

Design of a Hydrostatic Wind Turbine

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Abstract

One of the main issues with conventional wind turbines is their reliability and expensive maintenance. To address this issue, the Innovative Engineers student group and the Center for Compact Efficient Fluid Power at the University of Minnesota came together to form a research team to develop and test a relatively new wind turbine technology in the field: a hydrostatic transmission for wind turbines. A hydrostatic transmission is a pump and motor fluidly coupled using hydraulic lines. This has several advantages including increasing the reliability of the wind turbine, making its maintenance easier and improving the efficiency of mid-sized wind turbines by allowing the turbine to set the rotor rpm independently of the generator rpm. Research at the University of Minnesota has indicated that the energy output of a conventional mid-sized wind turbine can be increased on average up to 4% by adding a hydrostatic transmission (Thul, 2011, p. 40). To test this, a small (~1kW) wind turbine will be constructed and will be fitted with sensors including hall sensors, a pressure transducer, and a wind speed anemometer. An Arduino microcontroller was used to read all the sensors, store the data and control the wind turbine by controlling the current through the generator and the displacement of the hydraulic motor. The rotor RPM and pressure measurements for the pump were compared to the RPM and current outputs of the generator to determine the efficiency of the hydrostatic wind turbine. While the efficiency results are not conclusive yet, the turbine shows promise to be an efficient and reliable solution. Leakage, high efficiency loss at low wind speeds and weather all pose challenges for the design of this sort of a turbine, but these issues can be overcome.

Table of Contents

1 Introduction.....	5
1.1 Origins of Project.....	5
1.2 Motivation for Hydrostatic Transmission for Wind Turbine Development	5
1.3 Relevant Wind Turbine Background.....	8
2 Design Optimization.....	10
2.1 Fluid Power Design Optimization	10
2.1.1 Hydraulic Pump Efficiency.....	10
2.2 Electrical Design Optimization.....	12
2.2.1 Generator Efficiency	12
2.3 Overall System Modeling	13
3 Design.....	17
3.1 Mechanical Design	19
3.1.1 Rotor Drive Shaft Design for Infinite Fatigue Life.....	21
3.2 Fluid Power Design	22
3.2.1 Pump and Motor Selection	23
3.3 Electrical Design.....	26
3.3.1 Buck Converter Selection	27
3.3.2 Generator Selection.....	28
3.3.3 Energy Dissipation	28
4 Results and Conclusions	28
4.1 Early Results	28
4.2 Future Tests.....	30
4.3 Related Technologies	31
4.4 Conclusion	32
5 References.....	33

Table of Figures

Figure 1: Innovative Engineers Logo.....	5
Figure 2: CCEFP Logo	5
Figure 3: Simplified HST Schematic (Thul, 2011)	7
Figure 4: Regions of Operation in Wind Turbine (Thul, 2011).....	10
Figure 5: Hydraulic Pump Efficiency vs. Pressure Plot (VPPL, Variable Displacement Axial Piston Pumps for Intermediate Pressure)	12
Figure 6: Motor Efficiency Vs. Load (Mohan, 2012, p. 263)	13
Figure 7: Hydraulic Motor Displacement vs. Wind Speed	15
Figure 8: Hydrostatic Transmission Pressure vs. Wind Speed	16
Figure 9: Overall Theoretical System Efficiency vs. Wind Speed.....	16
Figure 10: Powertrain Component Efficiency vs. Wind Speed	17
Figure 11: Overall Turbine Design	18
Figure 12: Nacelle CAD Rendering	20
Figure 13: Belt Transmission CAD Rendering.....	21
Figure 14: Rotor Drive Shaft Loading Diagram	21
Figure 15: Fluid Power Schematic	22
Figure 16: Power vs. Wind Speed	24
Figure 17: Probabilistic Distribution of Wind Speeds.....	24
Figure 18: Basic Electrical System Schematic	26
Figure 19: Buck Converter	27
Figure 20: Typical Wind Turbine Data	29
Figure 21: Theoretical and Projected Wind Turbine Efficiency	30

List of Variables

Variable	Definition
ρ	Density
μ	Dynamic Viscosity of Hydraulic Fluid
ω	Angular Velocity
A_{swept}	Swept Area of Wind Turbine Blades
B	Bulk Modulus of Hydraulic Fluid
C_f	Coefficient of coulomb (dry) friction
C_p	Power Coefficient for Wind Turbine Blades
C_s	Coefficient of Slip
C_v	Coefficient of Viscous Drag
D	Hydraulic Motor/Pump Displacement
I	Current
k_E	Motor Voltage coefficient
k_T	Motor Torque coefficient
n	Number of Turbine Blades
P	Power
p	Fluid Pressure
Q	Volumetric Flow Rate
R	Resistance of generator windings
T	Torque
V	Voltage Applied at generator terminals
V_r	Volume Ratio of Hydraulic Unit
x	Fractional Displacement of hydraulic motor or pump

1 Introduction

1.1 Origins of Project

Through conversations between faculty at the University of Minnesota, a common interest in developing more efficient and reliable wind turbines were found. These conversations led to action that eventually formed the Hydrostatic Wind Turbine Project. The Hydrostatic Wind Turbine Project consists of members associated with both the Innovative Engineers student group and the Center for Compact and Efficient Fluid Power.



Figure 1: Innovative Engineers Logo

Innovative Engineers is an undergraduate student group at the University of Minnesota. Their mission is to provide alternative energy solutions to under privileged countries. The group is run almost entirely by students but the faculty advisor for the group is Professor Imbertson.



Figure 2: CCEFP Logo

The Center for Compact and Efficient Fluid Power is an inter-collegiate organization committed to research, and education in fields of fluid power. Both of these organizations came together through Professor Van de Ven, Li and Imbertson and the Hydrostatic Wind Turbine Project was created from their shared interests.

1.2 Motivation for Hydrostatic Transmission for Wind Turbine Development

In 2011, the total summer generating capacity in the United States was 1,050.9 Gigawatts of power. In the United States, 10,500 Gigawatts of average potential power is available on average throughout the year in the United States at a height of 80 meters in areas deemed

suitable for wind development. If only a little greater than a tenth of that potential was captured, the United States could provide all its energy needs from wind on average throughout the year. (Schwartz, Haymes, Heimiller, & Scott, 2011) In 2010, NREL completed an analysis of all the off shore wind energy available in the United States and found that 4,150 Gigawatts of power is available at a height of 90 meters. (Schwartz, Heimiller, Haymes, & Musial, 2010) This analysis did not exclude land that would be reserved for other industrial, human or environmental reasons. It also limited the power was limited to the rated capacity of 5kW with each turbine requiring a square 1 km separation. This shows the great potential of offshore wind if it was to be harnessed properly.

Much of the motivation and inspiration for the research was derived from a research paper completed by Brennen Thul at the University of Minnesota. The paper completes a detailed comparison of wind turbines utilizing a hydrostatic transmission and conventional wind turbines utilizing standard fixed gear transmissions. It was found that a hydrostatic wind turbine could generate approximately 4% more energy per year than a fixed turbine, despite the lower efficiency of the hydrostatic transmission. (Thul, 2011, p. 40) Thul found that applying a hydrostatic transmission would allow the blades to run at an aerodynamically efficient speed and this improved efficiency more than offsets the additional losses associated with the hydrostatic transmission. Preliminary tests and models predict a hydrostatic transmission will reduce harmful loading created wind gusts by softening the loading with a small amount of fluid compressibility. This will help components last longer and save on maintenance costs.

Conventional wind turbines utilize a rotor and a generator with a fixed gear ratio between. Under most wind speeds, the blades will rotate much slower than the speed of the generator so the transmission will step up the speed input from the rotor. If the turbine happens to employ a synchronous generator that is fixed directly to the grid, the generator will be forced to rotate at a constant and relatively high speed. In other cases, such as with a permanent magnet AC motor or a doubly fed induction motor, the generator is allowed to vary its speed and expensive power electronics are used to control alternating voltage leaving the wind turbine and flowing into the grid. The wind does not always blow at high speeds, so wind turbines with a fixed gear ratio can mitigate some of this issue by varying the pitch of the blades. This changes the tip speed ratio of the blade set and moves the blades into a higher efficiency region at low wind speeds to keep the blade speed up. For the specific turbine considered in this thesis, the blade pitch is fixed so the effects of this capability will not be studied any further.

A hydrostatic transmission, as shown in Figure 3, consists of a pump and motor fluidly coupled using hydraulic lines. In a hydrostatic wind turbine, the transmission is placed between the

rotor and the generator. The principle is that the pump is turned by the blades on the rotor. This creates high pressure fluid which flows through lines down the wind turbine tower to the hydraulic motor. The high pressure fluid turns the motor and this turns a generator. The main advantage of this is that the rotor is allowed to spin at a speed independent of the generator. If a controller is properly designed, the rotor and generator will be spun at their most efficient speed at all wind speeds.

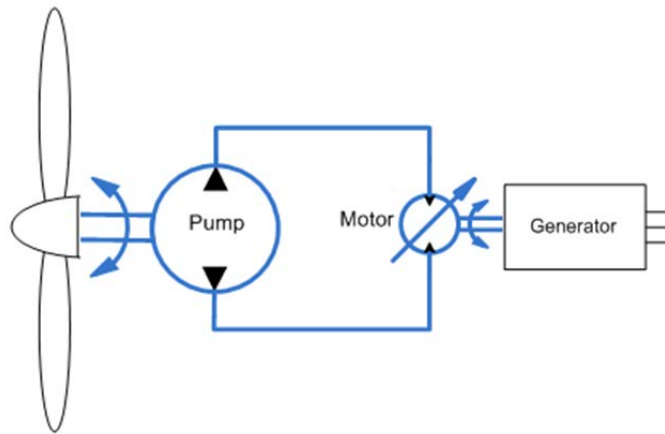


Figure 3: Simplified HST Schematic (Thul, 2011)

The torque and angular velocity relationships for an ideal pump and motor are described by Equations 1 and 2. 'x' stands for the fractional displacement of the pump and motor and V_{disp} stands for the maximum displacement per shaft rotation of either the hydraulic motor or pump. The fractional displacement, x, can be continuously varied at any time between 1 and down to 0. This effect of changes the ratio of the torque and angular velocity output to the input in an energy conserving manner. In this way, it is the same as changing the gear ratio on the gear or belt transmission. Since this can be done continuously, it is truly a continuously variable transmission with two fractional displacements that can each independently change the gear ratio. This is one of the greatest advantages provided by hydrostatic wind turbines.

Also, since the generator and hydraulic motor are down on the ground, this makes for easier maintenance and takes some undesirable weight out of the tower. Finally, since the hydraulic pump and motor are fluidly coupled, harmful transients in the rotor torque will be damped out and this will reduce wear on the hydraulic motor and generator.

$$T_{out} = \left(\frac{x_{motor} V_{disp,motor}}{x_{pump} V_{disp,pump}} \right) T_{in} \quad \text{Eq. 1}$$

$$\omega_{out} = \left(\frac{x_{pump} V_{disp,pump}}{x_{motor} V_{disp,motor}} \right) \omega_{in} \quad \text{Eq. 2}$$

Hydrostatic transmissions also come with some disadvantages to minimize. Most leakage is internal and necessary to lubricate components in the pump and motor. During maintenance, however, the risk of ground and water contamination is an added concern. Since the system is running out in the weather, the fluid viscosity will vary with ambient temperature. In some regions of world, such as the upper Midwest, the variation in temperature will be significant throughout the year. This means that either the temperature variations in the fluid will have to be carefully controlled within a specified range and/or the fluid will have switched out with the change of seasons. Finally, fluid power systems run most efficiently overall in high power situations. If the transmission is allowed to be run at a low power level, the efficiency may suffer. This presents an additional challenge for the technology.

1.3 Relevant Wind Turbine Background

In order to understand the principle operation of wind turbines the fundamental equations describing the principle operation of the turbine are detailed here. The power generated in the rotor is characterized by Equation 3.

$$P_{rotor} = \frac{1}{2} \rho A_{swept} C_p v^3 \quad \text{Eq. 3}$$

Note that the power is proportional to the wind speed cubed. The parameters that related to wind turbine blade design are C_p and A_{swept} . As defined in Equation 4, C_p is defined as the ratio of the useful power generated in the blades to the kinetic energy existing in the wind.

$$C_p = \frac{P_{rotor}}{P_{wind}} \quad \text{Eq. 4}$$

In this way, C_p is a sort of efficiency factor for the wind turbine blades. Theoretically, the C_p of wind turbine blades can never exceed a value of 0.593. This limit is known as the Lanchester Betz Limit. (Burton, Jenkins, Sharpe, & Bossanyi, 2011, p. 43) This limit has to do with the fact that not all momentum can be transferred from the wind to the blades. In order to maximize the C_p value of a set of wind turbine blades, the optimum tip speed ratio must be achieved. The Tip Speed Ratio is defined as:

$$TSR = \text{Tip Speed Ratio} = \frac{\text{Speed of turbine blade tip}}{\text{Speed of wind } (V_{wind})} = \frac{\omega r}{V_{wind}} \quad \text{Eq. 5}$$

The tip speed ratio defines the speed that the wind turbine blades must spin to achieve their optimum efficiency. The Tip Speed Ratio has been empirically determined to be Eq. 6.

$$TSR (\text{max power}) = \frac{4\pi}{n} \quad \text{Eq. 6}$$

'n' is defined as the number of blades on a wind turbine rotor. Eq. 5 and 6 together describe the principle behind wind turbine blade design. The tip speed ratio can be conceptually understood by imagining the air flowing through the wind turbine as a plug of air. The optimal tip speed ratio is the speed where the blades spin such that the entire volume of air passing through the swept area of the blades is disturbed and generates lift on the blades. As the number of blades increase, the tip speed ratio where the turbine will spin at max efficiency decreases. This is because the blades need to rotate a smaller fraction of a turn to disturb all the air passing through the turbine. Wind turbine blades will not naturally operate at the optimal tip speed ratio when the blades unless they are properly loaded. (Ragheb & Ragheb, 2011, p. 30) As expected, rotors heavily loaded by the generator will have trouble reaching their optimal tip speed ratio. Unloaded blades are prone to a runaway condition where the blade reaches a tip speed ratio much greater than optimal. Under this condition, great turbulence is generated by each of the blades that both reduces the potential torque generated and causes damages all the blades on the rotor with intense and irregular vibrations.

There are three regions of operation for wind turbines. Region 1 is described as the wind speeds where the wind is not great enough to turn the wind turbine blades. When the wind speed is great enough to start turning the blades, the system is operating in region 2. Within this region, the blades are allowed to operate at their optimal TSR and the system must be controlled to operate at maximum efficiency over a varying range of power inputs. Region 3 is defined as the wind speed that generates a power level that over loads at least one component in the turbine. Naturally, there is a rated power limit to transmissions and generators. Within this region, the turbine must be designed to limit the power that comes in through the wind turbine blades. In this case, the turbine is "furled" or yawed out of the wind in order to limit the power coming into the generator. This completed by passively controlling the yaw with the vane. Mid to large wind turbines often control the yaw of the turbine using a large mechanical drive. Often, however, large turbines instead vary the pitch of their blades in order to extend the energy collected from the wind into region 2. If the wind speed becomes too great, the blades need to be stopped using a brake system.

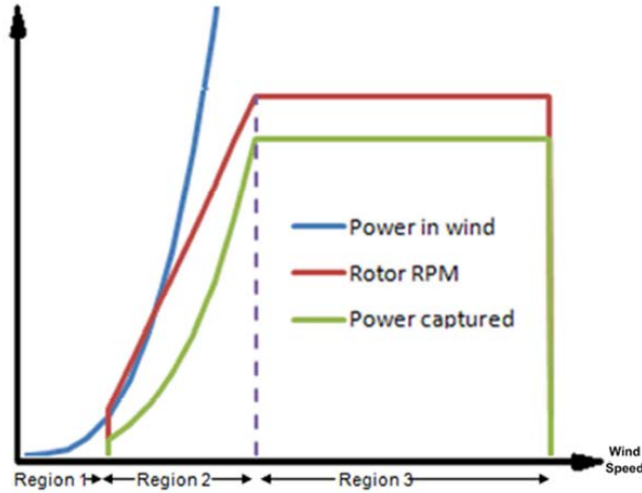


Figure 4: Regions of Operation in Wind Turbine (Thul, 2011)

2 Design Optimization

2.1 Fluid Power Design Optimization

In order to maximize the efficiency of the hydrostatic transmission, the hydraulic pump and motor were chosen to produce as high of a pressure as possible at all power levels. In particular, they were designed to produce 2000 psi at the max speed designated in region 2. This corresponds to the maximum overall efficiency in both the hydraulic pump and motor.

2.1.1 Hydraulic Pump Efficiency

The following equations show how the efficiency of a hydraulic pump vary with several variables including displacement, pressure and angular velocity.

$$Q = x\omega D\eta_V = x\omega D \left[1 - \frac{C_s}{x} \left(\frac{p}{\mu\omega} \right) \left(V_r + \frac{1+x}{2} \right) \right] \quad \text{Eq. 7}$$

$$T = xpD/\eta_m = xpD \left[1 + \frac{C_v}{x} \left(\frac{\mu\omega}{p} \right) + \frac{C_f}{x} \right] \quad \text{Eq. 8}$$

(McCandlish & Dorey, 1984) The coefficients C_s , C_v , C_f , V_r can be determined by fitting a least squares analysis to the actual pump performance data. (Van De Ven, Li, & Olson, 2008, p. 9) In order to estimate the system performance before seeing the performance of the pumps and motors, the following coefficients were used. These coefficients were used on another axial piston pump, but they are not correct for all axial piston pumps and only a starting point.

$$C_s = 1.8846 \times 10^{-9}$$

$$C_v = 4.9098 \times 10^5$$

$$C_f = 0.0240$$

$$V_r = 1.1113$$

All the coefficients above are unitless. In order to understand how the variables change under varying operating conditions, the following table helps.

Table 1: Pump Efficiency Variation with Operating Conditions

Variable	η_v	η_m
p	-	+
x	+	+
ω	+	-

The plus sign indicates that the efficiency value is increased with the variable value. Figure 5 was taken from the data sheet for the hydraulic pump that was actually used in the wind turbine hydrostatic transmission. Consistent with Table 1, Figure 5 shows that the volumetric efficiency decreases with pressure. The enhancements in mechanical efficiency, however, are overriding because the total efficiency increases as the pressure rises. This led to the design criteria of choosing a pump that minimized the flow rate and maximized the pressure in the hydrostatic transmission. This corresponds to a pump and motor with a very low displacement. To maximize the overall efficiency of the transmission, only variable displacement axial or radial piston pumps were considered. Therefore, the VPPL-008PCX-R00B/20N pump was chosen. Since this pump is being used as a hydraulic motor, it is possible that that the efficiency is less than is proven in the data sheet but this was considered an acceptable penalty.

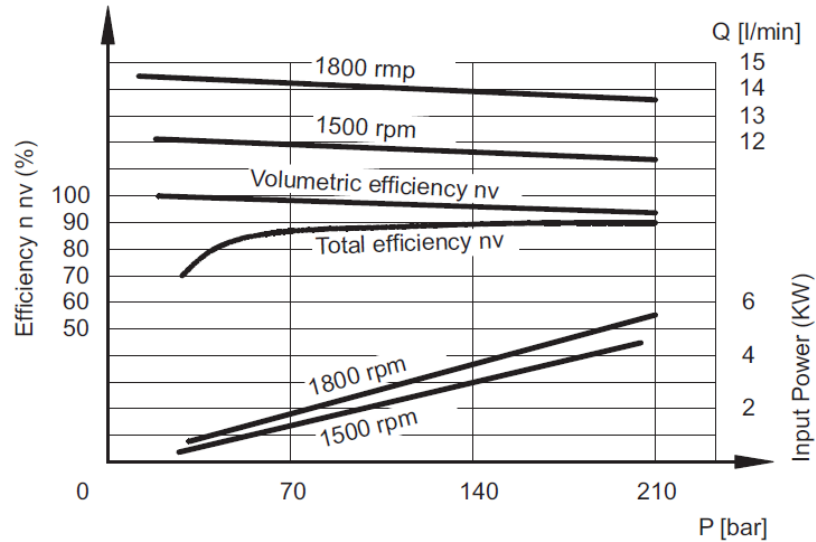


Figure 5: Hydraulic Pump Efficiency vs. Pressure Plot (VPPL, Variable Displacement Axial Piston Pumps for Intermediate Pressure)

2.2 Electrical Design Optimization

2.2.1 Generator Efficiency

In order to maximize the efficiency of the generator, the speed of the generator was held constant at its rated speed and current was drawn as needed. In order to understand why this is an optimal operating condition, it helps to cover some background material on how DC generators work.

$$T = k_T i \quad \text{Eq. 9}$$

$$\omega = \frac{V - iR}{k_E} \quad \text{Eq. 10}$$

$$k_T = k_E \quad \text{Eq. 11}$$

$$Power_{gen, steady\ state} = T\omega = i(V - iR) \quad \text{Eq. 12}$$

As shown in Equations 9 and 10, the current is proportional to the torque and the voltage (in the absence of current) is proportional to the speed of the generator. Two constants for the motor, k_T and k_E , can be determined easily by experimentation with the motor. It turns out that by Equation 11 they are equal so the expression for the steady state power in the generator falls out (Equation 12). As shown in Equation 12, the current and winding resistance are the only terms that bring about efficiency loss. There are several other terms not accounted for including friction, windage, and load loss. The friction, windage and core losses tend to increase with motor speed. The stray-load loss in is the catch all motor loss category.

The actual source of these losses is hard to determine. The stray-load loss increases with the square of the load. As shown in Figure 6, at a fixed speed, only the I^2R and stray-load losses are important.

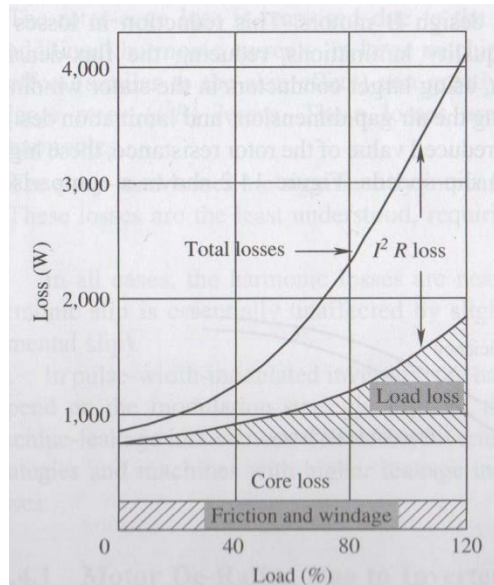


Figure 6: Motor Efficiency Vs. Load (Mohan, 2012, p. 263)

Figure 6 models the losses from a 50 hp, 4 pole, 3 phase induction motor. Even as the generator is a brushed DC, the trends and principles are the same. Since one the main constraints of the project is that the turbine operate as a turbine producing power to the grid without the need for power electronics, the speed of the generator must be held constant and the load varied. It turns out that this is a very efficient mode of operation and would only slightly benefit from varying the speed at low loads.

2.3 Overall System Modeling

In order to size mechanical and hydraulic components, the wind turbine needs to be modeled. A Matlab script was used to simulate the various components in the power train of the wind turbine. Using the models described in sections 2.1 and 2.2, a script is constructed that calculates the speed, pressure, torques, ect. through each stage in the wind turbine. It starts with the speed and torque generated in the rotor from a given wind speed by assuming the optimal TSR and CP value is achieved. It next uses Equation 7 and a rearranged version of Equation 8 to calculate the pressure and Flow rate generated by the pump in the hydrostatic transmission. Equation 7 and 8 are used again to calculate the torque and speed in the hydraulic motor. The torque and speed are modified using the pulley size ratio and an efficiency factor. Finally, the voltage and current output by the generator is calculated using

Equation 9. This process is repeated for several wind speeds and so curves for the output of every component can be generated. The script calculates the efficiency of the turbine in the end by comparing the input power to the output power. The following parameters were used for all calculations.

Wind Turbine Parameters:

Cp	= 0.4;
ρ_{air}	= 1.2 kg/sec
TSR	= 3.5;
Radius rotor	= 1.48 m
hub radius	= 0.1143 m

Hydraulic Pump and Motor Parameters

Cs	= 1.8846x10 ⁻⁹
Vr	= 1.1113
B	= 1.72x10 ⁹ Pa
rho	= 960 kg/m ³
D	= 4.4563x10 ⁻⁶ m ³
nu	= 0.011 Ns/m ²
Cs	= 1.8846x10 ⁻⁹
Vr	= 1.1113
Cv	= 4.9098x10 ⁵
Cf	= 0.0240

Fixed Ratio Transmission

Ratio	= 13.5:1
η_m	= 0.97

Electrical Design

$k_E = k_T$	= 0.37057 Nm/A or V/rad
Max Armature Voltage	= 130 volts
Max Armature Current	= 18 Amps
Rated Generator Speed	= 3350 RPM
Power Limit	= 2 HP
Generator Resistance	= 1.1 ohms

When these calculations were run, a generator had already been selected. As mentioned before, the generator speed was fixed at its rated value in order to simulate the performance of a turbine adding energy to the grid. Also, the pump displacement was assumed to be fixed at full displacement. This decision was made to save on mechanical complexity for this turbine.

The hydraulic motor displacement was set so that the generator speed was always held at its rated value. Equation 13 was used to calculate the hydraulic motor fractional displacement.

$$x_2 = \left(\frac{\omega_{rotor,optimal}}{\omega_{generator,fixed}} \right) \eta_{V,Transmission} = \left(\frac{\left(\frac{TSRV_{wind}}{r_{rotor}} \right)}{\omega_{generator,fixed}} \right) \eta_{V,pump} \eta_{V,motor} \quad \text{Eq. 13:}$$

When calculating the volumetric efficiency of the hydraulic motor, it was assumed that the hydraulic motor speed was varied with 100% volumetric efficiency by the fractional displacement for simplicity. In other words, the speed of the hydraulic motor was overestimated slightly for all volumetric efficiency calculations. In all cases, the generator was the first component to be over loaded. It was assumed that the cut-in wind speed for the wind turbine blades are 6.71 MPH. For most relatively efficient systems that were properly sized, 27.87 MPH corresponded to the wind speed that marked the system’s transition from region 2 to region 3. Finally, the system was simulated under conditions that would control the rotor RPM such that the optimal Tip Speed Ratio and CP of the rotor is achieved. For the system selected and controlled under the conditions described in this section, the required displacement vs. wind speed was output in Figure 7.

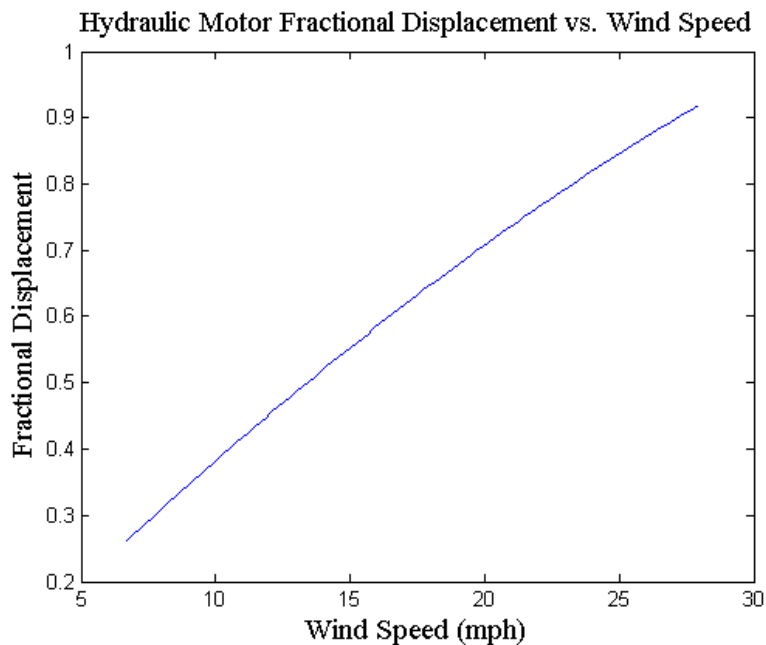


Figure 7: Hydraulic Motor Displacement vs. Wind Speed

As expected, this Figure shows that as the wind speed increases the fractional displacement of the hydraulic motor increases. Since the generator is fixed at a constant speed, and the rotor is increasing in RPM as the wind speed increases, the displacement of the hydraulic motor must increase to keep the generator from spinning faster. In order to maximize the efficiency, the transmission should be designed so that the max displacement occurs exactly at 27.87 MPH.

That is what was done with the sizing here. It is also interesting to look at the Pressure vs. Wind Speed in Figure 8.

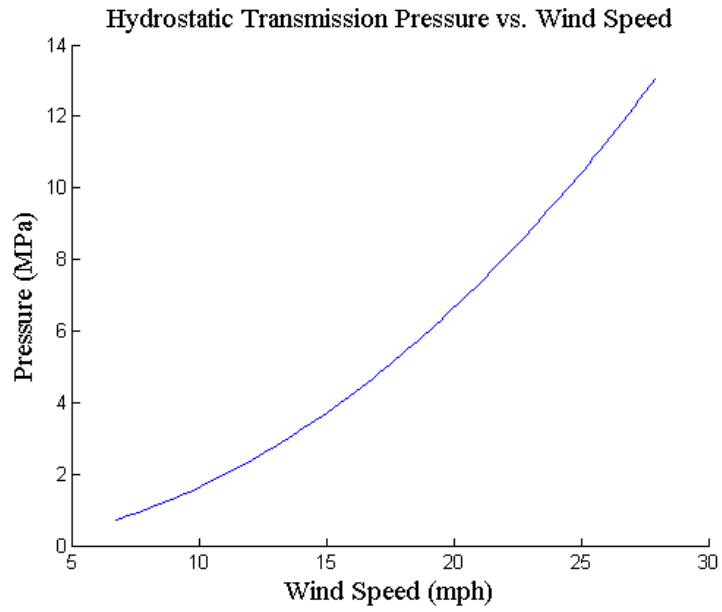


Figure 8: Hydrostatic Transmission Pressure vs. Wind Speed

As expected, the pressure increases as the power into the blades increases linearly. The increase in pressure does not, however, increase linearly because of the change in the efficiency as the wind speed increases.

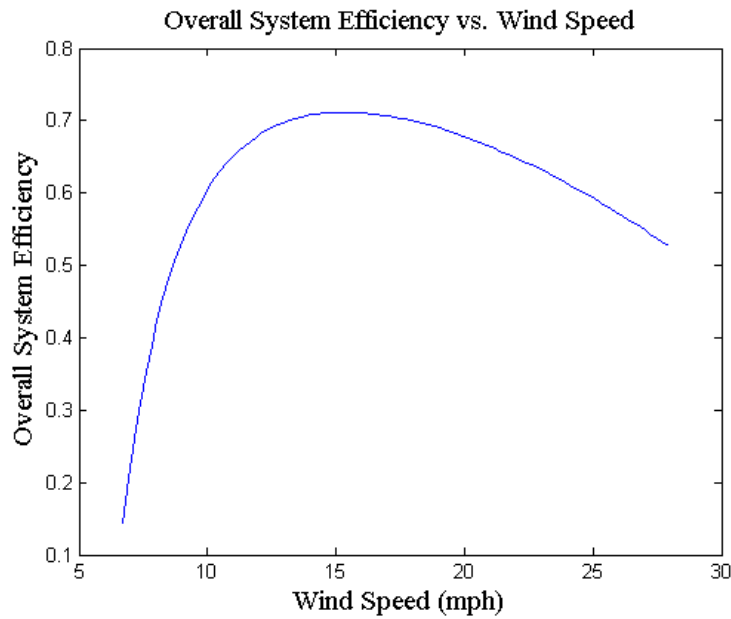


Figure 9: Overall Theoretical System Efficiency vs. Wind Speed

As shown in Figure 9, the overall system theoretical efficiency is maximized around 15 MPH. In order to understand why the efficiency curve has this shape, it helps to study Figure 10.

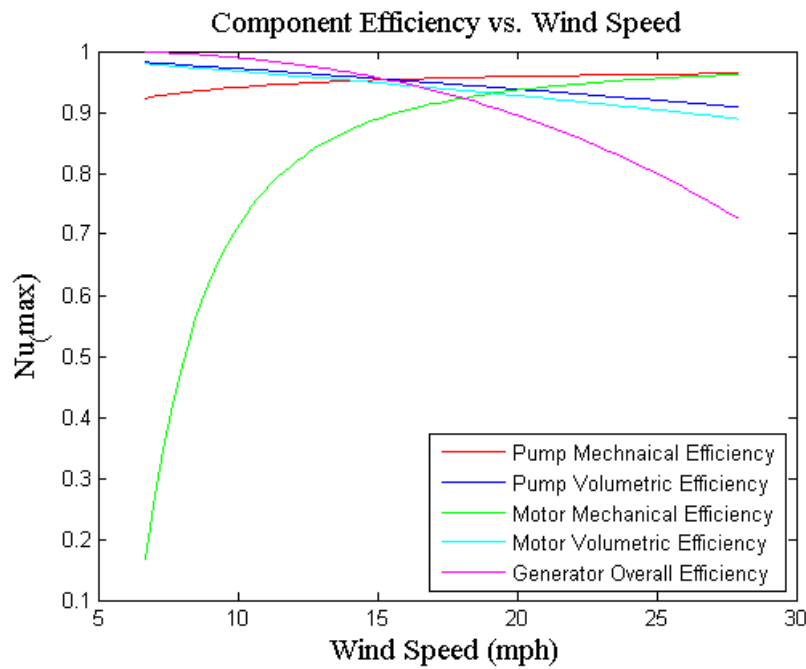


Figure 10: Powertrain Component Efficiency vs. Wind Speed

Figure 10 shows how the efficiency of each individual component's efficiency changes with wind speed. The major cause of a low efficiency at low wind speeds is the hydraulic motor mechanical efficiency. This motor loses efficiency because the displacement is quite low and the pressure is also low. Both of these factors greatly drive up the friction associated with the hydraulic motor. At high wind speeds, the current produced in the generator is maximized so the efficiency drops mainly due to i^2R losses.

3 Design

In this section, the design of the turbine will be described. Now that the theory behind component selection for the wind turbine drive train is understood, we can talk about the actual decisions that were made.

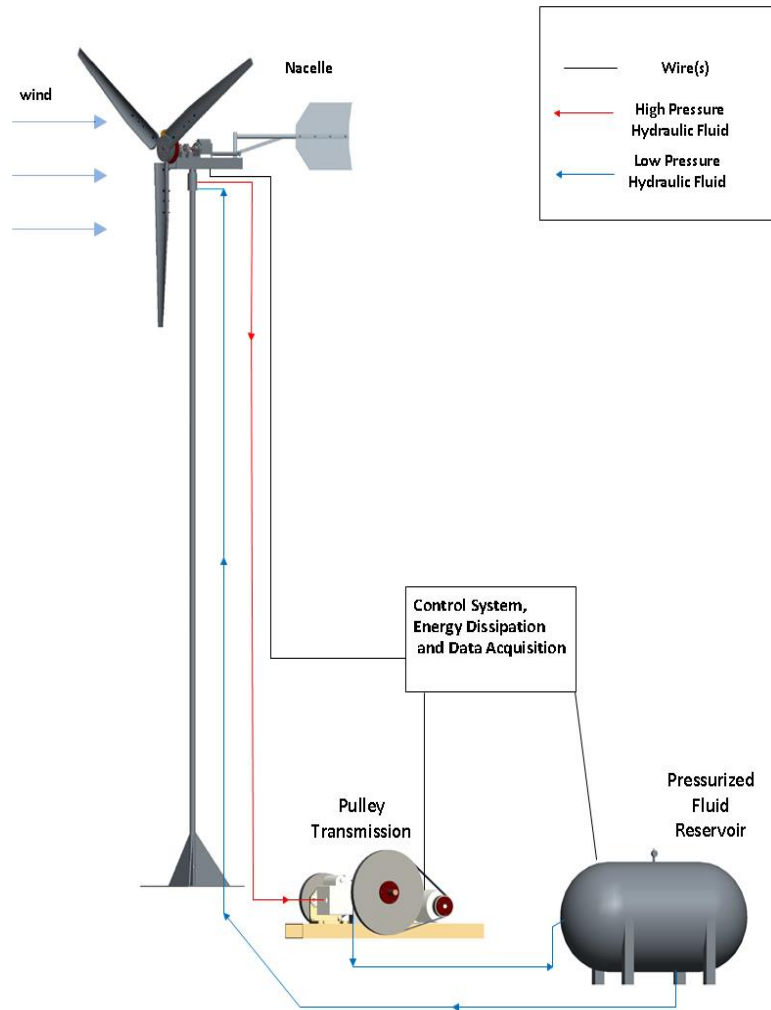


Figure 11: Overall Turbine Design

Through the rest of this document, systems will be discussed that were designed and built by various people. In order to avoid explicitly calling out credit for each design decision, the contributions of each member of the team are summarized in Table 2.

Table 2: Design Responsibilities

Team Member:	Contribution:	Affected Sections
Bryan Horvat	overall system simulation in matlab, some nacelle design and CAD modeling, complete fluid power design, early electrical design, involved in the machining of nearly all of the components in the turbine, completed welding on tower and adapters	2.1, 2.2.1, 2.3, 3.1, 3.2.1, 3.2.2, 4.1
Luis Cáceres	transmission modeling and design, nacelle design and modeling, assisted in assembly of turbine, spearheaded some sourcing and an outside company machining	3.1, 3.1.1
Thanh Phuc Huynh	intermediate electrical design, early prototype ordering and testing	3.3, 3.3.1
Matthew Kruse	general CAD modeling, final electrical design, machining	3.1, 3.3, 3.3.1, 3.3.2, 3.3.3
Mark Miller	machining of nacelle, turbine adapter pieces and other components	3.1
Jason Van Donsel	completed some part drawings, machined various components, assisted in testing of turbine	3.1
Yicong Lai	completed much of the assembly of the turbine	3.1
Nicholas Samoska	electrical design and assembly	3.3
Thai Pham	intermediate electrical design	3.1

3.1 Mechanical Design

The turbine can be described as having two major mechanical systems: the nacelle and the pulley transmission.

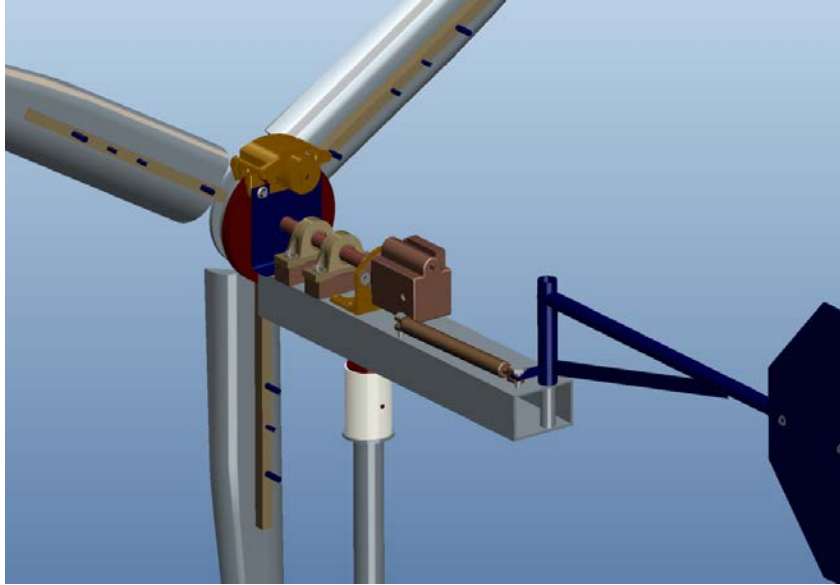


Figure 12: Nacelle CAD Rendering

As shown in Figure 12, the base component for wind turbine nacelle was 4"x6" rectangular tubing with 3/16" wall thickness. The rectangular tubing was chosen as a base for its torsional rigidity, ease of machining and flat surfaces that allow components to be mounted. The rectangular tubing material is 6061-T6 aluminum. The blades are attached to a rotor and this mounts directly to the drives shaft using two shaft locking collars. The drive shaft passes through two pillow block bearings mounted to the rectangular tubing and the shaft torque is passed to the pump through a spider coupler. A brake system originally designed for a Ford Taurus is also included on the turbine. The brake disk is mounted directly to the rotor of the turbine and a separate bracket supports the caliper. A single 1 inch diameter hole was drilled vertically through the rectangular tubing near the rear of the nacelle. A section aluminum 6061-T6 aluminum was press fit into the hole formed in the tubing. The vane was mounted by placing it over the section of aluminum tubing press fit into the nacelle. A hydraulic cylinder with spring return was mounted to the vane and rectangular tubing. This cylinder is used for the region 3 control system. The nacelle was attached to the tower using a two passage hydraulic rotary union. A custom welded tube adapter was placed on top of the tower so that the rotary union could be placed on top of the tower. The rotary union also serves the purpose of preventing the hydraulic lines from becoming tangled as the nacelle rotates on top of the tower. The tower and blades were reused from a past Innovative Engineers turbine. As stated in Table 2, much of the machining for the Nacelle was completed by Bryan Horvat, Mark Miller and Matthew Kruse.

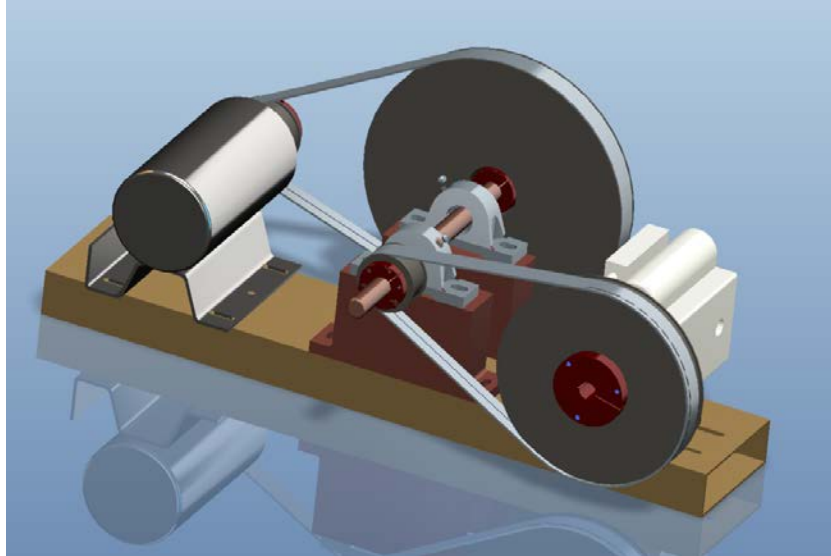


Figure 13: Belt Transmission CAD Rendering

The pulley transmission used a 2" x 6" aluminum 6060-T6 rectangular tubing base. The DC generator and hydraulic motor were both mounted directly to the structure using bolts with lock nuts. Slots were cut for the hydraulic motor so that the belts could be properly tightened during assembly. The generator hole mounts already included slots. Pillow block bearings were placed on top of large spacers so that they could be placed at the proper height and a keyed shaft was run through. A timing belt was so that the energy transfer could be at a higher efficiency.

3.1.1 Rotor Drive Shaft Design for Infinite Fatigue Life

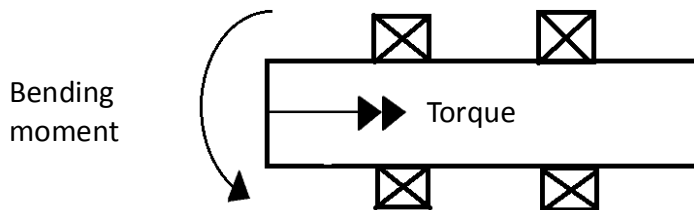


Figure 14: Rotor Drive Shaft Loading Diagram

In order to verify that the drive shaft would function as required indefinitely, the shaft was analyzed to determine its mode of mechanical failure. Fatigue was the obvious choice for the failure mode so it was analyzed as such. The material used for the analysis was Steel 1117. The bending moment due to the weight of the rotor and blades is 108 Nm. The range of torques are expected be between 11.13 and 55.64 Nm. For 99% reliability, a safety factor of 2 and infinite life, a minimum shaft diameter of 0.94 inches is required. [Source]

3.2 Fluid Power Design

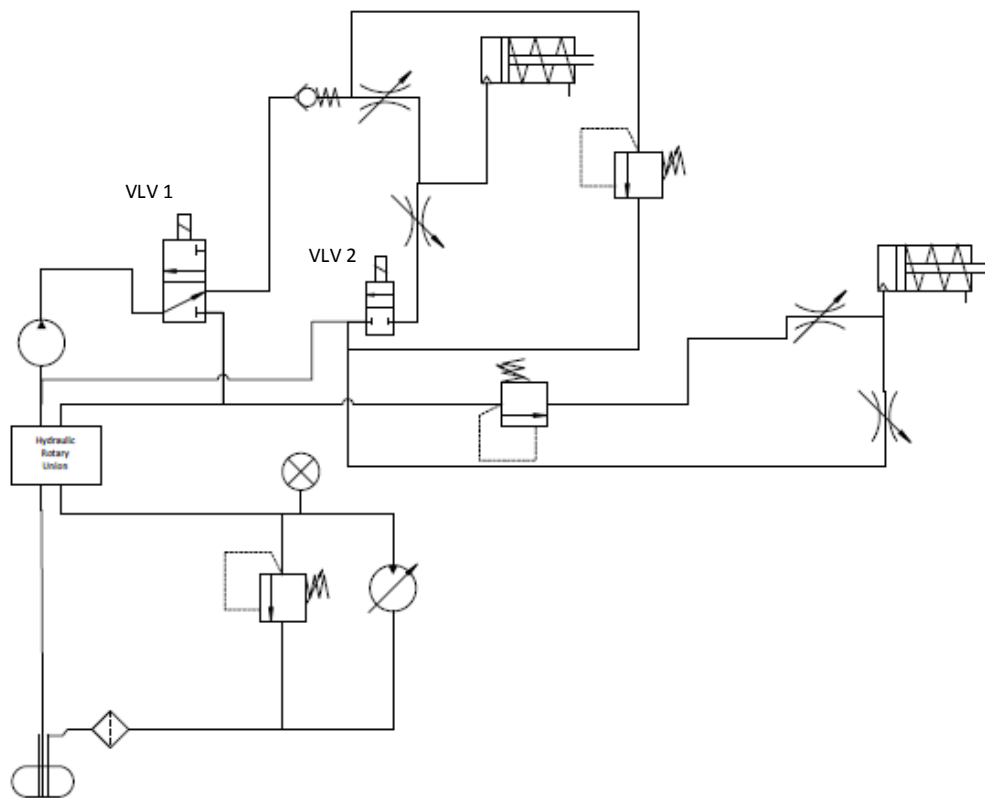


Figure 15: Fluid Power Schematic

The schematic for all the fluid power systems is represented in Figure 15. Most of the complexity of the schematic exists because brake system and region 3 passive control systems are added. Starting in the upper left hand part of the schematic, we have the pump represented. VLV 1 is present at the outlet of the pump to either activate the brake system or run the turbine as normal. When a voltage is not applied to VLV 1, the fluid leaving the pump is directed into the brake system. The resulting pressure increase at the caliper stops the turbine and the check valve keeps the pressure applied. A relief valve venting to low pressure of the pump is included to keep the pressure at the caliper from rising to dangerous levels. While 12V DC is applied, the solenoid valve allows flow down the second passage to drive the hydraulic motor as normal. The electronics are set up this way so that if something were to malfunction on the wind turbine and voltage was lost to the solenoid valve, the system could respond appropriately. When the second solenoid valve, VLV 2, is actuated the brake caliper is released and the turbine blades are allowed to spin as normal. The two needle valves are included to damp both the actuation and deactivation of the brake caliper.

The second system within the nacelle is the region 3 passive yaw control. This system activates when the pressure upstream of the pump rises to a level corresponding to region 3 of the wind turbine and the relief valve cracks. Some of the flow leaving the system goes into the hydraulic actuator and the rest flows down to tank. The two needle valves settings are adjusted so that the fluid is allowed to both extend and retract the actuator at an acceptable rate. As the actuator extends and pushes the vane out in to the wind stream, the nacelle is forced to yaw relative to the wind. As this yawing motion happens, the blades generate less power, the pressure drops in the hydraulic lines and the relief valve closes. The fluid is allowed to flow to tank and the cylinder retracts. The nacelle then turns back into the wind, the pressure increases in the lines and the process repeats. Using this passive back and forth tracking of the set point, the system is maintained at the proper power level under region 3 conditions.

After passing through the rotary union, the pressure is read using a pressure transducer. The flow passes through a hydraulic motor and filter before it returns to the pressurized fluid reservoir. A relief valve is placed in parallel with the hydraulic motor for an extra mechanical safety. The fluid reservoir is pressurized because of the large pressure drop expected as the fluid flows up the tower. If the fluid pressure was allowed to drop below the vapor pressure, cavitation will occur. Cavitation can damage hydraulic components so must be avoided.

3.2.1 Pump and Motor Selection

After the efficiency vs. wind speed of was produced for each simulated system, the turbine systems needed to be compared to one another. To do this, a single efficiency index needed to be calculated for each efficiency distribution. This parameter must describe the degree to which the turbine generated the most power over all wind speeds with the probability distribution of the wind taken into account. It would not be satisfactory simply to take the average of the efficiency because this says nothing about how much power the given system will produce under natural wind. The efficiency Matlab script successfully indicates both the efficiency and the power at all wind speeds so only the probability distribution of the wind is needed. Figure 16 is useful for describing the effect of how the power changes with wind speed. This Figure shows that at different power levels, the efficiency of the system matters much more than at high power levels. This effect should bias the pump and motor selection toward systems efficient at high power levels.

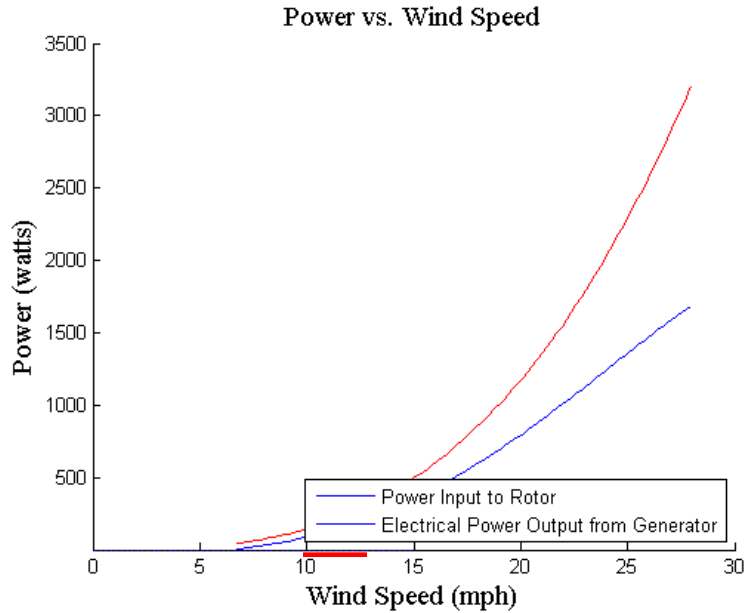


Figure 16: Power vs. Wind Speed

Studies performed at the University of Minnesota Morris found that the wind speed probability distribution can be estimated by a Weibull distribution with $k = 2.33$ and $c = 8.28$. (Thul, 2011, p. 29) This agrees with the Wind Energy Handbook which shows that a k value of 2.0 is quite typical for most locations. (Burton, Jenkins, Sharpe, & Bossanyi, 2011) The wind probability distribution determined at Morris, MN was used to determine the efficiency index here. Figure 18 shows a plot of this Weibull distribution vs. Wind speed.

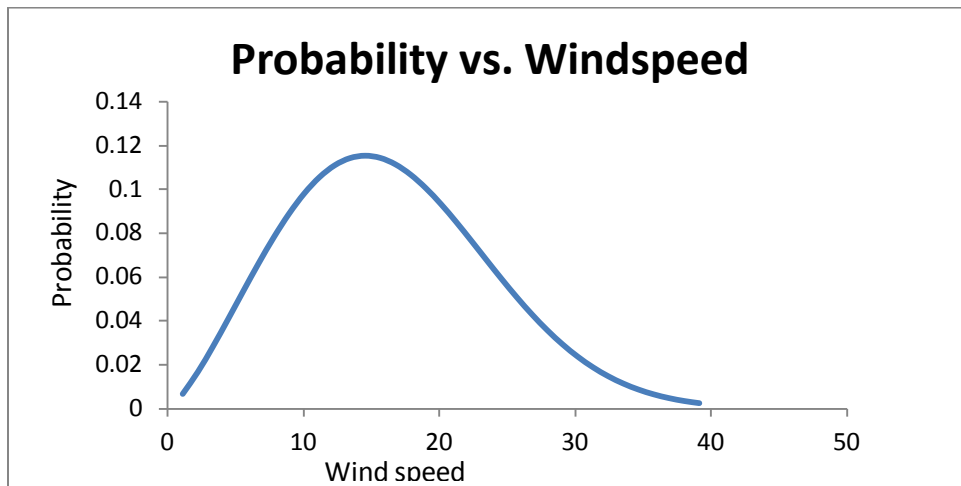


Figure 17: Probabilistic Distribution of Wind Speeds

With this information, the Efficiency Index can now be defined.

$$\text{Efficiency Index} = \frac{\sum_{\text{cut in wind speed}}^{\text{wind speed at start of region 3}} \eta_{\text{total}}(\text{wind}) P_{\text{rotor}}(\text{wind}) \text{Pr}(\text{wind})}{\text{number of wind speeds used}} \quad \text{Eq. 14}$$

$\eta_{\text{total}}(\text{wind})$ = Efficiency of the Turbine at a given wind speed

$P_{\text{rotor}}(\text{wind})$ = Power Generated in the rotor at a given wind speed

$\text{Pr}(\text{wind})$ = Probability of experiencing wind at given wind speed

The Efficiency Index can be conceptually understood to be the average probabilistic power produced by the turbine at any given time. This index is most useful for comparing wind turbine systems operating under the same conditions and use for any other purpose should be completed with care.

The system that was eventually chosen had the smallest volumetric displacement pump and motor. This is because it allowed the pressure to increase most rapidly as the wind speed increased the hydraulic motor mechanical efficiency (Figure 10) and moving the maximum efficiency curve to the left (Figure 9), resulting in the highest Efficiency Index.

Based on sizing and efficiency reasoning as described above, the VPPL-008PCX-R00B/20N pump manufactured by Duplomatic Oleodinamic was chosen. This pump was selected to be used as both the pump and motor for the hydrostatic transmission because it is was difficult to find a variable displacement axial piston pump or motor with a lower displacement. See Table 3 to see some of the important parameters of this pump.

Table 3: VPPL-008PCX-R00B/20N Pump Specifications

Pump Specification:	Value:
Maximum Displacement (cm ³ /rev)	8
Flow Rate at 1500 RPM (liter/min)	12
Operating Pressures (bar)	210
Rotational Speed (rpm)	Min 500 – max 2000
Rotational Direction	Clockwise (seen from shaft side)
Type of Mounting	SAE flange J744 – 2 holes
Oil Volume in the pump body (dm ³)	0.2
Mass (kg)	8

3.3 Electrical Design

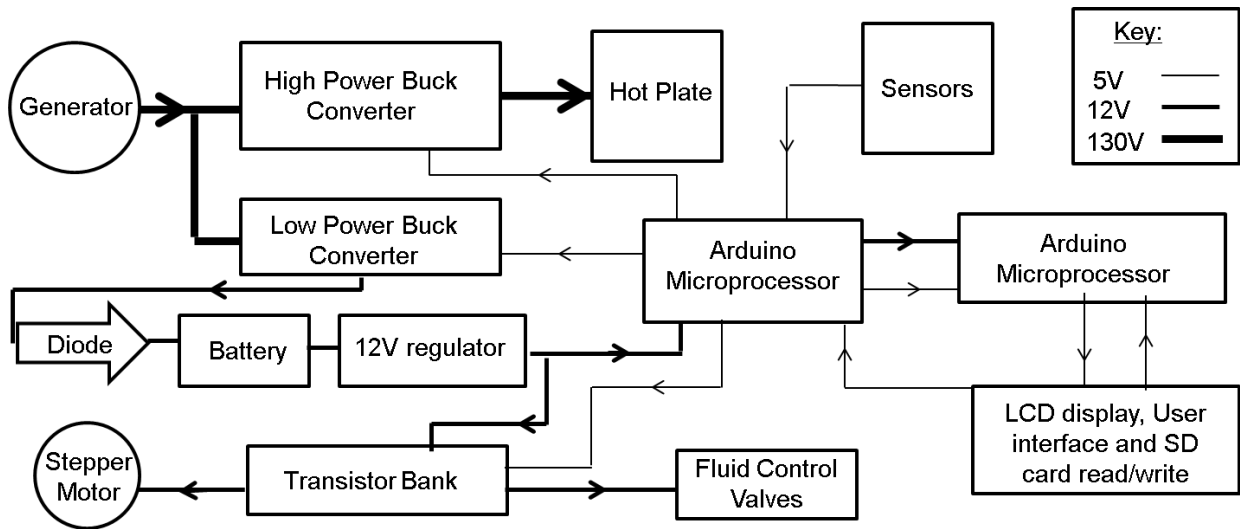


Figure 18: Basic Electrical System Schematic

Figure 18 shows a simplified operating schematic of the electrical control system. The needs met by this system are controlling the current in the motor, dissipating the power from the generator, reading sensors, changing the displacement of the hydraulic motor, changing the state of hydraulic valves, running the human interface and storing data and the performance of the turbine in an SD card. The high voltage electricity from the generator passes into both the high and low power buck converters. The low power buck converter uses a small fraction of this energy to power the rest of the systems in the controller. The rest of the energy goes through the high power buck converter and is dissipated on the hot plate. This simulates dumping energy into the grid from a wind turbine.

Starting at the output of the low power buck converter, the power next goes through a diode, and charges a battery. This diode prevents the energy within the battery from being dissipated when the wind is not blowing and the generator is not generating a voltage greater than the battery. The power leaving the battery passes through a 12V DC regulator to assure that the power is clean and consistent. The 12V used to power the Arduinos and transistor bank to be used by various electrical components. The primary Arduino (located near the center in Figure 18) is used to complete most of the control system computation necessary for the system to operate properly. It controls the buck converters, the transistor bank (and therefore the stepper motor and valves) and reads the states of all the sensors. The secondary Arduino completes all the computation necessary for interfacing with the user including reading the state of several potentiometers, and switches and displaying information on an LCD display.

The Arduino also reads all relevant variables from the Primary Arduino and writes the values to an SD card so that the data can be analyzed later.

3.3.1 Buck Converter Selection

Both buck converters were an important part of the design because they must be designed to handle the most voltage and current in the entire electrical system. In particular, the high power buck converter was one of the most expensive and important electrical components in the design.

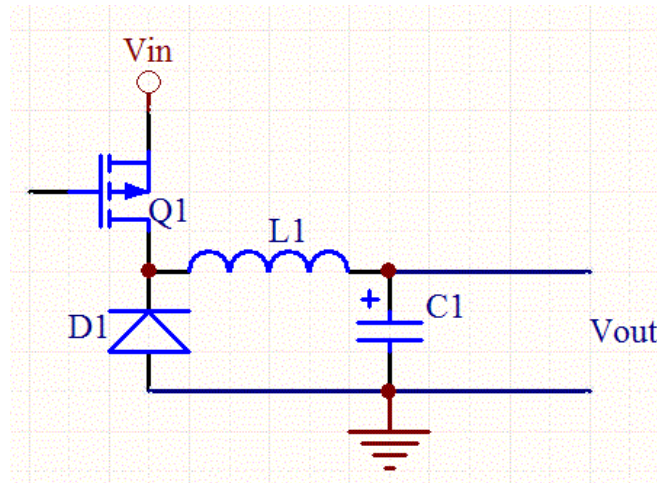


Figure 19: Buck Converter

A schematic for a buck converter is shown in Figure 19. The high power buck converter was designed to be capable of taking in up to 130 Volts at 18 amps and stepping down to any voltage and corresponding current. The transistor was used was an IGBT capable of handling 600 collector to emitter voltage and a current of up to 75A (part number: IXGH40N60C2). A $180\mu\text{H}$ inductor rated for over 20 amps and a $2200\mu\text{H}$ Capacitor. Together, the inductor and capacitor form a nearly energy conserving low pass filter with a cut-off frequency of 277.05 Hz. The Arduino clock frequency is 16MHz. In order to get a byte range of data, you divide this number by 256 to get a max switching frequency of 62.5 kHz. The Arduino was set to 62.5 kHz so this frequency was more than filtered out by the low pass filter. The high frequency also made sure that the change in current through the inductor and transistor was small.

Several lessons were learned during the process of designing this component. One of the lessons learned was that a resistor cannot be put between the controlling Arduino pin and the gate of the MOSFET controlling the DC-DC converter voltage because this increases the time it takes for the voltage to change on the gate with respect to ground. This is extra important at high frequencies.

3.3.2 Generator Selection

A brushed DC generator was chosen to be used because it allowed for a much similar control strategy. Through contacts at the University of Minnesota, a 2HP brushed DC motor was donated to the project. This motor was ideally sized because the blades were designed to be used on a 1 kW wind turbine which is roughly what was found.

3.3.3 Energy Dissipation

In order to dissipate the energy from the turbine during testing, two electrical burners were used. These were chosen for their high power rating of 1000 watts relative to their price. Each burner had a constant resistance of 15 ohms when used as a dissipation device. When these two burners were put in parallel, their equivalent resistance dropped to 7.5 ohms. This was well sized for the generator because it would allow the generator to put out exactly 14.9 amps at maximum. This is a safe current to sustain in the generator. If desired in the future, the system could be redesigned to include a plate of slightly lower resistance plate so that more current can be drawn from the generator.

4 Results and Conclusions

4.1 Early Results

After constructing the turbine, the system was tested out in the field. It was discovered early on that the blades that were used for the testing do not have the performance needed to run the turbine under a wide range of power levels. The blades were designed and built by another design team to be low cost and easily attainable in lower income countries such as Nicaragua. New blades are in the process of being built but were not completed in time to produce data showing the full performance of the system using wind power. The data collected for the rest of the analysis in this section was collected by turning the turbine blades by hand. Figure 20 shows some typical data collected in this way.

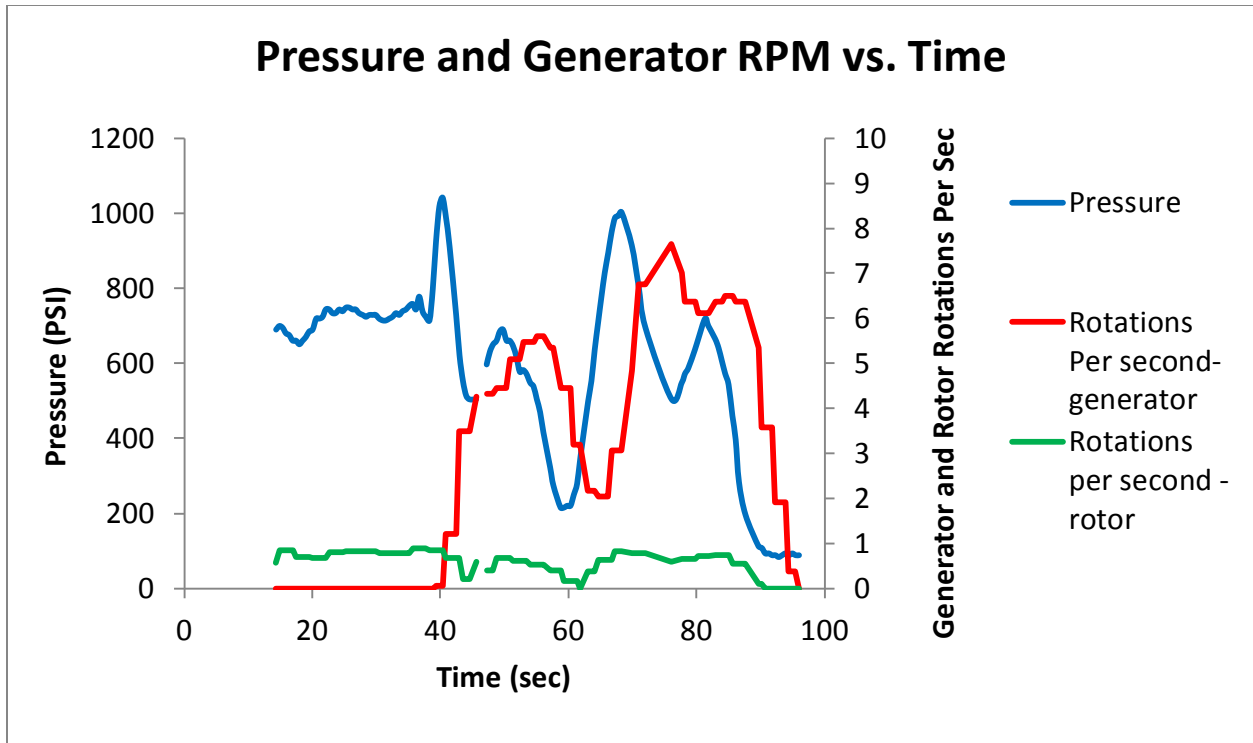


Figure 20: Typical Wind Turbine Data

As shown in Figure 20, the turbine generator started at rest. The wind turbine rotor is spinning at around 1 rotation per second consistently and the pressure remains constant at 750 psi. At around 40 seconds, the pressure suddenly spikes and the generator speed increases. For the rest of the time the system is operating completely, the rotational speed of the generator resembles a phase shifted wave form of a similar shape to the pressure. This is consistent with the generator speed integrating the pressure above the equivalent friction/loss pressure of the system. If a constant pressure drop is assumed across the system in this way associated with all the friction factors not originally modeled, the total system efficiency vs. wind speed can be estimated. Since the generator does not spin increase in speed until a pressure around 750 psi is experienced, this value was used for the constant pressure drop.

This pressure drop was added in the original Matlab used to model the entire turbine. The pressure drop was applied to the calculation for the torque in the hydraulic motor, so that an increased pressure is needed in order to run the hydraulic motor at the same speed. The rest of the script was solved like normal and a new efficiency value at each wind speed was calculated. Figure 21 shows this new estimated real system efficiency and the old theoretical efficiency plotted against wind speed. The new “adjusted real” system efficiency is much closer to the actual performance than the old theoretical model. The old model did not account for all the coulomb friction that the system will be experiencing in the transmission and generator. The generator also has core losses, load losses and windage that are not accounted for in the

previous model. All of these losses should be constant and independent of load since the speed of the generator is constant. Since the ideal model does not account for this fixed pressure drop through all power levels in the turbine, this real system efficiency should be much closer to the actual performance.

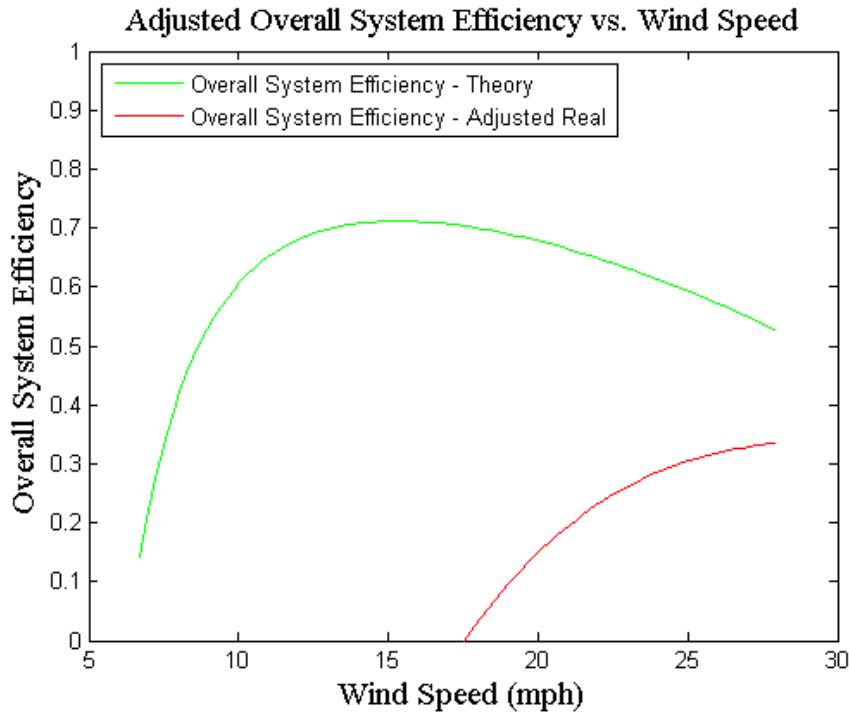


Figure 21: Theoretical and Projected Wind Turbine Efficiency

As shown in Figure 21, the efficiency is greater at high wind speeds which are desirable in an actual wind turbine where the wind speeds are expected to be relatively high. More energy is available to be captured at high wind speeds. Even with this fact, the efficiency is much lower than is desirable. The model shows that a cut-in wind speed of just over 17 MPH is expected. Future efforts to isolate the specific sources of the relatively large constant pressure drop would be well spent. Also, the lower efficiency has implications for the sizing of components and the mechanical design of the turbine since a greater wind speed would be needed in order to output the rated power of the generator.

4.2 Future Tests

The turbine has several tests that need to be completed before the design can be fully validated and the potential of hydrostatic wind turbines can be fully demonstrated. The tests that need to be completed include:

1. Turbine efficiency at its full Region 2 operating range
2. Field demonstration of the Region 3 passive control system
3. Long term reliability demonstration

Turbine efficiency at its full Region 2 operating range

For this test to be completed, the turbine must be allowed to run under a complete spectrum of wind between its cut in wind speed and the start of region 3. Since the turbine is designed to operate independently for an extended period of time, this can be accomplished by allowing the system to run under natural wind for an extended period and periodically recovering the data off the SD card.

Long term reliability demonstration

Tagging along with the turbine efficiency test, the reliability test should use parameters including the total energy generated by the turbine and the nature of the peak loading of the turbine to model the long term reliability of the turbine. Reliability will naturally have to include information about the periods of time the turbine does not operate as desired when it is due to the hardware or specific technologies being tested.

4.3 Related Technologies

Testing and operation of the turbine could be enhanced by several technologies.

Adding an Arduino Wi-fi shield to the control system

Wi-Fi signal is faint but present out at the wind turbine test site so interfacing with the control system via the internet is possible if a Wi-fi shield is added to the control system. This would allow the data to read from a distance using the internet and may reduce the need to head out to the site and face the weather when collecting data. It may even be possible to program the Arduino from a distance using this method which would further reduce the need to be on site.

With current technology, Hydrostatic Wind Turbines already have much promise to be much more cost effective and productive than current turbines. Even so, new technologies are being developed at the University of Minnesota that would greatly compliment hydrostatic wind turbine design.

Adjustable 6 Bar Linkage Pump

At the University of Minnesota, a new pump designed to be efficient at a wide range of displacements has been developed. This pump utilizes a 6 bar linkage that changes the displacement of a piston. An initial prototype utilizing 1 piston has been built proving the principle and the efficiency at a relatively low power level. Efficiency values have not been

published for the pump but early tests have indicated that the pump has an efficiency much greater than conventional hydraulic pumps. This pump would obviously greatly help hydrostatic wind turbines by allowing them to operate at a much higher efficiency even at lower wind speeds.

Advanced Fluid Power Energy Storage

Also being developed at the University of Minnesota is a form of energy storage utilizing compressed air. The technology has been developed with hydrostatic wind turbines in mind. If energy storage could be applied to wind turbines, this would allow the operators to more accurately estimate the power that the turbine will generate over time and will help the turbines to provide the power when it is needed.

4.4 Conclusion

While direct efficiency results were not collected from this turbine, much was learned from the design process. If a wind turbine is to be developed, even a small scale one, it is important to include a reliable slip ring in the design. If possible, blade efficiency and TSR should be experimentally determined if data is not provided by a manufacturer. Systems to catch and sequester the oil leaked from the pump and motor at the fittings were inadequate. This should be considered for all hydrostatic wind turbines in the future because in all cases the leakage can be minimized but not eliminated. Extra care should be taken for off-shore turbines where environmental hazards can cause even more dire consequences. Also, testing conditions out on site cannot be overlooked. There were times during testing that the high winds and cold hurt team morale during testing and made the testing more difficult for comfort reasons. Just as important as the results are to collect themselves, conditions that the researchers will be exposed to should be considered. It should not always be expected that student researchers will be prepared for the extreme Minnesota weather unless warm clothing and other equipment is provided to them. In order to mitigate these issues, a semi-permanent heated structure to take researchers out of the weather would be a worthy investment.

All these issues together define the major design challenges associated with the project. While many things went right, there are several areas for wind turbine design improvement and quite a few more tests to be done. I hope that this project is continued for many years and the turbine is tested in all the ways that was originally intended, because Hydrostatic Wind Turbines show great potential to be reliable and efficient sources of power under changing wind loads. Hydrostatic Wind Turbine technology deserves the opportunity to be fairly tested and proven in the chance that it has a competitive advantage over conventional methods.

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