Low Speed Wind Turbine Design

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1. Introduction

The use of wind turbines for electrical power generation has been around for over one hundred years. Recent concerns over the price and environmental impacts of fossil fuels have spurred the proliferation of wind turbines in a wide range of powers. Today there is a wide variety of commercial wind power systems commercially available. Even the lower power rated turbines, however, are generally designed for relatively high wind speeds, typically around 10 to 15 m/s [4]. At lower wind speeds typical of many inland sites in South East Asia the commercially available wind power systems do not produce a significant amount of power. This either excludes them from use, or results in very inefficient power extraction in lower wind speed regions. With careful design of the turbine and generator, power production greatly in excess of commercial turbines is possible at lower wind speeds. This will allow the use of wind power in applications in remote areas of South East Asia and around the world where low wind speeds prevail. This would include power for remote meteorological telemetry stations, radio repeaters, rural habitations and schools as well as applications requiring spark free power supplies, such as in the proximity of petroleum extraction, refining, refuelling and transportation sites and military outposts. This chapter is dedicated specifically to the design of low wind speed turbine systems. As the available power in the wind is significantly lower at low wind speeds we will be focusing on smaller turbines in the sub 1kW range.

2. Wind Power

The wind power captured by a turbine is commonly expressed as a function of the turbine's swept area and a coefficient of performance, the air density and the wind speed [8]

$$P_{turb} = \tfrac{1}{2}\, C_p \rho\, A\, V^3 \tag{1}$$

Where:

P_{turb} is the mechanical power of the turbine in Watts

C_p is the dimensionless coefficient of performance

ϱ is the air density in kg/m^3

A is the swept area of the turbine in m^2

V is the speed of the wind in m/s

For wind sites near sea level the atmospheric pressure is approximately 1.18 kg/m^3 and decreases with altitude. The coefficient of performance is related to the turbine design, and has a theoretical upper limit of 0.593, referred to as the Betz limit [5]. Most sub 10kW wind turbines are rated for speeds from 8 to 12m/s. The coefficient of performance of commercial small turbines generally falls in the range of 0.25 to 0.45 based on manufacturers rated powers, speeds and diameters. The power of a turbine is directly proportional to the swept area, thus it is proportional to the blade length squared. The factor with the largest influence on turbine power, however, is the wind speed. From the turbine cut-in speed to the rated speed a turbine's power is proportional to the cube of the wind speed. That means that a 10m/s wind will deliver eight times the power of a 5m/s wind. This is why most turbines have a fairly high rates wind speed: it is the easiest way to achieve a high power output.

3. Small Turbines

Small turbines are of a limited variety of designs due to cost and performance constraints. The most common design is a stall regulated, variable speed, horizontal axis, fixed pitch 3-blade, direct drive permanent magnet machine [3]. Blade pitch control would be difficult to justify economically, so the blades are given a fixed pitch, and optimized for power production at the rated speed. This results in poorer performance at lower speeds than could be achieved by a turbine with active pitch control. The ultimate speed of the turbine is determined by the wind speed and the applied load. Usually a power controller is still required to prevent turbine over speed, and over charging of the batteries. This power controller may also incorporate power matching circuitry allowing optimized power extraction from the wind turbine at various wind speeds [6]. Turbine over-speed is avoided by applying a low resistance dump load to the generator, increasing the load torque to the turbine, slowing the blades, and resulting in aerodynamic stall.
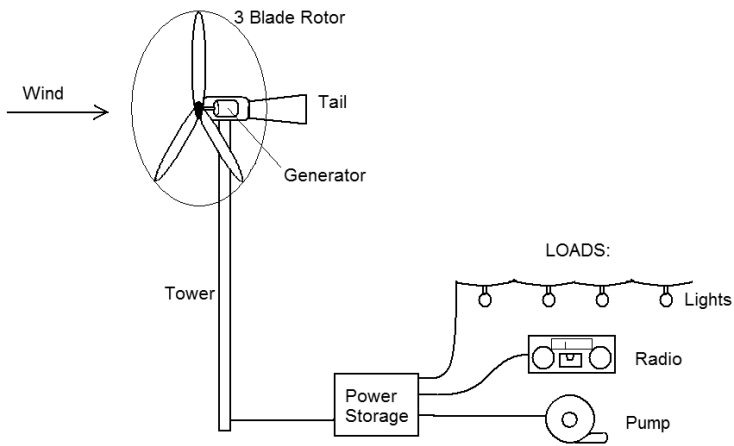
Figure 1. Schematic of typical small wind power system including wind turbine, storage system and loads

3.1. Commercial Small Turbines

There are significant differences between how various manufacturers state turbine specifica‐
tions, however it is generally understood that the turbine will produce the rated power at
the rated wind speed. Based on a survey of data published for small wind turbines we have
selected the following typical commercial turbine specifications:

Turbine Diameter	m	1.6	2.7	5.5
Rated Wind Speed	m/s	10	10	10
Rated Power	W	300	1000	5000
Rated Turbine Speed	rpm	400	300	200
Predicted Power at 3 m/s	W	8	27	135
Coeficient of Performance		0.25	0.30	0.36

Table 1. Typical commercial turbine specifications

When these turbines are installed in a lower wind region the actual power produced will be
significantly less than the rated power. In much of South-East Asia, for example, the average
wind speed is only 3m/s. While this may be below the turbines cut in speed (the lowest
speed at which it can produce power) assuming power is proportional to the cube of the
wind speed we can calculate the theoretical power production at 3m/s, as enumerated in the
table. It can be seen that the power production of these machines is far below the rated pow‐
er, underscoring the need for turbine optimization for low wind speed regions.

3.2. Analysis of speed, power and Cp

One of the biggest factors affecting the performance of a turbine is the blade pitch angle. The pitch angle is the angle between the blade and the plane of rotation. The attack angle is the angle between the chord of the airfoil and the relative wind, as shown in figure 2.
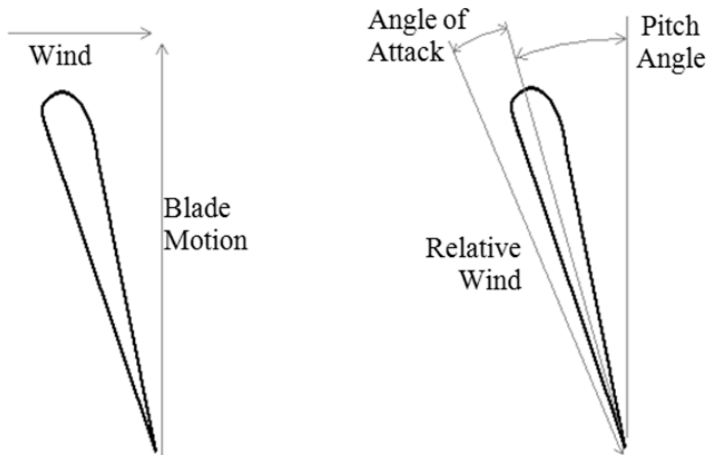

Figure 2. Wind vector, blade motion, pitch angle and angle of attack.

For most airfoils lift is maximized at an attack angle between 10 and 15 degrees. Obviously the angle of attack will depend on the wind speed and the turbine speed. A convenient parameter in the analysis of turbine performance is the Tip Speed Ratio (TSR) which is defined as the linear speed of the tip of the turbine blade divided by the prevailing wind speed. For a given wind speed, a lower pitch angle will result in a higher TSR at the maximum lift. A larger pitch angle will tend to give the maximum lift, and thus greater torque, at a lower TRS [11]. In the end higher coefficients of performance are achieved by blades with lower pitch angles and higher TRS, however at the expense of low speed torque which results in higher cut in speeds.

At very low wind speeds the turbine produces too little torque to overcome friction. Once the wind speed is sufficient to allow the turbine to rotate, the output power is approximately proportional to the cube of the wind speed. This remains true up to the rated speed. Above this speed the power production levels off, and with stall regulated turbines actually drops as wind speeds are increased. Finally at an even higher wind speed, the furling speed, the turbine is shut down to avoid damage to the machine. A typical turbine power curve is shown in figure 4.
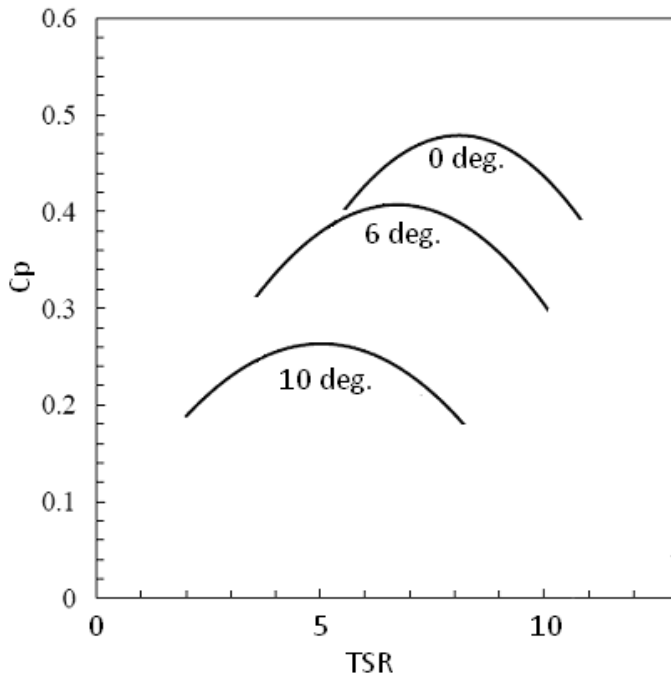
Figure 3. Coefficient of Performance variation with angle of attack versus TSR.
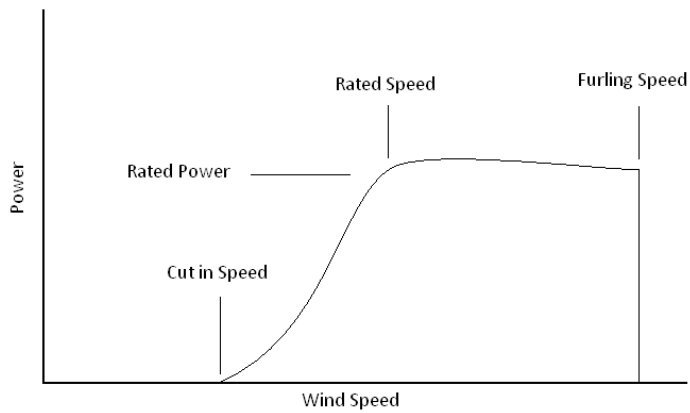

Figure 4. Turbine power versus wind speed.

Stresses in the turbine are related to the wind load, causing a bending of the blade in the direction of the wind, centrifugal forces, pulling the blades radialy outward, and various dy-

namic stresses. The centrifugal forces are proportional to the blade weight, blade length and square of the turbine speed, and limit the maximum speed of the turbine. Assuming similar materials and blade design, in order to achieve the same level of stress a larger, heavier, blade will have to spin at a lower speed than a smaller blade. This maximum speed of turbine operation becomes one of the limiting factors in the wind turbine, requiring either an extremely robust design or an active speed control system. Stall control systems are mechanically simple to implement, and thus common on small turbine systems. As the wind speed increases above the rated speed, a large electrical load, generally a high power resistor bank, is applied to the output of the generator. This increases the torque load on the turbine, slowing it. As the TSR is reduced, the angle of attack is raised above the optimum, and lift drops off as the blade begins to stall. This subsequently reduces the turbine's torque, slowing it further. This technique has been shown effective at preventing over speed in small turbines.

4. Design of Slow Wind Speed Wind Turbines

As previously stated, the problem of concern here is that existing commercial turbines are generally designed for wind speeds greatly in excess of typical wind speeds for major portions of the planet. Rather than simply exclude wind power from the potential energy scenario for these regions, we would like to design a small wind turbine especially for low wind speed regions [9]. Most of South East Asia (SEA) lies in a region of relatively low wind speeds. Wind speed data form a test site in Malaysia is shown in figure 5. Wind power probability is derived by multiplying the wind speed probability by the cube of the wind speed. The highest wind power probability is at approximately 3 m/s. At this wind speed commercial turbines will produce very little power.
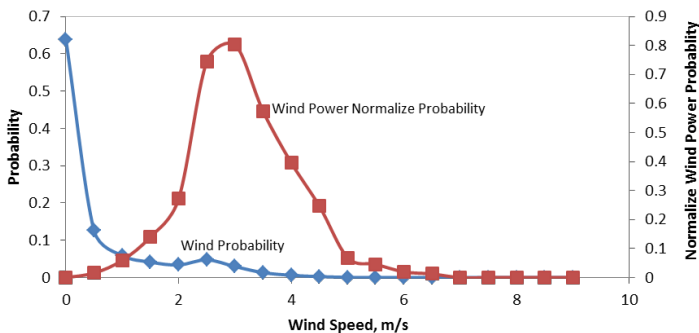

Figure 5. Wind and normalized wind power probability from a low wind speed test site

In order to improve power extraction the wind turbine requires a fundamental redesign. Equation 1 provides us the first indication of how to proceed. For a given wind speed we are left with modifying the turbine area, and optimizing the coefficient of performance. Control over the ambient air density is beyond the scope of this text. Lengthening the blades will

increase the cross sectional area of the turbine, increasing the power of the turbine. This will, however, also increase the load on the turbine and tend to result in a slower rate of rotation. Electrical power production from a generator is proportional to the square of the rotational speed, so it may be advantageous to adjust the pitch angle in order to maximize the TRS, and thus increase the generator speed. For low wind speeds both the turbine hub and generator will need re-optimization for the larger blades required to achieve a reasonable level of power production.

4.1. Overall Turbine Design

As a starting point for the design we will chose a system capable of providing power for a model rural dwelling typical of the remote regions of SEA. Such dwellings generally use rechargeable automotive lead acid batteries to power electrical lights, radios and televisions. These batteries are transported weekly to a diesel powered generator station for recharging. Transporting the batteries weekly is a significant burden to the rural residents which can be alleviated with the use of a wind power system. With improved access to electrical power the electrical power consumption will probably increase significantly. Additional power is likely to go to improved lighting, and additional appliances such as fans and even refrigerators. The actual power required will vary widely, but we will assume here that the typical house will consume approximately 1kWh per day.

The wind power system should have sufficient storage capacity for at lease one week with no power generation, thus we require at least 7kWh of electrical storage. As in most small off grid electrical power applications power will be stored in 12V automotive batteries. To minimize power transmission losses we will chose the highest system voltage considered safe for such applications. An operating voltage of 48V can be achieved with 4 batteries in series, and the constraint of 7kWh of energy storage then translates into a battery capacity of about 150Ah, similar to common truck batteries.

With good turbine sighting on a hill top, peak power probabilities of around 5m/s are possible in some costal regions of SEA. From long term measurements we can determine that the wind may achieve this target speed about 20% of the time, or 4.8 hours per day. Assuming that the turbine needs to generate about 1/3 more than the daily required power to compensate for loses in the system, we'll require about 1.3kWh per day of electrical power production. At 4.8 hours of power production per day the system will have to produce approximately 270W in the 5m/s wind. Assuming a generator efficiency of 80% and a Cp of 0.29, from equation 1 we can determine the area of the turbine to be 15.9m^2, yielding a blade length of approximately 2.25m. If we accept a conventional TSR of around 8, the turbine will be spinning at 170 rpm. Based on some initial measurements it was determined that a conventional generator design would require a much higher rotational speed to achieve the desired power output, so we will target twice this speed, or 340rpm. The operational TSR will be optimized via turbine blade pitch adjustment during field testing of the system, but we will target a TSR of 16, twice the conventional ratio. The operating current of the generator at this point will be approximately 5.8A.

Leveraging off of existing small turbine designs [1] the generator is to be a 3-phase, axial flux synchronous permanent magnet generator. We have selected a 12 pole design with 25 x 50mm, 11mm thick nickel plated NdFeB magnets. The generator is based around an automotive wheel bearing and disk brake, thereby defining the rotor diameters. The initial specifications for the turbine are listed in table 2.

Wind Speed	m/s	5
Power	W	272
Balde Legnth	m	2.25
Cp		0.29
Generator speed	rpm	340
Generator Efficiency	%	80
Voltage	V	48
Current	A	5.8
Poles		12
Phases		3
Rotor ID	mm	125
Rotor OD	mm	360

Table 2. Wind turbine and generator initial specifications

5. Experimental Results

Taking the well publicized small turbine design of Hugh Piggot as the starting point, we studied several generator and turbine parameters in order to optimize the design for the lower speed wind [10]. Generator measurements were performed on an electric motor driven dynamometer allowing simultaneous measurements of both mechanical and electrical power. The final generator was then placed in service on a turbine with adjustable pitch blades. The turbine power output was measured along with the wind speed for turbine optimization.

5.1. Generator Optimization

Initially a basic study of open circuit voltage was performed. Several coils with varying numbers of turns were prepared from 1mm diameter enamel coated magnet wire. In each case the coils were wrapped on a 20 x 40mm oval shaped core, slightly smaller than the rotor magnets. The thickness of the coil in the axial direction, which defines the thickness of the stator, was kept constant at 10mm. As the coils grow larger, the space between adjacent coils decreases, resulting in a maximum coil size of approximately 150 x 100mm. As can be seen in figure 6 the open circuit voltage increases linearly with the number of turns.
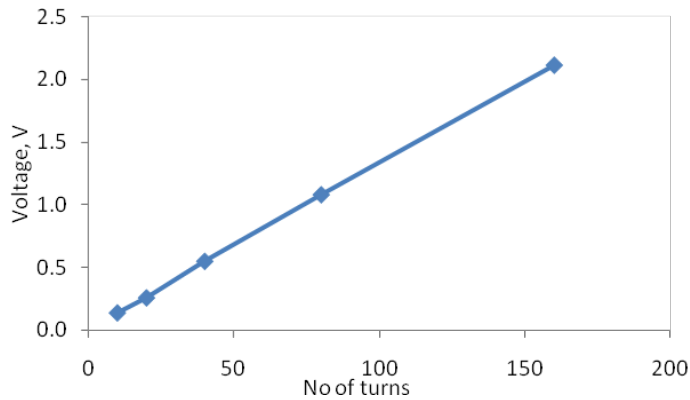
Figure 6. Individual coil open circuit voltage vs. number of turns at 50 rpm

If the coils were allowed to grow larger eventually contradictory flux from adjacent magnet pairs could enter the larger coils reducing the net flux and thus the voltage. With the current design the largest coils possible for a given stator thickness will deliver the maximum power.

For maximum flux transfer through the coils of motors and generators the coils have cores of laminated soft iron, or other magnetically conductive materials in an electrically insulating design (to reduce eddy currents). These soft iron cores provide a low resistance path for magnetic flux to pass through the coils. This however will also cause a significant "cogging" torque as the magnets tend to stick in positions over the cores [10]. High cogging torque will raise the turbine cut in speed, thus most low speed turbines are produced without magnetic materials in the cores, resulting in "core less" or "air core" coils. While the utility of this is appreciated, we decided to test both an air core coil and an identical coil with a core of steel baring epoxy. This epoxy was found to have very high electrical resistance, and significant magnetic susceptibility. The cores were tested on the generator dynamometer rotating at 125 rpm yielding the results in table 3. As only a single coil was installed, the resulting power extraction and efficiencies are very low. Both the electrical and mechanical power increase with the use of the epoxy in the coil's core as expected from the greater flux transfer. The efficiency of the epoxy core coil is also slightly higher than the air core coil. The cogging torque was measured to be significantly smaller than the rotor's bearing friction, thus the epoxy core coils were selected for the final configuration generator.

	Torque (Nm)	Mechanical Power (W)	Voltage (V)	Current (A)	Electrical power (W)	Efficiency
Epoxy Coil	1.13	14.2	2.3	0.98	2.25	0.16
Air Coil	0.91	11.4	1.9	0.81	1.54	0.14

Table 3. Comparison between air core and metal filled epoxy core coils

Another important optimization was the stator axial thickness. A thicker stator will allow more turns of wire, increasing the output voltage, however it will also require a greater rotor spacing distance. As the rotors are spaced further apart, more flux from the magnets will tend to "short circuit" to the adjacent magnets, rather than traverse the stator to the magnet on the opposite stator [3]. This situation is shown in figure 7
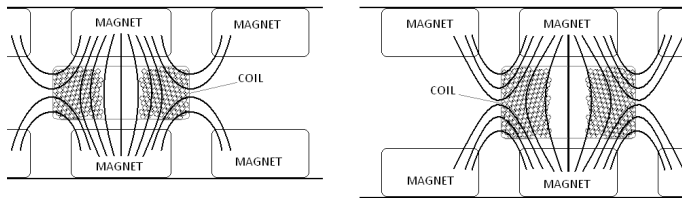

Figure 7. Lateral flux short circuiting to adjacent magnets increases (right) with increased rotor separation distance.

The induced voltage per turn can be seen to drop rapidly as the rotors are spaced further apart in figure 8.
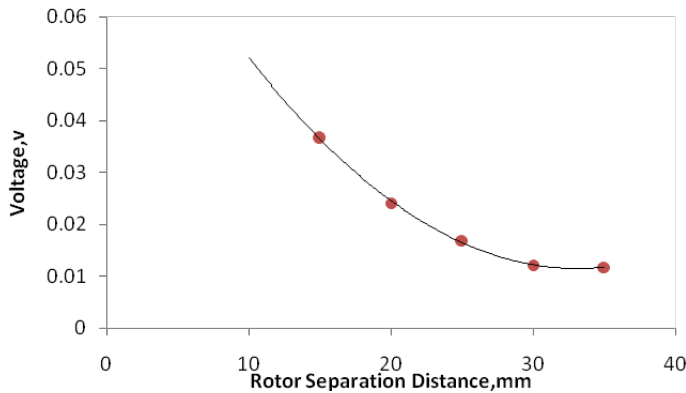

Figure 8. Voltage per turn versus rotor separation distance at 125 rpm

For a given rotor separation distance there is a maximum number of coil turns which will fit between the rotors. A margin of 2.5 mm is provided between the magnet surfaces and the stator to avoid physical contact, and allow air flow to cool the stator coils. Thus for a 10mm rotor separation, the stator is limited to a 5mm thickness which will allow about 50 turns per coil.

Coils of 5, 10 and 15mm thicknesses were prepared for 10, 15 and 20mm rotor separations respectively. These coils were then tested on the generator dynamometer at 125 rpm yielding the data of table 4.

Rotors Separation Distance (mm)	10	15	20
No. of Coil Turns	50	100	150
Total Open Circuit Voltage (v)	2.25	3.7	3.6
Coil Thickness (mm)	5	10	15

Table 4. Open circuit voltage and coil parameters for various rotor separation distances.

As the rotors are moved closer together, the magnetic flux passing through the coil increases producing a higher open circuit voltage per coil turn. However the smaller separation distance results in a smaller number of turns per coil. To achieve maximum open circuit voltage, there is a compromise between number of turns and rotors separation distance. As shown in the Table 4 the 15mm rotor separation distance will give the maximum open circuit voltage.

A generator was fabricated with the largest coils possible in a 10mm stator, and the cores were filled with metal bearing epoxy. The generator was then tested on the dynamometer with various loads. Figure 9 shows the results of electrical power measurements with the generator connected to various resistance loads.
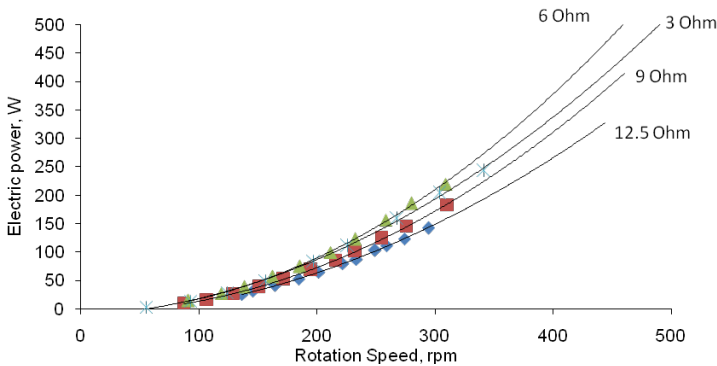

Figure 9. Power versus rotational speed for various loads

The maximum power of the system was produced with the 6 ohm load which is approximately equal to the internal resistance of the stator as the resistance per coil is 0.67ohm and there are 9 coils in series. Our initial design required approximately 270W of power production at 340 rpm. This power was above the capabilities of the relatively low power dynamometer, but falls within the range of power production predicted based on the square of the speed (black trend line) for the 6 ohm load.

5.1. Turbine Optimization

The generator was then placed in service on the roof of the mechanical engineering building as shown in figure 10. The 2.25 meter long wooden blades were fabricated with a NACA 4412 profile commonly used for low speed turbines. During testing the turbine blades were set to a given pitch angle and the generator was connected to a fixed resistance load. Wind speed and electrical power production data was then continuously logged. After several weeks of testing the turbine would then be adjusted to a new angle of attack and/or the load resistance would be changed.

Due to inconsistencies in the wind, not all configurations were tested at the same speeds for the same durations. Overall trends, however, were readily apparent. During the period of field testing the maximum instantaneous wind speed recorded was 8m/s while the maximum sustained wind speed was around 4 to 5m/s.

Figure 10. Wind turbine with optimized generator during turbine evaluation. Notice the anemometer in the background to the left.

The data generated during testing at the 9 degree attack angle shown in figure 11 was typical of the testing. The turbine's cut in speed is around 2m/s, and power output increases rapidly with wind speed for all load resistances. Data for the 3 and 6 ohm loads show the 3 ohm load having slightly higher power output below 3 m/s and the 6 ohm load giving greater power above 3 m/s. Theoretically the 6 ohm load should give the greatest power extraction as the load is well matched to the generator. In general the 6 ohm load gave the best power extraction, and was selected for further analysis.
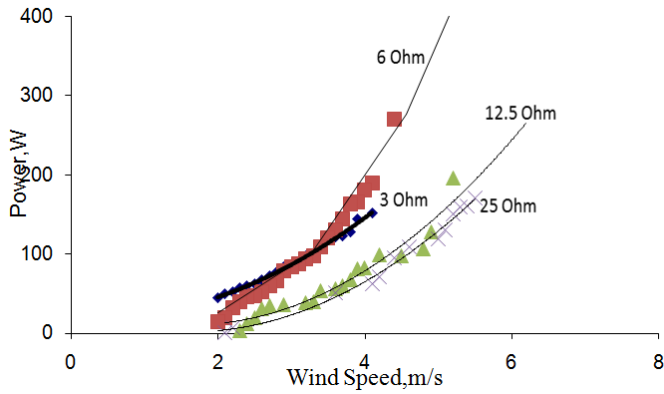
Figure 11. Electrical power versus wind speed at various loads for 9 degree angle of attack
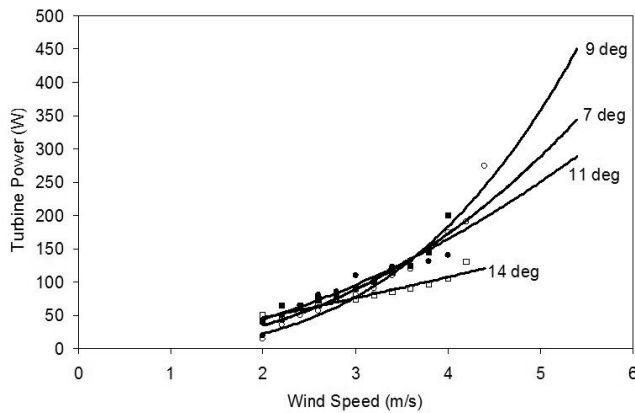

Figure 12. Electrical power vs wind speed at various angles of attack for the 6 ohm load

The power production was not a strong function of angle of attack in the 7 to 11 degree range, but dropped significantly at 14 degrees. Based on extrapolation of the data to higher speeds, the 9 degree angle of attack is expected to give the highest power production in the 3.5 to 5 m/s wind speed range.

Taking the best fit curve to the 9 degree angle of attack blade pitch with the 6 ohm load (figure 13) we can calculate that the turbine should produce about 200W at a 4.2 m/s wind speed. Taking this with the known turbine blade length of 2.25 meters and an assumed generator efficiency of 80% [7], we can use equation 1 to calculate the coefficient of performance to be 0.36, somewhat better than the assumed value of 0.29.

Additional measurements made on the turbine bearings indicated frictional losses account for 23W at 300 rpm. This is approximately 10% of the electrical power produced. The use of automotive bearings is perhaps not optimal from a friction stand point, thus with improvements in the bearings it may be possible to improve the turbine output by something on the order of perhaps 5% or so.
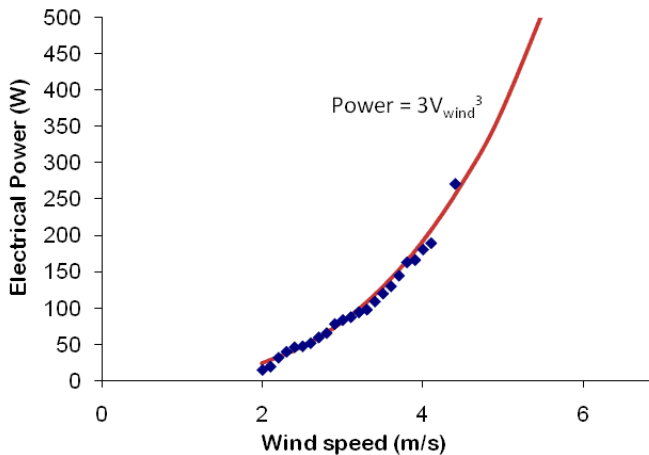

Figure 13. Electrical power versus wind speed at 9 degree attack angle with 6 ohm load

Looking back at figure 9 we can see that a 200W output should occur at approximately 300rpm with the 6 ohm load. Using this to calculate the TSR at a 4.2m/s wind speed we come up with a TRS of 17, close to our assumed value of 16, and significantly higher than the conventional value of 8.

6. Performance Comparison

Taking the measured turbine performance we can predict the power production versus wind speed. Based on manufacturers published performance curved our turbine can be compared to existing commercial turbines. Wind data was recorded at a proposed turbine test site on a costal facing ridge at an altitude of 400m at Banjaran Relau in Kedah, Malaysia. This gave slightly higher wind speeds than the turbine test site atop the mechanical engineering building. A sample of the wind data is shown in figure 14.

The wind speed data exhibits a diurnal pattern with some marine layer pumping associated with the proximity to the coast with the highest winds speeds in the afternoon. Additionally is can be seen that there can be several days, eg. day 13 to 18 in figure 14, with very little wind underscoring the need for significant storage capacity.
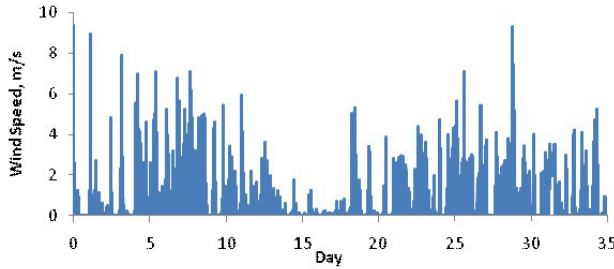
Figure 14. Wind speed the Banjaran Relau turbine test site in Kedah, Malaysia
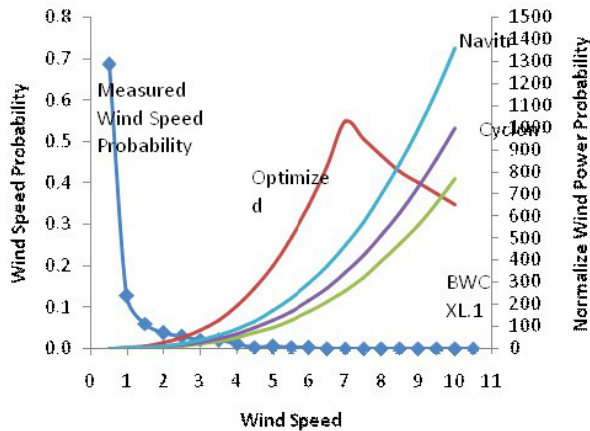

Figure 15. Wind probability and predicted electrical power production versus wind speed for several commercial turbines, and the turbine developed in this study.

Figure 15 shows the power produced by three small commercial turbines, and the one developed in this study versus wind speed, as well as the wind probability at the turbine test site. As the optimized turbine will be spinning at a higher rotational speed than the other turbines, the controller will begin electrical breaking at wind speeds above 7m/s, effectively negating the turbine's output above this speed. This is not overly restrictive as the wind rarely blows at speeds above 7m/s for more than a few minutes per month.

It can be seen that the optimized turbine produces significantly more power than the commercial turbines at the lower wind speeds, and of course significantly less power at the higher speeds the other turbines are rated for. This is expected as the optimized turbine has a larger swept area, and has been tuned for low wind speed operation.

Multiplying the generator's power times the wind speed probability at each wind speed, we can derive the normalized power production curves of figure 16. Peak power probability for this data set is at 3m/s, with a lower peak in the power probability curve at 4.5m/s. As the wind speed at the test site never exceeded 7m/s for any significant amount of time the optimized turbine is shown to generate 3 to 4 times more power than the commercial turbines over the whole available wind speed range. There is a dip in the wind probability data at around 4m/s in the data over the period sampled due to the limited amount of data. In general we would expect a fairly smooth wind probability profile with a peak between 3.5 and 4.5m/s at this wind site.
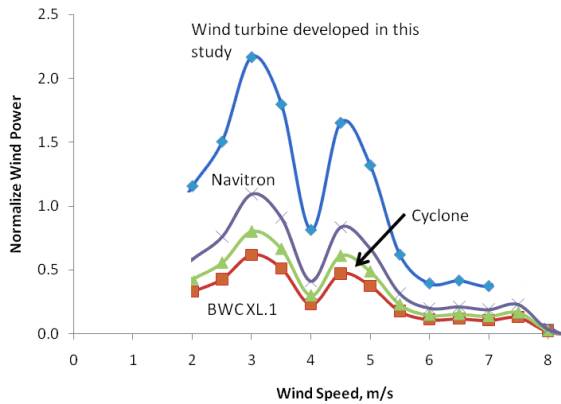

Figure 16. Comparison of normalize wind power for various wind turbines

Power production in a 5 m/s wind is expected to be around 350W, and in a region producing this wind for 4.8 hours of production per day, should result in 1.68 kWh of energy production per day. Assuming storage losses of 30% associated with charge/discharge of batteries and power transmission this will result in about 1.2kWh of usable energy per day, close to our initial estimate of 1.3kWh per day required for a rural dwelling. Thus it is expected that a purpose designed 2.25m radius wind turbine of relatively simple construction is sufficient to power a single rural dwelling in the windier parts of SEA.

7. Conclusion

Most commercial turbines are designed for relatively high wind speeds, around 10m/s, produce insignificant amounts of power below 5m/s. Taking a conventional axial flux, direct drive horizontal axis 3-blade wind turbine as the starting point we were able to optimize the turbine and generator for lower wind speed operation and achieve a significantly higher power output than existing commercial turbines at lower wind speeds. Further optimization of the turbine is possible and should focus on airfoil shape, blade weight and construction

and bearing friction. While the use of larger blades will increase the cost and weight of the turbine and tower it is still believed that wind power can be a viable alternative even in regions of relatively low winds.

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