www.ijecs.in
International Journal Of Engineering And Computer Science ISSN:2319-7242
Volume 3 Issue 10, October 2014 Page No. 8469-8475

Performance analysis of a newly designed three frame VAWT having cavity vanes

Ahmed Y. Qasim[1]*, G.A. Quadir[2], Salih Hameed[3], Waleed A. Obaid[4] and Adel Abdalrahman Ziyed[5]

[1,3,4,5] Ministry of Industry & mineral, Alkarama General Company, Iraq.
Ayhk66@yahoo.com

[2]School of Mechatronic Engineering, UniMAP, Pauh Putra, 02600 Arau, Perlis Malaysia
gaquadir@unimap.edu.my

Abstract: ***A vertical axis wind turbine model having three frames with cavity vanes has been designed, fabricated and tested in a low speed wind tunnel. This type of model has a high drag coefficient when the vanes close the frame on one side while rotating with wind direction and capturing the wind efficiently. On the other side, the frame rotates in the opposite direction of the wind which opens the frame causing the wind to pass through the frame with low resistance. The model is tested in a wind tunnel with the wind speeds varying between 3 m/s and 17 m/s. The present model gives the maximum power coefficient of 0.32 at a wind speed of 8.2 m/s and tip speed ratio of 0.31 which is higher than those of the vertical axis wind turbines in the literature for the purpose of comparison. The performance of a similar prototype VAWT having a scale ratio of 10:1 is also predicted using the dimensional analysis.***

Keywords: Vertical axis wind turbine, Power coefficient, Cavity vane, Tip-speed ratio, Performance analysis

1. Introduction

Wind energy is one of the cheapest and cleanest of renewable energy technologies. Wind power is the conversion of wind kinetic energy into a useful form, such as mechanical or electrical energy that can be harnessed for practical use by using wind turbines. Wind power generators use mainly aerodynamic lift force and drag forces acting on their blades or vanes surfaces. Today many researchers say that horizontal axis wind turbines (based on lift force design), theoretically, have higher power efficiencies than vertical axis wind turbine (based on drag force design) [1].

There are also researchers who state that under turbulent conditions with rapid changes in wind direction more electricity will be generated by vertical turbines, despite their lower efficiency.

There are many advantages of using vertical axis wind turbines (VAWT). It is Omni directional– accepts wind from any angle which results in no power loss while the rotor turns towards the direction of the wind. It can capture ground – Level winds, and its components (the generator and the gearbox of such systems) can be mounted at ground level. Its towers are also of lighter weight. Under turbulent conditions, and for rapid changes in wind direction, the VAWT is more efficient than the HAWT and has a high starting torque (Savonius rotor).

The theoretical maximum power coefficient of a wind turbine of any design operating in an open atmosphere is lower than 59.3 % [2], which is known as the Betz limit. It is reached by setting up the ratio between the maximum power extractable from the turbine rotor and the energy in the wind. However, the real world limit is well below the Betz limit with values of 0.35-0.45 for the best designed wind turbines.

The vertical axis wind turbine (VAWT) is mainly propelled by drag forces and the rotor cannot rotate faster than the wind velocity. Therefore, written the power coefficient of VAWT depends on the drag coefficient of the rotor frame and the maximum power coefficient (Cp_{max}) is equal to $\frac{4}{27}CD$ [3].

Saha and Rajkumar [4] investigated the feasibility of twisted blade Savonius rotor for power generation by conducting experiments on a three-bladed rotor system having twisted blade in a low speed wind tunnel. Its performance was compared with that of a rotor system of conventional semicircular blades (with twist angle of 0°). Performance analysis was made on the basis of starting characteristics, static torque and rotational speed. Their experimental evidence shows the potential of the twisted bladed rotor in terms of smooth running, higher efficiency and self-starting capability as compared to that of the conventional bladed rotor.

Saha et al. [5] carried out experiments in wind tunnel to assess the aerodynamic performance of single-, two- and three-stage Savonius rotor systems having both semicircular and twisted blades. They manufactured a family of rotor systems with identical stage aspect ratio keeping the identical projected area of each rotor. An optimization was carried out to optimize the number of stages, number of blades (two and three) and geometry of the blade (semicircular and twisted). They found that the optimum number of blades is two for the Savonius rotor whether it is single-, two- or three-stage. Also, the twisted geometry blade profile had good performance as compared to the semicircular blade geometry and the two-stage Savonius rotor had better power coefficient as compared to the single- and three-stage rotors. Further, the valve-aided Savonius rotor with three blades showed better performance coefficient as compared to the conventional three-bladed rotor.

Muller et al. [6] have analyzed the Sistan type windmill, and discussed modern adaptations of this drag force type energy converter for building integration. They found that their improved design can lead to an increase of the theoretical efficiency to about 48% (conservative) or 61% (optimistic), Initial experiments with a scale model have shown that wind turbine efficiencies higher than 40% can be achieved.

Mohamed et al. [7] have considered a considerably improved design in order to increase the output power of a Savonius turbine with two or three blades. Their improved design leads to a better self-starting capability. They carried out the automatic optimization by coupling an in-house optimization library (OPAL) with an industrial flow simulation code (ANSYS- Fluent). They proved that the optimized configuration involving a two-blade rotor is better than the three-blade design.

It appears from the literature review that there is a need to improve the performance of a vertical axis wind turbine by improving its power coefficient. An attempt has been made in this regard in the present paper by designing a new impeller type wind turbine and evaluating its performance by conducting experiments in a low speed wind tunnel.

2. The proposed design of VAWT impeller

The present impeller type vertical axis turbine design consists of three frames with angles of 120^0 between each one. Three movable vanes in vertical position are attached to the bars located on the sides of the frames. The vanes are designed with cavities that increase drag force substantially. Under the action of the wind force, vertical vanes turn until a stopper provided on the neighboring bars to avoid clashing and open and close the frames' holes. The torque created by the wind force rotates the frames with the output shaft, which transfers the torque via gearing to the electric generator.

For the positive direction of the wind, vanes are closed on one side and bear the wind force in full. The vanes on the other side are open for the negative direction of wind causing the wind to pass freely through the frame. In this condition the wind resistance reduces and the negative torque decreases.

Fig. 1 shows the front view the impeller rotor with vanes opened and closed under the action of the wind force. Fig. 2 presents the top view of the impeller wind turbine rotor with three frames. It shows clearly that the wind passes freely from the two frames located on the right side of the impeller whereas the frame with vanes on the left side of the impeller produces high drag. The detailed design of the present impeller type vertical axis wind turbine can be found in Qasim et al. [8].

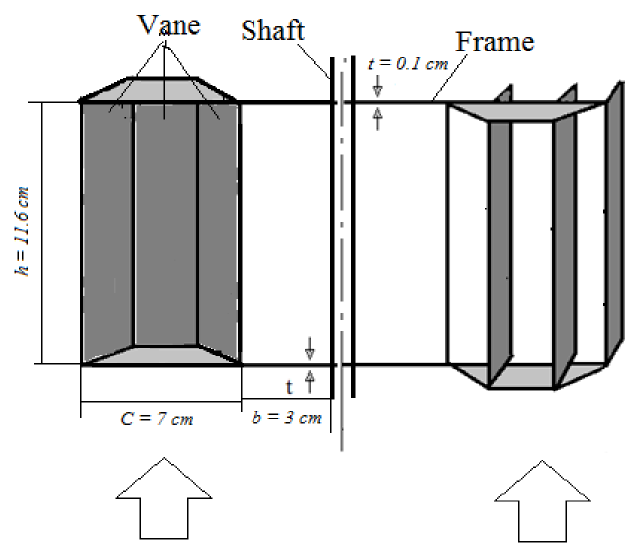

Figure 1. Front view of the impeller type wind turbine rotor

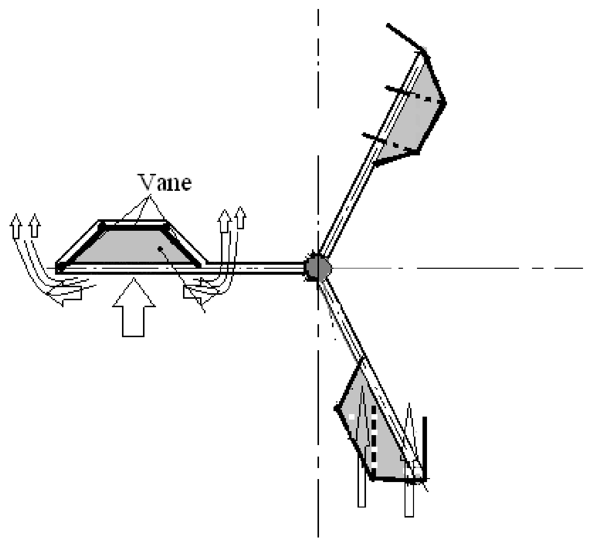

Figure2. Top view of the impeller type three frame wind turbine rotor

3. Model Tests in a low speed wind tunnel

A three frame vertical axis wind turbine model was fabricated and tested in a low speed wind tunnel to determine the power output and number of revolutions per second of the rotating shaft for different air velocities. The model has the dimension as 200 mm in diameter, 70 mm as width of the vane, and 116 mm as its height. The test section dimension of the wind tunnel is 300x300x300 mm^3. The model of the impeller-type wind turbine was held on a shaft located in the middle of the wind tunnel test section which was mounted on ball bearing and connected to a generator. For the low speed wind tunnel, it is assumed that the compressibility effect of air is negligible and also the wind tunnel walls do not interfere with the aerodynamic drag on the model. The wind speed was varied between 3 m/s and 17 m/s. The Compact Instrument Advent Tachopole was used to measure the rotational speed of the wind turbine shaft.

4. Dimensional Analysis

Wind turbines come in different sizes. They experience a wide range of variables when in operation. These variables complicate the process of comparison of different size of turbines in terms of their performance. To deal with this, the help of dimensional analysis is taken. One of the qualities of dimensional analysis is that geometrically similar turbines will produce the same non-dimensional results. This allows one to make comparison between different size wind turbines in terms of power output and other related variables.

There are 6 parameters which are relevant to the power of wind turbines. They are:

$$W = f\,(V_{wind}, \rho, D, \mu, \omega)$$

where, W is the power delivered to the grid, V_{wind} is the wind speed, ρ is the wind density, μ is the wind dynamic viscosity, and ω is the angular velocity. Thus, we have (6 - 3) Π = 3 Π, the dimensionless group of variables as a function of the other according to Buckingham Pi-theorem [9]. The functional relationship of these dimensionless groups is expressed as:

$$\Pi_1 = f\,(\Pi_2, \Pi_3)$$

The required repeating variables are chosen to be

$$\rho,\ \omega \text{ and } D$$

Following the method of Buckingham Pi theorem, the three dimensionless Π terms are found as:

$\Pi_1 = \dfrac{W}{\rho\,\omega^3 D^5}$, called as the power coefficient, C_P

$\Pi_2 = \dfrac{\omega D}{V_{wind}} = \lambda$, called as the tip-speed ratio and normally expressed as: $\dfrac{\omega R}{V_{wind}}$

and $\Pi_3 = \dfrac{\mu}{\rho \omega D^2} = \dfrac{1}{\mathrm{Re}}$, called as the Reynolds number.

The functional relationship between the three Π terms is given as:

$$\frac{W}{\rho\omega^3 D^5} = f(\lambda, Re) \qquad (1)$$

The non-dimensional terms ($\frac{W}{\rho\omega^3 D^5}$), can also be expressed as equal to ($\frac{W}{\frac{1}{2}\rho A V_{wind}^3}$), where A is the swept area of the rotor.

The efficiency with which a rotor can extract power from the wind depends on the dynamic matching between the rotor and the wind stream. Hence, the performance of a wind rotor is usually characterized by the variations in its power coefficient with the tip speed ratio. As both these parameters are dimensionless, the *CP-λ* curve represents the rotor performance, irrespective of the rotor size and site parameters. Once such a relationship is deduced for a typical rotor design, it can further be translated to the velocity power curve of the rotor for practical applications.

5. Results and Discussion

In this section the model test results are presented first. Then the performance of a prototype wind turbine is predicted for the same range of wind velocities. Lastly, the performance of the proposed VAWT is compared with that of some other vertical axis wind turbines reported in the literature.

5.1 CP – λ variation for the proposed VAWT

From the experimental tests on the model, the results are presented in terms of the power coefficient and tip speed ratio as shown in Fig. 3. It can be seen from this figure that the tip speed ratio (λ) varies from 0.192 to 0.342. The power coefficient is equal to 0.188 at the lower value of λ. It increases to a maximum value of 0.32 at λ = 0.31 and thereafter it decreases with the increasing tip speed ratio. It should be noted that the decrease in C_P after its maximum value is mainly due to the increase in wind velocity (over 8 m/s) because the tip speed ratio does not vary much after the maximum C_P.

The shape of this curve is made plausible with the following reasoning:

- At λ = 0 the rotor does not rotate and hence cannot extract power from the wind.

- At very high λ (here at λ = 0.341) the rotor runs so fast that it is seen by the wind as a completely blocked disc. The wind flows around this "solid" disc (as if it was a solid building), so there is no mass transport (wind) through the rotor, and hence no possibilities to extract energy from a moving mass (the wind).

- Somewhere between λ = 0 and λ = 0.341 there will be an optimum value (here at λ = 0.31) for which the maximum power is extracted.

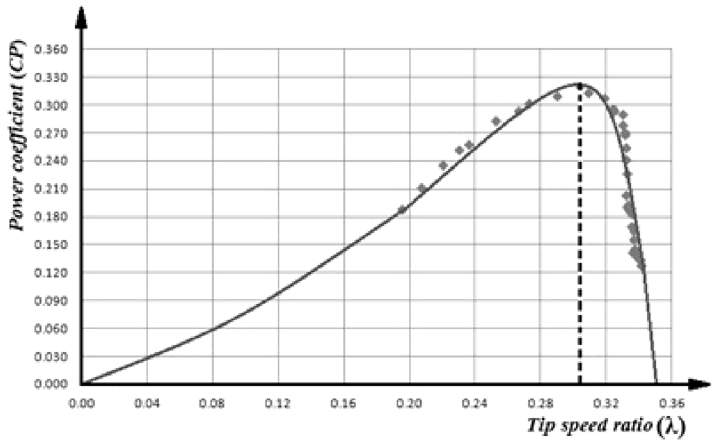

Figure 3. Experimental results of Power Coefficient versus tip speed ratio for the proposed wind turbine model

The above figure can also be expressed in terms of the rotational speed of the rotor. As the wind speed changes, the rotational speed of the rotor also changes according to:

$$\lambda = \frac{\omega R}{V_{wind}} = \frac{2\pi n r}{60 V_{wind}} \qquad (2)$$

where n is the rev/min of the rotor at a particular V_{wind}. Fig. 4 shows such a relationship which is similar in pattern with that of Fig. 3.

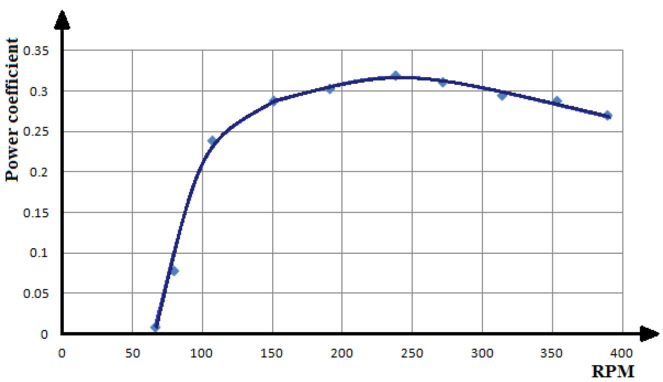

Figure 4. Power coefficient versus rotor speed (RPM) for model at wind speeds varying from 3.75-12 m/s

5.2 Performance prediction of the prototype VAWT

In order to predict the performance of a prototype wind turbine (having similarity with the proposed model in all respects), the model test data are used according to the dimensional analysis functional relationship expressed by Eq. 1. It is to be noted that the performance of the prototype wind turbine has to be evaluated at the same wind speeds at which the model test data are obtained.

From Eq. (1), the CP- λ curve should be the same for the model and prototype wind turbines for any scale ratio, which is achieved by [10]:

a) Maintaining the tip speed ratio same

b) Maintaining the blade profile, and the number of blades same, and

c) Making proportional adjustments to all dimension for the scale ratio chosen)

Thus, for λ to be same for the model and the prototype, we have

Or, $$N_p = N_m \left(\frac{r_m}{r_p}\right)\left(\frac{V_p}{V_m}\right) \tag{3}$$

Assuming the scale ratio to be 1:10, i.e. the prototype being 10 times larger in scale than the model, it is observed from Eq. 3 that the prototype wind turbine rotational speed will be 1/10th of that of model at the same wind velocity, Vwind. The same ratio is valid for the angular speed, ω as well.

The power that the prototype wind turbine will develop can be found by similarity relationship of the power coefficient as derived earlier and expressed as:

$$\frac{W_m}{\rho_m \omega_m^3 D_m^5} = \frac{W_P}{\rho_P \omega_P^3 D_P^5}$$

$$W_P = W_m \left(\frac{\omega_P^3}{\omega_m^3}\right)\left(\frac{D_P^5}{D_m^5}\right) \tag{4}$$

The power of the prototype wind turbine (WP) at each wind speed is calculated by using Eq. 4 where Wm and ωm are the power and angular velocity of the model as obtained in the model test at a particular wind velocity. The calculated results of WP are tabulated in Table 1

Table 1: Power of prototype wind turbine (scale ratio (10:1) predicted for different wind velocities

V_{wind} m/s	ω_m rad/s	λ_m	W_m W	ω_P rad/s	W_P W	C_P
3.75	6.8	0.18	0.007	0.68	0.7	0.01
4	8.21	0.205	0.07	0.82	7.0	0.08
5	11.10	0.222	0.422	1.11	42.2	0.24
6	15.71	0.262	0.893	1.57	89.3	0.29
7	19.90	0.284	1.45	1.99	145	0.305
8	24.82	0.310	2.36	2.48	236	0.32
9	28.38	0.315	3.16	2.84	316	0.312
10	32.78	0.328	4.28	3.28	428	0.296
11	36.86	0.335	5.49	3.69	549	0.29
12	40.63	0.339	6.82	4.06	682	0.271

For the prototype wind turbine with scale ratio (1/10), the *A = 2.23* m^2, the variation of power with the variation in wind velocity (W_P - V_{wind}) is shown in Fig. 5. This figure shows the cut-in speed at 3.75 m/s and the cut-out speed at 25 m/s. The cut-in speed is the speed at which the turbine starts generating electricity from turning and the cut-out speed is the wind speed at which the machine will be turned out of the wind to prevent damage. As regards rated speed, Jatzeck, et al. [11] reported that the optimum value for the rated wind velocity varied between 30 km/hr to nearly 50 km/hr (i.e. 8.5 m/s to 14 m/s). The rated speed is defined as the minimum wind speed at which the wind turbine will generate its designated rated power, Widodo et al. [12] stated that V_{rated} =1.5 $(V_{average})_{wind}$. For the proposed wind turbine design in this work the rated wind speed is taken as 12 m/s, which lies in the range as mentioned by other researchers.

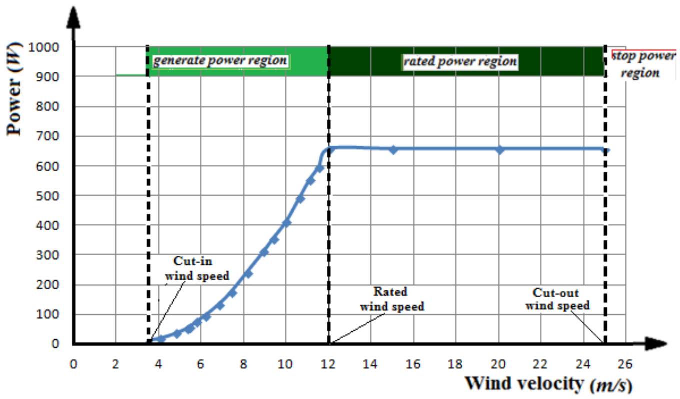

Figure 5. Power generated versus wind speed for prototype scale ratio (1/10)

6. Conclusions

The present work relates to the design of a new impeller type vertical axis wind turbine and its performance for varying wind velocities carried out in a low speed wind tunnel. This design presents a three frame impeller wind turbine having cavity shaped vanes located on vertical bars installed in hinges of the frames. The frames are designed with angular inclinations of vanes that create cavities when vanes are closed. On the other side of the impeller, when the movable vanes are open, and the frame is under wind action, the air passes freely through the frame, and decreases the negative torque. The cavity shaped vanes use 45˚ as vane angle.

The results are presented in the form of power coefficient against tip speed ratio for wind velocities varying from 3 m/sec to 17 m/sec. The performance of the model is compared with similar type of wind turbines (Savonius wind turbine) operating on the drag force and each having three frames/blades, available in the literature. The present model gives the maximum power coefficient of 0.32 at a wind speed of 8.2 m/s and tip speed ratio of 0.31 which is higher than those of the vertical axis wind turbines in the literature for the purpose of comparison. The performance of a similar prototype VAWT having a scale ratio of 10:1 is also predicted using the dimensional analysis.

The proposed new impeller type vertical axis wind turbine can be used worldwide due to its high efficiency, simple construction, and simple technology. Further, the proposed wind turbine can also be made from cheap materials.

References

[1] R. Nobile, M. Vahdati, J. Barlow, A. Mewburn, Dynamic stall for a Vertical Axis Wind Turbine in a two-dimensional study. World Renewable energy congress, Sweden. (2011).

[2] S. Mathew, Wind Energy Fundaments, Resource Analysis and Economics. 1st ed. Springer 2006.

[3] M. Kaltschmitt, W. Streicher, and W. Andreas, Renewable Energy. Technology, Economics and Environment, Spring, New York, 2007.

[4] U.K. Saha, J. Rajkumar, On the performance analysis of Savonius rotor with twisted blades, Renewable Energy 31 (2006) 1776–1788.

[5] U.K. Saha, S. Thotla, D. Maity, Optimum design configuration of Savonius rotor through wind tunnel experiments, Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 1359– 1375.

[6] G. Muller, F. M. Jentsch, E. Stoddart, Vertical axis resistance type wind turbines for use in buildings, Renewable Energy 34 (2009) 1407–1412.

[7] M.H. Mohamed, G. Janiga, E. Pap, D. Thévenin, Optimization of Savonius turbines using an obstacle shielding the returning blade, Renewable Energy 35 (2010) 2618-2626.

[8] A.Y. Qasim, R. Usubamatov and Z.M. Zain, Investigation and Design Impeller Type Vertical Axis Wind Turbine. Australian Journal of Basic and Applied Sciences, 5(12): (2011) 121-126.

[9] Yunus A. Cengel, Heat and Mass Transfer: A Practical Approach, 3rd Edition (Boston: McGraw Hill, (2003).

[10] R. Gasch, J. Twele, Wind Power Plants: Fundamentals, Design, Construction and Operation, Second ed. Springer-Verlag Berlin Heidelberg. (2012).

[11] B.M. Jatzeck, A.M. Robinson, D.O. Koval, Estimation of the optimum rated wind velocity for wind turbine generators in the Vicinity of Edmonton, Alberta. Proceedings of the IEEE Canadian Conference on Electrical and Computer Engineering Shaw Conference Center, Edmonton, Alberta, Canada. (1999).

[12] W.S. Widodo, A.C. Chin, H. Sihombing and M.Y. Yuhazri, Design and analysis of 5 kW Savonius rotor blade. Global engineers & technologists review. 2(8), (2012).

[13] K.N. Morshed, Experimental and numerical investigations on aerodynamic characteristics of Savonius wind turbine with various overlap ratios. Master thesis. Georgia Southern University Georgia (2010).

Author Profile

Ahmed Y. Qasim received the B.S. and M.S. degrees in Mechanical Engineering from Al-Mustansirya University in Baghdad and received the Ph.D. degree in mechanical engineering (turbine) from university Malaysia Perlis in 2013. He now in Al-karama General Company - Ministry of Industry & mineral, Iraq.