Design, Development, Manufacturing and Testing of Aerofoil Blades for Small Wind Mill

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Abstract- In India the average per capita electricity consumption for domestic utilities is from 1-1.5kWhrs, which means a small wind mill of 1 kWp is reasonably sufficient to cope up with every day need of a family. This paper has dealt with design, manufacturing and performance testing of aerodynamic rotor blade for 1kWp small wind machine. It is observed that the small wind mills available in this range are not indigenous and are designed for higher rated wind speeds. A new design methodology was established for indigenous development of small wind machine technology, which considers aerodynamic rotor blade design for rotor blade performance and finite element design practices for strength of rotor blades. This has facilitated to consider the cut in speed from 2m/s onwards, rated speed 11-14m/s and cut out speed of 25m/s. The FRP/ERP rotor blades having light weight and highest strength to weight ratio was selected and has fulfilled the conditions of low initial torque for lower cut in speeds. The power curves obtained by testing wind machines by IEC 61400-121 methods shows improved performance over market similar capacity wind machines.

Keywords- Small wind mill design, Aerofoil section for wind mill, testing of small wind mill, performance of small wind mill, rotor blade design of small wind mill.

1. Introduction

Windmills have been used for at least 3000years, mainly for grinding grain or pumping water, while in sailing ships the wind has been an essential source of power for even longer. Locally, wind velocities are significantly reduced by obstacles such as trees or buildings. The survey carried out for representative samples at Kolhapur, states that the energy consumption per capita per day ranges from 5 to 6 units (kWhrs) for domestic applications. This leads to energy source/supply @ 1 to 1.5 kW per day available for 5 to 6 hrs.

A renewable energy source will be ideally suited to comply these energy needs. The sources available easily are wind, solar, biogas, etc. out of which wind energy is studied in length in this paper.

2. Design of rotor blades for small wind machine

2.1. Design methodology

The research has established that the new design methodology need to be worked out for small wind machines < 10 kW. The various books and literature survey shows the different aspects and component design including aerodynamic rotor blade design. The finite element method can be used, instead complex computer aided rotor blade designs as in case of large wind mills of MW scale where complexities are important. However for small wind a mill following methodology is set herewith.

a) The localized wind speed pattern establishment.

b) Power in the wind calculations.

c) Selection of wind mill type namely HWAT or VWAT etc.

d) Find the swept area, diameter and speed of the rotor vis-a- vis wind speed.

e) Find rotor blade lift, drag and chord length.

f) Blade strength considerations for the designed wind speed using finite element method with respect to aerodynamic profile.

g) Fixing blade aerodynamic and twist.

2.2. The Power in the Wind

No device, however well-designed, can extract all of the wind's energy because the wind would have to be brought to a halt and this would prevent the passage of more air thorough the rotor. The most that is possible is for the rotor to decelerate the whole horizontal column of intercepted air to about one-third of its free velocity. A 100% efficient aerogenerator would therefore only be able to convert up to a maximum of 59% (Betz limit) of the available energy in wind into mechanical energy.

Assumptions considered for design:

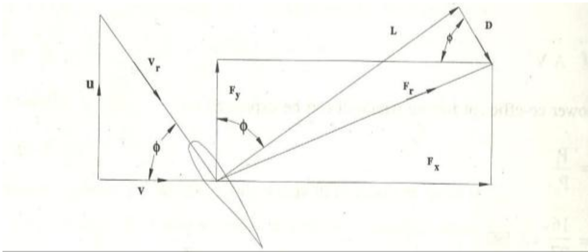
1) Efficiency of the generator
2) The design wind speed for the wind mill is
3) The mechanical efficiency of the wind mill
4) The transmission efficiency of the wind mill
5) The aerodynamic efficiency
6) The 20% for nacelle are accommodated.
7) Density of the air ρ = 1.125 kg/m3

3. Results

1) Propeller diameter = 1.75 m
2) Rotational speed = 455 r.p.m.
3) Effective blade length = 0.875 m
4) Power output = 1 kW

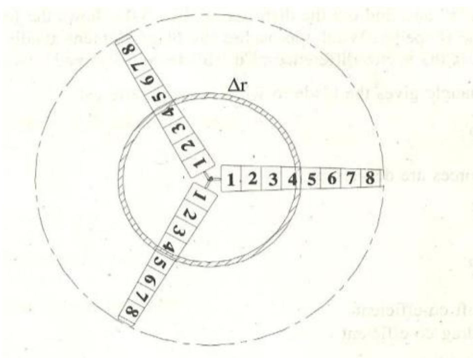
The blades are designed on two principles, as drag design and lift design. Drag designed turbines are characterized by slower rotational speeds and high torque capabilities while lift designed turbines are characterized by much higher rotational speed with corresponding lower torque. Drag and lift are the forces exerted by wind flowing over the aerofoil section of the blades. Blade strength is based on either drag or lift forces.

The forces acting on the blade element are also shown in the figure. The resultant of lift and drag forces is Fr, which has axial and tangential components (Fx and Fy)



3.1. Design of blade using sectional method

The blade is designed for mechanical strength. The blade is the main element that converts wind energy into useful work and in doing so is loaded to deliver the desired power. Blade load is then transferred to the shaft and then to the generator. Hence it is very essential to establish the forces acting on the blade. The blade being considerably long is loaded with varying forces from the inner root to the outer tip. The best way to consider such loading is to write down expressions for an immeasurably small section of the blade at radius 'r' and find out the distribution. This is the "blade element theory".



Evaluation of Fx and Fy for an elemental segment has to be done and rotational velocity N has already established, the functional requirements that lead to define Φ. For good aerofoil design, the ratio of Cd/Cl can be assumed initially and then reverified. For an aerofoil this value is to be very low such as less than 0.1 for the wind turbine under consideration, the blade element is considered to be 0.175 meter along its radius and calculations are done.

The table is prepared for the various parameters of each element of the blade the List the values of Fx and Fy for Δr = 0.175 and

r = 0.262, 0.437, 0.612, 0.787, 0.962.

Table 1. List the bending moments of Fx and Fy about the points R = 0.175, 0. 350, 0.525, 0.700, 0.875.

Radius R	Angle of attack Φ	Bending moment in X direction Bmx N-m	Bending moment in Y direction Bmy N-m
0	0	231.32	38.62
0.175	27	174.46	26.79
0.350	53.41	120.08	16.40
0.525	66.01	72.20	8.81
0.700	72.38	34.07	3.73
0.875	76.12	8.93	0.898

The maximum bending moment acting on the blades in Y direction is considered it gives the torque acting on machine. So check the power developed:

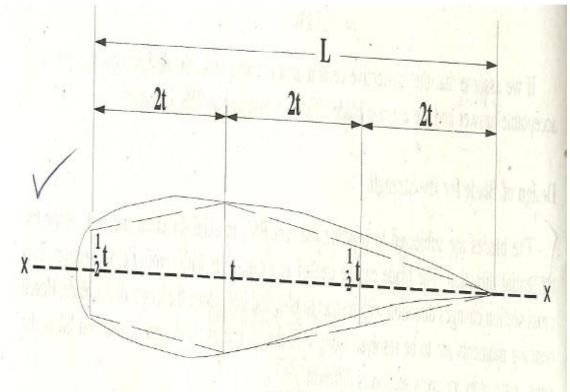
Counter check the power by iterative procedure.

If we assume that the ineffective central area is about 10 %, the design presented gives an acceptable answer of 1000 watts and average blade efficiency assumed as 75 % is correct.

3.2. Design of blade for strength:

The blades are subjected to bending moment Bmx along the axial direction and Bmy along the tangential direction. The blade can be treated as a cantilever with aerofoil cross section. This cross section changes direction with respect to Bmx and Bmy along the length of the blade. Hence bending moments are to be resolved along with lift line as the design is based on lift, as the vane angle at every cross section is different.

Initially it has been assumed to some portion of the aerofoil in terms of any one dimension and estimate modulus of section Zxx in terms of single variable. Though we have estimated bending moments for the normal operating conditions, it is generally recommended to base the design for the worst operation of the wind, i. e. gust, which is five times the operational wind speed. Although the wind speeds of 250 km/h occur very rarely, the hurricane velocities are about 150 km/h. hence strength components calculations will be based on wind speed of 150 km/h and further safeguarding will be provided by furling action. So all values of forces and bending moments are to be estimated for wind velocities of 150 km/h. however, it is seen that the wind force is a function of Vu2 and therefore for 3 times velocity, the forces and bending moments are to be simply multiplied by factor of 9.



Over and above the design margins, a factor of safety of 2 is generally recommended.

The proportions adopted for an aerofoil cross section are shown in the above figure. Its modulus of section about X-X axis and cross sectional area is estimated as,

Zxx = 0.2 x t3 Area A = 3.5 t2

Bending moment due to Fx and Fy will have their components along the lift and drag lines. This design being based on the lift design principle, bending moment due to these forces along lift line will decide the section size of the aerofoil.

Bending moment along lift line = (BMx sin Φ + BMy cos Φ) / no. of blades

The bending moments along lift line are calculated from the above formula for the values of Φ as = 27, 53.41, 66.01, 72.38, 76.12 and listed in the table below

Calculation for the L and t for the aerofoil section:

For the calculation of the section unknown values such as L and t the following formula is used.

BMlift x 9 = Zxx x (ultimate Strength of material / FS) x no. of blades

For the blades the composite material of ultimate tensile strength 150 Mpa is selected. And for each BMlift the values for the L and t are calculated and tabulated as below in table

Calculation for the twist of blade:

The twist of the blade is defined in terms of the chord line. Blade twist angle is a synonym for the pitch angle; however the twist defines the pitch settings at each position along the blade according to local flow conditions.

Radius R	**Φ**	**BMlift N-m**	**L meters**	**t meters**
0	0	0	---	----
0.175	27	34.35	0.0439	0.00732
0.350	53.4	35.39	0.0443	0.00739
0.525	66.0	23.18	0.0385	0.00642
0.700	72.3	11.20	0.0302	0.00503
0.875	76.1	2.96	0.0193	0.00323

The pitch angle b is large near the root, where the rotational speed is (Vt = rω) low and small at the tip where the rotational speed is high. This situation suggests a match between the twist and rotational speed, since the relative wind velocity W is

Here is a decision to be made:

1) Fixing ω and searching for the optimum twist ß, or

2) Fixing ß and searching for the optimum ω.

The first choice is better because it is easier for designing the gear and the generator. ω was chosen to be 130 rpm for 4 m/s. As a first estimate of the twist, we use the equation for twist of the zero lift line:

ß = [(RΦt/ r) - Φt] - k (1-r/R)

Therefore

U = 2 x π x N/60 = 13.6 m/s

Rotational speed = Vt = rω = 113m/s

For calculation of twist u is taken 13.6 m/s

Therefore,

Φt = tan-1(u/Vt)= 6.860

Since ß is the angle of twist, for the first radius it is considered 00 ≤ ß ≤ 20 taking ß= 20 gives

$\Phi t = (\alpha - ß) = 6.86 - 2 = 4.860$

The equation for the twist of the blade for zero lift line is

$ß = [\ (R\Phi t/\ r) - \Phi t] - k\ (1\text{-}r/R)$

In the above equation the value of k should be greater than zero.

For the value of r= 0.175, 0.350, 0.525, 0.700, 0.875 the values of the twist angles are calculated and tabulated in the table below.

Radius R	**Φ**	**BMlift N-m**	**L meters**	**t meters**
0	0	0	---	----
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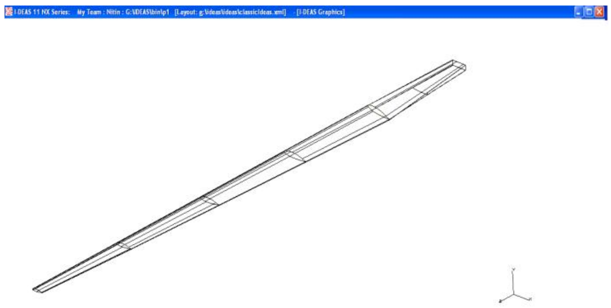
Model of blade drawn in IDEA -11software

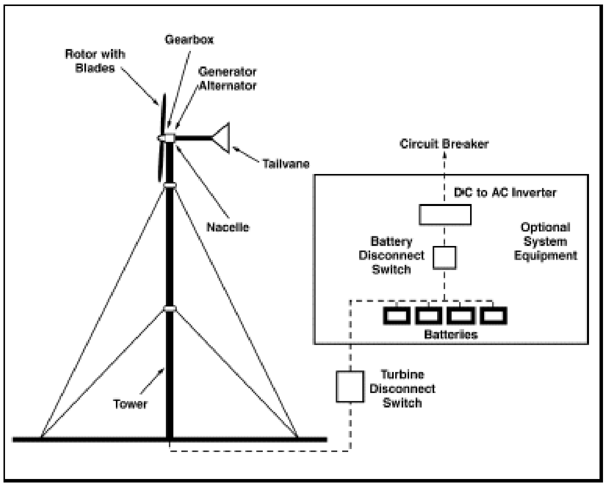


Testing and Performance of small wind mill

a) The 1 kW small wind machine is a three bladed, up -wind, horizontal axis, variable speed wind turbine, that uses tilting of the rotor for power regulation and speed control. The turbine uses a direct-drive PMG generator, to produce three-phase, variable-frequency, variable voltage, AC power. This power is directed thorough rectifier located in the nacelle to the turbine's controller.

b) The wind turbine was connected to a 48 V battery bank with a storage capacity of C10=260 Ah,

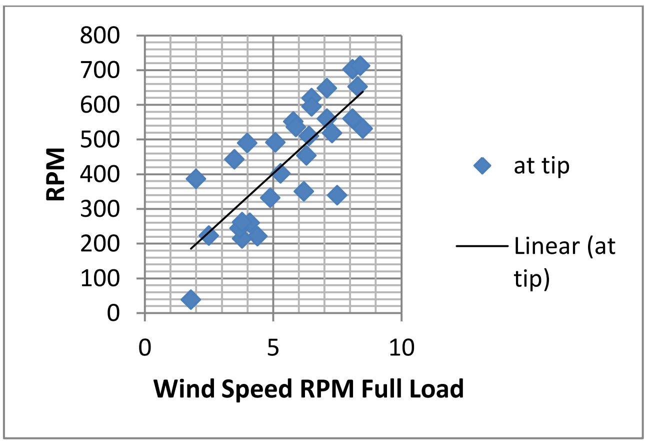
c) Test is performed in accordance to the IEC 61400-121 Ed. 1: "Power Performance Measurements of grid Connected Wind Turbines", and in particular following the specific guidelines of the annex H: "Power Performance Testing of Small Wind Turbines"



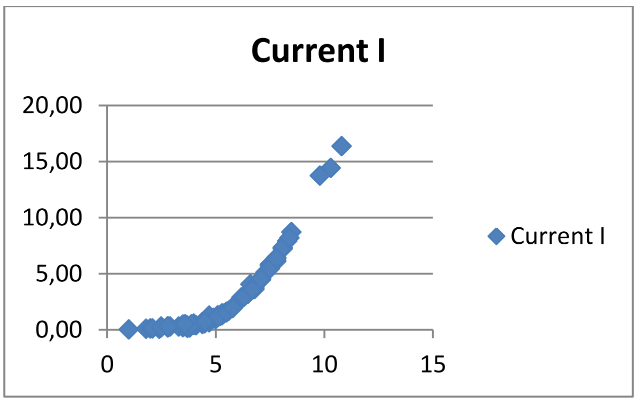
Analysis:

The analysis is as per the guidelines available in IEC 61400-12-1, design requirements of small wind mill turbines. The duration testing provides the information about structural integrity, quality of environmental protection (safety, noise etc.) and dynamic behavior of small wind machines. Though IEC standards indicate 250 hrs of testing periods, in the present case the IEC procedure was followed for performance characterization of small wind machine.

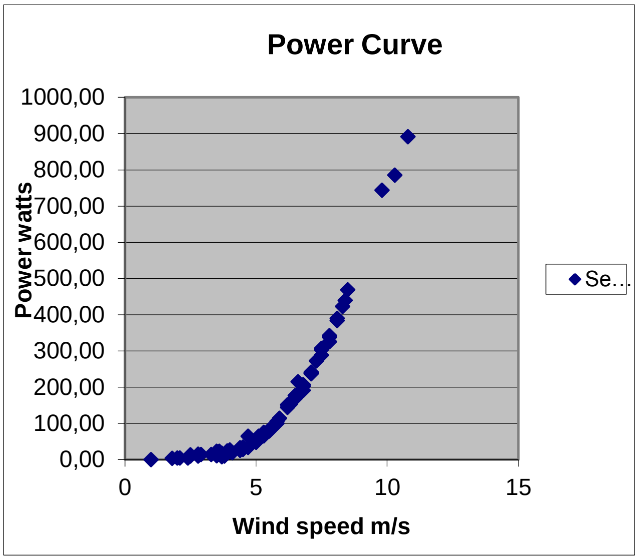
Wind speed Vs RPM- at load



Wind speed Vs current



a) Wind speed Vs Power



4. Conclusion

A new design methodology was established for indigenous development of small wind machine technology, which considers aerodynamic rotor blade design for rotor blade performance and finite element design practices for strength of rotor blades. This has facilitated to consider the cut in speed from 2m/s onwards, rated speed 11-14m/s and cut out speed of 25m/s. The FRP/ERP rotor blades having light weight and highest strength to weight ratio was selected and has fulfilled the conditions of low initial torque for lower cut in speeds. The mounting plates, power transmission, coupling, shaft bearings are designed based on regular practices of ASME, ASTM and BIS standards.

While tested as per guideline procedures of IEC 61400-12-1 standards for performance characterization, it is found that the small wind machine manufactured and developed has resulted with one of the best average performance among available small wind turbines. Though it was designed for 10-14m/s rated speed the actual maximum efficiency is observed at 8-10m/s wind velocities. The machine has started at the cut in speed of 2.8m/s and has run at 1.8m/s. Due to limitations of wind velocities at site, it is not possible to calculate the performance at higher wind speeds above 12m/s. The lower cut in wind speed and maximum efficiency at lower wind speed than designed rated speed could be because of selection of aerofoil section NREL S-822, light weight rotor blades, bearing and tail vane selection and also low rpm high permanent magnet strength generator used during the testing. The performance testing at higher wind speed is required, since maximum rotor blade tip rpm observed is @ 1000 rpm. The further wind speed testing requires safety measures.

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