Worcester Polytechnic Institute

ECE 3501 Wind Turbine Generator Design

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Introduction

The increase in the demand for oil and other fossil fuels over the past few years has resulted in the depletion of our natural resources. Our non-renewable energy sources are being consumed far faster than they are being produced due to the fact that it takes hundreds of millions of years to create fossil fuels. Our need for fossil fuels to power our lives has driven up the cost per barrel of crude oil significantly over the past ten years. “Green” technology such as windmills and photovoltaic panels actually produce power, while green roofs and more efficient equipment will reduce energy usage overall. Many offices across the country are finding ways to “Go Green” and reduce the amount of wasted energy and become more efficient and environmentally friendly buildings. The object of our project is a high school building that is planning on subsidizing their entire energy usage through the use of wind power. Our plan of attack will consist of conducting an analysis of the current wind conditions around the school, make determination on power requirements of the school, and to design a generator to produce this necessary power.

Literature Review

In order to extract power from the wind we will be exploring the possibility of several Wind turbine designs, that all work around the same principle of energy production. Rotors that capture the energy of the wind spin, which intern spin a shaft which is connected to an electrical generator, usually through some gearing arrangement, which intern creates electrical energy through induction. Based on the equation in figure 1 we can make these assumptions turns of power production and the velocity of the wind. As wind speed increases and increases, the faster the turbine blades will spin, resulting in an increase of energy. We can also choose a larger rotor size which will increase our power parabolicly; unfortunately this can also have its drawbacks due to the mass of the physical rotors the wind with have to push. Finally density of the air also retains this same property but the effects are not as drastic and power gain remains linear with changes of air density.

$$P = \frac{1}{2}\rho u^3 A$$

Figure 1 Power of Wind

Possible wind rotor Designs

There are two general types of wind turbine designs. They are determined by the orientation of the turbines blades, which are either vertical or horizontal. Each design type has there drawbacks and benefits. Vertical wind turbines are mostly visible overseas in Europe while the United States focus has remain on Horizontal axis turbines.

Vertical-axis wind turbines' main design attribute is that main rotor shaft is mounted vertically. This allows the Vertical-axis turbine's gearbox to be place close to the ground instead of suspended high in the air. The most obvious benefit of Vertical turbine is that they don't need to be oriented towards to wind because they can capture wind energy from all directions. Unfortunately the vertical designs have weakness due to pulsatory torque, which occurs during every rotation and the large flexing moments of the blades themselves. This pulsatory torque creates unwanted vibrations on the rotor of the turbine and this stress can result in damage to the turbine.

Horizontal-Axis turbines main attribute is that there rotating shaft runs parallel with the ground. The benefits of having a horizontal axis is that you have can control blade pitch giving the turbine blades the optimum angle in relation to the wind. They generally have very tall towers which allow them access to high wind speeds at the higher altitudes. This is possible because of an effect called wind shear, creating almost 20% increase in wind speed per 10 meters. Finally the faces of their blades are struck by the wind at a consistent angle regardless of the position in its rotation. This creates consistent wind loading through entire revolutions of the blade. This will also reduce vibration, creating much need stability which is needed in these tall towers.

Horizontal-axis turbines also have draws of their own, which is a result of their unique construction and size. First of all, the tall towers and blades, which can reach 90 meters long can be extremely difficult and costly to transport. They are difficult to install because of the large mass which is retain in the head or tower top of the turbine. The main drawback of these turbines is that they must be facing the wind to be efficient, meaning that they require yaw control for orientation. These controls add to the cost and complexity of the turbines construction.

Components of a Turbine

Around the world there are many different arrangement and setup on how the turbine should operate, but they are share several characteristics of construction. Most importantly, all turbines have some type of rotor that they use to capture the wind. The blades can range in size, number and arrangement depending on application. The orientation of these blades can also differ among design, usually depending on location. The design of these blades direct effect the future output maximum and efficiency of the turbine. All these designs in the end are governed by laws of aerodynamics and depend in what you are looking for in shaft speeds and torque possibilities, you will need to determine certain drag and lift characteristics of these blades.

The next component in line with the rotor is the gear box, or gear ratio. This gear box provides certain mechanical advantages which are desirable because of the general low velocity of the wind. In order to gain a suitable electrical energy output from our generator we will needs a relatively high sustained rotor speed. The gear ratio allows the low external rotor speed to be increased in sacrifice of available torque; there is also some efficiency loss within the gear ratio themselves, but they are generally rated above 95% efficiency.

The next element in line is the electrical generator itself. This generator is usually connected to a clutching or braking system that protects the generator. There are two possible generator designs for converting mechanical energy to electrical energy. They are the synchronous generator and the asynchronous or squirrel cage design.

The synchronous generator operates on the concept that as a magnet, or usually an electromagnet, rotates in the presence of a coil of wire; this changing magnetic field induces a current in the coil, resulting in a voltage in the coil. In our case, the electro-magnet is on the shaft of the rotor inside the generator. This magnet is encircled by coils of wire. As the rotor rotates the electromagnet creates a changing magnetic field in the presence of the coils, which are surrounding it. This induces a current in these coils which intern produces the electrical energy on the output of the generator. Synchronous generators are the more expensive of the two but provide the best power factor and the best efficiency.

The Asynchronous generator differs from the synchronous design because instead of using a permanent magnet or electromagnet in its core it uses a squirrel cage. This cage is made of bars arranged in a cylindrical pattern and shorted across each other at their ends. The stator remains similar to the synchronous motor; in that fact this it surrounds the squirrel cage with coils of wire called poles. The downside to these generators is that they must be started by the grid because they cannot produce the necessary magnetic forces within the squirrel cage at low or no wind speeds. As the current from the grid passes through the coils stator, a current is induced in the cage rotor itself; causing opposing magnetic fields in the cage, and as a result turning the rotor. Power generation occurs when the wind causes the rotational speed of the rotor to increase above this idle speed caused by the grid. This will surprisingly create large voltage increasing in the receiving stator. Since this machine must operate at relative constant wind speeds above a certain threshold, it installation locations can be very limited. Comparatively with the synchronous motor it is relatively less expensive to produce, but isn't as energy efficient.

Turbine Design

The first objective of the project was to determine wind speed based on our given wind distributions. Our data was given in the form of the chart shown below in Figure 2.

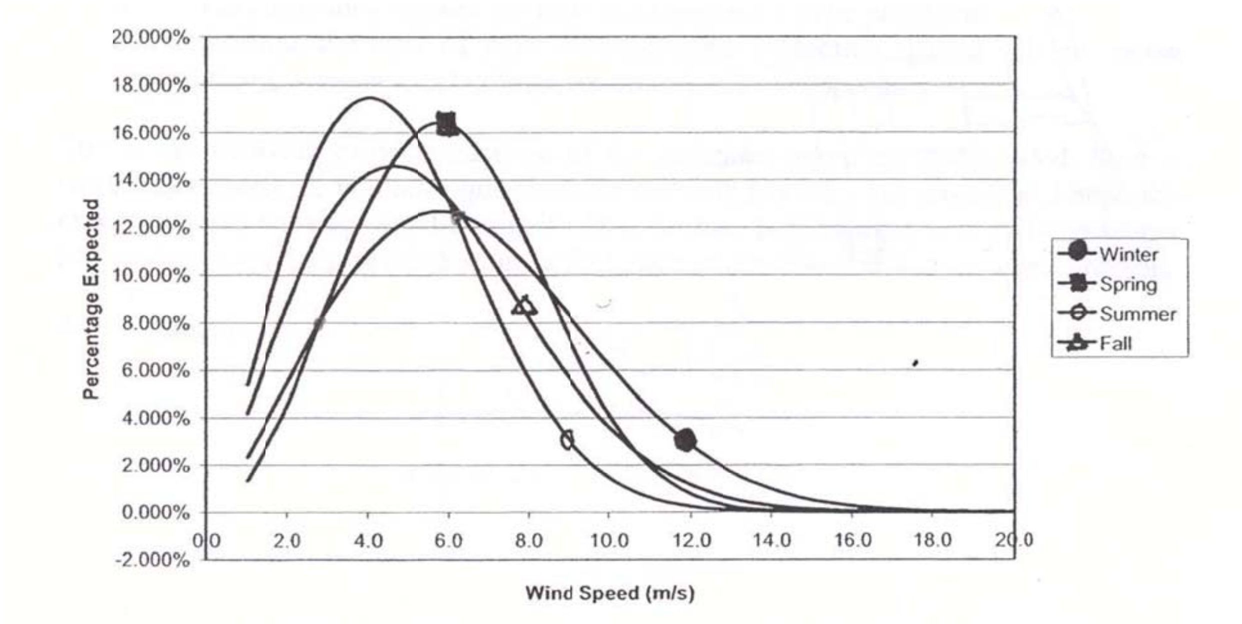
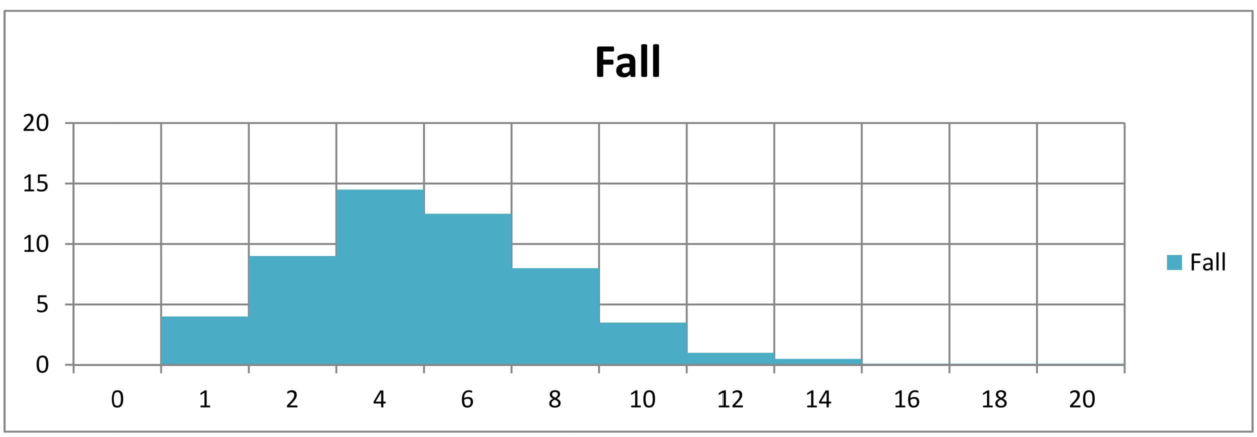
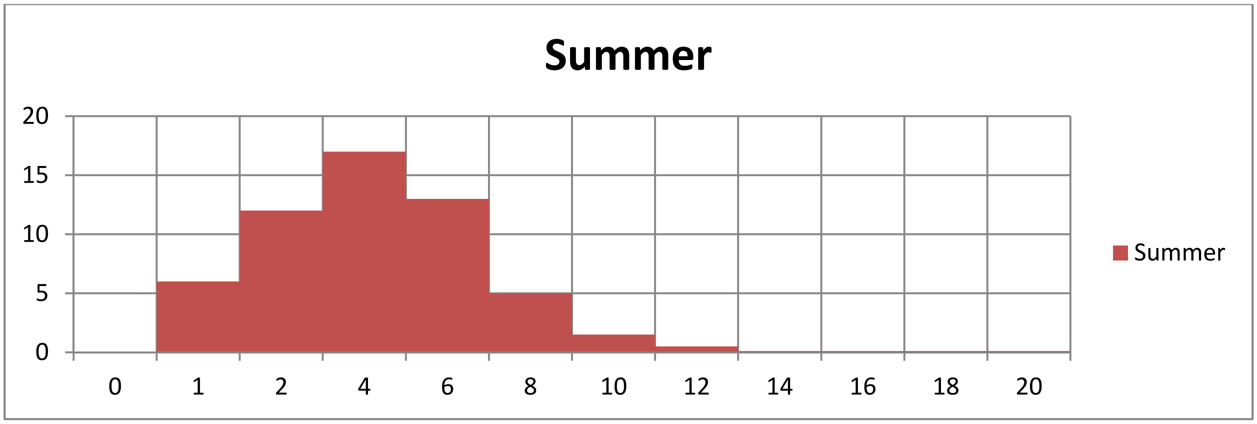
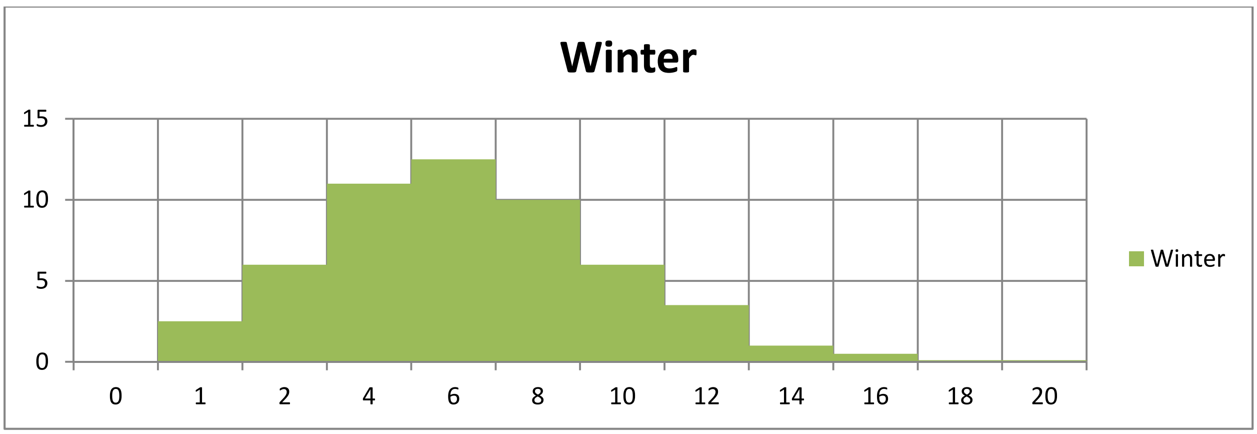


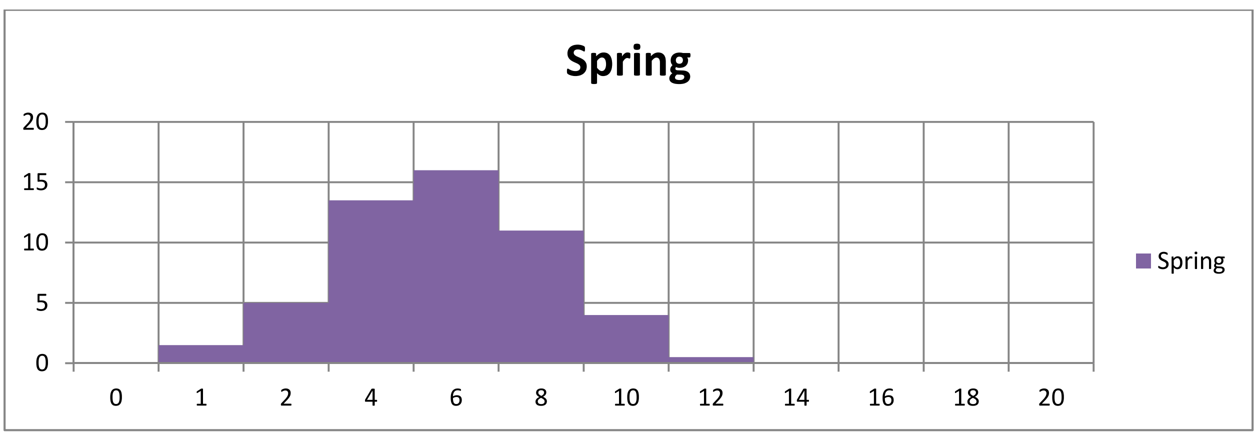
Figure 2 Wind Velocity Distribution

To better understand this arrangement I split this graph into four separate graphs, one for each season. Then I converted them to bar graph for every 2m/s wind speed change. These graphs are seen below.









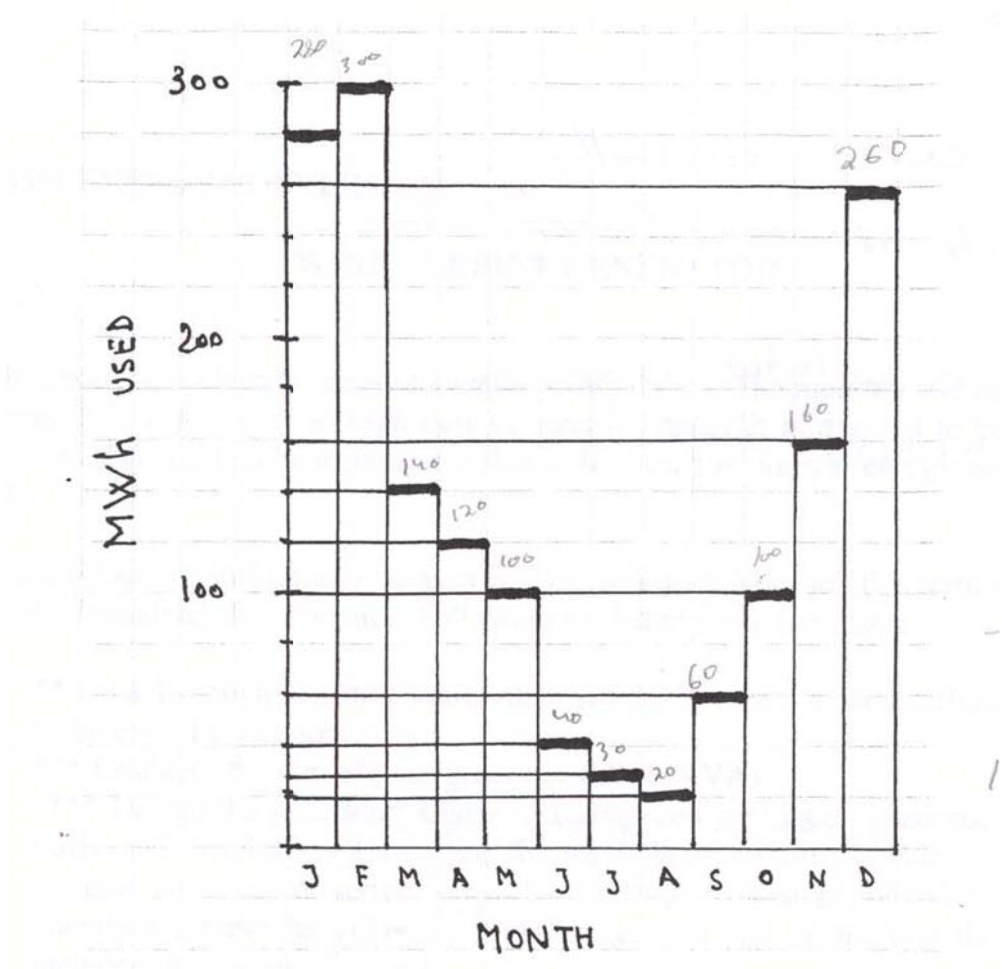
Each wind velocity was broken down according to percentage. Next we combined all of our speed intervals times the wind speed of that interval over the combined average speed percentage distribution. This gave us our average wind speed per season. Finally we found the average of our seasonal speeds by combining them and dividing by the number of seasons

$$\text{Average Seasonal Wind Speed} = \Sigma \frac{Interval\ of\ Speed\ x\ Wind\ Speed}{\Sigma\ Average\ of\ Speed\ Percentage}$$

$$Average\ Yearly\ Wind\ Speed = \frac{Average\ Fall + Summer + Winter + Spring\ Wind\ Speeds}{4}$$

$$My\ calculated\ wind\ speed\ was\ \mathbf{5.61}\ \boldsymbol{m/s}$$

Next we needed to analyze our power consumption bar graph given. The graph shown below show the power usage of the school over a year's period based on Megawatts Hours.



The first step was to find the average power per month used by the school. This was done by adding together all the power usages and dividing them by the time period 12 months. From this value we were able to calculate the instantaneous power usage for any given moment. This was done by dividing our Megawatt Hours per month by the amount of hour in one month.

$$Instanteous\ power = \frac{Average\ Megawatt\ Hours\ Per\ Month}{Hours\ in\ One\ Month} = \frac{137.14\ MWh}{30.5\ Days\ X\ 24\ Hours} = 183292\ Watts$$

Once we have the instantaneous power needed we can determine our rotor blade size. This is found by assuming the average wind density is $1.225\frac{kg}{m^3}$. We used the equation below to solve to our rotor size at 35% efficiency, which is conservative.

$$Blade\ Radius = \frac{\sqrt{2\ x\ Power\ Needed}}{\sqrt{Efficiency}\ x\ \sqrt{\rho\ x\ \pi\ x\ u^{3/2}}} = \frac{\sqrt{2\ x\ 183292}}{\sqrt{.35}\ x\ \sqrt{1.225\ x\ \pi\ x\ 5.6^{3/2}}} = 39.37m$$

Generator Design

General Power

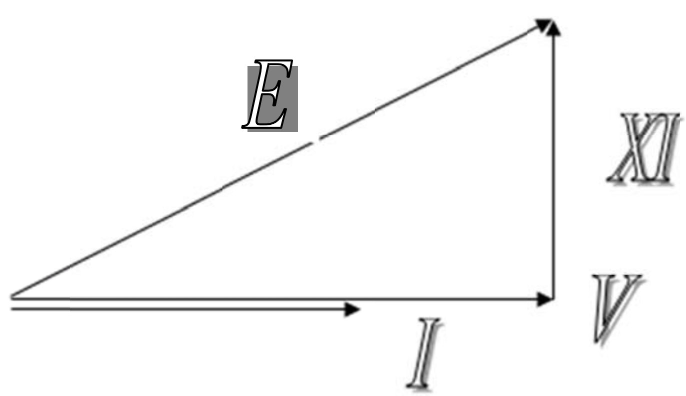
The first steps in our generator design were to make several determinations or assumptions. This began with the assumption of Power Factor Unity ($PF = 1.0$) and from my calculations about the power I need to product instantaneously is $183292W$. My expected Line to Line voltage is 550V which would make my Line to neutral max voltage =449V. Since $X_S I$ roughly equal to V line to line we make the assumption that they are equal. Finally we determined our E_{MAX} , which is quite easy because of our unity power factor.

$$S = 183292\ VA \qquad PF = 1.0$$

$$V_{LL} = 550V \rightarrow V_{LN\ Max} = 550\frac{\sqrt{2}}{\sqrt{3}} = \mathbf{449V}$$

$$X_S I \approx V_{LL} = 550V$$

$$E_{MAX} = \sqrt{{V_{MAX}}^2 + X_S I^2} = \sqrt{449^2 + 449^2} = \mathbf{635V}$$



Stator Design

We begin our stator design similarly by making several determinations. First of all, our assumed flux density in the gap is 1.0T. My design will be taking advantage of 12 Poles at a frequency of 60Hz.

$$Poles = 12 \rightarrow Number\ of\ Coils = 6$$

$$Frequency = 60Hz \rightarrow Speed = 720\frac{rev}{min} \rightarrow \omega = 75.4\frac{rad}{s}$$

$$E_{MAX} = NPl\omega R$$

Based on the equation above for E_{MAX}, we can make the following graph which we see dip as we change our values for our stator radius.

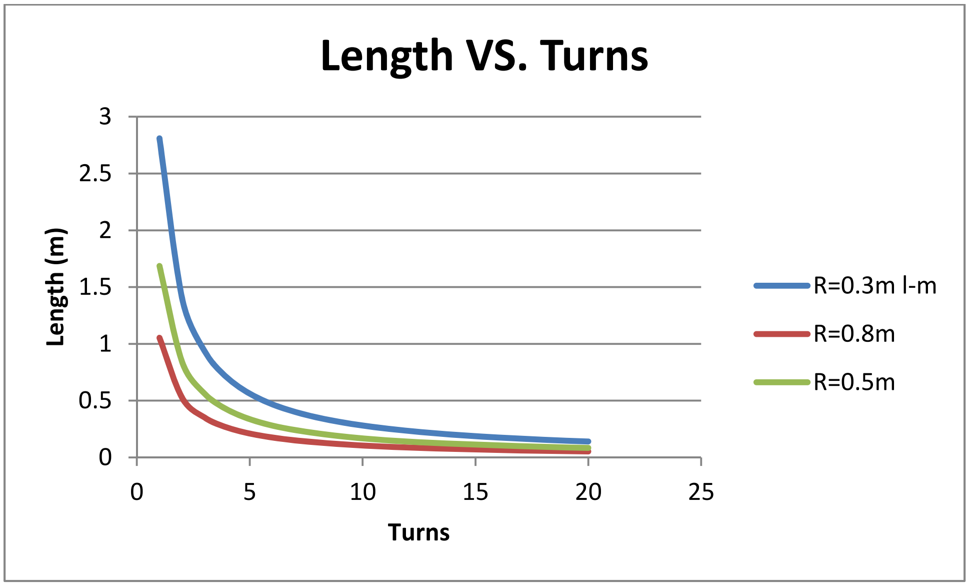


Figure 3 Length VS. Turns for Different Radi

Now we can make a determination of our current in our stator based on our line to line voltage and expected power.

$$I = \frac{S}{\sqrt{3}V} = \frac{183292VA}{\sqrt{3}(550V_{LL})} = \mathbf{192.4\ A}\ \textbf{Stator Current}$$

After we know the current through the stator we must arrange our conductors within the teeth. Based on the material of my stator and current in stator I chose a $j = 1.924$. This will give me a cross sectional area of $100mm^2$. Based on this dimension I decided to go with an arrangement of 3 by 9 of 25 Parallel conductors. If I have 25 conductors they will be 2mm by 2mm, but since are only 25 conductors I will have 2 holes to fill with insulation.

$$j = 1.924\ \frac{A}{mm^2} \rightarrow A_C = \frac{I}{j} = \frac{192.4}{1.924} = \mathbf{100mm^2\ Cross\ Sectional\ Area}$$

$$Each\ Conductor = 2mm\ X\ 2mm \rightarrow \frac{100\ Cross\ Section}{2X2mm\ for\ each\ Block} = \mathbf{25\ Conductor\ Sections}$$

Figure 4 Single Conductor with Insulation

Figure 5 Single Conductor without Insulation

I further continue choosing values such as gap size $11.95mm$, which allows me to determine my tooth pitch $\zeta = 26.18mm$. These numbers take into account the needed insulation that raps around each conductor, the bundle of conductors and the size of the conductors themselves. From this I can determine my complete conductor slots or all 72 teeth that are in my stator.

$$(3\ Teeth\ Wide\ x\ 2.5\ Teeth\ Thickness\ with\ Insulation) + (5.7mm\ Inner\ Tooth\ Insulation) + (1.0\ Extra\ Insulation) = \mathbf{14.2mm\ Wide\ Tooth}$$

$$(9\ Teeth\ High\ x\ 2.5\ Teeth\ Thickness\ with\ Insulation) + (5mm\ Inner\ Insulation) + (2mm\ Wedge) + (2.5\ Extra\ Insulation) = \mathbf{32mm\ High\ Tooth}$$

$$\zeta = Tooth\ Width + Gap\ Width = 14.2mm + 11.95mm = \mathbf{26.18mm}$$

$$Z = 3NP = \mathbf{72\ Teeth\ in\ Stator}$$

Finally we can now determine our Rotor Radius which is based on the above pitch we found. Since I decide that I am installing 2 turns per coil I can now determine the length of the rotor also, which will be the length of the stator as well. From this I found that my length is $1.405m$, which correlates with my graph from figure 3.

$$Internal\ Radius\ of\ Stator = \frac{Z\zeta}{2\pi} = \frac{72 * 26.18}{2\pi} = 30 = .30m$$

$$Turns\ Per\ Coil\ (N) = 2 \rightarrow Length\ of\ Rotor(l) = \frac{.843}{.30 * 2} = 1.405m$$

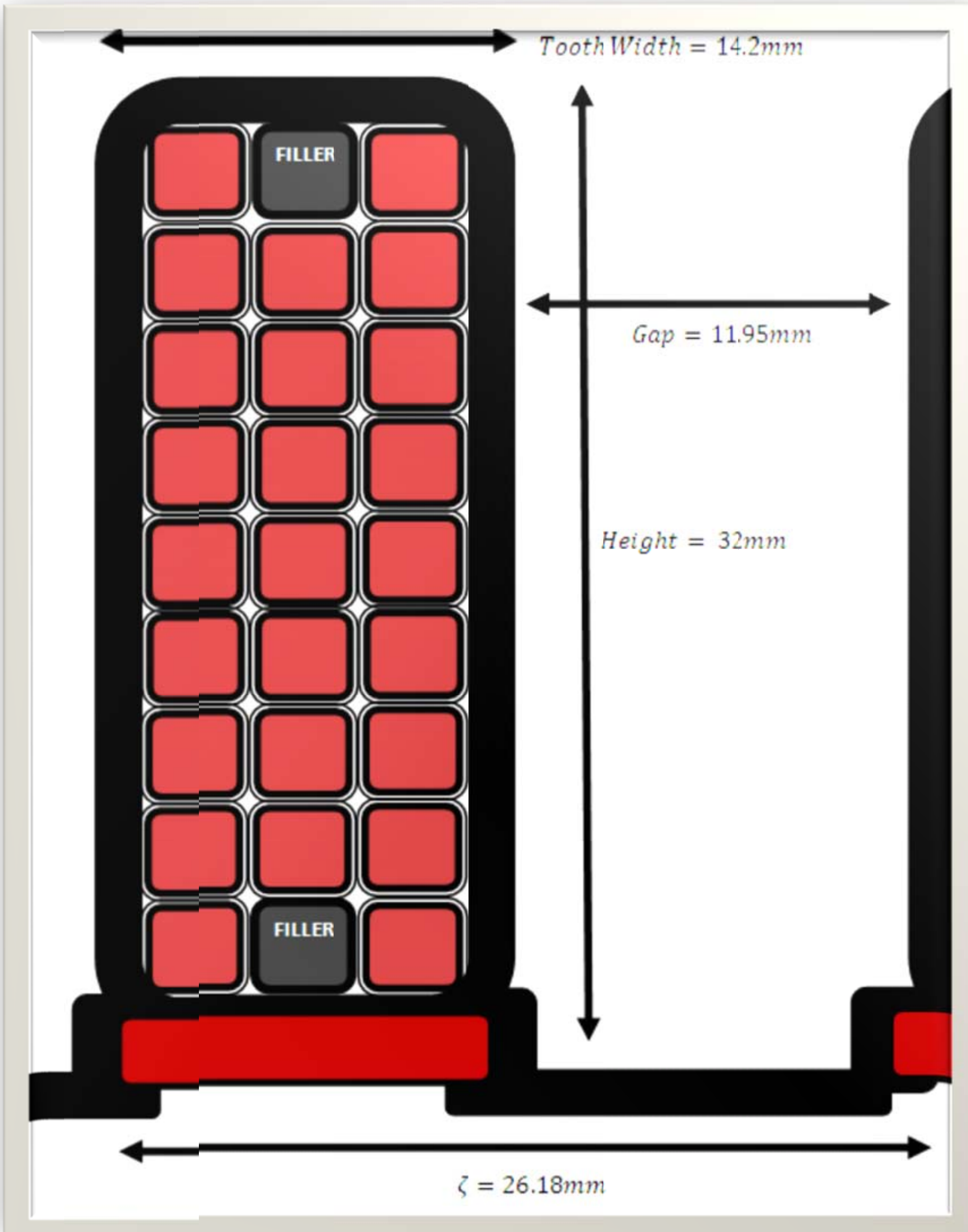


Figure 6 Conductor within Teeth Layout

Resistance

Now that we have our stator's dimensions down we can begin to look at the coils that rap around the teeth of the stator. Since we have 2 raps per phase we can determine that all three phases will cover 6 teeth. Now we can calculate the length of our complete winding which raps around all 6 teeth, and eventually determine the resistance of these coils. These calculations are primarily based up the length our stator which was calculated above to be $1.405m$, and the assume resistance of air at 75°C → $\rho = \ 0.0216\Omega\frac{mm^2}{m}$

$$Height\ of\ Winding = l + Bending = 1.405 + .02 + .02 = 1.445m$$

$$Width\ of\ Winding = (6\,Teeth\ x\ \zeta\ Pitch)Bending\ Factor = (6\,x.02618)x\ 1.2 = 0.1885m$$

$$l_{winding} = (length + width)x2x(N\ Turns)\frac{Poles}{2} = (1.445 + 0.1885)x2x2x6 = 39.204\text{m}$$

$$Resistance\ of\ Coil = \rho\frac{l_{winding}}{A} = (0.0216)\frac{39.204}{100} = 0.008468\Omega$$

Base on this resistance and the previously calculated stator current we can determine our power losses in the Windings.

$$\Delta P_W = 3RI^2 = 3\ x\ 0.008468\ x\ 192.4^2 = 940.4\ W\ Lost$$

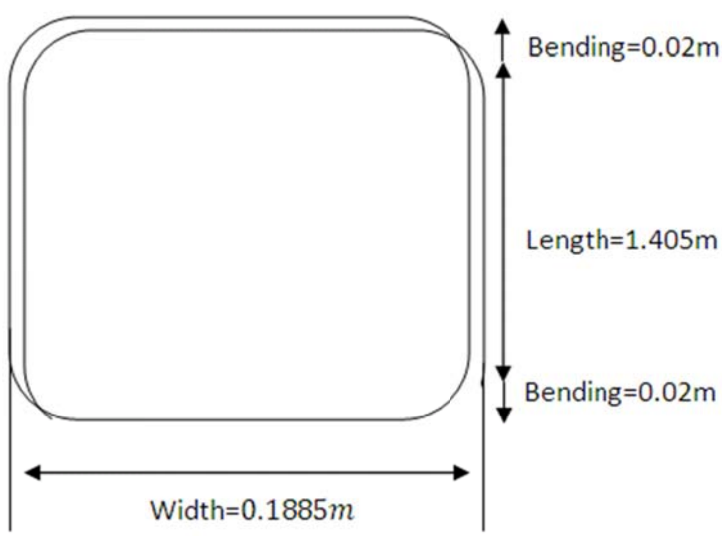


Figure 7 Coils Raps in Stator

Rotor Dimensions and Coil Inductance

Now that our stator design is complete we can begin to look at the design of the rotor. The design our rotor with follow the synchronous rotor designs, containing an electromagnet powered by an exciter current. The only two determinations about of rotor we have made so far are our Radius of the rotor 0.30m and our number of Poles 12. We will continue by designing the physical dimensions our rotor and determine its magnetic characteristics. The first we will begin by finding the area of the tooth that flux will be entering or exiting the stator from. Then we will determine our reluctance in air based on this area, and finally determine the inductance of our complete coils.

$$Degrees\ Between\ Poles = \frac{360}{12} = 30\ Degrees$$

$$Distancce\ between\ Center\ of\ Poles = \frac{30Degrees}{180}\ \ \pi R = \frac{30}{180}\pi(.30) = 0.157m$$

$$Area\ of\ Air\ Gap = Phases\ X\ \zeta\ X\ l = 3\ x\ .02618\ x\ 1.405 = .1103m^2$$

$$Gap\ Size\ =\ 0.000439m$$

$$Reluctance\ of\ Air = \frac{10^7}{4\pi}\frac{gap}{Area} = \frac{10^7}{4\pi}\frac{.00045}{.1103} = 3165.8\Omega$$

$$Inductance\ of\ Coil = \frac{N^2}{Reluctance\ of\ Air} = \frac{4}{3165.8} = 0.001263H$$

$$L_{Total} = \#of Coils\ X\ L_{coil} = 6(0.001263) = 0.007581H$$

$$X_S = \omega L = 377\ x\ .007581 = 2.858\Omega$$

$$X_S I = 2.858\ x\ 192.4 = 550V\ which\ is\ equal\ to\ my\ assumed\ 550V$$

$$Teeth\ Over\ Each\ Pole = 4 \rightarrow 48\ Teeth\ Covered \rightarrow 24\ Teeth\ in\ Gap$$

$$Head\ Size =\ \zeta\ X\ Teeth\ Over\ Head =\ 26.18mm\ x\ 4 = .10472\text{m}$$

$$Head\ Gap\ Size = \zeta\ X\ Teeth\ Not\ Over\ Head = 26.18mm\ x2 = 0.052m$$

$$Head\ Thickness\ =\ .0415m$$

$$Width\ of\ Neck\ of\ Pole\ on\ Rotor\ =\ 0.07m$$

$$Internal\ Gap\ Size = (Head\ size - Neck\ Size + Head\ Gap\ Size) =\ .10472 - .07 + 0.052 = .087m$$

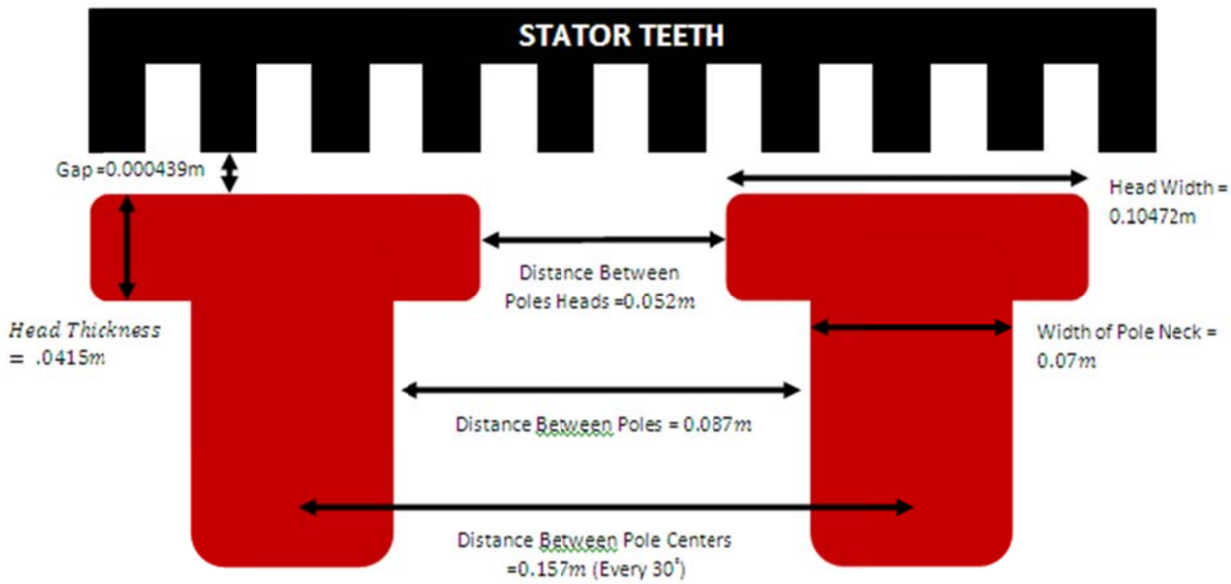


Figure 8 Dimensions of Rotor Poles

Field Excitation

The next part of the design is to determine the most appropriate field excitation Voltage and Current. The entire past of the flux which is created in the poles of the rotor follow through the N pole of the rotor, through the air gap, through the teeth of the stator, then through the yoke of the stator, back through the teeth of the stator, back across the air gap, then finally into a South pole of the rotor. This long and complex path makes it possible to the generator to produce current and as a result power. To calculate the necessary Ampere Turn for the field we need to determine the Flux density in every part of the flux path and the distance that flux needs to travel. These densities are based upon the material that makes up the rotor and stator. I chose a material called Vacoflux 50, which has a very high maximum flux density at 2.2T, and an exceptional Density verses Inductance curve. To begin I must solve to all the flux densities and distances as follows.

$$\textbf{Overarching Equation} \rightarrow \boldsymbol{2N_F I_F = 2H_p h_p + H_R h_R + 2H_g g + 2H_T h_T + 2H_Y h_Y}$$

$$2H_g\ g = 2\frac{10^7}{4\pi}(0.000439) = 698.7\ A\ Turns$$

$$\phi = B_g\ X\ Area\ of\ Pole\ Head = 1\ X\ 1.405\ X\ 0.10472 = 0.1471Vs$$

$$B_P = \frac{\phi}{Width\ of\ Neck\ X\ l} = \frac{0.1471}{.07\ X\ 1.405} = 1.50\ T$$

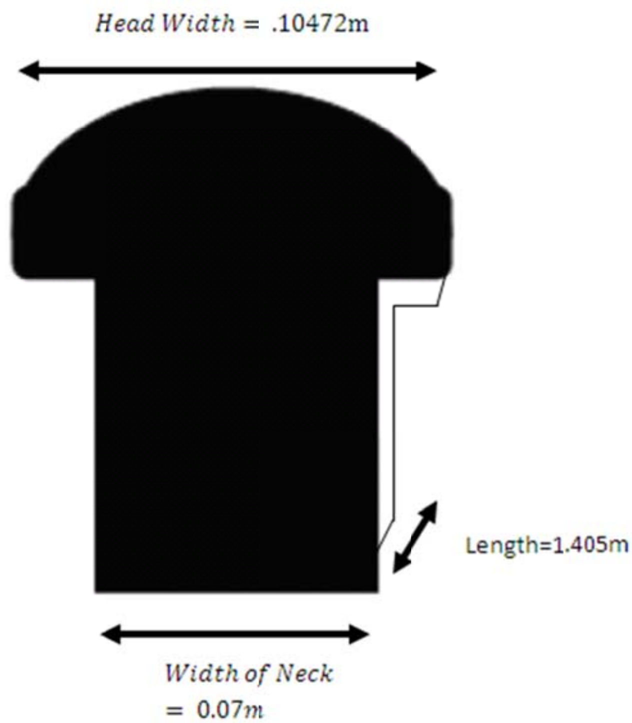


Figure 9 Rotor Pole Dimensions

The next flux density to calculate is that of the Rotor shaft itself. This part of is directly connect to the gear box of my turbine and supply the torque to turn the poles of the generator.

$$R' = \frac{Width\ of\ Neck\ X\ Poles}{2\pi} = \frac{0.07m\ X\ 12Poles}{2\pi} = 0.134m$$

$$h_p = R - R' = .3 - 0.134 = \ .166m$$

$$B_R = \frac{\phi}{R'\ x\ l} = \frac{0.1471}{0.134\ x\ 1.405} = 0.781\ T$$

$$h_R = Width\ of\ Neck\ of\ Rotor = 0.07m$$

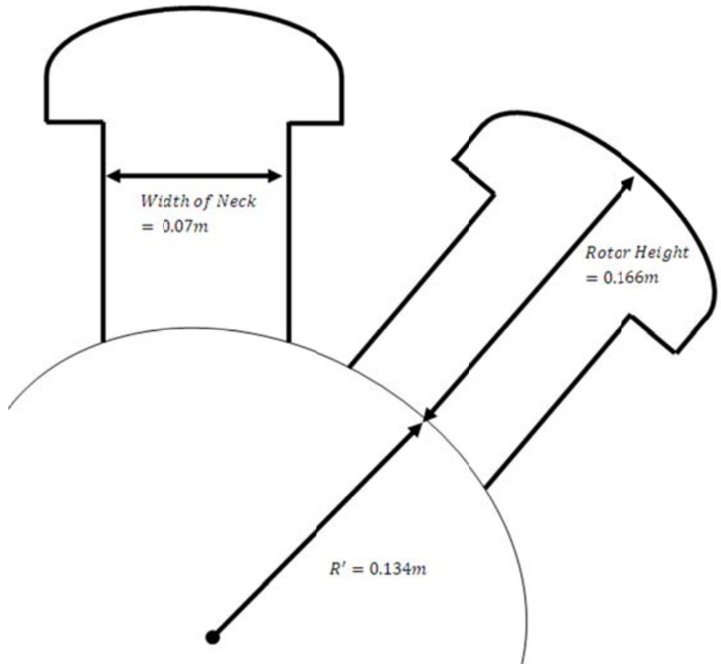


Figure 10 Width of the Rotor Shaft in Relation to Poles

Now we can move on to the flux through the teeth of the stator themselves. For our design there are at least 4 teeth over each pole at any given time. This means that there are two teeth always in the gap between the rotor heads.

$$B_T = \frac{\frac{\phi}{4}}{Width\ of\ Tooth\ x\ l} = \frac{\frac{0.1471}{4}}{0.0115\ x\ 1.405} = 1.84\ T$$ Under 2.2T limit of Vacoflux 50

$$h_T = 0.032m\ Taken\ From\ above$$

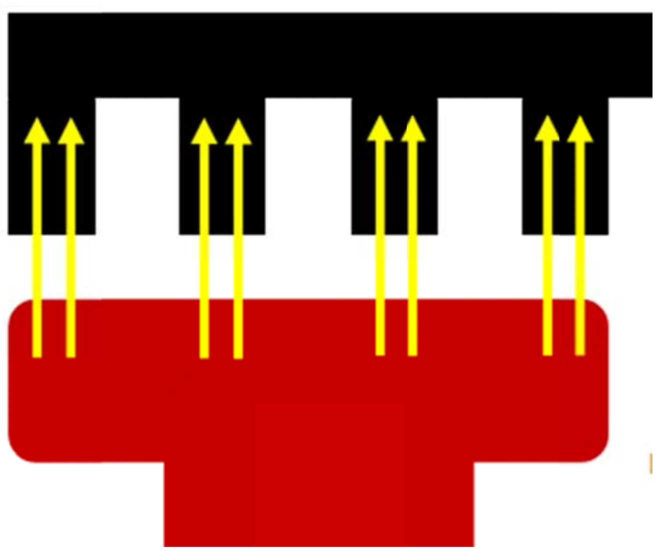


Figure 11 Flux off the Rotor into Stator

Our Last flux density path we need to calculate is that of the yoke, which is the thickness of the alloy that the teeth in the stator are attached too. The yoke allow the current to flow between the teeth and then back into the rotor.

$B_Y = 1.6\,T$ Assumed

$$\omega_Y = \frac{\phi}{B_Y\ x\ l} = \frac{0.1471}{1.6\ x\ (1.405)} = 0.065m$$

$$h_y = \frac{2\pi(R + h_T + (.5)\omega_Y)}{Poles} + \omega_y = \frac{2\pi(0.3 + .032 + 0.0325)}{12} + 0.065 = 0.256m$$

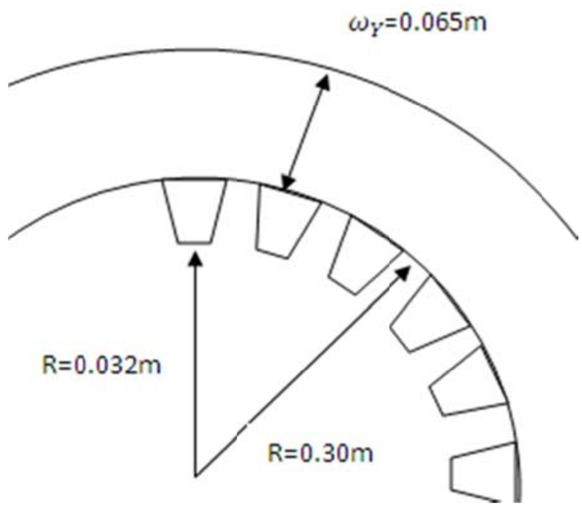


Figure 12 Yoke of Stator

We can now reorganize the flux densities and flux path distance calculated above. We will then determine the inductance produced dude to the chosen Vacoflux 50 material. All our flux densities correlate to cert H values on our B vs. H curve received by the manufacturer. A further datasheet on the material Vacoflux can be found in the appendix.

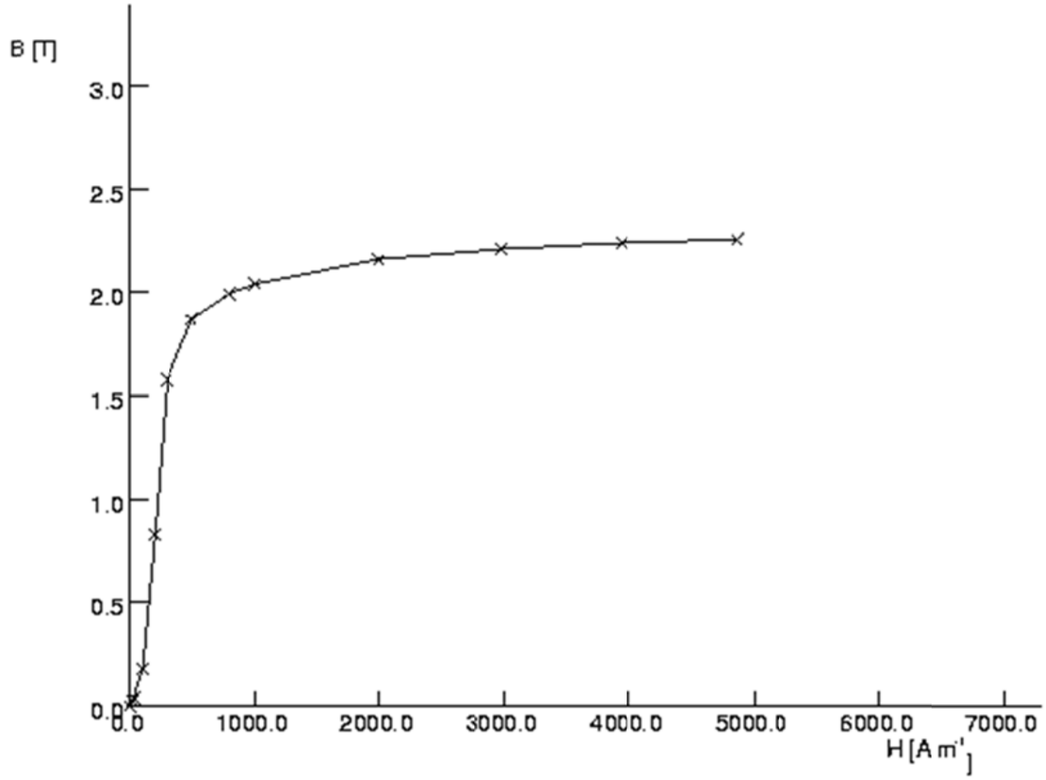


Figure 13 Magnetic characteristics of Vacoflux 50

	B(T)	H(A/m)	Length (m)	Hl (A Turns)
GAP	1	796000	0.000439	349.444
POLE	1.5	292	0.116	33.872
ROTOR	0.781	180	0.035	6.3
TOOTH	1.84	498	0.032	15.936
YOKE	1.6	320	0.128	40.96
				446.512

From this table above we can determine that we need an $N_F I_F = 447 \frac{A\,Turns}{Pole}$. We must chose an excitation current which will then allow us to determine the amount of turns needed per pole. We are assuming that our $j = 3\frac{A}{mm^2}$, and based on our material we should have enough room for the coils to rap around the poles.

$$j = 3\frac{A}{mm^2}$$

$$I_F = 10A \rightarrow N_F = 44.7\ Turns/Pole$$

$$Cross\ Sectional\ Area\ (A_C) = \frac{I_F}{j} = \frac{10}{3} = 3.33\ mm^2$$

$$Conductor\ Diameter = \sqrt{\frac{4\ x\ A_C}{\pi}} = \sqrt{\frac{4\ x\ 3.33}{\pi}} = 2.06mm$$

$$44.7\ x\ 2.06^2 = 189.7mm^2 = 1.897cm^2$$

$$Area\ Taken\ Up\ by\ Coils\ in\ Rotor = 2 * 1.897cm^2 = 3.794cm^2$$

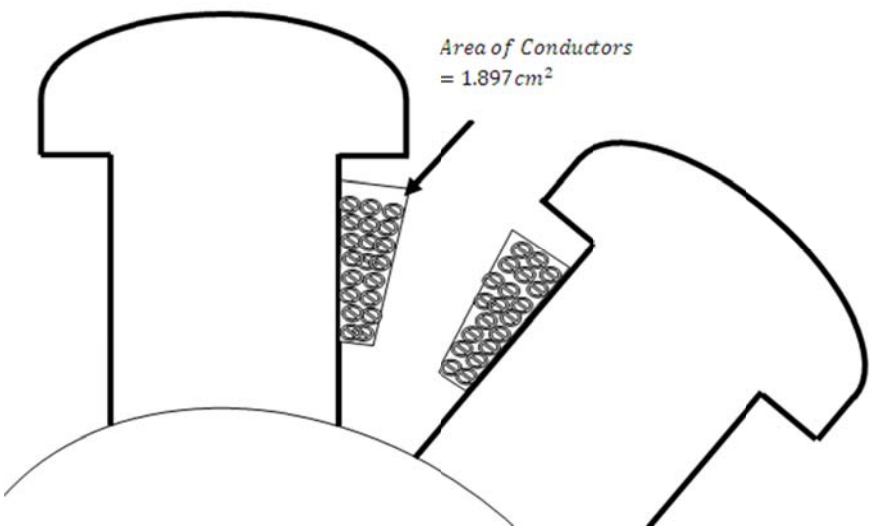


Figure 14 Available Area in Rotor

Due to our impressive allow that makes up our generator we only need 44.7 turns per pole around our rotor. This should leave us more than enough space for left over if we need more insulation.

$$Area\ Available\ in\ Rotor = 12.45cm * \frac{8.7cm}{2} = 54.16cm^2$$

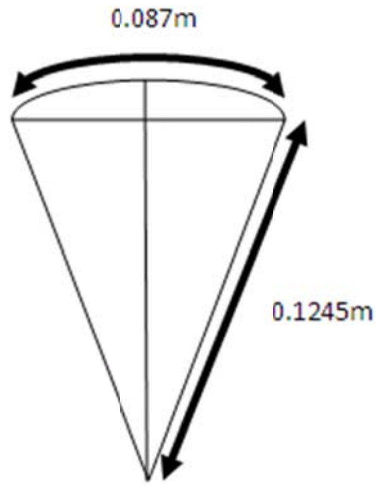


Figure 15 Available Area in Rotor

Based on our calculations above we can determine that we have a massive amount of space available compare with the space our windings. Even if the insulation on the windings was absolutely massive, there still would be room left between the poles. The only calculations left to make are do determine the length of the coil in the field (around the poles), its resistance, and the field voltage.

$$l_{Coil\ Field} = Nl_{AV} = 44.7((l + Insulation) + (Pole\ Width + Insulation)2$$
$$= 44.7\big((1.405 + 0.02) + (.07 + .02)\big)2 = 135.4m$$

$$Resistance\ R_F = Poles\ x\ \rho\ \left(\frac{l_{Coil\ Field}}{A_C}\right) = 12\ x\ 0.0216\ \left(\frac{135.4}{3.33}\right) = 10.54\Omega$$

$$V_F = R_F I_F = 10.54\ x\ 10 = 105.4V$$

Gear Ratio

To keep our motor at the appropriate speed we will need a unique gear ratio because of the slow speed at which are turbine blades are spinning. Wind turbines generally rotate from 16 to 22 RPM, so I will assume based on blade length that I'm spinning at 18RPM and my rotor is spinning at 600 RPM. As a result I will need a gear ratio of 3:100.

$$Gear\ Ratio = \frac{Speed\ of\ Blades}{Rotor\ Speed} = \frac{18}{600} = \frac{3}{100}$$

Overall System

The overall system of our wind turbine will contain a rectifying module, inverter, and a six pole controlled rectifier. Depending on the design some of these components may remain in the housing of the turbine atop the tower, or may be place closer to a grounding source, at the ground. The complete system should look as follows below.

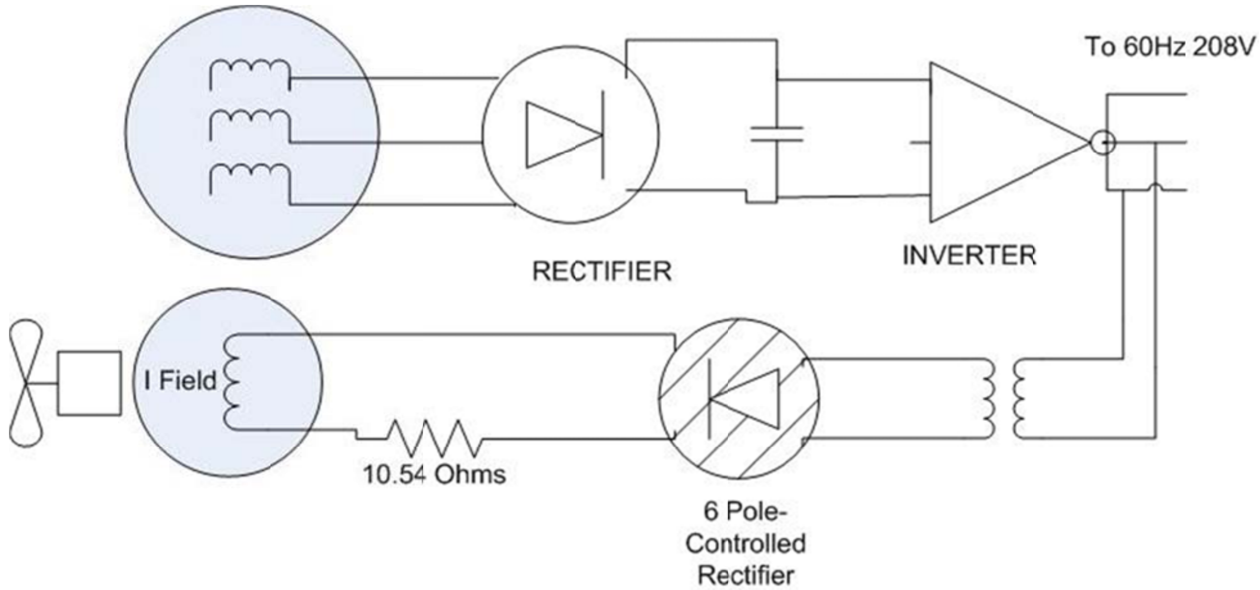


Figure 16 Overall System Diagram

Efficiency

There are many different ways to improve efficiency for a wind turbine design. One of the most import aspects is power factor. The close you can remain towards a power factor of 1.0, the more power you can receive from your generator. Another more difficult option to examine is the possibility of a steady wind speed. Since this is almost impossible to determine, we can look to alternatives such as CTV (continuously variable transmission) gearing systems. These systems are basically infinitely gears and instead of linear gains in speed due to a simple gear ratio with your turbine, you can determine your slope of your speed increase with this simple concept. Unfortunately they have limited torque capability and make be unusable at certain turbine sizes.

One of the easiest ways of increase efficiencies is by decreasing your power losses within the generator itself. This can be done by decreasing length of coils, changing alloy type within the generator itself, and lengths that flux must travel to complete a circuit. Unfortunately these options can become quickly very fast, especially if you decided to build you generate out of the same material (Vacoflux 50) as I decided on. Especially at my chosen rotor size the cost would be astronomical.

Economics

Depending on the wind distribution in your area a turbine can be very economical. Especially since it is a popular green technology funds are available from the Department of Energy and locally the Massachusetts Technology Collaborative, which supply grants for such projects. Unfortunately because of my design of my generator, this device could never pay itself off. This is due to the material it is constructed of, but if I did choose a cheaper material such as an iron core, which based on minor calculation is definitely possible it would be economical. The average payoff period is typically between 10 and 20 years. (Streubel, 2006)

Protection

There are many dangerous situations that can occur to a wind turbine, but the main fear it over spin, which can through blade and damage a large amount of equipment. Based on my research I have determined three solutions to this problem. The first and most obvious would be a simple braking system. Brakes would be relatively cheap, and allow for the most user interaction with the turbine. The second option I was exploring is to install a synchronous clutch between the gear box and the external turbine shaft. This would disengage the clutch when the turbine was spinning to fast , which would stop damage from occurring to the generator and gearbox. Unfortunately synchronous clutch usually require a large amount of maintenance, are relative expensive and will be in constant use.

The third and finally option that I was examining is the possibility of using a CTV (continuously variable transmission) to protect the generator. The CTV could be setup in an arrangement that its velocity slope become very flat around a certain peak speed, preventing the generator from accelerating.

Other hazards that can occur to wind turbine are lightning and overvoltage. These are relatively simple problem to overcome. A large capacitance can be place in series with the group that would prevent damage to electrical component during a lightning strike. Overvoltage protection is a common tooled used in power generation. A typical solution would be to protect instruments and components with fuses, or some type of breaker system.

Ride Through

When the voltage in the grid is temporarily reduced because of a fault or load change that occur in the grid. In ride through voltages may drop in one or several phase of the grids AC voltage and this can cause damage to the components, especially in asynchronous motors. The harshness of the voltage drop is defined by the voltage level during drop and the duration of the voltage drop. There are three ways to overcome this. One is to disconnect temporarily from the grid, then reconnect one the drop has passed (seen this current transformer). The turbine can remain connected to the grid and stay at operation, but it isn't recommended. Finally you can remain connected to the grid and try to push out the drop with your own power product; depending on the size of your turbine you may not be powerful enough to do this effectively.

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Appendix A

Appendix B

Simulations

(Wind Turbine, 2009)

(Vertical axis wind turbine, 2009)

(Young, Jensen, Forbes, & Foley, 2006) (Danish Wind Industry, 2009) (Holdsworth, 2009) (Meyers, 1978) (Streubel, 2006) (Streubel, 2006) (Vertical axis wind turbine, 2009) (Wind Turbine, 2009) (Young, Jensen, Forbes, & Foley, 2006) (Akagi & Edson Hirokazu Watanabe, 2007) (Low voltage ride through, 2009)