COLLEGIATE WIND COMPETITION
U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF ALASKA FAIRBANKS

AURORA-BOREAS

Control and Power Systems

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Table of Contents

Executive Summary

The alternative energy industry has seen dramatic growth in the last few years in the United States, and in the current market the ability to design and incorporate renewables has become more vital. Therefore the US Department of Energy is challenging young engineers to tackle the issue of designing, building, and testing a competitive wind turbine. This wind turbine will deliver 10 W of continuous power from varying wind speeds of 9 to 18 m/s to a designated load bank. The final goal is to produce a small wind turbine that will be capable of withstanding various realistic weather conditions, and perform reliably with constant output voltage and power.

Wind energy is one of the largest growing renewable energy sectors. Wind power produces 4% of the US total energy generation. The industry has created over 1 million jobs worldwide as of 2015. Projections in this sector anticipate an increase in wind power generation on the magnitude of 1% growth per year, meaning that by 2025, approximately 15% of the US power will be generated from wind resources. With this massive growth, hundreds of thousands of jobs will be created for the research and development of wind turbine technology [1].

The purpose of this project is to design, build, and test a small-scale wind turbine to specifications set by the goals of CWC 2017. Aurora Boreas started with the model turbine from the 2016 CWC Team, and made multiple improvements, most importantly; adding yaw capabilities. The first goal was to gain a full understanding of the 2016 system and how it operates. By understanding how the turbine operates, we were able to make design changes and upgrades to increase the efficiency and power production of the system. The final goal for this project was to develop and manufacture components that could aid the power generation system to help achieve a constant power output of clean, useful energy. A typical wind turbine power generation system has many components and sources of inefficiencies. Evaluating where these inefficiencies occur and determining the significance of them allowed the team to make a plan of action to improve its overall performance.

The primary design challenge with current turbines is obtaining a steady power output at various wind speeds. In order to tackle this issue, components of the wind turbine must be designed to accommodate its performance at varying wind speeds. Different methods can be used to approach this issue. The method we have chosen involves using an active yaw mechanism and a braking system to curtail the rotational velocity. The active yawing mechanism allows the turbine blades to rotate out of the wind; consequently less wind will make contact with the blades and the energy captured by the swept area of the blades is heavily reduced. In addition to the active yaw system, a mechanical braking system has also been implemented on the primary shaft of the turbine to help maintain steady power production.

The yaw mechanism is a custom design intended for this project specifically. It is built with dimensions that fit the specifications of the testing parameters provided by the competition. It is built as a four story cylindrical housing that contains a primary worm gear drive. This worm gear rotates to transfer the motion along a shaft and into a set of steel spur gears. These gears provide the turbine head with rotation of 6 rpm, equating to one full rotation in 10 seconds. The worm drive servo operation requires 2 watts to function and actuate the mechanical system. Therefore, this makes the yaw system applicable for a system producing more than 12 watts of continuous power.

The yaw was implemented utilizing a 5:1 gear ratio to ensure proper torque and mechanical power in order to safely rotate the 2.75 kg turbine housing and head unit at speeds approaching 18 m/s effectively. Steel was used as the primary material for all gears and servo connections to prevent failures and damages to the system.

In order for the yaw mechanism to initiate rotation, it must first detect the direction of the wind to be able to move and react accordingly. In order to accomplish this, a wind-sensing unit had to be adapted to the turbine to provide wind data. This data in turn is processed and a corresponding signal is sent to the worm drive servo directing it which direction to move. The wind-sensing unit is ultimately a standard wind vane design that is attached to a potentiometer. As wind force turns the vane parallel to the direction of the wind, the potentiometer relays a signal to the worm drive system. The system will then operate to turn the head of the wind turbine until the potentiometer is back to its datum point. This wind-sensing unit will sit on top of the turbine housing, allowing it to accurately react to the change in wind direction.

The gearbox incorporated in this project is a single drive system. This system utilizes a timing belt and pulley system in order to translate power from the primary shaft that is attached to the blades, to the power generation system. To accommodate for the load and forces applied to the generator, a separate generator-housing mount was created to hold the device in place and ensure that it rotates as concentrically as possible. This was done by reinforcing the area on the shaft where the belt is connected. Installing a bearing on both sides of the driven pulley increased the rigidity of the system, allowing for increased wind speed testing and analysis. A 2:1 gear ratio allows for maximum power generation, while still maintaining a viable cut-in speed for the turbine.

The generator used provides the turbine with the ability to generate more power at lower RPMs, allowing for the operation of the yaw mechanism at lower wind speeds. This increases the ability of the wind turbine to reach and maintain a constant power output for the system. In conjunction with the fixed gear ratio identified on the single drive system; a small centrifugal clutch has been implemented to allow the system to reduce the cut-in speed. This is accomplished by allowing the primary shaft to spin freely without engaging the generator until the primary shaft has reached a designated rpm value. By implementing this clutch, the turbine can more easily overcome the holding torque of the generator before engagement.

The current generated by the power generation system is three-phase AC, which is then rectified to usable DC using a relay between the DC-DC regulators. The primary power controlling element in the electrical system is the addition of a buck-boost converter, which adjusts the current and voltage to the designated values regardless of the change in the wind conditions. Once steady state operations of the turbine have been reached, the converter acts as the primary controller to regulate the power output of the turbine. This allows the electrical system to supply the yawing mechanism servo with adequate power to operate. Incorporating this converter allows the wind turbine to maintain a constant power curve, while also being able to adjust the direction of the turbine head unit. The turbine blades thus turn with respect to the change in wind direction.

Technical Design

Design Objectives

The primary objectives of Aurora Boreas are to build a safe, durable, and efficient turbine within the given constraints by the Collegiate Wind Competition rules. The first objective is the safe operation of all components of the turbine. The turbine components which must be especially safe are the yawing mechanism, the gearbox and the power generation system. These components have to operate safely in high wind speeds and extreme weather conditions. Therefore, in any event, for example a hurricane, the blades have to be slowed down and the yaw has to make sure that the wind turbine stays locked in place. The shutdown of the turbine has to be done using reliable electrical controls. Aurora Boreas' wind turbine takes hazards as described into account and was designed accordingly. For the CWC competition, "shutdown is defined as dropping below 10% of the maximum 5-s bin average rpm achieved during the power performance testing. This reduction in rpm must occur within 10 s and remain below the limit indefinitely" [2]. The shutdown will be achieved by using a primary braking system and the yawing mechanism. The yaw helps the shutdown process by turning the turbine out of the wind, to minimize the rpm's more quickly. The shutdown is controlled by an Arduino to ensure a safely operated and controlled turbine.

The second objective is durability. Durability is especially important in the wind industry, as well as in Alaska where extreme weather conditions are endured on a daily basis. Snow, Ice and cold temperatures are some of the many challenging factors in Alaska and important in design consideration. The whole turbine, especially the yaw mechanism has to withstand a high torque if the turbine has to shut down in an extreme wind situation or other shut down scenario. The control mechanism has to be the most durable, allowing the turbine to start up again without any trouble in the case of multiple extreme events [3]. If the control mechanism fails, the whole turbine would be uncontrollable and hazardous. If any of the other parts are not durable enough, the whole mechanism could fail and a safety issue will be a major concern.

The last objective of the turbine is to be efficient. The turbine therefore has to be able to react to changing wind direction as accurately as possible. In order to do this, the yaw has to be controlled by a microcontroller. The microcontroller receives the input from the wind direction sensor. With the data inputted the controller must operate the yaw mechanism. The yaw mechanism has to rotate the turbine back into the wind in at least five seconds for a 180 degree wind change. By reducing friction within the primary and generator shafts, the turbine can start producing power at lower wind speeds. The control and electrical components have to convert the varying wind speed to a constant electrical output, so the energy can be used effectively or inputted to the power grid.

Overall Design

The overall wind turbine design, as seen in **Figure 1,** meets the size and power constraints for the competition. The turbine utilizes a single drive design attached to the wind turbine blades and rotates the generator using a timing belt and pulley system. The generator will generate power for the auxiliary systems such as the control system and yaw. In order to rotate based on wind conditions, an active yaw mechanism was implemented. The yaw attaches to the gearbox by a hub and utilizes the wind sensor on top of the gearbox to activate and change direction. The sensor is a continuous rotation potentiometer that provides output based on degrees off of the zero position. An Arduino reads this output and provides the servo motor power in order to rotate. The electrical system utilizes the generator to produce AC voltage which is then fed through a three-phase rectifier. The rectifier output powers the Arduino and control system and is then linked via a relay to the buck-boost converter. The buck-boost converter then acts to provide constant output power.

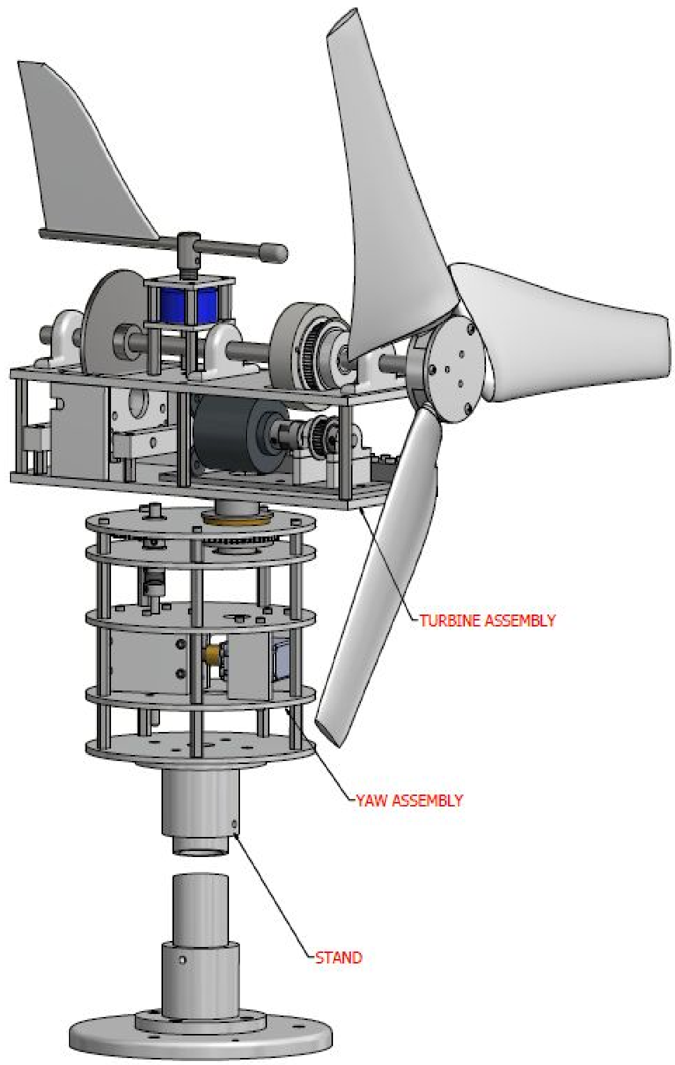

Figure 1: Overall Turbine Design

The Yaw Mechanism

The Yaw mechanism team has designed and built a yaw that is 15 cm in diameter, rotates at 6 rpm, and can be compatible with a 10 watt, 12 volt turbine. In order to be compatible with a 10 watt turbine, the assumption was made that the weight of the head that the yaw would support would be 2.27 Kg (5 lbs). The assumption of the weight was done after evaluating the wind turbine of the Arctic Winds [4] turbine from the 2016 competition. The power consumption of the yaw mechanism was minimized to allow the greatest power availability from the wind turbine.

The manufacturing of the yaw mechanism itself is complete and is in the optimization phase. Initial testing has played a vital role in design adjustments and overall changes. When the servo motor was first powered, the team noted that the single set-screw design connecting the worm drive to the shaft, as well as the spur gears to the shaft, would not be enough to reliably endure the stresses that would be applied under maximum load and power. The shafts would sometimes slip in their couplings under the high load conditions. A solution to this problem was to drill and tap a new set-screw location 90 degrees off of the existing screws eliminating the possibility of slipping under any expected load. Not only was the yaw capable of rotating at the goal of 6 rpm without a load, but the yaw also succeeded with a 2.27

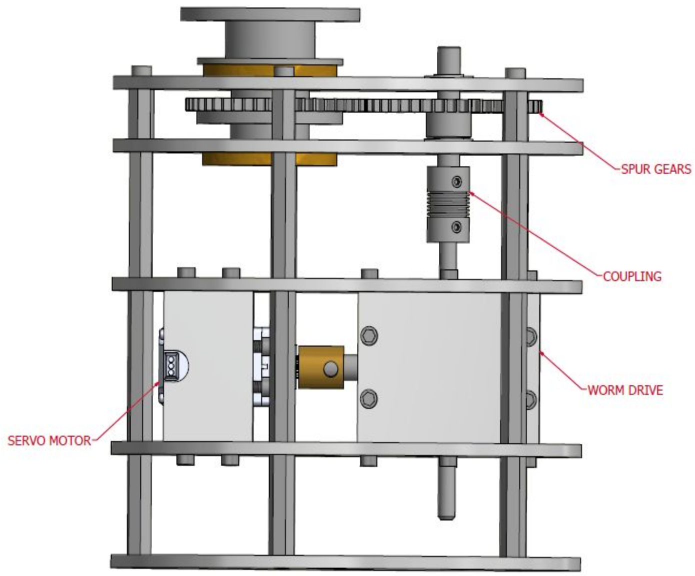

Figure 2: Final Yaw Mechanism Design

kg load evenly distributed atop mounting bracket without any noticeable change in power being consumed. In further testing a power consumption curve will be developed to see if the friction can be reduced during certain intervals of the rotation and improve performance.

The initial goal was to create a Yaw Mechanism that consumed no more than 4 watts under maximum load. Throughout testing the Yaw Mechanism consumed no more than 2 watts at any given time under full load. This small load would only account for 20.0% of a 10 watt turbine's overall power.

Concluded tests include wind tunnel testing, testing with other turbine components attached, and also reliability tests to ensure that the servo is durable enough to withstand 13 m/s winds. The idea of those tests are to show where the yaw mechanism limits are and how to improve them. There is a trade off between efficiency and performance, so tests will be used to find realistic improvements in the design. In order to keep power consumption low, there may need to be a sacrifice elsewhere. Examples of such tradeoffs might be not rotating the turbine head under high wind conditions if the components of the mechanism could yield or draw excessive power. The tests also help to finetune the coding and therefore add sensitivity of the wind sensing unit.

Design Concept of the Yaw mechanism

The final design concepts are shown in **Figures 2** and **3**. These are two different components that will work together in order to sense the wind direction and tell the yaw mechanism to rotate, and the yaw mechanism itself.

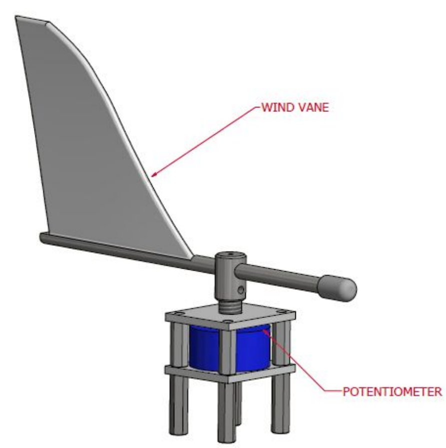

Figure 3: Final Wind Vane Design

Figure 3 shows the wind vane that is going to control the direction the yaw rotates. A potentiometer is used to measure voltage that corresponds to position in a full rotation. There is a zero point in the center where the wind turbine will sense that there is no need to rotate in either direction. The wind vane has a set screw on the shaft to allow for adjustments as testing goes on. The farther away the fin is from the potentiometer shaft, a higher torsion is applied from the wind. This allows the rotations to be controlled depending on the expected wind speeds. The potentiometer has a low coefficient of friction and has proven effective in wind speeds as low as 3 m/s.

Figure 2 shows the finished Yaw Mechanism that has been built. The worm drive is connected directly to the continuous rotation servo which will be driving the system. Coming off the top of the worm drive is a shaft has a spur gear meshing at a 1-to-1 ratio that spins the hub which the turbine head is attached to. The emergency yaw brake will be not on the final design due to a manufacturing mistake. The specifications of the brake do not match up with the specification of the design which were the base of the order. Not having the brake will not interfere with the safety of the yaw mechanism as the worm drive is self looking and the torques which are applied to the worm drive will not be high enough to overcome the worm drives holding torque.

Yaw Mechanism Analysis

Initial testing of the Yaw Mechanism separate from other turbine components has been performed. This means that the power supplied to the mechanisms servo is from a power source that can be manually adjusted unlike the real life situation of a variable source. In order to have a power supply simulate the variable source, the yaw servo will not use more power than the 12 watts the turbine could produce. A benefit of this is that Aurora Borea has been able to adjust and monitor the power consumption accordingly.

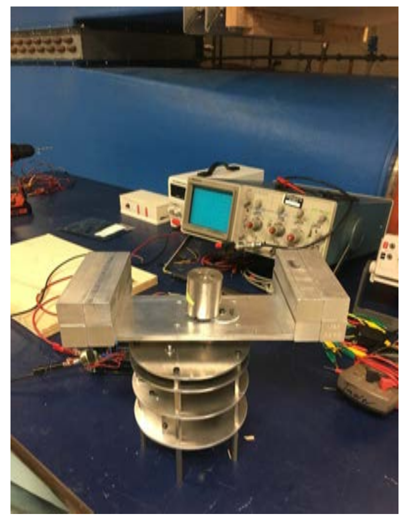

Figure 4: Testing the Yaw Mechanism

Upon initial testing a consistent jump in amperage at a given point of contact between the spur gears was noticed. This was due to minor binding, which was expected of two new, closely meshed gears. The use of an abrasive material was used to accelerate the process of breaking the gears in. The abrasive material is essentially sand with heavy gear grease that breaks down the sharp edges of the hard metal gears. After this operation, the binding amperage was dropped down from 400mA to 100-200mA. The goal was to use less than 4 watts under maximum load conditions, and with the 8 volt constant source the draw is far under that now. The yaw is currently consuming no more than 1.6 Watts at any given time. **Figure 4** shows testing with a 2.77 kg weight to simulate the turbine head. Testing has proved that as long as the turbine heads weight is evenly distributed the weight has negligible effects on power. The yaws power consumption in relation to the inertia of the rotating blades is the only thing left to analysis. The turbine head reliably turns at 6 rpm which is more than sufficient for the application. This number may change as testing commences with a new servo with slightly stronger gears and less required power. While this test is not

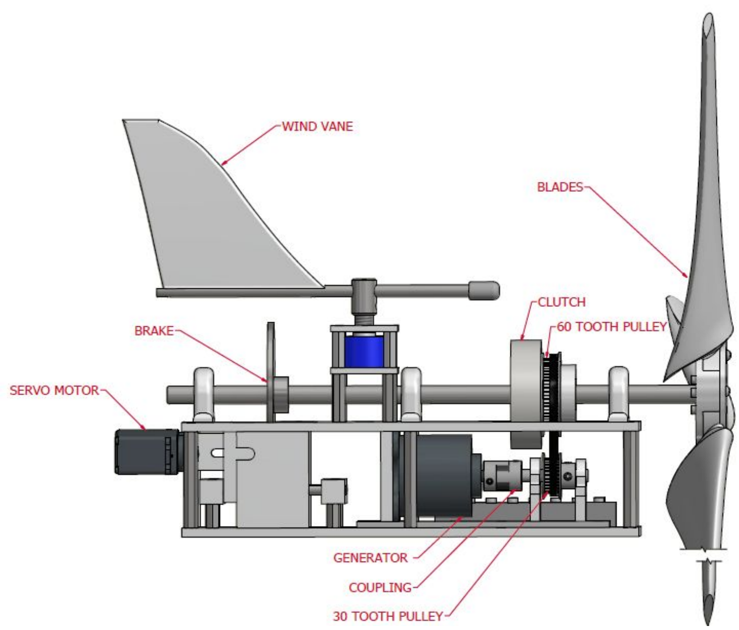

Figure 5: Wind Turbine Head

mandatory, one of the team's goals is to optimize this system any way possible. The ongoing testing under wind conditions will help the team define guidelines for this yaw's use and how it can be best used in real life applications.

The yaw could not be tested in a windtunnel due to size constraints of the wind tunnel at the University of Alaska Fairbanks. Tests in the wind tunnel showed that the turbine cuts in at around 4.2 m/s with the current clutch. At 5 m/s the turbine will produce around 2 W which is enough power to rotate the yaw. The control system needs 7 V which is reached at 5.5 m/s, this means the yaw is theoretically fully operational at 5.5 m/s. In order to test the yaw the turbine has been placed outside the wind tunnel in front of industrial blower. The blower allows the testing of the mechanism at a constant rpm of the blades.

The Gearbox

The gearbox team has designed and built a gearbox that efficiently generates power for a 12 Watt turbine. Determining the means in which the wind turbine generated power was one of the most critical decisions made throughout the entire design process. Ultimately, the team decided on a single drive transmission that incorporates a belt and timing pulley system to translate rotational motion to the generator. This is due to the fact that single drive transmissions are more efficient, contain fewer components, and require less overall maintenance than a traditional wind turbine gearbox.

The primary concern in the design of the gearbox was durability. The durability of the gearbox is of the utmost importance because gearboxes are where problems associated with wind turbines tend to originate; resulting in unplanned maintenance, increased costs, and turbine downtime [3]. Furthermore, the durability of the gearbox has a direct impact on the safe operation of the wind turbine. To ensure that this design objective was met the team set a goal to build a compact gearbox with as few parts as possible. Constructing a simple, efficient gearbox that follows this minimalistic design reduces the likelihood of gearbox associated failures.

It is worth mentioning that former UAF CWC teams, namely the 2016 Arctic Winds team, have employed single drive systems. The successes and failures of the single drive system were examined and improved upon. One of the key problems with the Arctic Winds turbine was the use a ¼" diameter primary shaft and ¼" bearings, as they were proven to be unfit for the rotational speeds and heat generated through turbine operation; evident from the wear of the components. To solve this issue and increase the durability of the gearbox a ⅜" diameter precision shaft made of 303 stainless steel was used as the primary shaft. Subsequently, three ⅜" diameter pillow block bearings were used since they are rated to withstand the increased rotational speeds and thermal stress that will be endured.

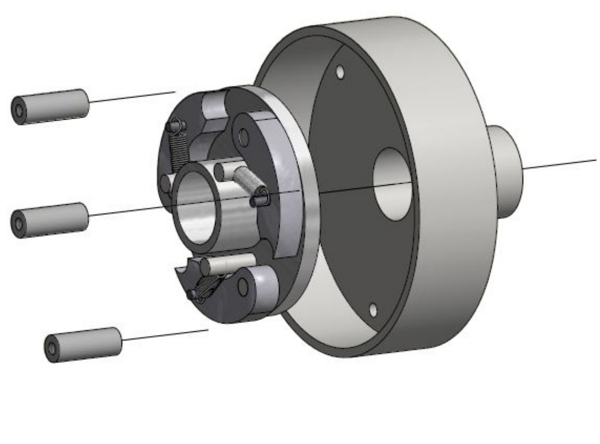

Figure 6: Clutch

As shown in **Figure 7** the belt and timing assembly is installed at the front of the turbine head and connects the primary turbine shaft to the shaft attached to the generator. The gearing ratio is set at a 2:1 ratio, with the 60 tooth pulley connected to the clutch housing on the primary shaft and a 30 tooth pulley bound to the generator shaft. This gearing ratio enables the generator to produce optimal power for the input torque. The generator shaft is a ¼” in diameter and holds the smaller 30 tooth pulley between two ¼” bearings to ensure stability while the shaft is spinning under load. Additionally, there is a spider coupling connecting the generator to the timing pulley system which accounts for any shaft misalignment that may occur during operation.

The braking system used in this year’s wind turbine is a mechanical braking system that incorporates a brake caliper design. The calipers are attached to a pair of rails, with plastic bushings installed in the calipers which freedom of movement. Springs located on the rails are used to align the caliper in a neutral state when the brake is not engaged. Continuing, the brake uses a servo motor as an actuating device and a power screw design is utilized to convert the rotary motion of the servo into linear motion. This is crucial because only then can a force be exerted on the resin bike brake pads [4]. The braking system is important because it will be used in conjunction with the yaw mechanism to halt the operation of the wind turbine upon demand, as well as to curtail power.

The gearbox contains a clutch attached to the primary shaft **Figure 6**. The clutch was incorporated upon initial wind tunnel testing where it was discovered that the inertia required to overcome the generator was too high, resulting in a very high cut-in speed. The clutch was adapted from a Homelite Gas Trimmer (Model No. UT32601), as it was the right size and fit for the application. The clutch is a centrifugal clutch that uses flyweights to engage at the desired RPM. Proof of concept of the clutch working successfully was provided, as it was able to reduce the cut-in speed from 7.7 m/s to 4.2 m/s. Despite this improvement, work is actively being done to improve the system further reduce the cut-in speed.

Design Concept of the Gearbox

The gearbox unit shown in **Figure 7** contains the single drive system and the mechanical braking unit, as well as the generator, the wind vane, and components for the power and control system. The baseplate was constructed with a minimalistic approach which focused on ensuring that each component operated properly in as minimal space as needed. A multi-level design was incorporated into the gearbox as a means of accomplishing this goal, because it maximizes the usable space of the gearbox without further increasing the size of the base plate.

Figure 7: Fully Constructed Turbine Head

The top mounting plate pictured in **Figure 7** includes the primary shaft, the large toothed timing pulley, the clutch, and the wind vane. The turbine blades are connected to the primary shaft, as well as the steel rotor disk that belongs to the mechanical braking system. The bottom mounting plate supports the mechanical braking system, the generator, and the power control system components. Additionally, it includes the generator shaft which is connected directly to the generator. The timing belt that connects the small pulley to the large pulley allows the generator to rotate.

Gearbox Analysis

The gearbox consists of a single shaft drivetrain that transfers the input power generated from the turbine blades to electrical energy. Below are the calculated values for each variable that is associated with the single drive system. With the precision ⅜" 303 stainless steel shaft, the safety factor is very high and won't be suspected as a failure point in the single drive system.

$$P_{max} = 0.5\rho_{air}C_pA_{blades}{V_{wind}}^3 = 0.5\left(1.23\frac{kg}{m^3}\right)(0.59)\left(\frac{\pi(0.45m)^2}{4}\right)\left(18\frac{m}{s}\right)^3 = 336.6\,W \qquad [1]$$

$$Tip\ Speed = V_{wind} * TSR = \left(18\frac{m}{s}\right) * 4 = 72\frac{m}{s} \rightarrow RPM = 3198\,rpm \qquad [2]$$

$$T_{shaft} = \frac{P}{2\pi(\frac{RPM}{60})} = \frac{336.6\,W}{2\pi(\frac{3198\,rpm}{60})} = 1.005\,Nm \qquad [3]$$

$$\sigma_e = (3{\tau_{shear}}^2)^{1/2} = (3(859.54\,psi)^2)^{1/2} = 1488.76\,psi \qquad [4]$$

$$S.F._{shaft} = \frac{75\,ksi}{1488.76\,psi} = 50.37 \qquad [5]$$

Aerodynamics

This year's team did not have an aerodynamic specific group, however, the rotor unit designed by the previous UAF CWC team was able to be incorporated. The rotor unit consists of a hub, the blades, and a nose cone. To summarize, the hub that fixes the blades to the rotor assembly utilizes a modified slotted dovetail root system [4]. Attached to the hub are three blades 3D printed with Onyx filament. Although the blades follow the same blade design constructed by UAF's Arctic Winds team, the blades vary because standard Acrylonitrile-Butadiene-Styrene filament was previously used to construct the blades. Onyx was chosen this year because it offers greater durability than standard ABS filament, due to the fact that it is constructed of nylon and carbon fiber. Lastly, the nose cone was designed to reduce the

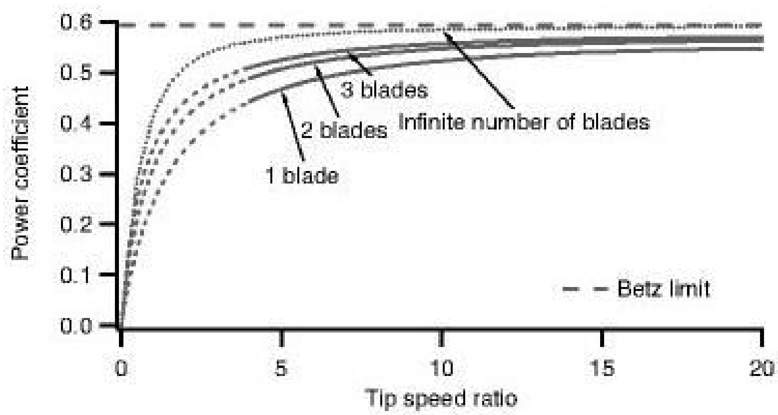

Figure 8: Comparison of Number of Blades and Efficiency [4]

overall drag effects that the blades experience. The blades are 45 cm in diameter equating to a 1590 square centimeters of swept area.

Figure 8 displays the effects that the amount of blades used has on the system's efficiency. This plot goes to show that there are significant diminishing returns per blade after four blades [4]. **Figure 9** showcases the Betz limit. These two figures were critical in the decision made by the Aurora Boreas team to use a three blade design and a tip-speed-ratio of 4.

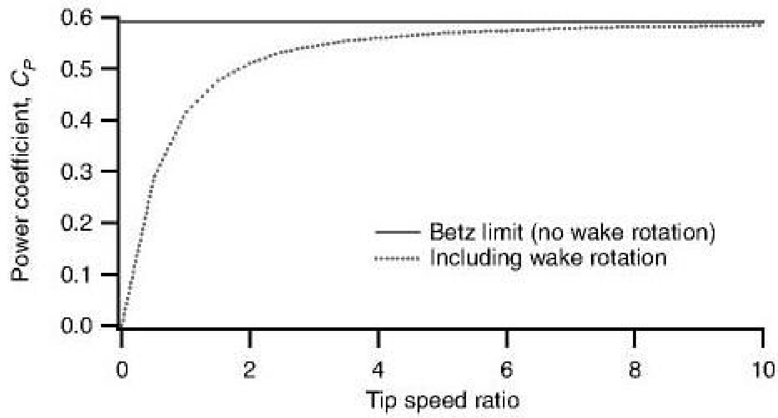

Figure 9: Betz limit [4]

Tower

The wind turbine tower was constructed of a uniform aluminum tubing stock with an I.D. of 1", an O.D. of 1.25", and a total length of 16". Attached to the tube on either end are aluminum flanges that secure the shaft via set screws and Loctite adhesive. The flanges have an overall diameter of 3". The flange at the top of the shaft connects directly to the bottom of the yaw structure via four ¼" bolts. The bottom flange secures the shaft to a 6" diameter mounting plate following the same four ¼" bolting pattern as seen in the top flange. This design enables electrical wiring at the mounting plate to feed directly through the aluminum shaft to the turbine head. The mounting plate consists of three ¼" bolts which will be used to secure it to the competition base flange. The mounting plate also features an additional hole on the outer edge that will be used to attach a stainless steel bolt for electrical grounding purposes.

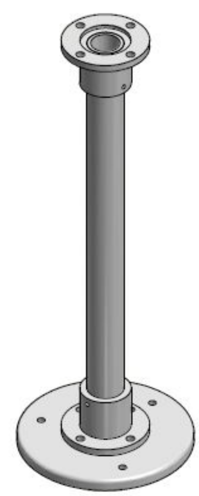

Figure 10: Tower Assembly

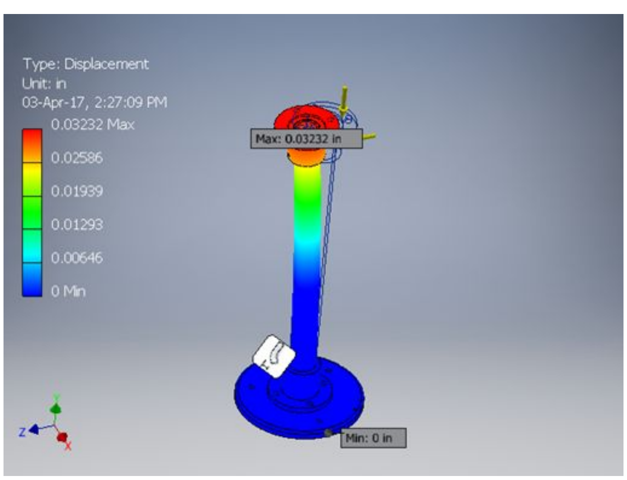

Figure 11: Displacement analysis of the tower under estimated maximum forces

Figure 10 shows the finalized tower and base plate design. **Figures 11**, **12**, and **13** displays images received from a SolidWorks simulation [B] that was testing the displacement, equivalent strain, and safety factor that the tower unit experienced. Per the simulation, a compressive 10 lb force on the y axis was applied to the top of the tower to represent the downward force exerted from the turbine head and yaw mechanism. A 15 lb force was applied to the z axis to represent the force exerted by the wind; this force was determined to occur at a wind speed of approximately 16 m/s applied to the swept area of the blades. **Figure 13** is critical as the tower was characterized as having a safety factor of 15.

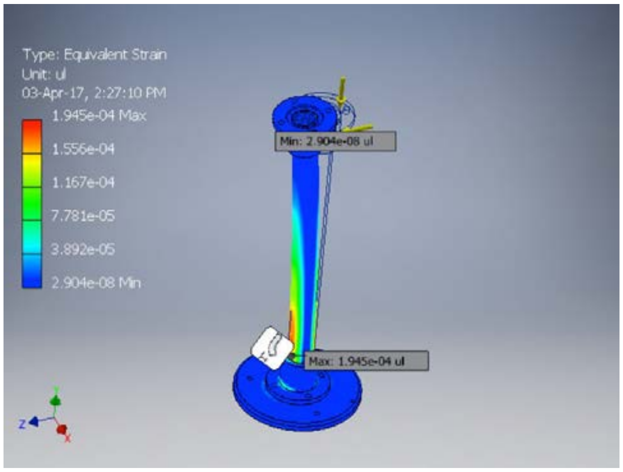

Figure 12: Strain analysis of the tower under the estimated maximum forces

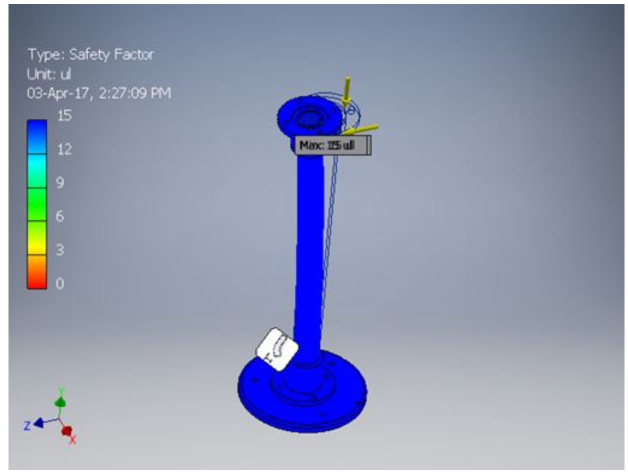

Figure 13: Safety Factor Analysis

Electrical System

The power flow of this design is shown in **Figure 14** below. Three-phase AC power is produced by a brushless DC (BLDC) machine. This AC voltage and current is rectified into unregulated DC voltage and current via a three-phase rectifier. A relay is then positioned between the DC-DC regulator, and the rectifier to provide a more stable power curve. The relay initially connects the rectifier directly to the

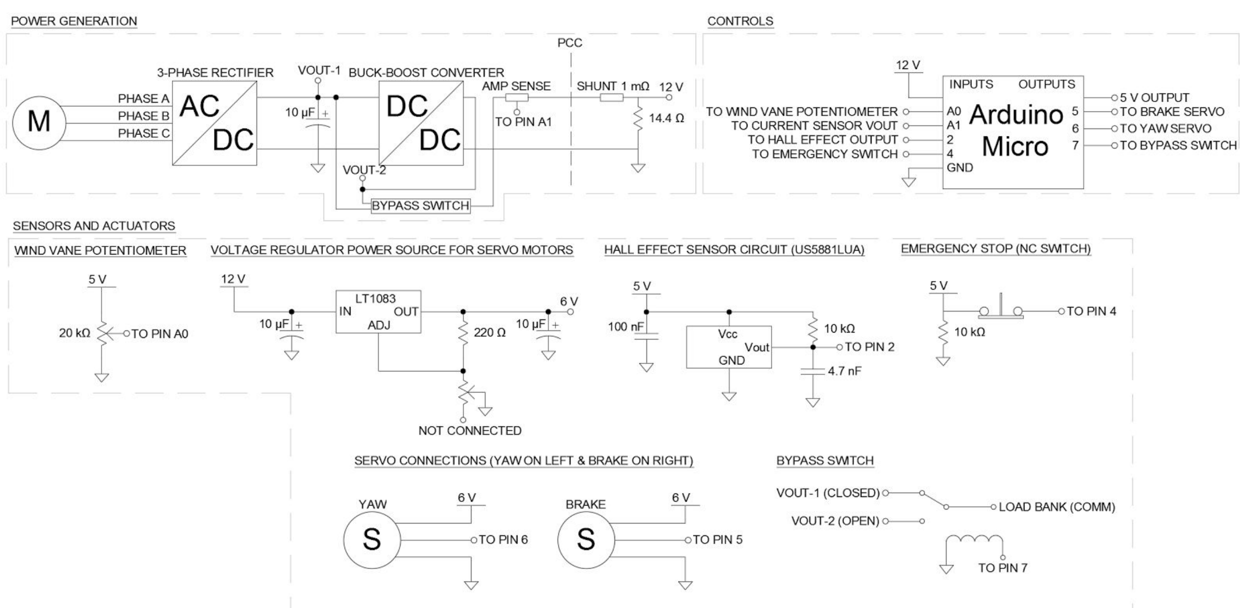

Figure 14: Electrical one-line diagram with required feedback controller

load, but once the critical buck-boost turn on is reached it switches to power the DC-DC Convert. The buck-boost converter modifies and regulates this DC voltage and current to 12 VDC and 833 mADC, respectively. With this voltage and current, 10 W will be delivered to the load bank. The input power to the converter is fed to a LT1085 linear voltage regulator. This regulator feeds 6 V to the yaw and braking servos for the turbine. Sensors wired to the Arduino Micro include a potentiometer rotated by a wind vane, a hall effect sensor to determine drive shaft RPM, current sensor, and a normally closed (NC) toggle switch for emergency braking.

Generator Modeling

Figure 15: Comparison of motor size between last year (left) and this year (right)

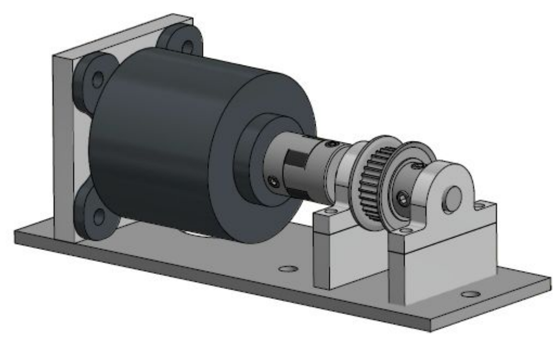

Figure 16: Coupling of motor w/ 30 tooth gear

The motor chosen for this year's competition is the Turnigy Aerostar 4340 which has a kv (RPM/V) rating of 500, as opposed to last year's model which was rated at 860 kv. The new motor will be able to output more voltage at lower wind speed due to the lower kv rating, but costs $57.72 as opposed to the previous year's motor that cost $17.68. This motor was also chosen based on the fact that it was still small enough to easily integrate into limited housing space on the turbine. Other models with lower kv ratings were considered, but most were significantly more expensive and larger in size. A comparison between the relative size of the motor used for last year and the one used for this year is shown below in **Figure 15**. The motor was mounted to a baseplate and a 30 tooth gear is attached to it's shaft as shown in **Figure 16**.

These brushless DC machines behave as synchronous generators in the wind turbine. For synchronous generators the electrical frequency (f_e) of the output power is related to the mechanical RPM on the shaft and the number of poles (P) in the generator in **Equation 6**. The internal voltage (E_A) created in the generator is related by the number of coil windings in the stator (N_C), the flux in the iron core (constant if driven to saturation), and the electrical frequency (f_e) in **Equation 7**. Equating the electrical frequency in **Equation 6** and **Equation 7** shows that the number of poles in the generator is directly proportional to the internal voltage generated as shown in **Equation 8**. This model explains how the 500 RPM/V motor having 18 poles outputs greater voltage at lower RPM than the 860 RPM/V motor having 12 poles.

$$RPM = \frac{120 f_e}{P} \rightarrow f_e = \frac{P * RPM}{120} \quad [6]$$

$$E_A = \sqrt{2}\pi\Phi N_C f_e \quad [7]$$

$$\therefore E_A = \sqrt{2}\pi\Phi N_C * \frac{P * RPM}{120} \quad [8]$$

$$V_{gen} = \frac{Drive\ Shaft\ RPM}{BLDC\ Machine\ kV\ rating} \quad [9]$$

The results of experimental tests in **Table 1** display the relation between the rotational speed of the BLDC machine shaft and the open circuit output voltage created based on **Equation 9**. Based on this test the target RPM at the BLDC machine shaft is 6440 RPM in order to maintain 12 V output voltage. For the 860 kV motor the blades would be rotating well past 10,000 RPM, compromising the structure of the blades

Table 1: Experimental operating no-load operating rectifier voltages vs. theoretical BLDC machine output voltage for variations of drive shaft RPM

Needed RPM	Measured RPM	Vout (Vdc)	Calculated Generated Voltage (500 kV)	Calculated Generated Voltage (860 kV)	Percent difference between Calc & Meas Vout	Rectifier Voltage Drop (V)	Electrical Frequency (Hz)
1000	1028	1.24	2	1.163	38.0%	0.76	154.2
2000	2075	3.14	4	2.326	21.5%	0.86	311.25
3000	3005	4.85	6	3.488	19.2%	1.15	450.75
4000	4000	7.18	8	4.651	10.3%	0.82	600
5000	5057	9.22	10	5.814	7.8%	0.78	758.55
6000	5960	10.96	12	6.977	8.7%	1.04	894
7000	6971	12.89	14	8.140	7.9%	1.11	1045.65
8000	8017	14.91	16	9.302	6.8%	1.09	1202.55
# of Poles:	18						

Figure 17 shows a graphical comparison based on the differences between the two generators and the need for the larger generator. Further the Vout line illustrates the information shown in **Table 1** for the difference between output from the generator and rectifier. A trend line was inserted to establish a theoretical equation for the rectifier output at any RPM.

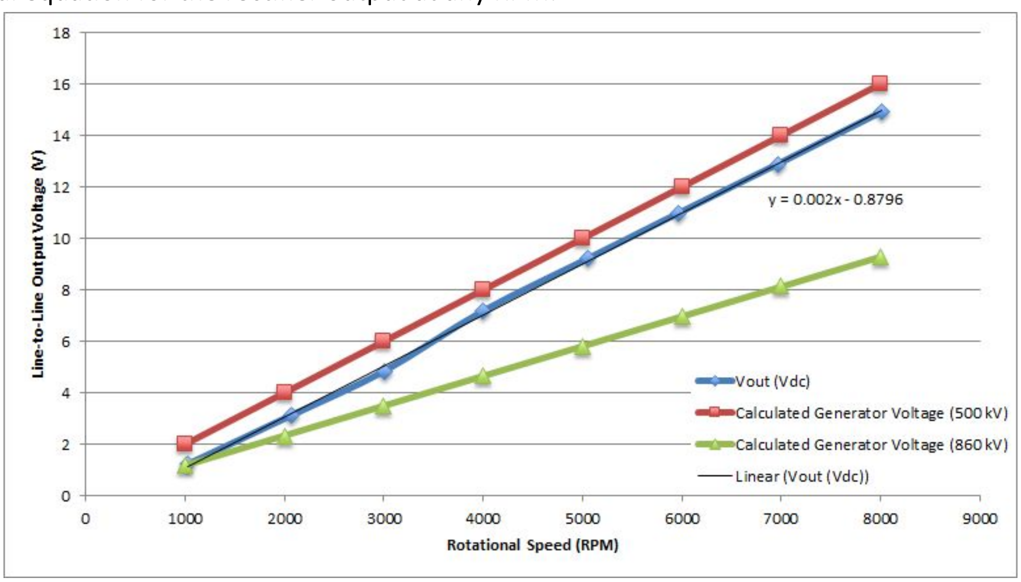

Figure 17: Comparison of generator voltages for variation in input rotation speeds

AC to DC Rectifier

In this design, the major modification to the basic diode rectifier is the addition of MOSFETs that the LT4320 Ideal Diode Bridge Controller [5] uses for its switching mechanism (see **Figure 18** for schematic of the three phase rectifier). Schottky diodes are utilized to keep the transition between phases in continuous conduction. Output capacitors for each phase are used to reduce the ripple voltage.

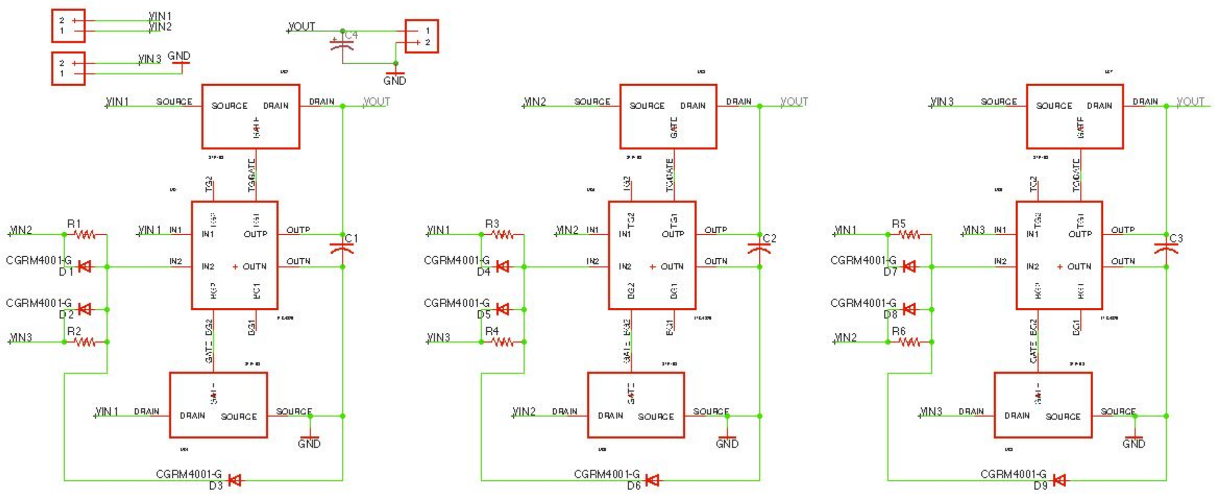

Figure 18: Three-Phase active switching rectifier w/ N-channel MOSFETs and LT4320 controllers

MOSFETs are selected based on the desired switching voltage and the max input current from the generator. This rating is based on the drain to source resistance of the MOSFET ($R_{DS(ON)}$). The selected switching voltage is 30 mV. The input current from the generator is variable, depending on the mechanical power. For this estimate, a max of 1 A average current for a single phase was selected. Therefore, the maximum required drain to source resistance was calculated in **Equation 10**. The STP160N3LL MOSFETs used in the initial prototype have $R_{DS(ON)}$ = 3.2 mΩ, well below the max resistance. The drain current needs a rating of at least 3 A continuous current (3*input current). The selected MOSFETs have a rating of 120 A to stay well within limit of safety.

$$R_{DS(ON),max} = \frac{Switching\ Voltage}{Max\ Input\ Current_{AVG}} = \frac{30\ mV}{3 * 1\ A} = 10\ m\Omega \quad [10]$$

No ripple voltage is specified in the CWC rulebook; however, a 5% max ripple voltage was selected for the purposes of creating a stable output power. For the resistive load of 14.4 Ω, a 5% ripple voltage is a 8% ripple in power, less than that required by the competition. To calculate the largest required output capacitor, the smallest frequency was used. The smallest frequency in the output power of the generator occurs when the generator shaft rotates at 6000 RPM which corresponds to an electrical frequency of 894 Hz. The output capacitor was calculated with **Equation 11**. Any capacitance equal to or larger than this calculated value will be sufficient for maintaining 5% max ripple voltage.

$$C1 = \frac{I_L}{2fV_{r,max}} = \frac{0.833\ A}{2 * 894\ Hz * 0.05 * 12\ V} = 0.078\ \mu F \quad [11]$$

Buck-Boost Converter

After power rectification the LTC3115-2 buck-boost converter from Linear Technology [6] provides programmable feedback controls that depend on external component values and regulates output voltage (**Figure 19**). This regulated output voltage is fed to a 14.4 Ω load bank.

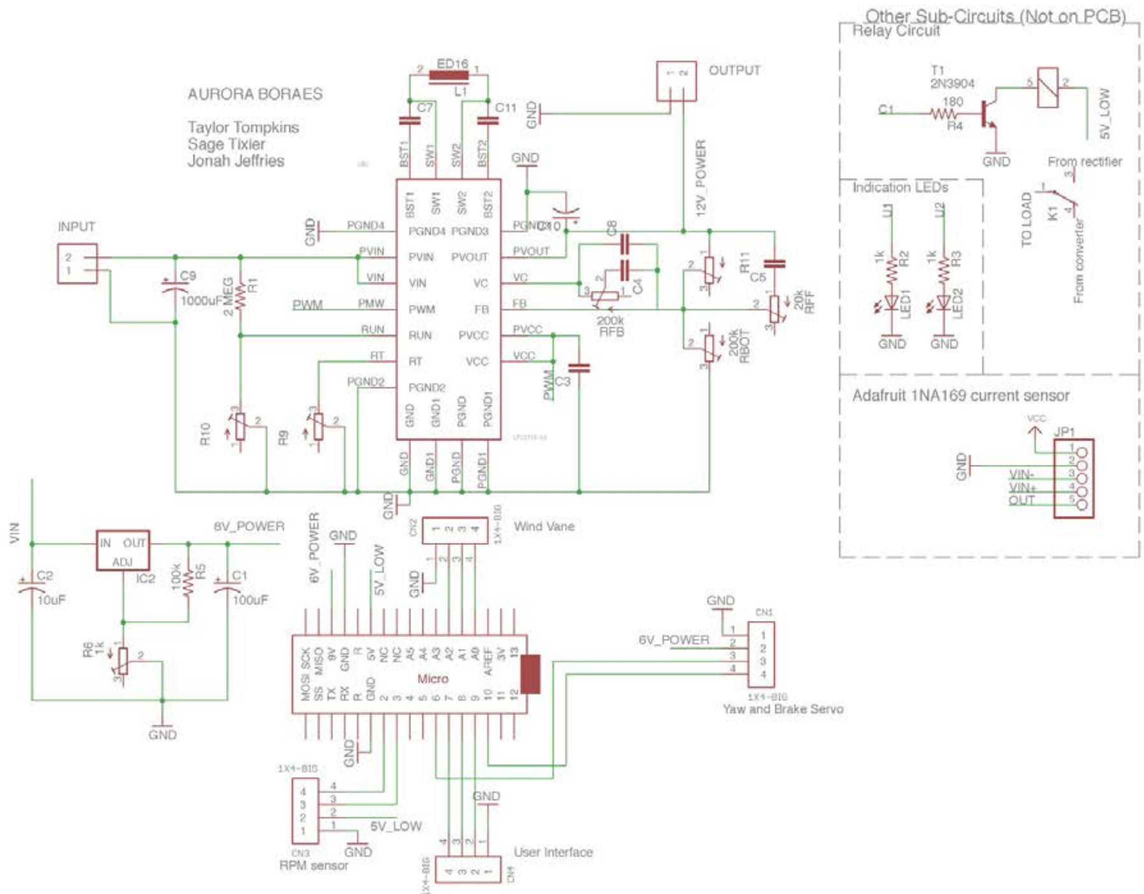

Figure 19: Circuit of buck-boost converter for power regulation

Output resistors R11 and R4 control the regulated output voltage. The resistor between the RT pin (R9) and ground controls the switching frequency. The adjustment of the switching frequency is a tradeoff between the size of inductors and capacitors and the conversion losses in the chip. **Equation 12** and **Equation 13** display the relationship between these passive components and the output voltage and switching frequency, respectively.

$$V_{OUT} = (1\,V) * \left(1 + \frac{R11}{R4}\right) \quad [12]$$

$$f_{sw} = \frac{35.7\,MHz}{(R9/1000)} \quad [13]$$

Refer to the schematic in **Figure 19** to locate these external resistors. For the RUN pin on the buck-boost converter **Equation 18** is used to discover the value of the voltage divider resistors. Typically, R1 is set to be greater than 1 MΩ. R10 completes the voltage divider and sets the turn-on voltage. This pin is used to protect the converter so that it does not try to boost a voltage too high and overheat during turn on or low voltage situations. For this particular design the turn-on voltage is established at 10.6 V. In order to have a voltage across the load below the converters turn on the rectifiers output will bypass the converter via a relay till the voltage returns above the converters turn on. The turn on for the converter is to protect the converter from boosting voltage that is to low.

$$V_{TH(RISING)} = 1.21\,V * \left(\frac{R1 + R10}{R10}\right)$$
[14]

Load Bank Design

To minimize loading effects on the turbine, a passive resistive load was chosen for this design. The load bank is required to have a resistance such that the output power is 10 W with a 12 V output voltage. The load bank also needs the power rating to withstand 10 W. ARCOL 50 W and 100 W resistors were used for this application. The resistors are wired in series for the desired resistance of 14.4 Ω, shown in **Figure 20** below. For safety reasons the load sits in a metal enclosure (not shown), this enclosure is grounded to insure no voltage potential is present on its outer casing.

Figure 20: Load bank configuration wired to provide connection points at upper left and lower right

Control and Feedback Systems

The control system is controlled through sensor data and actuating servo motors. Sensor data is retrieved from various electrical components attached to the turbine. Electrical sensors include a US5881 hall effect sensor and a continuous rotation 20 kΩ potentiometer. The hall effect sensor is placed in close proximity to magnets inserted into a hub that are attached to the drive shaft (see **Figure 21**). The hall effect sensor is non-latching and therefore is able to send a pulse to the Arduino when it detects a north pole and goes back to a zero state when nothing is detected. The magnets were then placed 180 degrees apart on the shaft to maximize the stability of the reading. The Arduino uses the time between pulses to calculate the RPM via the pulse sent to the Arduino's interrupt pin 2. When the potentiometer rotates the voltage divider from the center tap sends a signal to the Arduino. This signal is converted to a degree angle relative to the turbine head direction (see **Figure 22**). Data from these sensors provide feedback to determine how much the yaw servo rotates out of the direction of the wind. Under changing wind directions the yaw will rotate towards the wind.

Figure 21: Magnet Hub

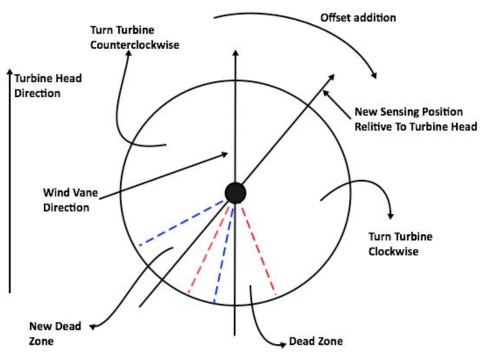

Figure 22: Yaw Positioning Diagram

Two servo motors are present in the turbine, one in the yaw base and one at the back of the nacelle that brakes the main drive shaft. The yaw base servo is programmed to adjust the turbine angle between positions 89 and 95 as read by the Arduino. Any offset calculated from RPM sensor data is subtracted from this programmed angle (see **Figure 22**). That is, if the controller detects a RPM greater than 6440 RPM. When the emergency normally closed (NC) switch is toggled or if the current sensor detects load loss, the primary shaft emergency brake actuates completely and then clamps on the brake disk to slow the turbine to safe limits. When the switch is toggled the offset calculation is also adjusted to rotate the blades perpendicular to the incoming wind. A summary of the control scheme used in this electrical turbine is shown in **Figure 23**.

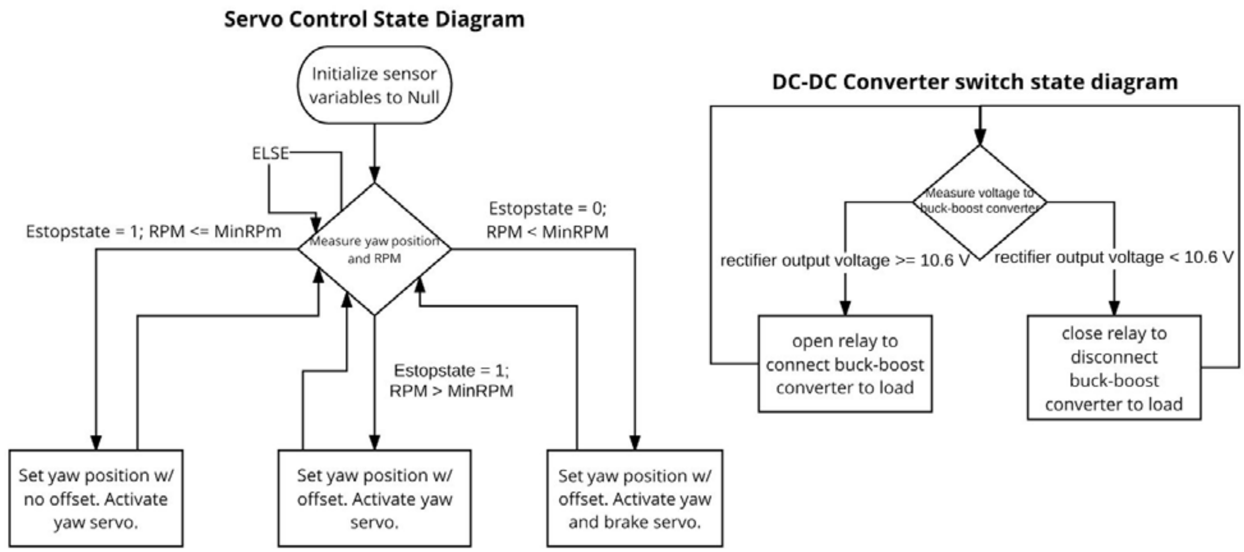

Figure 23: Control state diagram for yaw rotation, blade braking, and DC-DC converter switch

Buck-boost voltage control

The buck-boost converter for our system is used to maintain a constant voltage output for our DC-DC stage of the electrical system. In the internal Integrated Circuit (IC) from Linear Technology, a comparator is used to signal a PWM controller with then relays information to the gate drivers. This then allows the circuit to adjust the switching of the internal MOSFETs. This allows the converter to maintain a constant voltage output of 12 volts by increasing the input voltage (boosting) or reducing the input voltage (bucking).

Buck and boost modes consist of a small signal model that affects the feedback of the buck-boost converter. Loop compensation is used to ensure the circuit does not operate to oscillation. Oscillation in this case is defined when the output voltage displays a varying triangle waveform rather than a constant output voltage. The loop compensation is designed to dampen the buck/boost mode gain and to provide a phase boost of 50 to 60 degrees. When positioned at the crossover frequency (assuming sufficient attenuation and phase boost), the complete system will satisfy the stability criterion for negative feedback systems. In addition the crossover frequency will be set to one order of magnitude below the switching frequency for quick response to transient changes of input voltage. The tradeoff in this design is selecting a frequency such that both modes (buck/boost) are stable for varying operating conditions. The bode plots in **Figure 24** below illustrate loop compensation (labeled error_amp in **Figure 24**) optimized for buck mode stability.

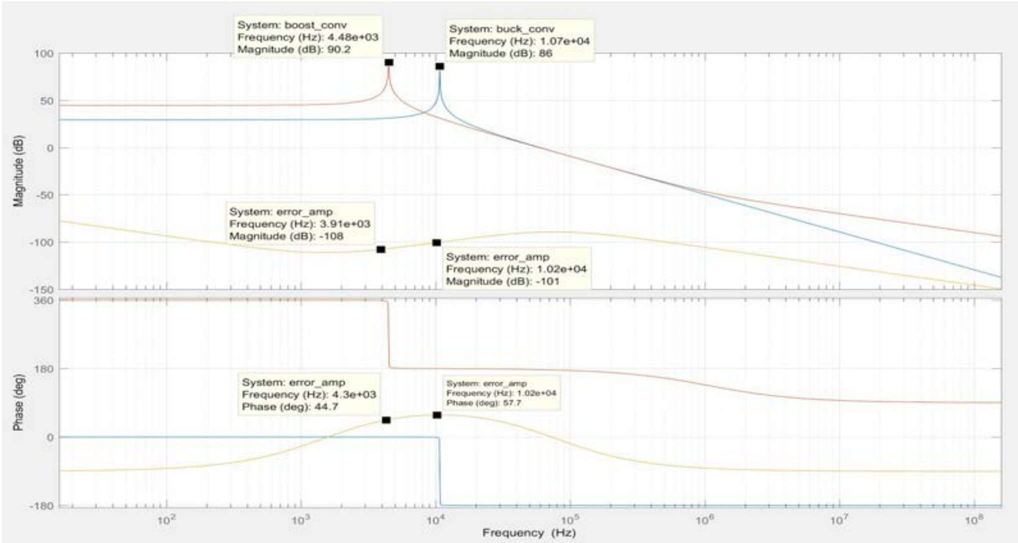

Figure 24: Bode plot of feedback network on buck-boost converter

Laboratory Testing

To determine the wind speed that would produce the required 10 W at the load bank, the wind turbine was tested in the wind tunnel for increasing wind speeds and unregulated output power. The cut-in speed for this particular design was at 5 m/s wind speed. Based on data and calculations, the achieved output power occurred between 8.5 and 9 m/s wind speed. The measured RPM at the was determined to be 3440 RPM, the maximum that these blades were designed to handle. After 8 m/s wind speed the buck-boost converter will regulate output voltage. At 9 m/s the Arduino controls will begin activating the yaw and brake servos. Note that 13.87 Ω was used for unregulated output power and 40 Ω was used for regulated output power in these particular trials.

	3-phase rectifier w/ buck-boost		3-phase rectifier	
Wind Speed (m/s)	Vout (V)	Pout (W)	Vout (V)	Pout (W)
0.5	0	0.00	0	0.00
1	0	0.00	0	0.00
1.5	0	0.00	0	0.00
2	0	0.00	0	0.00
2.5	0	0.00	0	0.00
3	0	0.00	0	0.00
3.5	0	0.00	0	0.00
4	0	0.00	0	0.00
4.5	0	0.00	0	0.00
5	6.01	0.90	5.96	2.56
5.5	7.03	1.24	6.47	3.02
6	7.61	1.45	7.03	3.56
6.5	8.7	1.89	8.2	4.85
7	9.46	2.24	8.96	5.79
7.5	10.4	2.70	9.74	6.84
8	12.18	3.71	10.45	7.87
8.5	12.18	3.71	11.22	9.08
9	12.18	3.71	11.86	10.14
Load (Ω):	40	13.87		

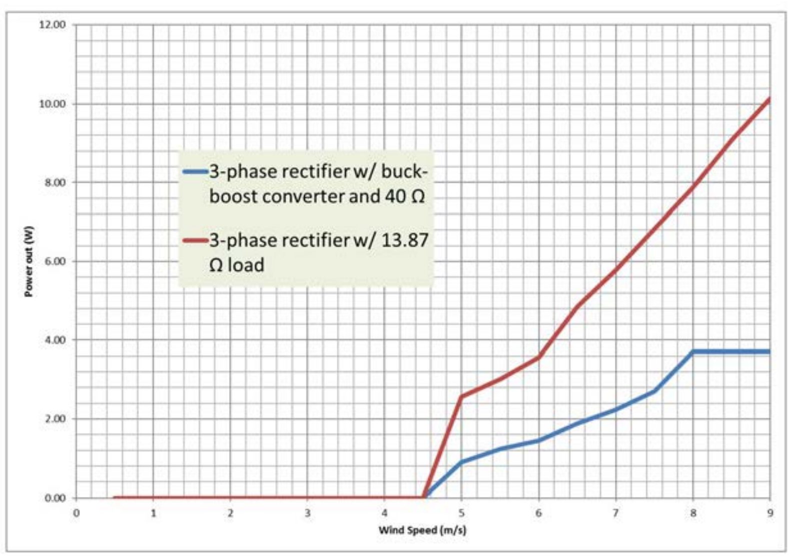

Figure 25: Wind Speed Vs. Power generated

For the annual energy production for the Aurora Boreas wind turbine the power curve in **Figure 25** can be used in not only determining power output for a given wind speed, but also useful insight to the placement of the turbine. For example if the turbine was going to be placed in a location with an average wind speed of 9 m/s or greater the turbine could maintain a constant 10 watts of production. This equates to 0.01kW. Over the course of a 24 hour day, 0.24 kilowatts of power can be generated. For a year the annual production would be 365 days times 0.24 kilowatts/day. This comes out to 87.6 kilowatts/year. The recommended placement for this turbine is that it should be place in a location with a wind speed average above 9 m/s to ensure maxim.

Software

There were multiple software programs used in the design of this wind turbine. Microsoft Office was the general software utilized by all teams for tables, plots, calculations, and reports.

AutoDesk Inventor 2015 [A] was used as the primary design software for the mechanical portion of the turbine, which included the wind vane, gearbox, and the yaw mechanism. This 3D modeling software was used to design individual components and create assemblies. It's important to note that certain companies that we purchased from offered CAD files of their parts, so we were able to import the file from the company websites to ensure that the parts could be properly implemented into the design. This method was utilized while ordering the worm drive, servo motors, pulleys, and bearings. This was very beneficial because having the exact CAD files enabled the team to get accurate renderings of the completed assemblies while the parts were on order.

Electrical software

For the electrical design in this project, four programs were utilized to prototype, design, and operate our system. LTSpice [E] was used to create circuit simulations and do preliminary prototyping of the buck-boost converter, and the rectifier. MATLAB [G] was then used to calculate all the necessary component value for the buck-boost integrated circuit to ensure operation in the correct feedback loop. Eagle [C] was used to create designs for PCB boards, that were then milled for final circuit construction. Lastly, Arduino [D] was used to program the control system for the turbine.

Conclusion

With renewable energy on the rise, researching ways to produce consistent power generation for society is crucial. This project focuses on the optimization of a small-scale wind turbine to evaluate the different methods of increasing efficiency from wind sourced energy generation. Being able to decrease the consumption of fossil fuels and coal fired power generation facilities not only can make a major impact on the health and wellness of people, but it can also decrease carbon emissions.

The design and construction of the single drive gearbox has proven to be efficient in generating power at low wind speeds. The main goal was to achieve a relatively compact, durable, and low resistance drivetrain to justify why small-scale turbines can thrive in rural areas. The disadvantage of current large scale wind turbines is that the gearbox cannot withstand the expected lifetime of the turbine itself due to its complexity, therefore resulting in unwanted and expensive maintenance. Providing a gearbox that can endure harsh weather conditions and remain operational for a long period of time is a breakthrough for future wind turbine developments.

Incorporating a yawing mechanism to the design allows the wind turbine to react to different wind directions. This design improvement increases the efficiency of the power generation system. The ability to track the wind and make adjustments accordingly was a major design challenge. However the yaw design that was developed by the Aurora Boreas team operates with minimal faults and was successful upon testing. It was able to take wind data using a wind vane and potentiometer system. This data was then processed by the electrical components and relayed to the worm drive servo, thereby initiating corresponding rotation to the turbine head. By keeping the turbine blades perpendicular to the wind, the turbine is able to maintain the highest capacity of wind energy captured.

The design of the power electronics for the Aurora Boreas wind turbine was successful in providing the 10 W needed for the loads power requirement. The main focus for the design was to make a safe and reliable system that was still cost effective. To do this, the microcontroller and the buck-boost converter were placed on one printed circuit board to save space and reduce cost. The rectifier also reduced the needed output capacitance as compared to its diode bridge counterpart. This improved safety by reducing the stored energy on the output. The control system was implemented using an Arduino micro for its reliability and ease of use. There are several areas in which the electronics of this turbine can be improved upon: The control system could be implemented on the rectifiers PCB so that a microcontroller does not need to be attached. The final improvement would be a safe storage energy device that could allow the control system to operate in no wind conditions to move the turbine into variable wind directions. Combining these changes together will maximize the use of power that is generated by the turbine.

The research and development conducted over the course of this project is valuable to the wind power industry. As the renewable energy sector continues to grow and wind energy becomes more prevalent to our nation's power grid, an influx in research and development will be required to continue the growth and improve the overall efficiency of the technology. The culmination of multiple engineering disciplines will be required to move this field of study forward as it expands. This project helps give understanding to the endless possibilities available for the wind industry. With renewable energy production increasing rapidly, the evolution of more intelligent and integrated systems will have to continue to be developed in order to maximize the potential energy harvesting capabilities. These improvements will continue to pave the way to a green, sustainable energy economy worldwide.

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