California State University, Chico

Collegiate Wind Competition 2019

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CALIFORNIA STATE UNIVERSITY, CHICO

CHICO STATE
ENGINEERING

Executive Summary

The California State University, Chico collegiate team consists of undergraduate students with interdisciplinary majors in the following areas of study: engineering, and natural science. Early in the project, the Chico State team understood that by working together with a preliminary goal in mind would enlarge and enrich the collaboration amongst the group. The main goal in the initial stages of this project was to exploit the strongest skills of each member and implement their individual knowledge that would enable the team to make progress as efficiently as possible. It is important to mention that despite CSU, Chico having participated in the competition in previous years, every single one of the members in this years 2019 team was new to the experience. It was therefore very important that the team work together as closely as possible exchanging and contributing ideas to successfully develop the project from the initial stages to the final assembly.

With that in mind, the Chico State Collegiate Wind Competition 2019 team would like to disclose its deliverables in this report which they are very much proud of. In an effort to meet the needs of this project, a strategic approach was implemented which is outlined in this summary to assess project requirements and deliver a final design for the U.S. Department of Energy Collegiate Wind Competition 2019 (CWC 2019). The core values of the CSU, Chico team were demonstrated throughout this project and implemented by adhering to sustainability practices upheld by the College of Engineering at California State University, Chico. Many of those practices are evident in the prototype stages of the project where decisions were made to re-use materials that were readily available.

This project was completed within a two semester period during which recruitment, student retention and project design development was prioritized in the first semester; iterative design refinement through trial and error was paid emphasis in the second and final semester to achieve an optimal final design. Despite progress being interrupted toward the end of the first semester by the California Camp Fire wildfire that devastated Northern California, the team managed to keep its composure and continued working cooperatively in the mist of that unfortunate event.

The final wind turbine design detailed in this report consists of the following components: a NACA 4412 turbine blade computationally generated via the turbine blade analysis software QBlade for maximum performance following aerodynamic principles, the nacelle which was designed adhering to design principles that improve overall aerodynamic efficiency and the main component that houses the electronic components, the wind vane that ensures the turbine continuously faces the wind head-on to generate maximum power, and, lastly, the emergency shutdown circuit controlled by the Arduino Uno microcontroller that performs the required electrical functions.

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Mechanical Design

Design Objective

The main challenge for the Collegiate Wind Competition 2019 is to research, design, and enhance a turbine for a grid scenario with a high contribution of renewables and to be able to operate in an islanded mode.

The objective for the design for this year's team for Chico State is to make a functional prototype that satisfies the minimum requirements for this year's competition while learning as much as possible in the process. By prioritizing simplicity and functionality, the team focused on achieving a mechanical design which promoted simplicity in assembly and obtainable parts to build a turbine which is efficient and operates within the competition's requirements.

By focusing on the blade design, generator selection, safety shut off, and testing performance, this year's team is striving to improve the progress made by previous teams. The team focused on improving their knowledge of aerodynamics and the functionality of the blades through the implementation of software analysis and wind tunnel testing. The DC generator was matched to the aerodynamics of the blades for optimal operating conditions.

The safety shut off was designed using an arduino microcontroller programmed to detect loss of current and therefore go into a safety mode which creates a short circuit in the motor causing a significant decrease in RPMs.

Blades

The design of the blade consisted of three main factors: airfoil selection, twist, and chord lengths. These three factors were selected by optimizing blade design for a wind speed of 11 m/s and optimal RPMs for the generator by running simulations on an open software analysis program Q- Blade that uses the Blade Element Method (BEM) to predict the efficiency of the Horizontal Axis Wind Turbine (HAWT).In general, BEM underestimates the overall performance of a turbine and overestimates the peak power. Although this isn't ideal, the blade element momentum method is widely applied in the wind turbine industry because the use of analysis techniques of lower order-accuracy greatly simplifies the turbine design. By using the BEM model, it is possible to rapidly develop and test different rotor designs against one another, commit small changes and test again, and in this way evolve a preliminary design that can be studied in greater detail with other techniques, like FEA, later. The power of this iterative approach and the verification of BEM simulations with wind tunnel and field measurements justify the use of BEM computational methods to analyze the blades from a two dimensional point of view. The BEM method's ability for robust analysis and low computational costs make up for most shortcomings and inaccuracies.

Airfoil Design

The two main factors for choosing the airfoils of the blade were optimizing the rated power output as well as a favorable cut in wind speed. The airfoils tested for the blade are all from the same family in order to maintain similar aerodynamic properties, but the relative thickness varies throughout the the different airfoils to ensure a blade design which considers rigidity and strength while also having superior aerodynamic properties to ensure rated power output. By analyzing the NACA 44 series the airfoil selected was: NACA 4412.

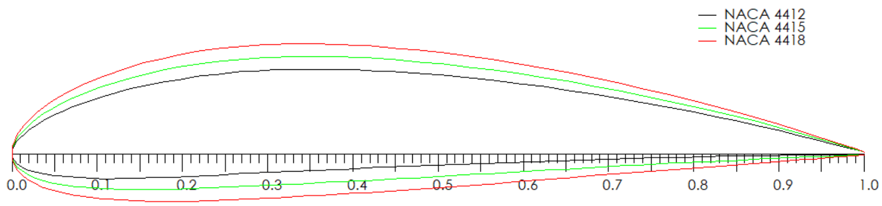

Figure 1: *Airfoil comparison*

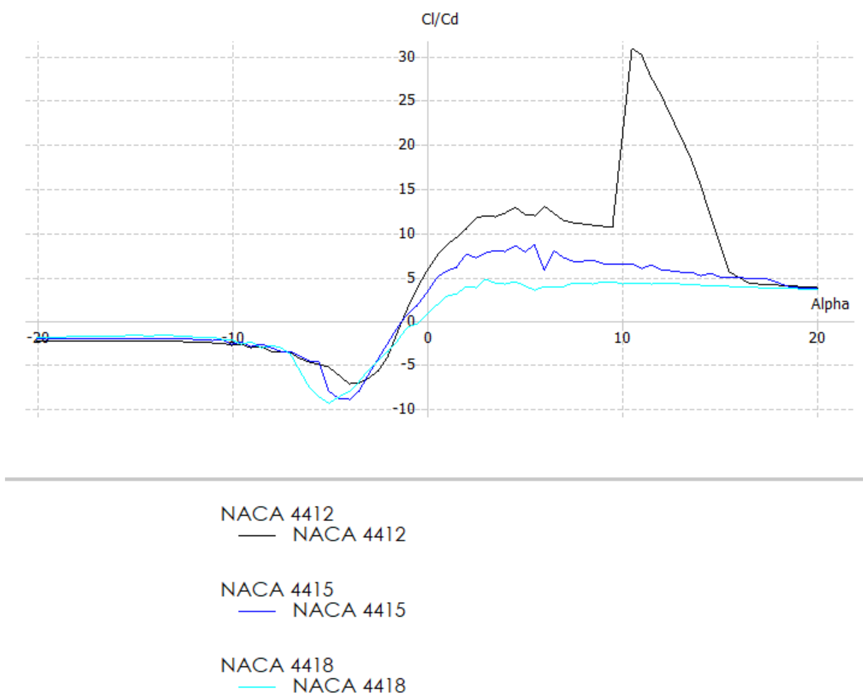

Figure 2: *Comparative airfoil data; Cl/Cd vs Attack Angle*

From the figure shown above, the airfoil chosen for the blade was the NACA 4412 having a max thickness of 12 % at 30 % of the chord due to its favorable Coefficient of Lift vs Coefficient of Drag.

Twist and Chord Lengths

The maximum possible power coefficient from a wind turbine, assuming no wake rotation or drag, was determined to occur with an axial induction factor of 1/3. If the same simplifying assumptions are applied to the equations of momentum and blade element theory, the analysis becomes simple enough that an ideal blade shape can be determined. The blade shape approximates one that would provide maximum power at the design tip speed ratio of a real wind turbine. By assuming no wake, drag, or losses from a finite number of blades the ideal blade is created, it is seen that blades designed for optimum power production have an increasingly large chord and twist angle as one gets closer to the blade root.

Table 1: Twist and chord distribution for a Betz optimum; r/R. Fraction of rotor radius

r/R	Chord, m	Twist Angle (deg)	Angle of Rel. Wind (deg)	Section Pitch (deg)
0.1	1.375	38.2	43.6	36.6
0.2	0.858	20.0	25.5	18.5
0.3	0.604	12.2	17.6	10.6
0.4	0.462	8.0	13.4	6.4
0.5	0.373	5.3	10.8	3.8
0.6	0.313	3.6	9.0	2.0
0.7	0.269	2.3	7.7	0.7
0.8	0.236	1.3	6.8	-0.2
0.9	0.210	0.6	6.0	-1.0
1	0.189	0	5.4	-1.6

Upon further research, the twist of the final blade design was evaluated referencing the ideal twist and chord distribution for a Betz Optimum blade as shown in Table 1. This objective was achieved by making changes to the twist angle and running simulations on QBlade to obtain the best angle distribution and chord lengths following the Betz Optimum chord distribution. The final design consisted of optimized twist and chord lengths that met this teams design requirements and that closely followed the Betz Optimum chord distribution values. The aforementioned final design values are recorded in Table 2 shown below.

Table 2: *Blade Design - Twist and Chord Lengths*

	Pos (mm)	Chord (mm)	Twist	Foil	Polar
1	0	45.5	27	NACA 4412	NACA 4412 Polar
2	18.9581	43.6	19.5	NACA 4412	NACA 4412 Polar
3	37.9162	41	14	NACA 4412	NACA 4412 Polar
4	56.8743	38.8	10.5	NACA 4412	NACA 4412 Polar
5	75.8324	34.5	8	NACA 4412	NACA 4412 Polar
6	94.7905	30.06	6	NACA 4412	NACA 4412 Polar
7	113.749	26.6	5	NACA 4412	NACA 4412 Polar
8	132.707	24.12	4	NACA 4412	NACA 4412 Polar
9	151.665	21.8	3.5	NACA 4412	NACA 4412 Polar
10	170.623	19.3	2.8	NACA 4412	NACA 4412 Polar
11	189.581	17.5	1.6	NACA 4412	NACA 4412 Polar

Blade Design Process

The blades were designed using simulation program Q-Blade to optimize performance while designing for low cut in wind speed, CP, TSR, and Angle of Attack. Using a Reynolds number of 50,000 (calculated using airfoiltools.com) an iterative process began to find the best performance at a wind speed of 11 m/s. By iterating between several TSR ranges, a blade that matches the desired outputs within operating conditions was selected.

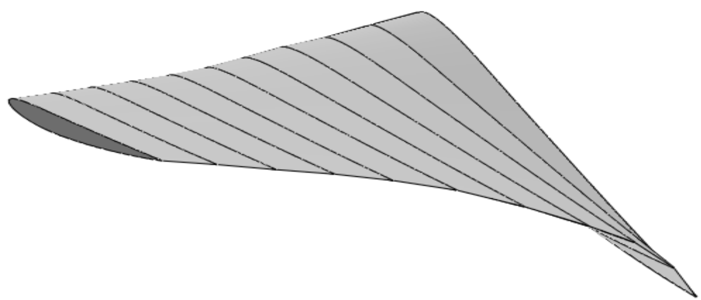

Figure 3: *NACA 4412 Blade*

After choosing a blade design the airfoils were plotted on airfoilplotter.com and then imported into Solidworks to create CAD models. The blades were then 3D printed on a Makerbot Replicator Plus in the Engineering Department on campus using PLA. Afterwards, the blades were sanded and reinforced using an epoxy resin to give them a smooth surface and added strength.

Static Analysis

Coefficient of Power vs TSR Plot shown below for operating wind speed of 11 m/s showing max CP of about 0.45 at a TSR value of 5.5. Where TSR is defined as $\lambda = \frac{\Omega R}{U}$, where Ω is the angular velocity of the blade, U is the velocity of the incoming wind, and R is the length along the blade.

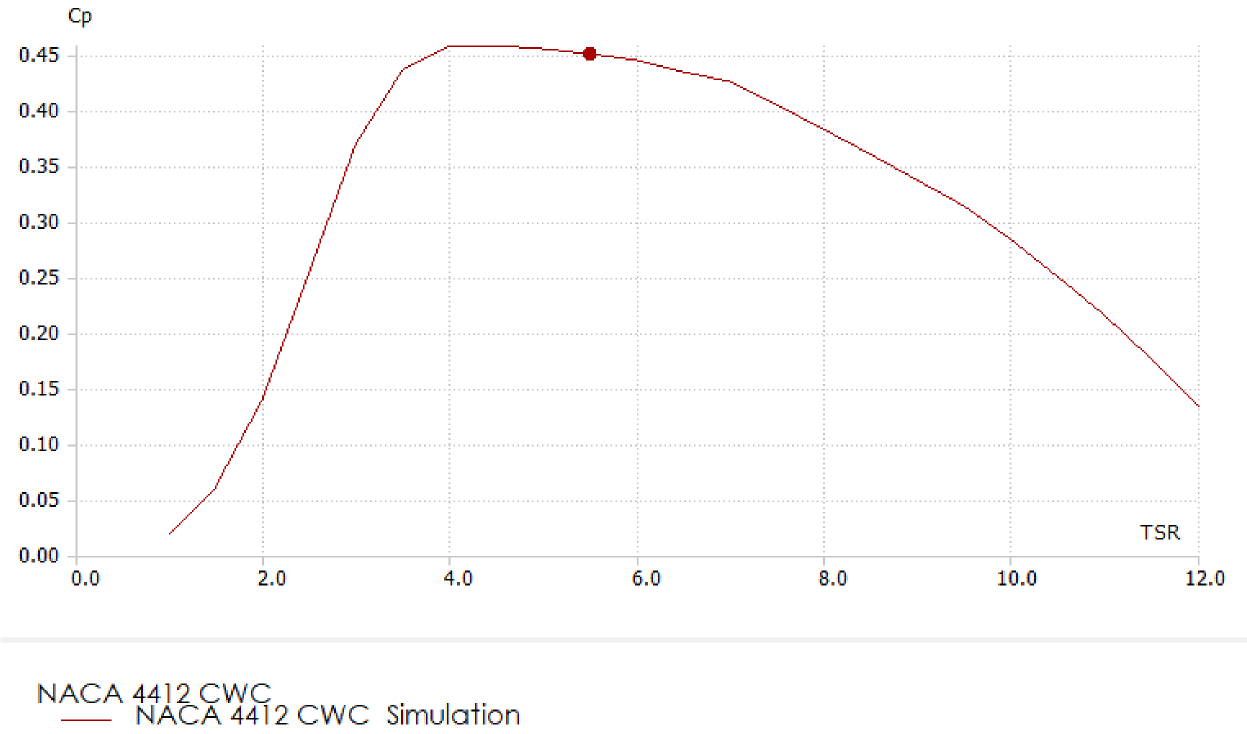

Figure 4: *CP vs λ Plot*

Static blade loading and deflection results assuming max loading conditions at 20 m/s wind speed. Results show that the drag force on the blades are the main cause of stress. Where drag force can be calculated by equation (1). Q-blade Q-FEM simulation estimated the max stress to have a value of 28.74 MPa which is concentrated closest to the root where the twist angle is largest. The turbine blade undergoes deflection due to applied stress resulting from the drag force generated by the wind. To minimize the effects of deflection, the turbine blade was coated with a thin epoxy layer which was predicted to increase overall blade strength, rigidity, and performance.

$$F_D = C_d A \frac{\rho v^2}{2} \qquad \text{(Eq. 1)}$$

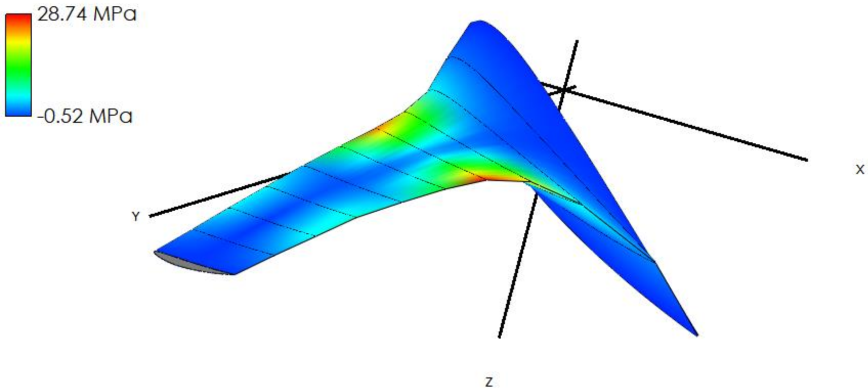

Figure 5: *Static Blade Loading and Deflection*

A preliminary stress analysis was performed on a single turbine blade using simplified geometry for comparison to FEA results via QBlade. The simplified geometry consisted of treating the blade as a simple cantilever beam with a corresponding length of 0.125 m, cross-sectional length of 0.0175 m, a base of 0.0025 m, a 0.00875m displacement value away from the neutral axis, and an applied force of 0.475 N (drag force). These values were then inserted into the maximum bending stress equation (2) to obtain a maximum bending stress value of 34.58 MPa. Finally, this calculated value was compared to the FEA generated maximum stress value of 28.74 MPa which yielded a 16.9% under-predicted stress difference.

$$\sigma = \frac{Mc}{I} \qquad \text{(Eq 2.)}$$

Tail Analysis

By using a passive system to control the yaw of the turbine, the turbine is ensured to continuously face the wind head-on and generate the maximum amount of power possible. Even with a change in wind direction, the turbine will continue to face the wind without any power consumption required to maintain its orientation into the wind.

The wind-vane of the turbine has been CNC'd out of aluminum. This ensures that it is strong enough to handle a sudden change in wind direction while also keeping it lightweight. Although printing the vane out of PLA was considered, the strength of aluminum proved more desirable as well as precision of CNC machines. When using 3D printers, it was difficult to maintain a precise flatness with thin, large features. An added benefit of using an aluminum vane is with being more dense prevents the possibility of oscillations under natural or resonance frequencies. The dimensions of the vane also creates an issue with printing under the size constraints of the printing platform.

Through research on design of wind-vanes specifically used for wind turbines, we learned that shape does not play a crucial part in its performance when needing to turn the turbine in the direction of the wind. Members looked at various designs from triangular, rectangular, and trapezoidal but the difference was not significant. The most important part in the design of the tail-vane was making sure the area was no less than 5% of the sweep area of the blades.

In order to perform an FEA test on the wind-vane, a simplified assembly of the vane and nacelle was created. A force corresponding to 20 m/s wind speeds was calculated and placed on the wind vane itself. Bolts, contacts, and proper fixtures were implemented in order to create a response similar to what would be seen in the real setting. According to the SolidWorks FEA, a maximum Von Mises stress of 1.81 Mpa would be experienced near the bolt hole connectors. These results are realistic in location as well as stress value as not much force is being created from the wind. The maximum stress is well below the yield strength of both the PLA used in the Nacelle as well as the Aluminum from the wind-vane. See Figure 6 for the FEA results.

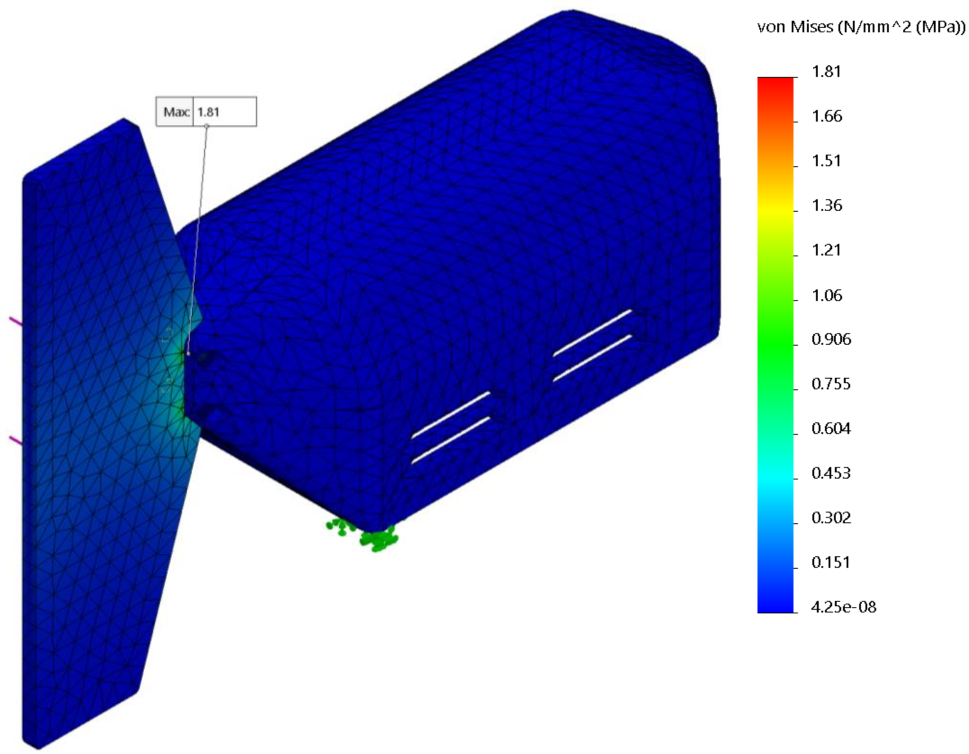

Figure 6: *Stress in simplified assembly of nacelle and wind-vane*

Nacelle Design and Full Assembly Drawings

The main goal in designing the nacelle was to maintain aerodynamics while ensuring there is adequate room for all electrical components. The base of the nacelle was made rectangular to maximize the mounting space for solder boards and other components required for controls while the top of the nacelle was rounded to minimize unused space. A tapered section was also added upwind and downwind on the nacelle to add to the aerodynamic effects and reduce turbulence that would otherwise be created by a sudden change of geometry or air flow. A nose cone was also incorporated into the hub. This allows for a smoother transition in the pathway of air flow, reducing turbulence at the hub. This helps maximize the power that can be extracted from the rotation of the turbine blades.

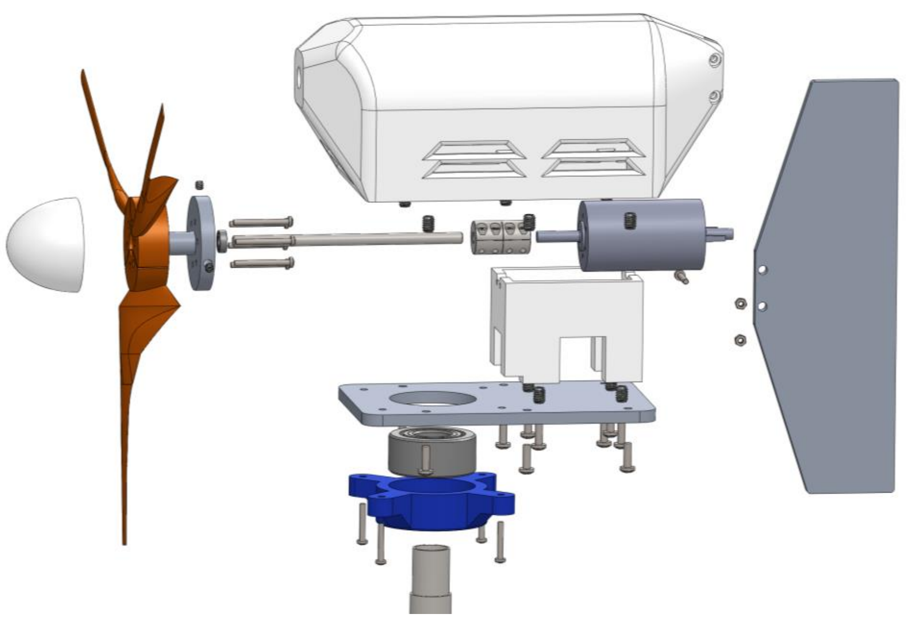

Figure 7: *Turbine exploded view*

Electronics

Overview

The electrical system has a few basic functions: adequately shutdown turbine when load is disconnected or during manual shutdown and bring down to a sufficient speed, detect reconnection and restart turbine normally, and deliver as much power as possible to the load. Furthermore, the turbine should be able to calculate the revolutions per minutes as well as power produced at any given time. The logic flow chart below shows a description of the algorithm used to control the turbine.

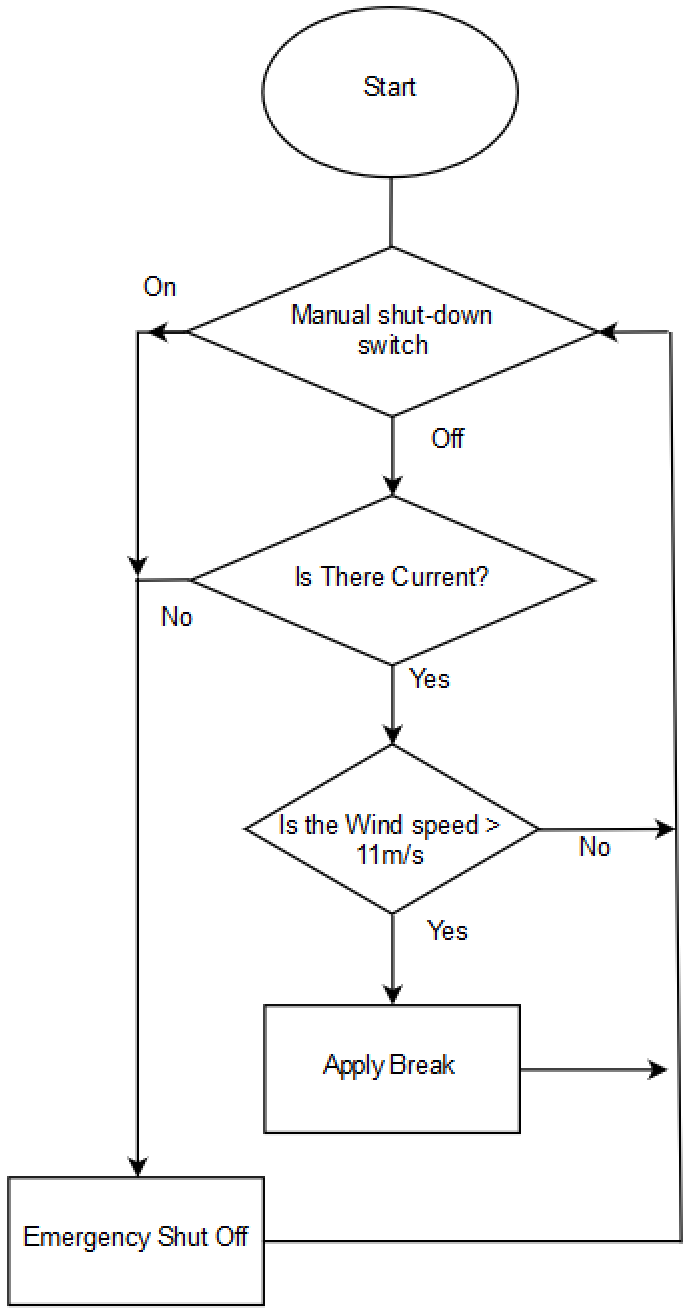

Figure 8 : Logic Flowchart

The logic starts when the microcontroller receives power, It then checks if the manual shutdown is ON or OFF, if the switch is in the ON position, the motor goes into Emergency Shut off mode, which means we short the motor. If the manual shut off switch is OFF, then the system checks in with the current sensor, if it does not sense any current coming from the PCC it will also use the relay to short the generator, causing a dramatic decrease of rotations. If there is current coming from the PCC, then it checks the RPMs of the generator, thus helping us check the speed of the wind. If the RPM sense that the wind speed is anything higher than 11 m/s it will apply a break which is caused by using a series of resistors, working like the Emergency break but on minor scale.

Detecting Emergency Shutdown

The electrical system uses a SMAKN® ACS712 current sensor module. This sensor is wired in series with the load. Therefore, this system can detect an open circuit (i.e. emergency shutdown) if no current is detected at terminal going to the load.

Once emergency is detected, a relay disconnects the generator from the load terminals and short circuits the generator. This allows a sudden decrease in angular velocity of the turbine due to the reverse EMF voltage. If decrease of speed is not sufficient, however, additional deceleration is needed through another device.

Detecting Manual Shutdown

The JST RCY cables are connected to an analog input pin and +5V. Once the the arduino detects that the circuit within the cable is open, the arduino will undergo a shutdown procedure similar to that of the emergency shutdown.

Detecting Reconnection

A capacitor is in parallel with the PCC. As the turbine generates power, this capacitor gets charged. When the load is disconnected to the PCC and the turbine undergoes shutdown, the capacitor remains charged. Once the load is connected to the PCC, the capacitor will have a path for discharge. The current created by this discharge will be detected by the current sensor, which will initiate start up of the turbine.

Decreasing Rotational Speed During Shutdown

In order to sufficiently decrease the speed of the turbine during shutdown, the design utilizes a solenoid in order to accomplish this task. The solenoid is placed so that, when actuated, the plunger pressed against the rotating shaft providing a frictional torque to slow down the turbine. The solenoid is actuator via a signal from the Arduino. A solenoid driver circuit is implemented in order to prevent voltage spikes during on and off use.

Measuring Rotations per Minute (RPM)

In order to measure the angular speed of the turbine, the design uses a hall-effect sensor, which measures magnetic field strength. When a strong enough magnetic field is near the device, the sensor outputs a high signal, around 3.5V. When a weak magnetic field is present, the output is low, or ground. In order to ensure the arduino could detect the high output signal, a comparator is used to bring the output signal from 3.5V to 5V when high. This signal is fed into an interrupt pin. Every time the interrupt is triggered, the interrupt service routine measures the time difference between each time the interrupt was triggered. When placing the sensor near the shaft where the shaft has a magnet attached, the rotations per minute can be measured by measuring the time between when the sensor experiences a strong magnetic field (i.e. when shaft is in a position so the magnetic is near the sensor) and a weak magnetic field (i.e when the shaft is in a position where the magnetic is away from the sensor).

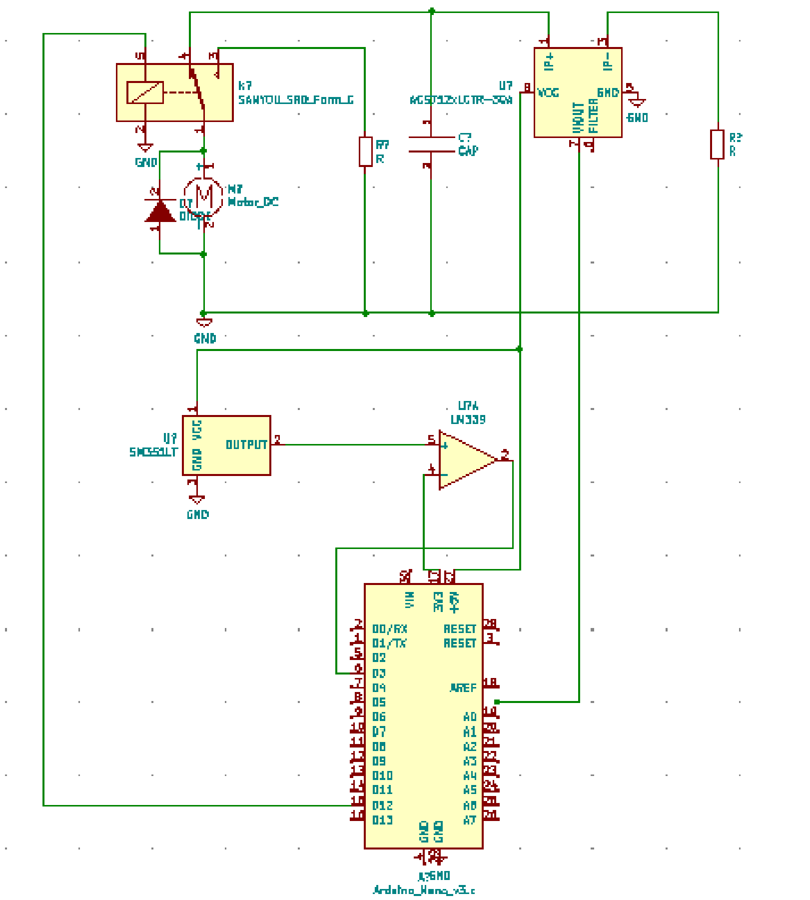

Figure 9. Electrical schematic of the emergency shut-off circuit.

The electrical schematic for the emergency shut-off circuit, is run by a Arduino Nano, the team used a Hall Effect sensor output which is connected to an op-amp since the signal emitted wasn't strong enough for the microcontroller to read.

Motor Selection

When selecting the motor, team members were looking into efficiency, Wattage and Back-EMF constant. Another aspect we looked into was a small friction torque and stall torque to aid in the startup speed of under 5 m/s. After looking into different options, it was decided to use Faulhaber 3863H012C. The data sheet indicates that it has an 85% efficiency with a no -load speed of 6600 RPM as well as high output power.

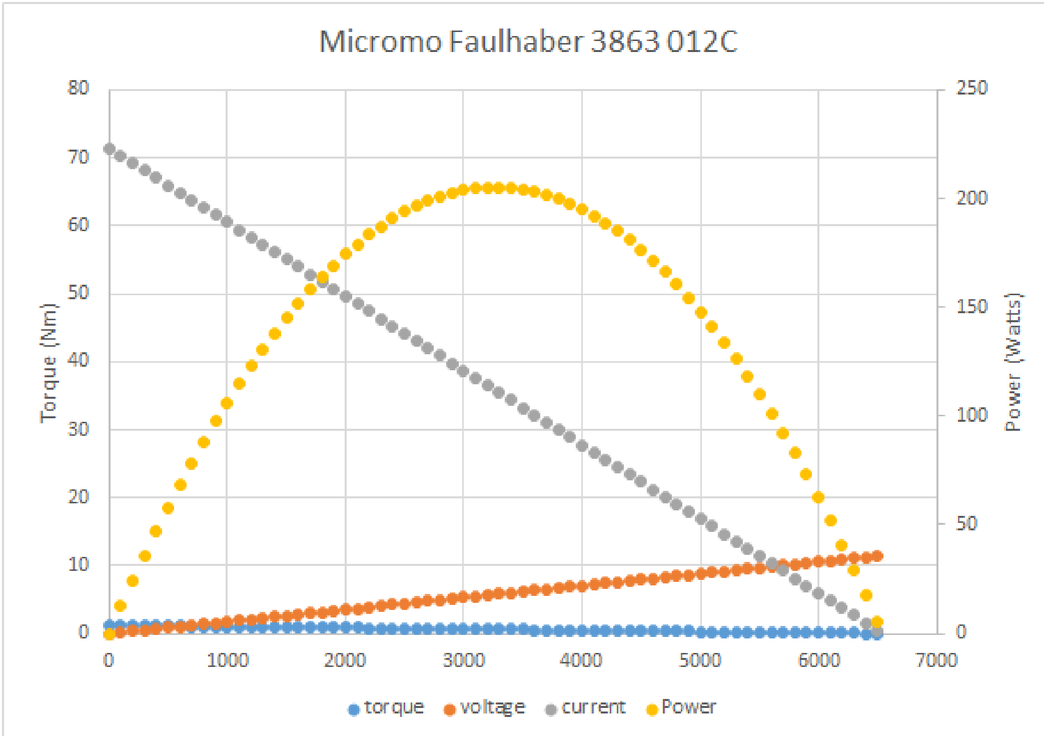

Figure 10: *Motor's Performance depicted by Torque, Voltage, Current and Power*

Load Design

The load was designed for the optimal performance of our blades with the generator's performance. By selecting a generator which will operate within our range of RPM's and necessary torque requirements, the electrical team focused on finding the max output of rated power at a wind speed of 11 m/s.

By calculating the Thevenin equivalent circuit, an equivalent simplified circuit, the resistance of the load required for the motor was determined to be $R_S = R_L = 5$ Ohms. The maximum power transfer theorem states that the maximum amount of power will be dissipated in the load resistance if it is equal in value to the source of the network supplying the power then that will theoretically provide the turbine with maximum power transfer.

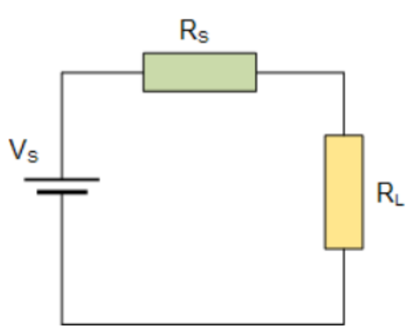

Figure 10 : *Thevenin Equivalent Circuit where* $R_S = R_L = 5$ *Ohms*

Performance Analysis

The performance of the final blade design, and initial models, were tested using the wind tunnel in the college of engineering laboratory at CSU, Chico. Prior to printing prototype models of the blades and testing them in the wind tunnel, desirable models to meet the demands of power generation and airfoil parameters to maximize performance were first generated. The main program used to generate these computer models was QBlade, an open source wind turbine modeling and calculation software. After running simulations and obtaining favorable results, the prototype was placed in the wind tunnel perpendicular to the wind direction. With the limitations of the wind tunnel on hand, the wind speed that the prototype became planar with the wind direction was marked down as the wind tunnel was powering up. After 5 tests an averaged initial speed of approximately 4 m/s was recorded; which satisfied our test requirement of having a cut in wind speed of less than 5 m/s.

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