Design and Performance Evaluation of Low-Cost, Innovative, Efficient Small-Scale Wind Power Generation for Rural Community of India

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Keywords Small HAWT designs · Light weight rotor blades · Balancing of rotor blades · Hub design · HAWT tail end designs · PMG · Performance curves · Rated output

Nomenclature

GFRC	Glass fibre reinforced composites
HAWT	Horizontal axis wind turbine
R&D	Research and development
RPM	Revolutions per minute
C-WET	Centre for Wind Energy Technology, Chennai
kW	Kilowatt
mW	Megawatt
GW	Gigawatt
NACA	National Advisory Committee of Aeronautics, USA
NREL	National Renewable Energy Laboratory, USA
PMG	Permanent magnet DC generator
ρ	Density of air
A	Swept area
V	Wind speed
C_p	Power coefficient
λ	Tip speed ratio
λo	Actual tip speed ratio
η	Efficiency
ω	Linear velocity in m/s
τ	Torque
R	Total radius

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r	New desired radius
C	Chord width
N	Revolution per minute
α	Angle of attack
S_p	Shape parameter
B	No. of blade
C_i	Initial chord width for each section
C_l	Lift coefficient

1 Introduction

The foundation for this research is recognition of the need for sustainable practices and development of renewable energy sources, and acknowledgment of the benefits that such forms of energy can have for individuals and communities, especially when conventional grid-supplied electricity is not available.

This paper envisions the design and appropriate implementation of a 500 W electricity producing wind turbine. The turbine will ideally be intended for implementation in remote communities to power individual house's electrical needs. The aim of the project is to design a wind energy converter comprising of the rotor system, and a generator that will successfully produce the specified electrical power.

The performance criteria necessary in the design of small wind turbine (SWT) are examined, as well as some of the theory and calculations necessary to develop such performance standards. Also, an investigation into the associated design standards and a discussion of how they relate to performance criteria are presented. High initial costs and significant structure of the Large Wind Turbines have given rise to cheaper, Small Wind Turbine market. Small Wind Turbines are lightweight, which allow them to function with the lightest wind. Technical developments have increased the efficiencies of these turbines, which are now being used to power homes and businesses. Due to the advanced technology; the wind turbine blades have become lighter, smaller, but more efficient. Further, a countable number of Small Wind Turbines are also available with wireless connectivity, which enables owners to control the turbine dynamics from a distant location, while some Wind Turbines are fitted with electronic displays. New Wind Turbines can also be used on and off grid, as expected by an owner. Such technological up gradation has made these Wind Turbines more reliable as a source of energy and driven the market for the Small Wind Turbines [1–3].

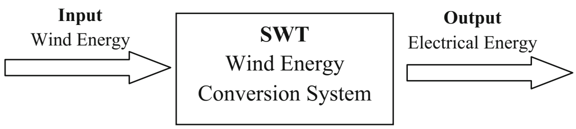
The most useful and shared type of wind turbine found today is the horizontal axis wind turbine which can be most easily identified by its propeller-like rotor design.

2 Design of HAWT System

The design details of 500 W Horizontal Axis Wind Turbine System is given below in this section (Figs. 1 and 2).

The fundamental principles that govern the operation of a HAWT will be investigated to develop further understanding of the system requirements. These principles will assist in identifying the elements of the design. The major components of this type of design have been designated as Rotor, Generator, Tower and foundation Yaw mechanism with tail, Furling mechanism, Slip rings and electrical cabling, Energy storage or conversion system, Electrical control system, with over-speed and lightning protection One of the fundamental theories of rotor aerodynamics is the one-dimensional (1D) Betz's Elementary Momentum Theory. Betz's simple momentum theory considers a stream of air moving through a circular disk. The analysis is based on the following assumptions: (1) Homogeneous, incompressible, steady-state fluid flow (2) No frictional drag (3) An infinite number of blades (4) Uniform thrust over the entire rotor area (5) Non-rotating wake (air stream after passing through rotor) (6) Upstream and downstream static pressures are equal to the undisturbed ambient static pressure. One-dimensional theory considers a moving stream of air passing through a circular disk (Fig. 3). The kinetic energy equation gives the energy in the moving stream of air [4, 5]:

Fig. 1 System diagram



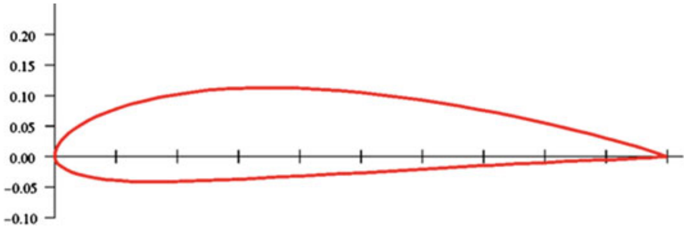


Fig. 2 NACA 4415 aerofoil

Fig. 3 Rotor blade

$$E = \frac{1}{2} mV^2 \tag{1}$$

Energy per unit time gives the power in this air stream:

$$P = E/t = \frac{1}{2} mV^2/t = \frac{1}{2}\frac{m}{t} V^2 = \frac{1}{2} mV^2 \text{ (W)} \tag{2}$$

where ‘m’ is the mass flow rate of the air stream, and is given by,

$$m = \rho A \nu \text{ (kg/s)} \tag{3}$$

Thus the power of a moving stream of air, with density ρ and velocity v, that flows through a disk of area A is:

$$P = \frac{1}{2} \rho A \nu^3 \tag{4}$$

This expression gives the power available in a moving stream of air, but the power that can be extracted from this moving stream is what is required. Thus we can consider a ratio, known as the power coefficient, between the power in the wind, and the power of the rotor:

$$C_p = \text{Rotor Power/Wind Power}$$

In theory, the maximum possible rotor power coefficient is given by the Betz Limit, C_P = 16/27 = 0.593 [6] . In practice, however, further inefficiencies cause a decrease in the maximum achievable output power:

So the power output of the SWT can be summarized as:

$$P = C_p \times \eta \times \frac{1}{2} \rho A \nu^3 \tag{5}$$

2.1 Design of Blade

The blade is one of the most important parts of the wind machine, which converts the kinetic energy into electrical energy. From root to tip the blade is loaded with varying forces. The way to consider such loading is to write the expressions for a small section of the blade at radius ‘r’ and find out the distribution; this is the “blade element theory.”

$$\text{Power} = \frac{1}{2} \times \rho \times A \times V \times C_p \times \eta_g \times \eta_g \tag{6}$$

Using tip speed ratio and blade Solidity graph we have to select the Aerogenerator tip speed ratio.

For that we have to calculate first angular velocity

$$\lambda = R \cdot \omega \tag{7}$$

More factor of safety more reliability hence increases the blade length and cost.

Now, Angular velocity ω is calculated by

$$\therefore \lambda = 0.85 \times \omega \tag{8}$$

Now from following equation speed is calculated.

$$\omega = \frac{2\pi N}{60} \tag{9}$$

Hence Tip speed Ratio at ‘r’ is calculated by eq.

$$\lambda r = \lambda o \times \frac{r}{T} \tag{10}$$

Chord width is calculated from equation

$$C = r \times \frac{SP}{CL} \times B \tag{11}$$

Torque is calculated by following equation

$$\text{Torque,} \quad \rho = \frac{2\pi N}{60} \tag{12}$$

2.2 Selection of Aerofoil Section

By preferring Blade Element Theory, Now preferring NACA 4415—airfoil i.e. 40% chamber height 40% chord length 15% Thickness of chord length, Now as per design foil software max. Lift occur in NACA—4415, 0018, 63-215 While, CL/C ratio is maximum for 4415. And at =50 i.e. angle of attack is 50. So the airfoil selected for our wind machine blade is NACA 4415 which is shown below and the coordinates for drawing the profile is also given in the table below.

3 Construction of HAWT

Figures 4, 5, 6, 7, 8, 9 and 10

Fig. 4 Rotor hub plate and bush

Fig. 5 Nacelle bed plate with yawing assembly

Fig. 6 Tail vane assembly

Fig. 7 Tower assembly

Fig. 8 PMDC generator assembly

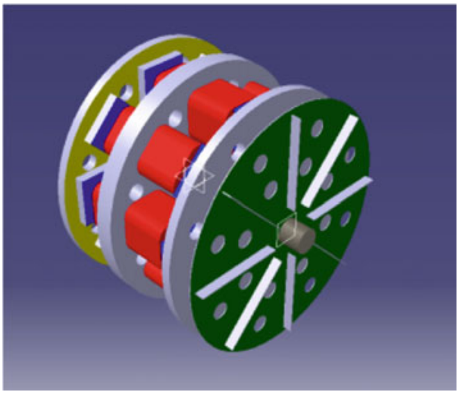


Fig. 9 Wind speed measurement on Anemometer

Fig. 10 Assembly of HAWT

4 General Characteristics of 500 W Small Wind Turbine

Cut-in wind speed	2.7 m/s	Voltage	24 V
Rated wind speed	10 m/s	Tower	Tubular concrete fitted
Cut-out wind speed	15 m/s	Material	Mild steel
Rotor situation	Up wind	Height	3 m
Number of blades	Three	Height from ground	30 m (building + pole ht.)
Blade material	FRP	Yawing system	Fitted at the top of the pole
Rotor diameter	0.55 m	System regulation	Rotor tilting
Generator	PMDC	Emergency brake	Generator short circuit
Rated power	500 W	Weight	30 kg without pole

5 Testing of HAWT

The 500 W small wind turbine is installed on the roof of the International school of Technology, Department of Technology building of the Shivaji University for testing. As micro-siting is done previously the points of maximum wind speed were located, and the wind turbine was installed by constructing the column on a tower of 3-m height, supported by heavy angles which can be quickly lowered to roof level for turbine inspection and maintenance (Table 1).

Table 1 Sample readings of HAWT

S. No.	Wind speed (m/s)	Speed of turbine (RPM)	Voltage (V)	Current (A)	Actual power (W)	Th. power (W)	Efficiency (%)
1	1.2	72	20.5	0.7	14.35	1.07	7.46
2	1.9	122	21.2	1.5	31.8	4.25	13.37
3	0.9	65	21	0.5	10.5	0.45	4.30
4	0.7	52	21.2	0.2	4.24	0.21	5.01
5	0.6	52	21.3	0.19	4.04	0.13	3.30
6	1.7	90	21.5	1.2	25.8	3.04	11.80
7	1.5	75	21.1	1	21.1	2.09	9.91
8	2	110	21.2	1.7	36.04	4.96	13.76
9	2.5	130	21.1	3.4	71.74	9.68	13.50
10	1.2	79	21	0.7	14.7	1.07	7.28
11	0.5	60	20.7	0.17	3.51	0.07	2.20
12	1.4	75	20.8	1	20.8	1.70	8.17
13	4.4	279	21.1	5.3	111.8	52.81	47.22
14	2.3	145	21.1	3.1	65.41	7.54	11.53
15	4.5	270	21.2	5.3	112.3	56.49	50.28
16	3	192	21	3.7	77.7	16.74	21.54
17	3.7	195	21.3	3.4	72.42	31.40	43.36
18	2.7	142	21.1	2.2	46.42	12.20	26.28
19	2.9	171	21.2	3.1	65.72	15.12	23.00
20	4.6	295	21.4	5.9	126.2	60.34	47.79
21	5.4	342	21.7	6.5	141.0	97.62	45.21
22	4.6	280	21.7	5.5	119.3	60.34	50.56
23	0.8	71	21.1	0.5	10.55	0.31	3.00
24	1.1	78	21.2	0.6	12.72	0.82	6.48
25	1.2	78	21.2	0.6	12.72	1.071	8.42

6 Performance Evaluation of Horizontal Axis Wind Machine

The analysis is as per the guidelines available in IEC 61400-12-1, design requirements of a small wind turbine. Through IEC standards 250 h of testing periods, in the present case the IEC procedure was adopted for the performance, characterization of a small wind machine, as time available before monsoon was 1.5 months.

Only power performance guidelines, as per the IEC 61400-12-1, power performance measurements of electricity producing wind turbine for small wind machine is followed. That leads to power curve, power coefficients (Cp curve) and estimation of annual energy production. For small wind turbines, the average data of 15 min was collected and sorted to 0.5–12 m/s wind speed bins. The data collection is complete when the wind speed bins between 1 and 12 m/s of 15 min interval.

Some graphs have been shown related to Performance of Wind Machine.

Graph Fig. 11 shows a variation of turbine speed with wind speed. It is a common phenomenon that as wind speed increases the speed of rotation of turbine enhances. With the system described it is possible to generate sufficient amount of electrical energy.

Graph Fig. 12 shows Wind Speed versus Current. Wind Speed is plotted along X-axis and Current along Y-axis. As the linear wind speed increases from 0 to 6 m/s the current increases from 0 to 10 A.

Graph Fig. 13 shows Current versus RPM. RPM is plotted along X-axis and Current along Y-axis. With the linear increase in Turbine speed from 0 to 600 rpm the current increases from 0 to 10 A.

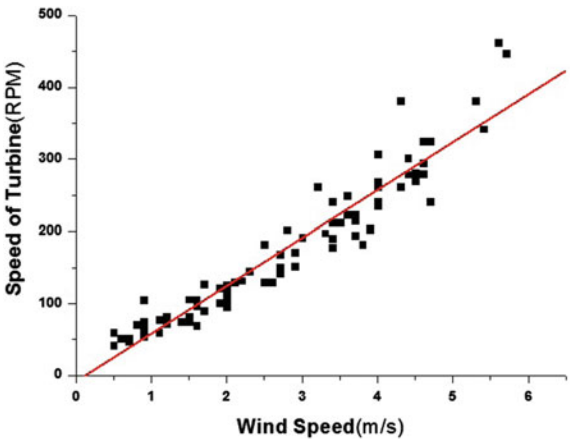


Fig. 11 Wind speed versus RPM

Fig. 12 Wind speed versus current

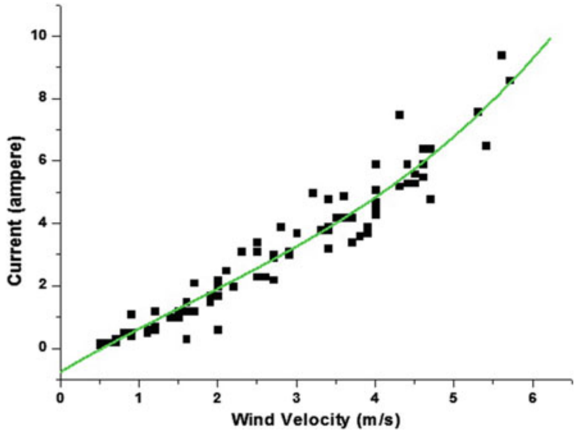
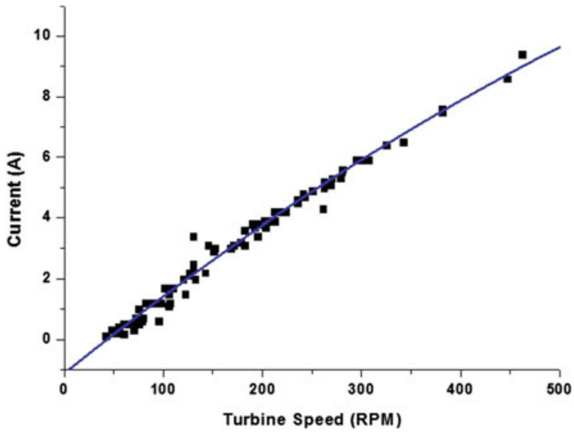


Fig. 13 Current versus RPM



7 Performance Comparison

Graph Fig. 14 shows Wind Speed versus Theoretical power. Wind Speed has been plotted along X-axis and Theoretical power along Y-axis. As the wind speed increases linearly, from 0 to 6 m/s the power increases from 0 to 120 W.

Graph Fig. 15 shows Wind Speed versus Actual power. Wind Speed has been plotted along X-axis and Actual power along Y-axis. As the wind speed increases linearly, from 0 to 6 m/s the power increases from 0 to 200 W.

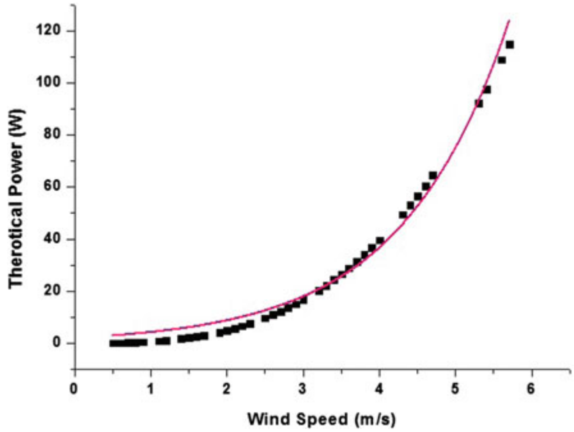


Fig. 14 Wind speed versus theoretical power

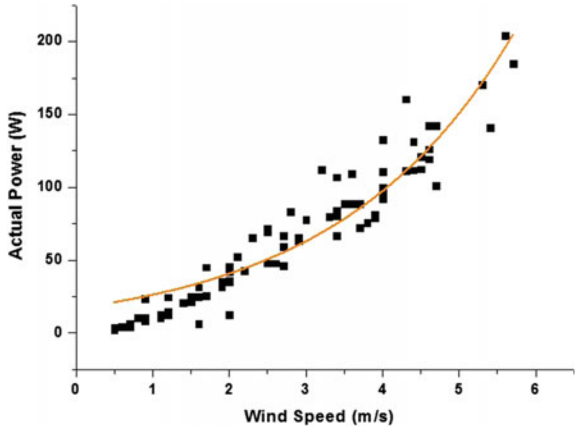


Fig. 15 Wind speed versus actual power

8 Conclusions

Based on the study, the following conclusions are listed

1. Considering the small family of 4–5 persons the daily requirement of electricity is concluded to 1.5 kW for a family.
2. The project work reveals that there is a necessity of developing horizontal axis small wind machines having capacity 200–1500 W which can run at low wind speeds. The project work has therefore considered design, development and testing of a prototype horizontal axis small wind machine of 500 W.
3. The project concludes manufacturing FRP rotor blades and allied PM Generator with suitable components like Shaft, Yawing, Bearing and Tail end, etc.
4. The testing of 500 W horizontal axis small wind machine results is as given below.

(i) The wind machine was tested in the month of December and January with a minimum wind speed of 0.6 m/s to a maximum wind speed of 10.9 m/s.
(ii) During testing the machine start at 2.7 m/s at 100 rpm as against design cut in wind speed of 3.5 m/s.
(iii) The maximum 957 RPM has been observed at 10.9 m/s. Once rotated machine kept running up to around 1.2 m/s. Due to inertia, it has gained but does not generate enough current to charge the battery.
(iv) The Power Curve Fig. 12 shows that cut in speed of our machine is 2.7 m/s where other is having 4 m/s. Also at rated wind speed it generates 350 W where prototype machine produces 500 W.
(v) It has been concluded that the machine developed through the Research and Development gives better results and performance than the similar capacity machines available in the market. The prototype device is more feasible than imported machine for local wind conditions.

References

1. Hau E (2000) Wind turbine fundamentals, technology, application, & economics, 2nd edn. Springer Publication, Germany
2. International Electro technical Commission (2005) Wind turbines—Part 12—1: Power performance measurements of electricity producing wind turbines, IEC 61400-12-1:2005(E), International Electro Technical Commission, Geneva, viewed 19 May 2010. http://www.saiglobal.com.ezproxy.usq.edu.au/online/autologin.asp
3. Chalmers BJ, Spooner E (1999) An axial-flux permanent-magnet generator for a gearless wind energy system. IEEE Trans Energy Convers 14(2):251–257
4. IEC-61400-12-1. Wind turbine generator system, Part 12, Power performance measurement technique
5. IEC-61400-2. Wind turbines, part-2: design requirements for small wind turbines
6. Manwell J, McGowan J, Rogers A. (2002) Wind Energy Explained: theory design and application, John Wiley & Sons, Chichester, England