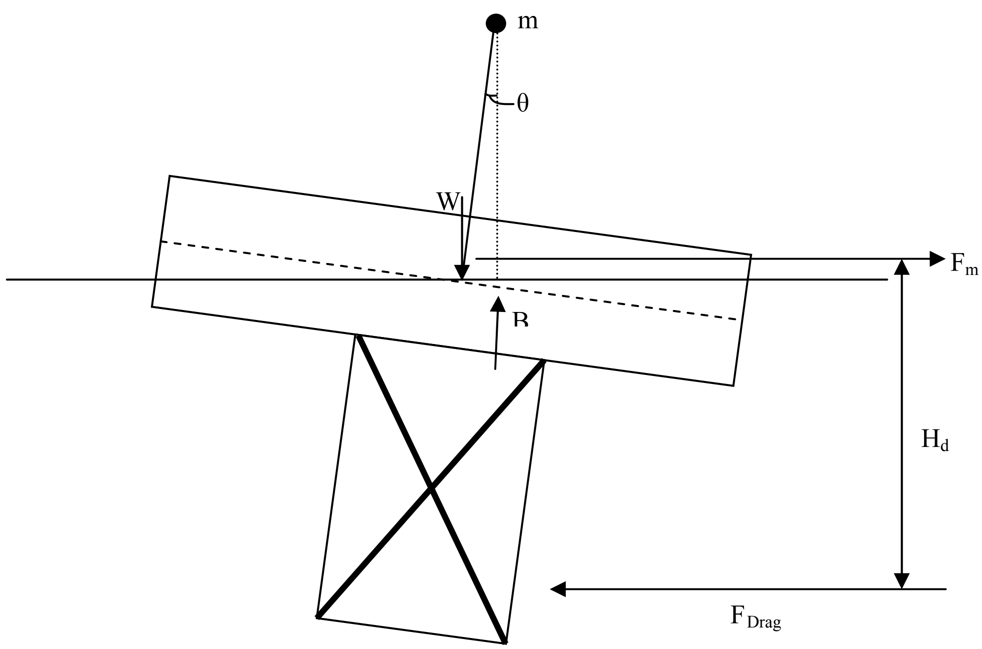
Pontoon boat base in the water



Tipping Moment:

Note: these calculations are only valid for tipping angles of less than 10^o.





Where:

W: Center of weight of the components

B: Center of buoyancy

F_m: Mooring forces

F_{Drag}: Drag forces

H_d: Distance between the mooring forces and drag force

m: Metacenter

θ: Angle of tipping

Using standard buoy mathematics and simplifications one can find the metacentric height, which can then be used to find the angle of tipping of the boat.

The metacentric height is found using:

$$\overline{gm} = \frac{I_y}{V} - \overline{bg}$$

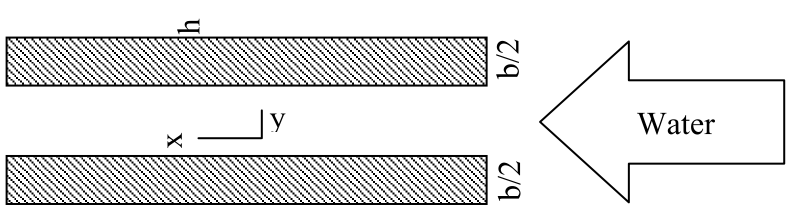
Where:

m: Metacenter

V: Volume

$\overline{bg}$: Distance between boat's center of gravity and center of buoyancy, which will be neglected for these calculations as it is unknown and also much smaller than the $\frac{I_y}{V}$ term

I_y: Area Moment of intertia of water plane area = $\frac{b \cdot h^3}{12}$



The moment of concern is the ability of the drag force to tip the boat, M_D, which is counteracted by the boat's righting moment, M_R.

$$M_D = F_{Drag} \cdot H_D$$

$$M_R = B \cdot \overline{gm} \cdot SIN\theta$$

$$W = B = \gamma \cdot V = g \cdot \rho \cdot V$$

Where:

γ: Specific weight of water

V: Volume displaced

g: gravitational constant

ρ: Water density

Setting the moment formulas together allows one to see the tipping that needs to be counteracted by the righting moment. Note: Since this is a small angle approximation, SINθ = θ [radians].

$$M_D = M_R$$

The moments become:

$$F_{Drag} \cdot H_D = \gamma \cdot V \cdot \frac{I_y}{V} \theta$$

Where:

$$F_{Drag} = \frac{1}{2} \cdot C_d \cdot \rho \cdot A_{proj,t} \cdot v^2$$

C_d: Drag coefficient of turbine

ρ: Water density

$A_{proj,t}$ = Projected area of the turbine and fixture

v: Water velocity

Thus one find the small angle approximation using the following formula, where θ is in radians:

$$\theta = \frac{\frac{1}{2} \cdot C_d \cdot A_{proj,t} \cdot v^2 \cdot H_D}{I_y \cdot g}$$