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A Review on Design of Low Wind Speed Wind Turbines

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Abstract: To meet the increasing global demand for renewable energy such as wind energy, more and more new wind parks are installed worldwide. Most of the commercial turbines are designed for relatively high wind speeds, around 10m/s, produces insignificant amounts of power below wind speed of 5m/s. Taking a consideration of conventional axial flux, horizontal axis 3-blade wind turbine system this paper as discussed about design aspects of low wind speed turbines.

Keywords: HAWT, Small Turbines, TSR, Low Wind Speed

I. INTRODUCTION

Because of increasing energy demand worldwide and the willingness to reduce greenhouse gas emissions, renewable energies such as wind energy are rapidly growing: The global cumulative installed capacity of wind energy increased from 6GW in 1996 to 396GW in 2014 and is expected to reach 596GW in 2018 (GWEC, 2014).

In the recent years concerns over the price and environmental impacts of the fossil fuels have increased the interest of wind turbines for a wide range of powers. Today there are a wide range of commercial wind power systems are available commercially. Even the lower power rated turbines are also generally designed to relatively high wind speeds, normally around 10 to 15 m/s [9] so, at the lower wind speeds typical of many internal sites in South Asia the commercially available wind power systems produces a insignificant amount of power as the average wind speed is around 5m/s. With careful design of the generator and turbine, power production greatly in excess of commercial turbines is possible even at lower wind speeds. This will encourage the design of low wind speed turbines suitable to remote areas of South Asia and around the world where low wind speeds available. This would include the 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, refueling and transportation sites and military outposts.

This paper is specifically dedicated to the design of low wind speed wind turbine systems. As the available power at low wind is significantly lower this paper is focusing on smaller turbines in the sub 1kW range.

II. WIND FORCE SCALE

Historically, the Beaufort wind force scale gives wind speed description on base of observed sea conditions [7]. There are general terms that differentiate winds of different average speeds such as a breeze, a gale, a storm, tornado, or a hurricane. Shown in table I and different classes of wind power densities are shown in table II.

Table:1General Wind Classification Depending on 10min Average Speed

General wind classifications		
Beaufort scale[13]	**10-minute sustained winds (knots) 1knot=1.8571km/h**	**General term[14]**
0	<1	Calm
1	1-3	Light air
2	4-6	Light breeze
3	7-10	Gentle breeze
4	11-16	Moderate breeze
5	17-21	Fresh breeze
6	22-27	Strong breeze
7	28-33	Moderate gale

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8	34-40	Fresh gale
9	41-47	Strong gale
10	48-55	Whole gale
11	56-63	Storm
12	>64	Hurricane

Table:2 Classes of Wind Power Density

30 m (98 ft)			**50 m (164 ft)**	
Wind Power Class	**Wind Power Density in W/m²**	**Wind Speed in m/s**	**Wind Power Density in W/m²**	**Wind Speed in m/s**
1	≤160	≤5.1	≤200	≤5.6
2	≤240	≤5.9	≤300	≤6.4
3	≤320	≤6.5	≤400	≤7.0
4	≤400	≤7.0	≤500	≤7.5
5	≤480	≤7.4	≤600	≤8.0
6	≤640	≤8.2	≤800	≤8.8
7	≤1600	≤11.0	≤2000	≤11.9

III. WIND POWER

The turbine power produced is expressed as a function of the turbine swept area, the wind speed, coefficient of performance and the air density [9].

$$P_{turb} = \frac{1}{2} C_P \rho A V^3 \qquad (1)$$

Where:
P_{turb} → the turbine mechanical power in Watts
C_p → coefficient of performance (dimensionless)
ρ → density of air in kg/m3
A → the turbine swept area in m2
V → the wind speed in m/s

The air density at the wind sites near sea level will be approximately 1.18 kg/m3 and it decreases with the altitude. The coefficient of performance (C_p) is dependent on the turbine design, and it has a theoretical upper limit of 0.593 according to the Betz limit [2]. For commercial small turbines the value of coefficient of performance are generally falls in the range of 0.25 to 0.45 based on wind speeds, manufacturers rated powers and diameters. Generally most of sub 10kW wind turbines are designed for speeds from 8 to 12m/s. The turbine mechanical power is directly proportional to the turbine swept area, thus it is proportional to the blade length squared. The factor which has largest influence on turbine power, however, is the wind speed. Between the range of turbine cut-in speed to the rated speed a turbine's mechanical power is directly proportional to the cube of the wind speed. It means that a power delivered at 10m/s wind will be 8 times greater than the power delivered at 5m/s wind. This is the reason why most wind turbines have a fairly high rates wind speed, which is the easiest way to achieve a high power output.

IV. SMALL TURBINES

Due to the performance and cost constraints the small wind speed turbines are having a limited variety of designs. The most common design is a horizontal axis/vertical axis, 3- blade, stall regulated, fixed pitch, variable speed, direct drive permanent magnet machine [11].

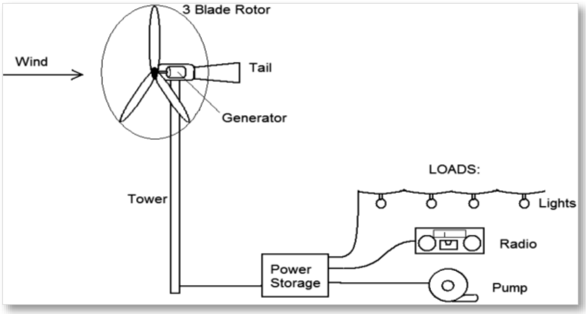

Fig. 1. Schematic design of small wind turbines

Blade pitch control is not economical for small wind turbines, so the blades are given a fixed pitch, and optimized for rated power production at the rated speed. So, this results in a poor performance at lower wind speeds compare to achieved by a turbine with the active pitch control. The ultimate speed of the turbine is determined by the applied load and the wind speed. Usually a power controller is required to prevent over charging of the batteries and turbine over speeding. This power controller can also incorporate with the power matching circuitry for allowing the optimized extraction of power from the wind turbine at various wind speeds [3]. Turbine over-speeding is prevented by the low resistance dump load to the generator, slowing down the blades, increasing the load torque to the turbine, and which resulting in aerodynamic stall. The schematic design is shown in fig 1.

A. Commercial Small Turbines

The turbine specification differs significantly from manufacturer to manufacturer, however it is generally understood that the turbines will produce the specified rated power at the rated wind speed. Table III shows the typical commercial turbine specifications.

Table:3 Specifications of Typical Commercial Turbines

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

When these high wind speed rated turbines are installed at low wind speed sites the actual power extracted will be significantly low compared to rated power. The average wind speed in the most of the south Asian sites is only 3m/s to 5m/s. While this may be below the turbines cut in speed (which is the lowest speed at which wind turbines can produce power) as we know turbine power is directly proportional to the cube of the wind speed, in table III the theoretical power generated at 3m/s is enumerated. It can be seen from the table that the power production of these machines is far less compare to the rated power, this shows the importance of optimized turbine design for low wind speed sites.

B. Analysis of Cp, power and wind speed

The main factor affecting the performance of the turbines is blade pitch angle. The pitch angle is the angle between the plane of rotation and the blade. The angle of attack is the angle between the relative wind and the chord of the airfoil, as shown in figure 2.

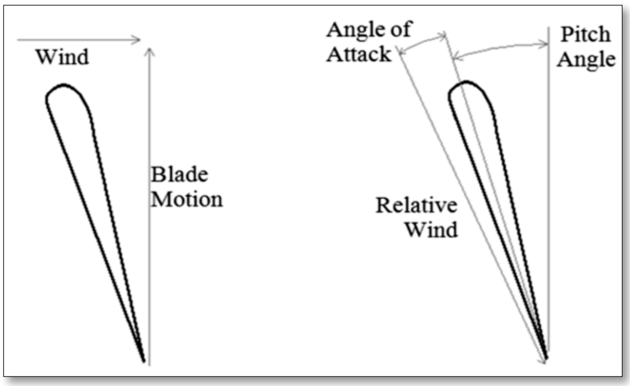

Fig. 2. The angle of attack and pitch angle.

In general at an angle of attack between 10 and 15 degrees the airfoils lift can be maximized. The angle of attack is dependent on the turbine speed and the wind speed. But the best parameter to analyse the turbine performance is the TSR (Tip Speed Ratio).

$$\mathrm{TSR} = \frac{\text{The linear speed of the tip of the turbine blade}}{\text{The prevailing wind speed}}$$

The lower the pitch angle results in a higher TSR at the maximum airfoils lift. The larger pitch angle tends to give the maximum airfoils lift, and thus greater is the torque developed at a lower TRS [10]. At the last higher coefficient of performance (CP) are achieved by blades with higher TRS and lower angle of pitch, moreover the low speed-torque results in the higher cut-in speeds shown in fig 3.

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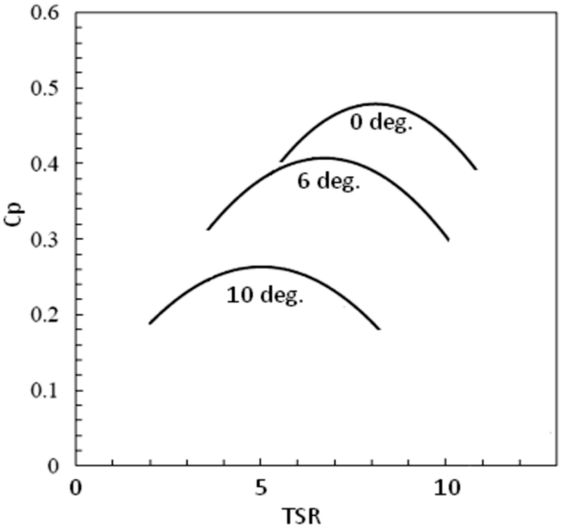

Fig. 3. Variation of coefficient of performance with angle of attack versus TSR.

The wind turbine produces low torque at the lower wind speeds to overcome friction, when the wind speed is sufficient to pull the wind turbine to rotate, the turbine power is directly proportional to the cube of the wind speed. This relation remains true up to it reaches the rated speed. Above this wind speed the power generated gets reduced. In stall regulated turbines the power generation drops as the wind speed increases. When the wind speed reaches furling speed shutdown of turbine takes place to avoid damage.

A typical wind speed verses turbine power is shown in figure 4.

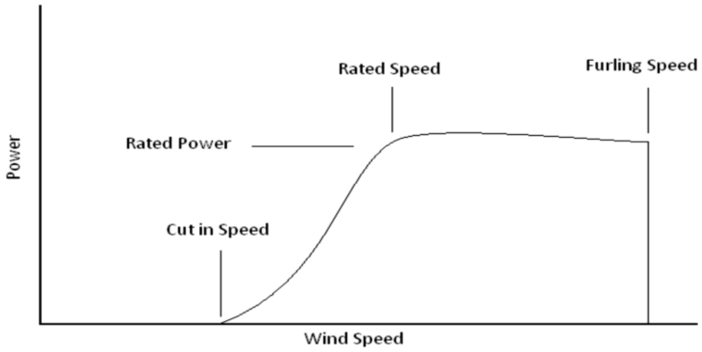

Fig. 4. Wind speed versus turbine power.

Fig. 5.

The stresses on the turbines are dependent on the wind load. Which causes bending of the blades in wind direction, pulls the blades radialy outwards, centrifugal forces and dynamic stresses. The centrifugal forces are directly proportional to the square of the turbine speed, the blade weight and blade length, which limit the maximum speed of the turbine. The maximum speed of the turbine operation becomes one of the main limiting factor in the wind turbine, requiring either an active speed control system or an extremely robust design. The stall control systems are mechanically simple to install, and thus it is common on small turbine systems. When the wind speed increases beyond the rated speed, a large electrical load (generally the high power resistor banks), is applied to the output of the wind generator. This increases the torque load on the wind turbine and slow down the speed. As the TSR is reduced, the angle of attack gets increases above the optimum, and the airfoils lift drops off as the blade begins to stall. This consequently reduces the wind turbine’s torque, slowing it further.

V. DESIGN OF LOW WIND SPEED WIND TURBINES

As previously discussed, the problem of concern here is that the existing commercial turbines available in market are generally designed for higher wind speeds. But typical wind speeds for major portions of the planet are having lower wind speed. So it is needed to design low wind speed turbines. Most of South Asian regions are having a relatively low

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wind speeds. Wind speed data for a sample test site 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 approximately at 5m/s. At this wind speed commercial available turbines in market will produce very low power. Fundamental redesign of the wind turbine required in order to improve power extraction. Equation 1 helps us to go proper direction. For a given wind speed we are left with optimizing the CP and modifying the turbine area. Controlling the air density is not economical for these kind of turbines. Lengthening the wind blades will increase the cross sectional area of the wind turbine, increasing the turbine power. This will increases the load on the turbine and results in a lower rate of rotation.

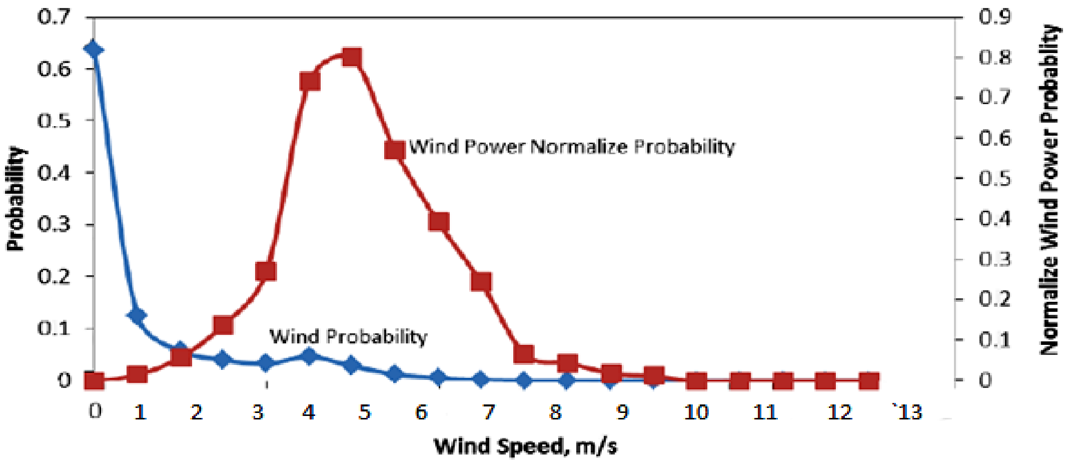

Fig. 6. Wind probability and normalized wind power probability from a low wind speed sample site

Electrical power production from a generator is directly proportional to the square of the rotational speed, so it is advantageous to adjust the angle of pitch in order to raise the Tip Speed Ratio (TSR), and thus increases the generator speed. For low wind speeds both generator and the turbine hub needs re-optimization for the larger blades, required to achieve the reasonable level of power production.

VI. OVERALL DESIGN OF TURBINE AND RESULTS

Table IV shows the dimension of designed HAWT (Horizontal axis wind turbine)

Table:4 Specifications of Blade

Blade height	3.5feet
Blade width	2feet
Thickness	1.2mm
Material	Aluminium.

Fig. 7. Designed horizontal axis wind turbine

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Table V shows wind power generation at various wind speeds corresponding to 2.5-7m/s wind speed, also voltage developed and current produced at respective speeds are shown in table. Maximum power of 86.48W is generated at 7m/s, corresponding voltage is 23V and current is 3.76A respectively.

Table:5 Wind Speed and Power Produced by the Wind Blades.

Speed in m/s.	Voltage in Volts.	Current in Ampere.	Power in Watts.
2.5	10	1.92	19.2
3	12	2	24
3.5	14	2.08	29.12
4	16	2.24	35.84
4.5	18	2.4	43.2
5	20	2.56	51.2
6	22	2.8	61.6
7	23	3.76	86.48

VII. CONCLUSION

Most of the commercial turbines are designed for relatively high wind speeds of around 10m/s, which produces too less amounts of power at lower wind speeds. By taking a conventional axial flux, horizontal axis 3-blade wind turbines with optimized starting point for lower wind speeds, it is possible generate high power. Optimization of turbine, blade weight, construction and bearing friction, it is possible to achieve higher power at lower wind speed.

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