Test of Impeller Type Vawt in Wind Tunnel

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Abstract: This paper proposes the vane wind turbine, which uses more effectively the wind energy and depends only on the acting area of the vanes. The vane wind turbine is designed to increase the output of a wind turbine that uses kinetic energy of the wind. This design enables the wind force to close left side vanes and simultaneously opens the right side vanes to allow wind move freely (reduce negative torque). It can be used worldwide due to its high efficiency, simple construction, and simple. Test wind turbine model in wind tunnel to verifying the ability of performance design.

Keywords: wind turbine, vane, VAWT, energy.

1. Introduction

Designing a wind turbine system that can generate power with high efficiency requires a thorough understanding of the principles of aerodynamics and structural dynamics of the rotor system. Various wind turbine mechanisms are proposed and built for capturing and converting the kinetic energy of winds. In area of the wind energy there are three basic types of wind turbine in common use today. The two primary types of wind turbine are the horizontal axis (HAWT) and vertical axis (VAWT) machines. The horizontal axis machines are highly developed and used in all current large scale wind farms. [1], and there are many variants of each design as well, as a number of other similar devices under development. The propeller type turbine is most commonly used in large-scale applications constituting nearly all of the turbines in the global market, while the vertical axis turbines are more commonly implemented in medium and small-scale installations. The technical characteristics of wind turbines are to be found elsewhere [2-3]. However, simple analysis of these wind turbine designs shows that these designs are not perfect and the wind force does not use in full-scale due to many geometric reasons.

New impeller type design of the vertical axis wind turbines without mentioned above lacks and with ability of use in wide area of application. First, new design should use the wind kinetic energy by maximum of the Betz limit [4]. The active area of blades, vanes or other elements of the new wind turbines should give less geometrical sizes one. This design of the vertical axis movable vanes type wind turbine has simple construction, technologically simple in production, uses the drag force by active area of the working elements.

The theoretical maximum power efficiency of any design of wind turbine operate in open atmosphere is $C_e = 0.59$ - the Betz Limit [4-5]. The real world limit is well below the Betz Limit with values of 0.35-0.45 common even in the best designed wind turbines. Except this one there are other energy losses in a complete wind turbine system (the generator, bearings, power transmission, etc.) and only 10-30% of the power of the wind is ever actually converted into usable electricity.

The wind turbine generators use mainly aerodynamic lift force and drug forces acting on the surfaces of blades or vanes. Today researches are stating that horizontal axis wind turbines (lift force design) theoretically have higher power efficiencies than vertical axis wind turbines (drag force design). However, other research state that at conditions of turbulent with rapid changes in wind direction practically more electricity will be generated by vertical turbines, despite its lower efficiency. However, there is the following vital information: the power output of a wind turbine generator is proportional to the acting area of wind turbines and the power output of a wind generator is proportional to the cube of the wind speed. These peculiarities should be considered main factors of the output power to design new type of wind turbines.

The main objective is to maximize the coefficient C. In general drag factor C_d is function of the turbine element geometry, Reynolds number, Froude number. For a propeller wind turbine A is swept area of rotating blades, but actual area of blades 4-5 times less of the swept area. The wind between propellers passes freely and does not affect on the blades. The real output the power of the propeller wind turbine is 4-5 times less than theoretical power of the turbine. Tests with a cylindrical body (Flettner rotor) showed that the drag coefficient can be improved by adding disks at the top and bottom of the body; this increased the drag coefficient by 60-90%. The disks effectively change the finite cylinder into an infinite one (minus viscous losses near the disks) by ensuring 2D flow patterns. In the context of the proposed wind energy converter, it can be expected that by closing the rotor off at the top and the bottom by a disk which protrudes over the outer rim of the rotor, the drag coefficient can be increased from 1.2 to 2.0 [6].

The maximum efficiency for a flat plate rotor (excluding the potential effect of wind pressure acting on more than one rotor blade) therefore only reaches 18% for plate aspect ratios of less than 5:1. This rather low efficiency is usually the reason to dismiss the vertical axis resistance converter as an inefficient concept [7].

2. Experimental

2.1 Analytical Approach

The fundamental equation that governs the power output of a wind turbine is [8]:

$$P = 0.5*\rho*A*V^3*\lambda, \text{ Watt} \tag{1}$$

where: P - power produced by the wind turbine, W; ρ - air density, V - wind speed approaching the wind turbine, λ = wind turbine efficiency for common case; and A - projected area of the turbine perpendicular to the approaching wind.

λ is wind turbine efficiency that consists following factors and calculated by following formula: $\lambda = C_p C * N_g * N_b$,

where C_p - coefficient of performance ($C_p = 0.35$ for a good design); $C = C_l$ or C_d (or resulting of them) - are lift and drag factors respectively and depend on the shape and form of the blades or vanes and on orientation of the wind flow with respect to the object; N_g - generator efficiency (80% or possibly more for a permanent magnet generator or grid-connected induction generator); N_b - gearbox/bearings efficiency (95% for a good design),It is well-known that modern wind turbine is

designed with very complex optimality criteria involving more than aerodynamic efficiency.

The proposed vane type vertical wind turbine can be designed by two types of construction. The first is four frames with angles of 90° to each other and horizontally constructed bars with vanes that have ability to twist on 90°. The second is three frames with angles of 120° between each other. Increase the number of frames will not increase efficiency of the wind turbine because increases the vane interframe wind shadow area and increases the weight of turbine.

Frame's elements should be designed of aerodynamic form to reduce the drag force of the wind action on not working elements of the turbine. The frames are connected with the shaft and the shaft with the electrical generator. The vanes fastened on the bars that located on the sides of the frame. The frame vertical components can be designed as Darrieus type to increase the output of the wind turbine. Also, to increase the turbine efficiency the vanes construction can be designed with cavities that increase drag force dramatically. 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 open and a wind force is passing through the open 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.

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 [9-10].

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 is four sections of vanes assembled on frames, which are perpendicular to each other and joined with the main output shaft. The second one is three sections of vanes, which are 120° to each other and joined with the main output shaft.

Power output depends on a wind force and 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 some power of the wind speed. The first thing is to calculate the force acting on the vanes due to the momentum change of the air impinging upon them. The ultimate simplification is necessary for an analytical approach of considering the force acting on stationary vanes. This simplification leads to different results depending on the assumptions made. The important assumptions made are the following:

a) The wind turbine vanes are smooth.

b) The frictional resistance is negligible since the blades are smooth and short in the flow direction. 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 force component F acting on stationary vertical vanes of the left side frame is expressed by the following formula [2–4].

$$F = (1/2)C_d \rho A V^2 \sin\alpha \tag{2}$$

where all the parameters are specified in Fig. 1.

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, then the formula has the following expression

$$T = (1/2)AC_d \rho V^2 R \sin\alpha \tag{3}$$

where R is the distance from the shaft centre line to the centre of pressure of the vane surface, other parameters are as specified above.

The output power is calculated by the following equation

$$P = T\omega = (1/2)\rho AC_d V^2 R \sin\alpha * V/R$$
$$= (1/2)\rho AC_d V^3 \sin\alpha \ (Watt) \tag{4}$$

where ω is the angular velocity of the rotating turbine, ρ is air density, R is impeller turbine radius.

The next step is to develop the mathematical model of the resultant force acting on moving vanes. This entails determining:

a) the velocity of oncoming air relative to the front surface of the first frame vanes and

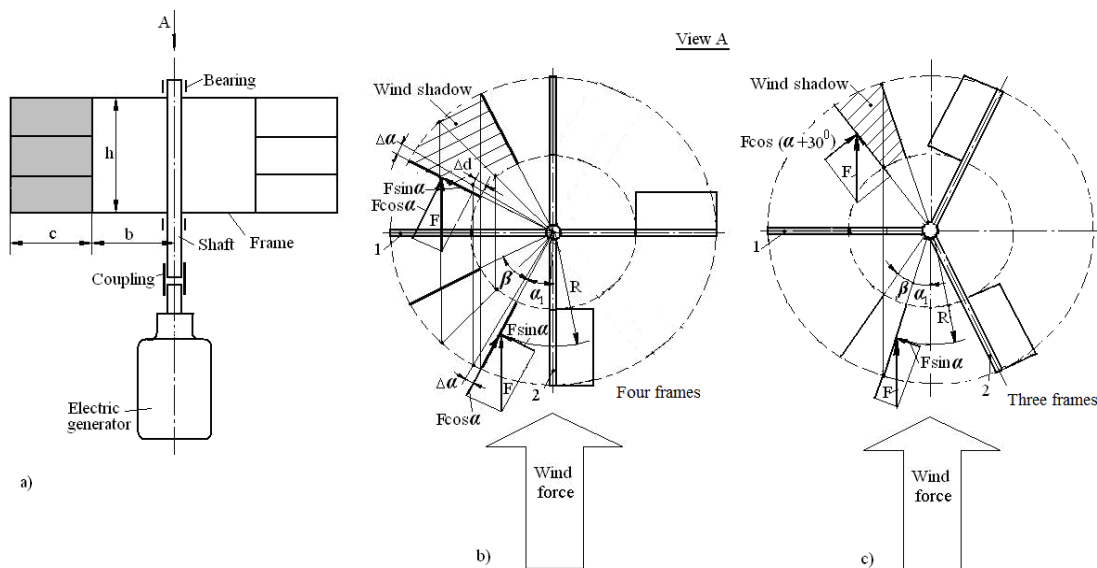b) the affect of the wind on the surface of the second frame vanes.

Figure 1. Vane-type wind turbine (b) of four Frame (c) three frames.

In rotation of the frames with vanes, pressure builds up along the surface of an object. A surface more perpendicular to the stream line of wind tends to have a higher pressure. The resultant force acts in the centre of pressure that is found by calculating the pressure distribution across the variable vanes location, then integrating it. The forces acting on the sides of the frames can be neglected due to small face-sided areas.

A good vane design will combine the aerodynamics, the mass properties of the vanes material, and the spin of the vane to permit the projectile to be pointy end forward for the entire airstream line. However, the very location of the frames with vanes contributes to instability of the forces acting on the vanes and instability of the output shaft rotation.

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

Practice shows that the value of the drag factor C_d is variable and depends on many factors like vane configuration, wind speed, the wind angle of attack with respect to vanes, etc. There is also a tangential component or 'skin friction' force [11].

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 vanes at the angle of rotation from 90^0 to α_1 without wind shadow

$$T_1 = C_d p[hc(b + c/2)]\sin\alpha \ \Big|_{90}^{\alpha_1} \qquad (5)$$

where C_d 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.

$$T_2 = C_{d1}ph(c - k\Delta\alpha)[(b + k\Delta\alpha) + (c - k\Delta\alpha)/2]\sin\alpha$$
$$+ C_{d2}p[hk\Delta\alpha)(b + k\Delta\alpha/2)\sin\alpha \ \Big|_{\alpha_1}^{\beta/2} \qquad (6)$$

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

$$T_3 = C_{d2}ph(c - \Delta d)[(b + \Delta d) + (c - \Delta d)/2]\sin\alpha$$
$$+ C_{d1}p[h\Delta d)(b + \Delta d/2)\sin\alpha \ \Big|_{\beta/2}^{\beta} \qquad (7)$$

4. The torque created by the first vanes at the angle of rotation from $\alpha_1 + \beta$ to $180^{\circ 0}$ without wind shadow

$$T_4 = C_{d1}p[hc(b + c/2)]\sin\alpha \ \Big|_{\alpha_1 + \beta}^{180^0} \qquad (8)$$

5. The torque created by the second frame vanes at the angle α of rotation from $0°$ to $90°$ without wind shadow

$$T_5 = C_{d1}p[hc(b + c/2)]\sin\alpha \ \Big|_{0^0}^{90^0} \qquad (9)$$

2.2 Experimental Setup in the Wind Tunnel

The wind turbine testing used the two model fabricated with dimensions presented in Fig. 1, [for 4 frame 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 $300\times300\times300$ 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 bicycle dynamo Model Golden Cat 8P-5, 6V and 3W. 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 on the wind turbine and without the dynamo. Obtained results proved the theoretical approach that four-frame wind turbine has a higher efficiency than the three-frame turbine Fig. 2. 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. The dynamo was used when the wind speed exceeded 12 m/s, because the acting area of the turbine vanes did not support stable rotation for the turbine with the dynamo, which did not generate stable power. The high speed of wind is not a statistically average condition for the wind turbine and this is the reason that power was not measured by the multimeter.

3. Results and Discussion

Fig. 3 enables the calculation of the coefficient of performance, the drag factor and the efficiency of the vane-type wind turbines. The coefficient of performance calculated by the formula:

$$Cp = \frac{P}{0.5 \times \rho \times A \times V^3 \times Ng \times Nb} \qquad (10)$$

where, N_b = 0.998 is the bearing efficiency, and N_g=0.8 is the generator efficiency.
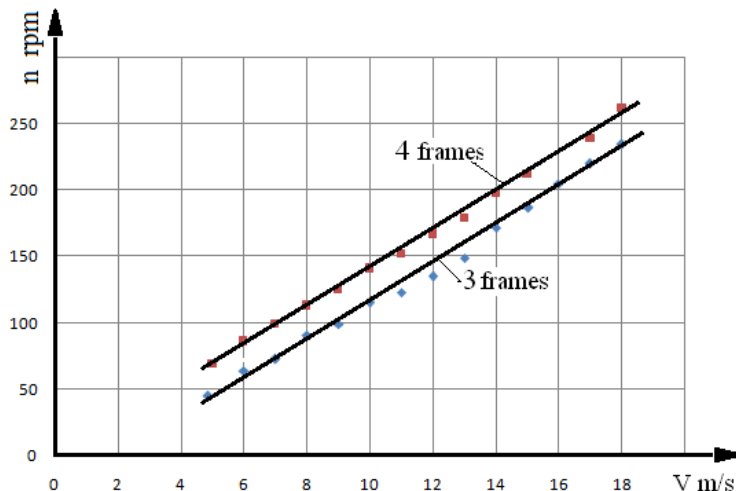

Figure 2. Number of revolutions of the wind turbine shaft versus the wind speed.

Calculated results of the coefficient of performance C_p of the vane-type wind turbines are presented in Fig. 3. This diagram shows that coefficients of performances for four- and three-frame turbines are different and increase with increase of the wind speed. For the low wind speed V the coefficient of performance ($V = 5…10$ m/s) of four-frame turbines is quite high and almost twice that for the three-frame turbine. This is important data of the vane-type turbine. The vane turbines are more efficient when the wind speed is low, which corresponds to statistical averages obtained of the natural magnitudes of the wind speed [5]. Such a result discovers new positive properties of the vane turbines that should be studied deeper.

Test of flat vane in wind tunnel are presented results of the drag factor C_d of the flat vane type with wind speed, Fig. 4. This diagram shows that drag factor are decreases with increase of the wind speed.
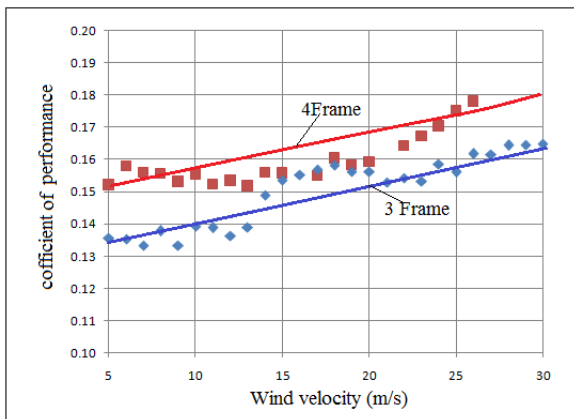

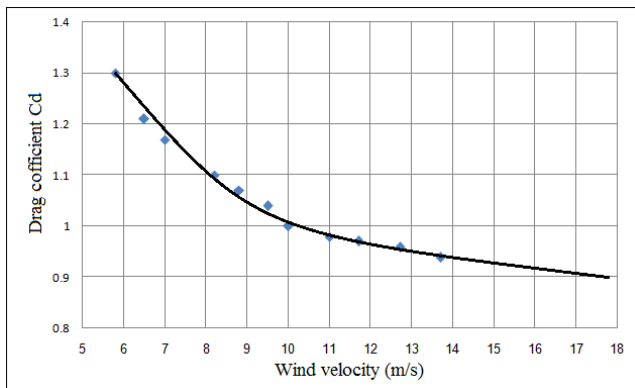**Figure 3.** Coefficient of performance versus the wind speed.

Figure 4. The drag coefficient of the vane type with wind turbine versus the wind speed.

The wind turbine efficiency calculated by the formula $\lambda = C_p C_d N_g N_b$ (Eq. 1). Cd and Cp take by figures 3, 4 respectively, $N_g = 0.8$, and $N_b = 0.998$, the wind turbine efficiency versus wind speed results are presented in Fig. 5.

Actual power is calculated on the basis of Figs 2, 3, 4, 5, and uses Esq. from (2) to (9).

$$P_{ac} = T\omega = F * r * \omega$$
$$= C_d 0.5\rho A V^2 * (b + c/2) * (2\pi n/60)$$

where r is the force arm (m), and n is angular velocity (red /sec).

Theoretical power generated ($_{th}$) by the vane-type wind turbine is calculated by Eq.:

$$_{th} = 0.5 * \rho * A * V^3$$

The vane-type wind turbine efficiency λ calculated by the formula

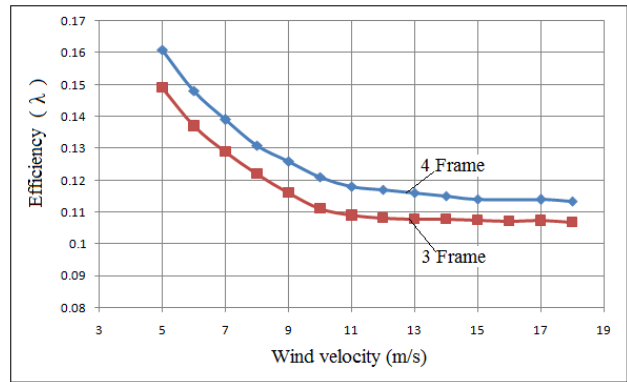$$\lambda = {}_{ac}/{}_{th}, \qquad (11)$$

Figure 5. The efficiency of the vane-type wind turbine versus wind speed.

Figures 6 and 7 show results of power coefficient, and torque coefficient with tip speed ratio for 3 frame wind turbine, we can see that maximum power coefficient is (0.18) at tip speed ratio (0.12), and maximum torque coefficient (1.46) at the same tip speed ratio.
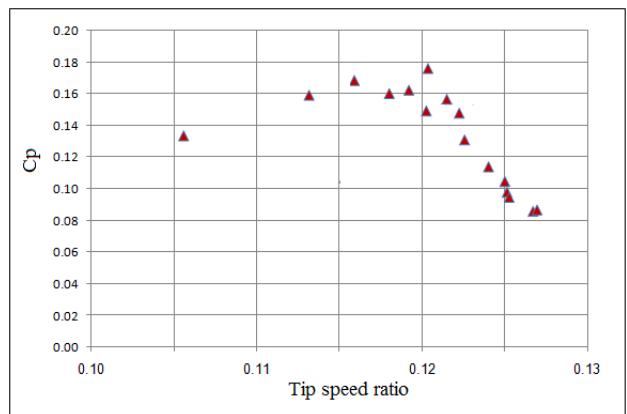

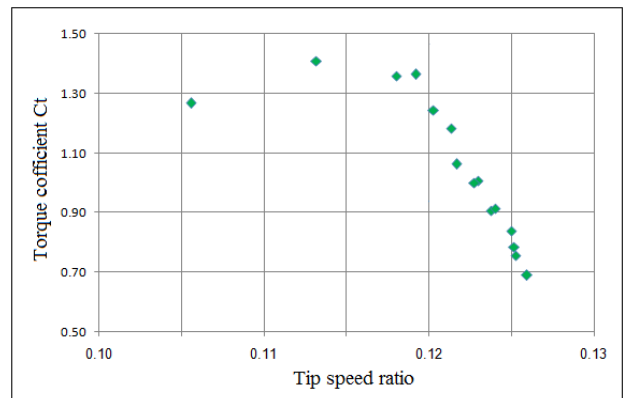**Figure 6.** Power coefficient various tip speed ratio for 3 frame wind turbine.

Figure 7. Torque coefficient various tip speed ratio for 3 frame wind turbine.

Figures 8 and 9 show results of power coefficient, and torque coefficient with tip speed ratio for 4 frame wind turbine, we can see that maximum power coefficient is (0.21) at tip speed ratio (0.113), and maximum torque coefficient (1.93) at the tip speed ratio (0.108).

The tested model of the vane-type turbines was designed with flat vanes. Nevertheless, it is possible to design the frame, which vanes create cavities that enable an increase in the drag factor ($C_d = 1.6…2.3$), i.e. increase the output power of the

vane-type turbines, increase the coefficient of performance $C_p = 0.4$-0.5 and the turbine efficiency $\lambda = 0.3$-0.5. These data enable it to be stated that the vane-type wind turbines possess a good opportunity to generate more power than known wind turbines and need further investigations.
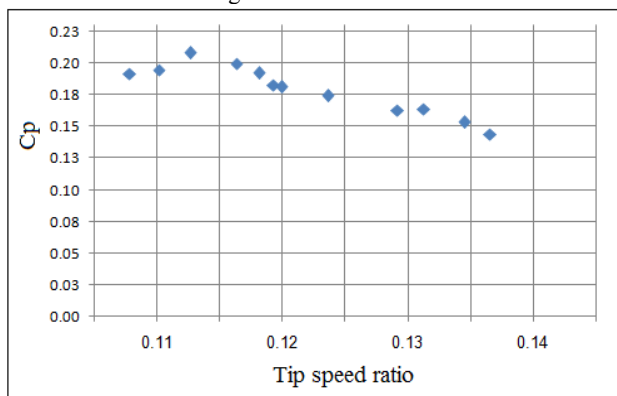

Figure 8. Power coefficient various tip speed ratio for 4 frame wind turbine.
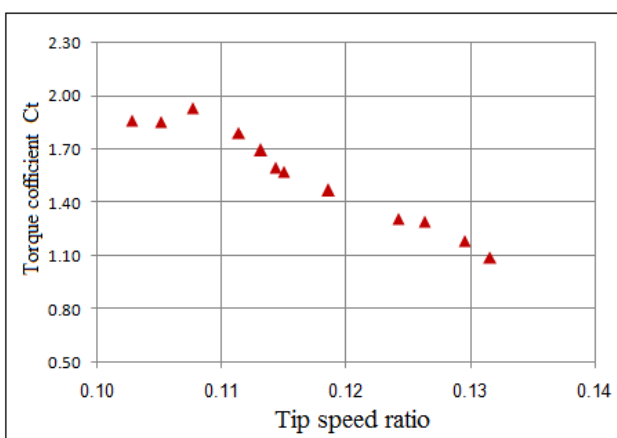

Figure 9. Torque coefficient various tip speed ratio for 4 frame wind turbine.

4. Conclusions

Based on the results of experiments, the results satisfy the theoretical approach (Eqs. 5-9). The four-frame wind turbines have a higher efficiency compared to the three-frame turbine. This is because the four-frame wind turbines have more area to capture wind energy. The rotation speed of the wind turbine with the dynamo shows a small drop of the turbine speed without dynamo at the same wind velocity. 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 are decreasing with an increase in wind speed. The vane-type turbines show the higher efficiency at the low wind speed. This type of wind turbine has good technical properties and can be used for generating a power more efficiently for the low speed of the wind.

Efficiency of the vane-type turbines can be significantly increased by change of the shape of the frames, which can create the vanes cavity and increase the drag factor. The vertical components of the frames can be designed as Darrieus-type wind turbine that can also add power and increase the efficiency of the vane turbine. The tests of the vane-type turbine in the wind tunnel gave new data regarding coefficient of performance and the drag factor and can be used for theoretical calculations. Proposed vane turbines can be designed from cheap material that is highly economical. The work of the vane turbine does not have restrictions. At strong wind conditions, it is possible to design the vane turbine with decreased acting numbers of vanes. The possible flipping of the vanes under action of the wind force can be avoided by simple constructive solutions.

New vane-type wind turbines possess many positive properties and can solve the problem of increased wind energy use. The vane-type wind turbine can be high efficiency and enables an increase in the vanes acting area and drag factor that can increase the output power. New vane-type wind turbines possess all advantages of vertical and horizontal types of turbines and can be concurrent for known wind turbine designs especially for the low speed of the wind.

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