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Design of flat vanes vertical axis wind turbine

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ABSTRACT

This work designs the rotor wind turbine, which uses more effectively for the wind energy and depends on the acting area of the vanes. The frame design consists of three movable vanes to reduce the negative torque of the frame that rotates contrary to the wind. The wind tunnel is used to measure the power coefficient, torque coefficient and angular velocity as a function of wind velocity. The power coefficient is measured experimentally to be equals to 18% and 21% for three and four frames, respectively. The rotor wind turbine is applicable internationally due to its high efficiency, simple construction, and simple technology.

Introduction

The power from the wind will never cease while the sun is still rising, and the earth is revolving. Wind exists everywhere on the earth, and in some places with considerable energy density. Wind has been used in the past to generate mechanical power. Nowadays, wind power has become a promising source to generate electricity because of wind power is clean, quiet and efficient. It reduces acid rain, smog and pollutants to the atmosphere. The theoretical maximum power efficiency of wind turbine operates in opened atmosphere is Ce = 0.59 - the Betz Limit [1-2]. The actual world limit is 0.35 - 0.45. Additionally there are energy losses in a complete wind turbine system (the generator, bearings, power transmission, etc.).

Muller et al. [3] have analyzed the oldest known form of wind energy converter, the Sistan type windmill, and discussed modern adaptations of this drag force type energy converter for building integration. They found that this design improvements can lead to an increase of the theoretical efficiency of a drag force type rotor to about 48% (conservative) or 61% (optimistic), and that efficiencies higher than 40%. Mohamed et al [4] have considered a considerably improved design in order to increase the output power of a Savonius turbine with either two or three blades. This 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). The optimization process takes into account the output power coefficient as target function, considers the position and the angle of the shield as optimization parameters, and relies on Evolutionary Algorithms. They proved that the optimized configuration involving a two-blade rotor is better than the three-blade design. Saha et al. [5] have used both semicircular and twisted blades in wind tunnel tests to to assess the aerodynamic performance of single-, two- and three-stage Savonius rotor systems. Also, 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) and investigated the performance of two-stage rotor system by inserting valves on the concave side of blade. Saha and Rajkumar [6] have investigated the feasibility of twisted bladed Savonius rotor for power generation. The twisted blade in a three-bladed rotor system has been tested in a low speed wind tunnel, and its performance has been compared with conventional semicircular blades (with twist angle of 01). 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.

To calculate of the power of wind turbines, the fluid dynamics theory gives one formula with minor variations for different wind turbine designs. The fundamental equation that governs the power output (P) of a wind turbine is [7]:

$P = 0.5(\rho.\ A.\ V^3.\ A)$, Watt (1)

where: ρ is air density, V is wind speed approaching the wind turbine, λ is wind turbine efficiency for common case; and A is projected area of the turbine perpendicular to the approaching wind.

For a propeller wind turbine A is a swept area of rotating blades, but actual area of blades is 4-5 times less of the swept area. The wind passes through propellers freely but does not affect the blades. The maximum efficiency for a flat plate rotor (excluding the potential effect of wind pressure acting on more than one rotor blade) is up to 18% for plate has aspect ratios of less than 5:1.

It is objected that our design consists of three movable vanes to reduce the negative torque of the frame that rotates contrary to the wind. The wind tunnel is used to measure the power coefficient, torque coefficient and angular velocity as a function of wind velocity. The first thing is to calculate the force acting on the vanes due to the momentum change of the air impinging upon them. The organizing of this article is as followings: the turbine design is in section 2. Section 3 describes the theoretical analysis. While the experimental setup, and results and discussion are in sections 4 & 5, respectively before the conclusion in the last section.

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Brief Description of the Designe

The proposed vane type vertical wind turbine can be designed by two types of construction (Fig.1). The first type has four frames with 90^0 angles and horizontally constructed vanes that have ability to twist by 90^o. The second type has three frames with 120^0 angles. Increasing the number of frames do not increase the efficiency of the wind turbine because of increasing the frame shadow area and the weight of turbine.

Frame's elements should be designed of aerodynamic form to reduce the drag force of the wind. The frames connected to the shaft than to the electrical generator. The vanes fastened on the bars that located on sides of the frame. The frame vertical components can be designed as Darrieus type to increase the output of the wind turbine. Under action of a wind force, vanes on left side of the frame are closed and bear the wind force in full-scale. The vanes on the right side of frame are opened and a wind force is passing through the opened frame. Left side vanes should be cinematically connected with right side vanes, so vanes can be double acting. This design enables the wind force to close left side vanes and simultaneously opens the right side vanes. The torque created by the wind force rotates frames with the output shaft, which transfers the torque via gearing to the electrical generator. Vertical frames should be connected by stringers to increase the construction stiffness. Other components of the wind turbine like the tower (pole) can be made from the metallic frame and designed according to the area of application of the wind station. The sketch of the vane type wind turbine is presented in Fig. 2.

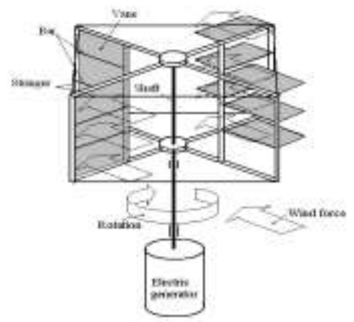

Figure 1 (a) Sketch of the vane type wind turbine, (b) general view of wind station

Simple analysis of the sketch of the vane type wind turbine shows many positive technical data and benefits. This vane type wind turbine possesses all advantages of vertical and horizontal acting wind turbines, and can be concurrent solution for known constructions [8-9].

Theoretical Analysis

For simplicity two models of the flat-vane wind turbines are analysed. A plan view of the vane-type wind turbine is presented in Fig. 1. The first model of the vane-type turbines has four sections of vanes assembled on frames, which are perpendicular to each other and joined with the main output shaft. The second one has three sections of vanes, which are 120^0 and joined with the main output shaft.

Power output depends on the wind force speed and the acting surface area A of vanes that are located at one side of the output shaft. The relationship between physical parameters acting on the vane can be considered by known approaches. Acting forces, location of the vanes, wind shadow and the wind pressure on the vanes are proportional to the power of the wind speed. The ultimate simplification is necessary for an analytical approach of considering the force acting on stationary vanes.

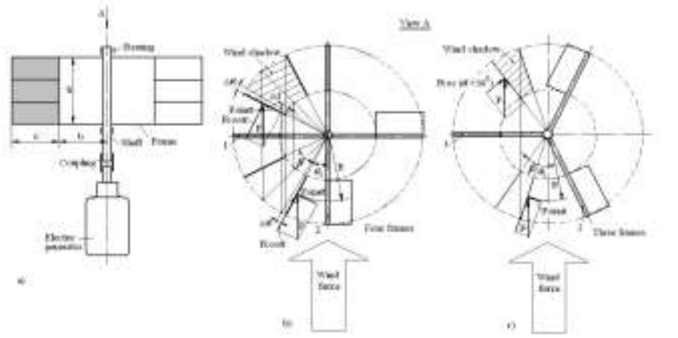

Figure 2, (a) Vane-type wind turbine (b) of four Frame (c) three frames

This simplification leads to different results depending on the assumptions made. The important assumptions are as the followings:

a) The wind turbine vanes are smooth.

b) The air hitting the vanes has no viscosity. It is further assumed that air, having struck on the vanes, moves off along the surface without causing a tangential frictional force.

c) The drag forces acting on the left and right frame components are equal.

The flat vane, with its plane normal to the air stream represents a common situation for wind force loads on the vane. For a flat vane with its normal plane to the wind flow, the only aerodynamic force will be one parallel to the wind flow, i.e. a wind force.

The drag factor C_D is variable and depends on vane configuration, wind speed, the wind angle of attack of vanes, etc. There is also a tangential component or 'skin friction' force [4].

The force component F acting on stationary vertical vanes of the left side frame is expressed by the following formula [1–3]

$$F = (1/2)C_D \rho A V^2 \sin\alpha \qquad (2)$$

Where C_D is drag coefficient, α is frame rotate angle. To determine the starting torque T on wind turbine vanes, it is necessary to define the whole vane area, and distance from the centre of the output shaft to the centre of wind pressure, as expressed

$$T = (1/2)AC_D \rho V^2 R \sin\alpha \qquad (3)$$

where R is the distance from the shaft centre line to the centre of pressure of the vane surface, The output power is calculated by the following equation

$$P = T\,\omega = (1/2)\,\rho\, AC_D V^3 \sin\alpha \text{ (Watt)} \qquad (4)$$

Where ω is the angular velocity of the rotating turbine, and T is the torque.

The torque created by the first and second frames with group of vanes calculated by the following equations:

1. The torque created by the first and second frames at the angle of rotation without wind shadow

$$T_1 = C_{D1} p[hc(b + c/2)]\sin\alpha \qquad (5)$$

where C_{D1} is drag factor, p is wind pressure

2. The torque created by the first vanes at the angle of rotation from α_1 to $\alpha_1 + \beta/2$ when of the second vanes begins create wind shadow

$$T_2 = C_{D_1} ph(c - k\Delta\alpha)[(b + k\Delta\alpha) + (c - k\Delta\alpha)/2]\sin\alpha + C_{D2}\, p[hk\Delta\alpha)(b + k\Delta\alpha/2]\sin\alpha \;\Big|_{\alpha_1}^{\beta/2} \qquad (6)$$

where C_{d2} is drag factor for vanes at zone of wind shadow

3. The torque created by the first vanes at the angle of rotation from $\alpha_1 + \beta/2$ to $\alpha_1 + \beta$ when of the second vanes ending wind shadow

$$T_3 = C_{D2} ph(c-\Delta d)[(b+\Delta d)+(c-\Delta d)/2]\sin\alpha + C_{D1} p[h\Delta d)(b+\Delta d/2]\sin\alpha \Big|_{\beta/2}^{\beta} \quad (7)$$

The negative torque in the opposite direction of wind is:

$F_n = [\sum 0.5\ C_D\ \rho\ A_{rod} V^2 + 6(\ Cf\ 0.5\rho Avane\ V^2)]\ \sin\alpha\ |^0_{180}$ (6 side vane area) (8)

$T_4 = F_n(b+c/2)$

Where, Cf is skin friction coefficient.

The ratio of shaft power (Ps) to the power available in the wind (P) is known as the power coefficient (Cp), and this indicates the efficiency of conversion. Thus:

$Cp = Ps / P$ (9)

Where P = $1/2\rho AV^3$, A is the projected area of rotor (m^2), and V is the airspeed (m/s) at the tunnel exit. The shaft power (Ps) is calculated from brake torque and rotational speed (RPM).

Experimental of the vane-type turbines in the wind tunnel

The object of the wind turbine test is to verify the ability of performance design compared with theoretical analysis efficiency. The wind turbine testing used two model fabricated by hard metal with dimensions presented in Fig.1, for four frames c = 0.048 m, h = 0.06 m and b = 0.052 m, and for 3 frame c = 0.044 m, h = 0.07 m and b = 0.066 m. The analyses considered power output test, and number of revolutions per second of the rotating shaft. The typical wind tunnel used stationary turbofan engines that sucked air through a duct equipped with a viewing port and instrumentation where models on the ball bearings shaft are mounted in order to study. The testing area of the wind tunnel length is the cube with dimensions 300x300x300 mm^3. The model of the vane-type wind turbine is located in the middle of the wind tunnel testing area and attached on the dynamo 1- 60V. The range of the wind speed used is between 5 m/s and 18 m/s. The digital anemometer model HV935 TF Instrument INC was used to measure the wind speed. The tachometer model Compact Instrument Advent Tachopole was used to measure the rotation speed of the wind turbine shaft with the piece of white paper attached, which reflects light. In the analysis data, experiments showed the four vanes is a higher speed compared to the three vanes. The situation occurs in both testing cases when the dynamo is attached to the wind turbine and without the dynamo. The obtained results vane proved the theoretical approach that four-frame wind turbine has a higher efficiency than the three-frame turbine (Fig. 3). The speed of revolution per second of two types of turbines experiences a decrease on 0.6 – 0.7 rev/s when the dynamo is connected on the turbine shaft.

Figure 3 wind turbine model test in wind tunnel

Results and discussion

Figure 4 enables the calculation of the coefficient of power and coefficient of torque, the drag factor and the efficiency of the vane-type wind turbines.

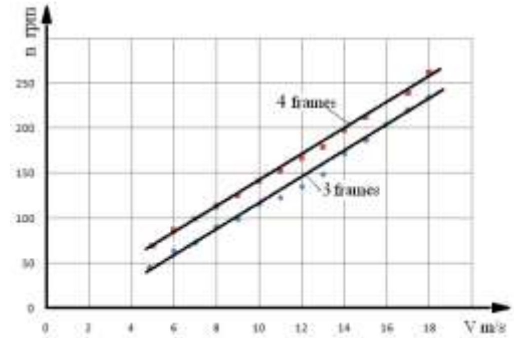

Figure 4 Number of revolutions of the wind turbine shaft versus the wind speed

Figures 5 & 6 show the results of power coefficient and torque coefficient with tip speed ratio for three frames wind turbine, we can see that the maximum power coefficient is 0.18 at tip speed ratio 0.12and maximum torque coefficient is 1.46 at the same tip speed ratio.

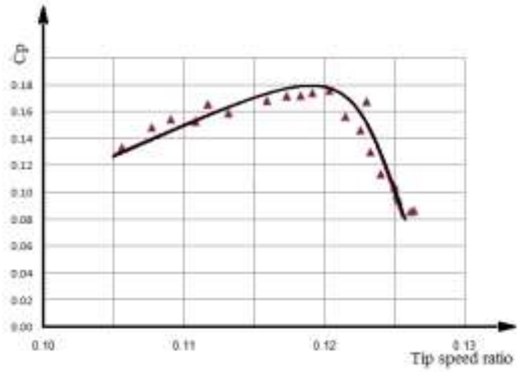

Figure 5 power coefficient various tip speed ratio for three frame wind turbine

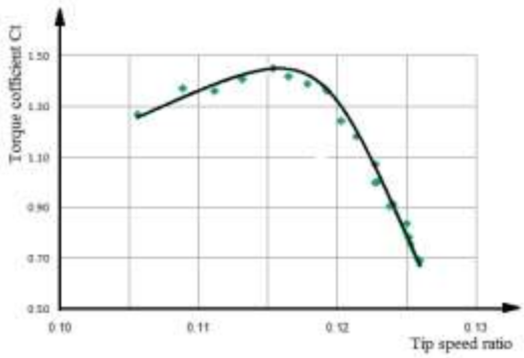

Figure 6 Torque coefficient various tip speed ratio for three frame wind turbine

Figures 7&8 show the result of power coefficient and torque coefficient with tip speed ratio for four frames wind turbine, we can see that the maximum power coefficient is 0.21 at tip speed ratio 0.113 and maximum torque coefficient is 1.93 at the tip speed ratio 0.108.

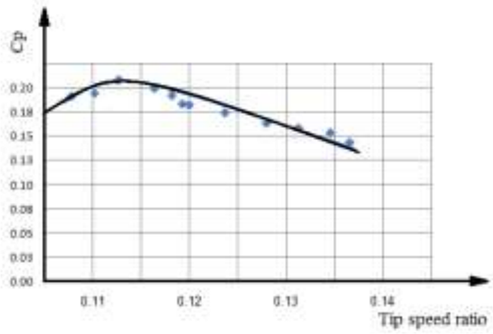

Figure 7 Torque coefficient various tip speed ratio for four frame wind turbine

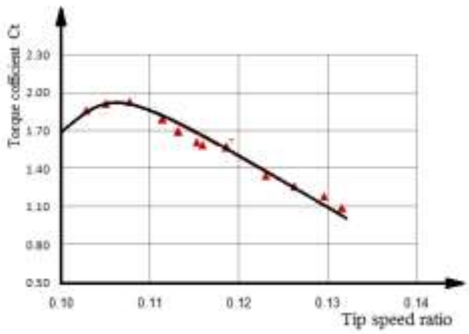

Figure 8 Torque coefficient various tip speed ratio for four frame wind turbine

Figure 9 show the results of power coefficient with wind velocity for three &four frames wind turbine, we can see for three frames the maximum power coefficient is 0.18 at wind speed 9 m/s. And the maximum power coefficient for four frames is 0.21 at the same velocity of wind.

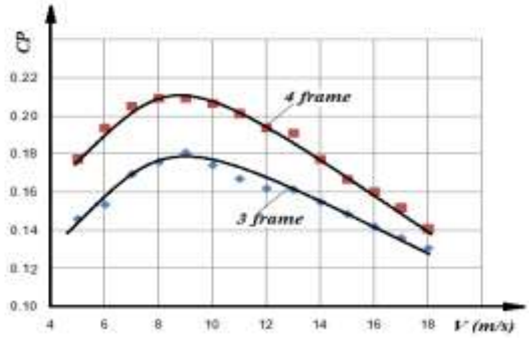

Figure 9 power coefficients various wind velocity for three &four frame wind turbine

Figure 10 show the results of torque coefficient with wind velocity for three &four frames wind turbine, we can see for three frames the maximum torque coefficient is 1.43 at wind speed 10 m/s. And the maximum power coefficient for four frames is 1.85 at the same velocity of wind.

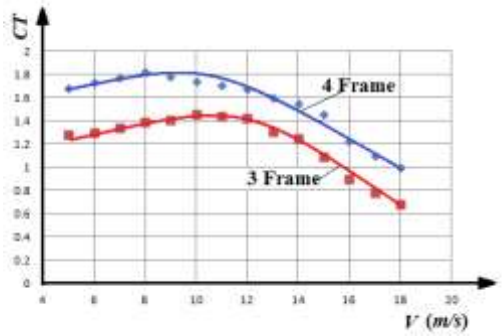

Fig.10 Torque coefficient various wind velocity for 3&4 frame wind turbine

Conclusions

For four frames the maximum power coefficient is 0.21 at wind speed 9 m/s, and maximum torque coefficient 1.85 at the wind speed 10 m/s. And for three frames the maximum power coefficient is 0.18 at wind speed 9 m/s, and maximum torque coefficient 1.43 at the wind speed 10 m/s.

The tested model of the vane-type turbines was designed with flat vanes.

It is noticed that the measured values of open flow is different than of bounded flow due to the vertical wind turbine has high solidity starting from the shaft until end of the frame [6]. The air will be squeezed between end of the frame turbine and the wind tunnel's wall; this causes additional force and torque to be differed of other results using open area. While, our work gives similarity of results of both open and bounded flows due to availability of movable vanes and 30% open area of each frame closes to the shaft.

The obtained results satisfy the theoretical approach Esq. (5 -8). The four-frame wind turbines have higher efficiency compared to the three-frame turbine due to a big area is to capture wind energy. Both test models had exposure in the same condition of wind speed by wind tunnel. Results show that the coefficient of performance and hence the efficiency of the vane-type wind turbine in the wind tunnel are decreasing with increasing wind speed over 9 m/s. The vane-type turbines show the higher efficiency at the wind speed 9 m/s in the wind tunnel. This type of wind turbine has good technical properties and can be used for generating a power more efficiently for lower speed of the wind.

Efficiency of the vane-type turbines can be significantly increased by change the shape of the frames, or use nozzle to construct wind to the impeller. The tests of the vane-type turbine in the wind tunnel gave new data regarding coefficient of performance and the drag factor can be used for theoretical calculations. Proposed vane turbines can be designed from cheap material that is highly economical. At strong wind conditions, it is possible to design the vane turbine with reducing the acting numbers of vanes. The possible flipping of the vanes under action of the wind force can be avoided by simple constructive solutions.

It is investigated the vane-type wind turbine has high efficiency drag factor can increase the output power. New vane-type wind turbines possess all advantages of vertical type of turbines and can be concurrent for known wind turbine design especially for lower speed of wind. The new turbine presents simple construction using simple technology produced from cheap materials. It is can operated at different conditions of wind force change. For future research, mathematical modelling of wind turbine work should be conducted on a basis of computational fluid dynamics and proofed by practical investigations of wind tunnel. Also, it is necessary to conduct investigations on the optimal design of new turbines (power as function of the vanes geometry, weight of turbine, aerodynamic shape, wind speed, etc.). Tests of vane-type wind turbine can give reliable data in order to design the vane-type wind turbine.

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