ISSN: 0974-5823 Vol. 7 No. 2 February, 2022

International Journal of Mechanical Engineering

Performance of Multi Buckets Vertical -Axis Wind Turbine with at Different Blades Angles

[*1]Ikhlas Qamber Ayuz. Fateh Ali, [1]Salwan Obaid Waheed Khafaji and [1]Dhirgham Al Kafaji

[1]Department of Mechanical Engineering, College of Engineering, University of Babylon, Iraq

Abstract

Utilizing wind energy in built-up locations to generate electricity via the turbines for home usage remains a challenge, despite extensive studies in this field. The variability and uncertainty in the wind conditions, manufacturing complexity, and the expenses are the main parameters that make the wind turbines unsuitable for domestic use. Vertical axis wind turbines (VAWTs) are suitable for use in built sites because to their outstanding features, attractiveness, low noise, and safety. To achieve these objectives, vertical axis wind turbines with multiple blades (blades are made from polyvinyl chloride (PVC) material) have been designed, manufactured and studied experimentally to investigate its performance. Turbine's blade is a half cylinder in its shape. The blades rotational speed of the blades, the resulted torque (T), and generated power (P) of each configuration of the suggested turbine were determined for different wind speeds (1.5m/s, 2.5m/s, and 3m/s) and rotor radius of (30cm, 40cm ,and 50cm), respectively. The graphical relation between coefficient of power (C_p) and the tip speed ratio (TSR) and between coefficient of power (C_p) and angles of the blades were constructed. It was noted that performance of wind turbine is largely depends on wind speed, blade locations, and blade angle. The maximum value of the power coefficients (Cp =13.056%) is noticed at 40cm and 1.5 m/s for blade radius and wind speed, respectively, specifically at TSR=1.3 and 45o blade angle**.** The maximum values of the Cp for all values of the effective parameters are noticed at 45o blade angle. In addition, higher values of Cp are achieved at the lower wind speeds and high blade radius, and that corresponds to higher TSR. Finally, VAWT is able to generate electricity for local use even at low wind speeds.

Keywords: wind turbine, power coefficient, wind speed, blade angle, blade location, tip speed ratio

Nomenclature

Symbol	**Description**
VAWT	Vertical axial wind turbine
HAWT	Horizontal
m	Mass of air
V	Velocity
E	Kinetic energy
v	The air volume
A_T	A cross sectional area
ρ_a	The air density
P	Power
P_T	Power of turbine
C_P	The power coefficient
F	Force
T	The rotor torque
C_T	The torque coefficient
TSR , λ	Tip speed ratio
ω	The angular velocity
N	The rotational speed
R	Radius of rotor

1. Introduction

World currently competes for energy resources of emission-free to save the environment. Where, renewable wind energy has developed dramatically in recent decades. Wind technology reduces emissions, eliminates harmful or radioactive elements, and eliminates thermal pollution [1]. Thus, the transitioning to renewable energy and optimizing energy output from environmentally friendly sources includes critical problems for research teams, engineers, and industry leaders [2]. Wind energy has a potential to become a substantial contributor to global energy production. In 2019, worldwide wind energy capacity reached over 651 GW, up 10% from 2018 and covering over 6% of global electricity consumption [3]. In general, the wind turbines can be classified as either horizontal axis (HAWTs) or vertical axis (VAWTs) [4]. VAWT designs fall into two broad categories: lift-based rotors (Darrieus) and drag-based rotors (Savonius) [5]. The second type (Savonius) is a simple vertical-axis rotor with two semi-circular buckets asymmetrically arranged on the vertical shaft [6]. The rotational motion of the blades is created by the generated torque as a result of the net value of the momentum force between the forward blade, affected by the oncoming flow on its concave surface, and the returning blade which is moving in the opposite direction of the oncoming wind. Aerodynamic torque is formed when the product of these two forces is not situated along on the axis of rotation [7]. The increased interest in Savonius wind turbines can be due to its simplicity and low manufacturing costs. They may also work in almost any direction of the wind and self-start easily [8]. They also provide low aerodynamic noise and are easily integrated into vertical constructions [9]. However, Savonius wind turbines face several limitations, including a small power coefficients [10] and substantial torque coefficient variations with negative values during certain rotation angles, which increases the mechanical vibrations and reduces the rotor's self-starting capability [11]. Savonius and Darrieus turbines are among the most exciting wind turbines used today. Both turbines use various wind technology, and their optimum operating circumstances and aerodynamic performance have been studied for several years. The design and performances of these two turbine blades have also been evaluated experimentally and numerically. A promising solution for increasing VAWT performance is the hybridization of Savonius and Darrieus wind rotors. This encourages improving the suggested hybrid Savonius/Darrieus wind rotors' geometrical and operational properties [1]. Figure (1) illustrates many typical (VAWTs).

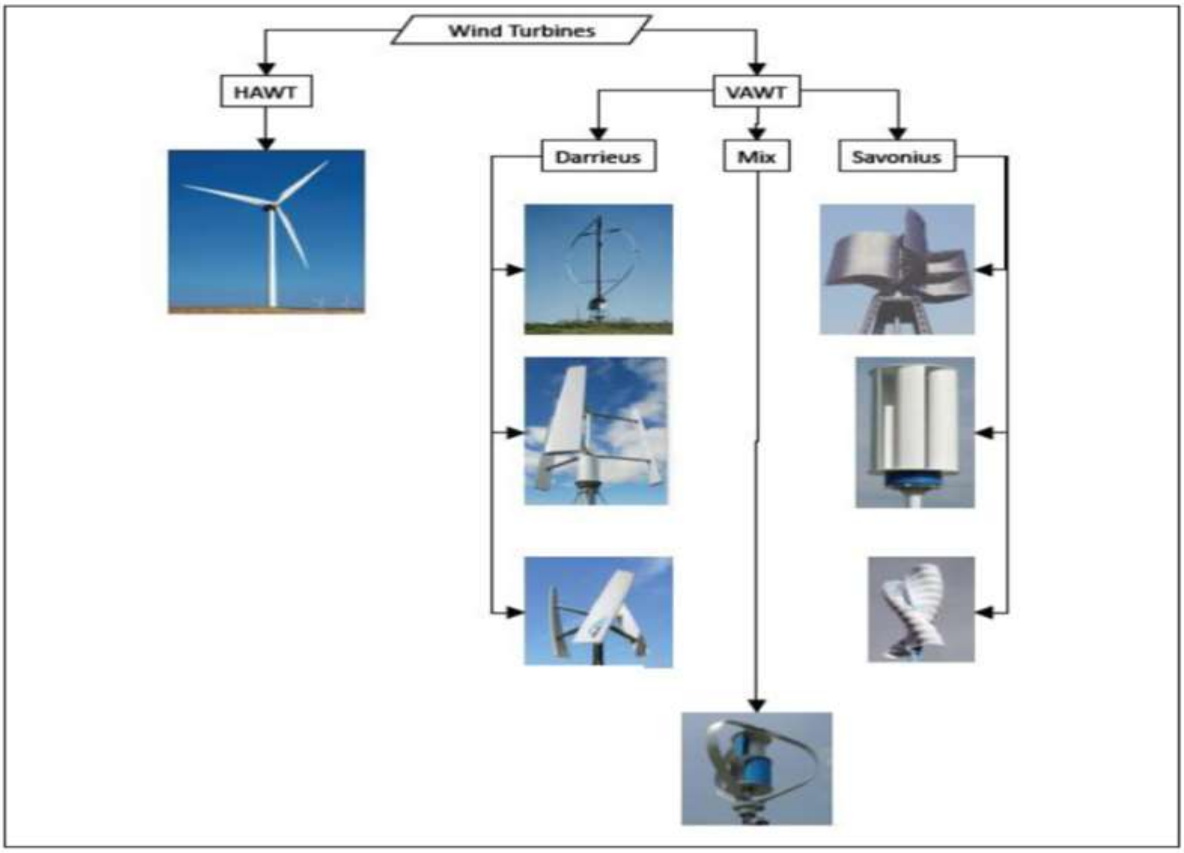


Figure 1. A variety of configurations for Vertical wind turbines [12]

In this work, the performance of a small vertical axis wind turbine is investigated experimentally, describing the effect of some parameters in terms of changing the radius of rotor and angle of blade corresponding to direction of the wind. Better blade angle and blade radius, which gives the better power factor and performance is obtained as well.

2. Methodology

2.1. Wind turbine model

The experimental work was conducted to design a (VAWT) of six blades, as shown in Fig. (2).The blades of the rotor are made of polyvinyl chloride (PVC) and attached to the turbine by several lightweight aluminium tubes. Each blade is connected to the tube by using a suitable slider mechanism so that the blade can be easily moved along the tube to change the radius of the rotor. The shape of the blade is a half-cylinder of 50cm in high and 20cm in diameter. A specific laboratory fan is used to generate wind for wind turbine experimental tests. The variable values of the wind speed were demonstrated by changing the distance between the fan and the test rig mentioned above. The wind speed (V) was set to (1.5 m/s, 2.5 m/s, and 3 m/s). Anemometry device show in Fig. (3) was used to measure the wind speed. Fig. (4). A device (three in one) for measuring rotational speed, voltage and current.

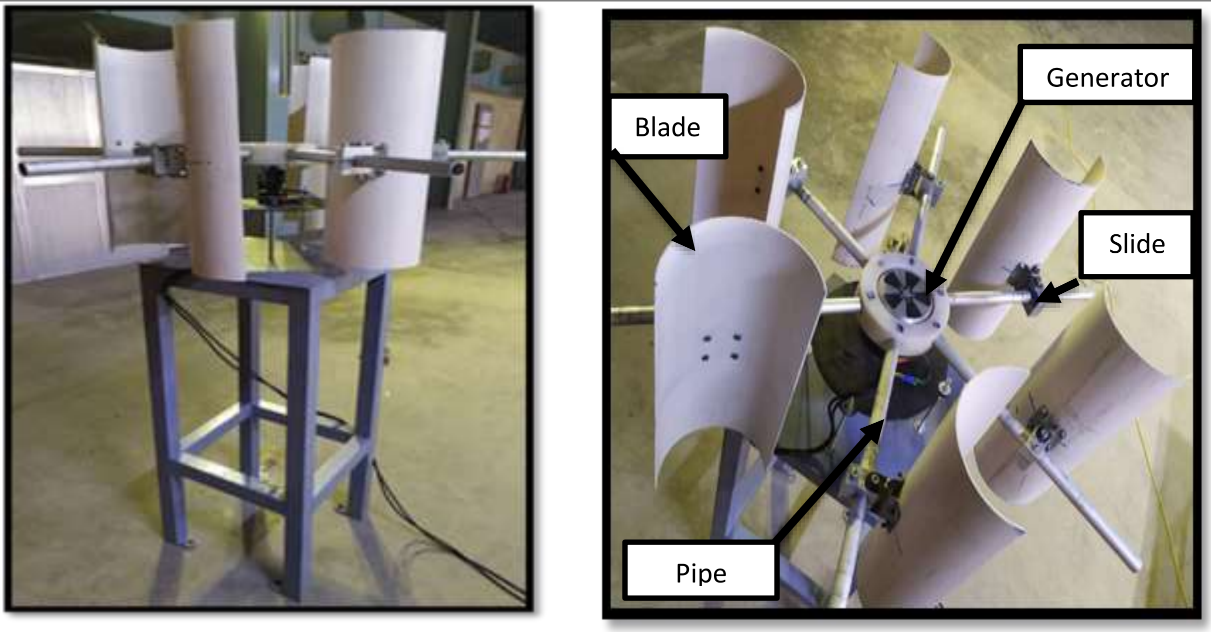


Fig. (2) Experimental model of the vertical axis wind turbine

Fig. 3. Anemometry device

Fig. (4). A device (three in one) for measuring rotational speed, voltage and current

Table (1). The VAWT model's geometric properties

Property	**Symbol**	**Value**	**Uint**
Blade number	N	6	_
Height of the blade	H	50	cm
Diameter of the blade	D	20	cm
Radius of rotor	R	30,40,50	Cm
Wind speed	V	1.5,2.5,3	m/s

2.2. Performance parameters

In a wind stream, the theoretical available power (P) is given by, [13]:

$$P = \frac{1}{2}\rho_a A_T V^3 \quad (1)$$

Where ρ_a is the air density, A_T is the projected area of the rotor and, V is the wind velocity. However, any turbine cannot completely produce this power from the wind. Thus, the actual power produced by the rotor will be affected by the efficiency at which the energy is transferred from the wind to the turbine rotor. This efficiency is often called the power coefficient (Cp), [14], and is given by,

$$C_P = \frac{2P_T}{\rho_{aA_T V^3}} \quad (2)$$

Where P_T is the actual value of the power of the turbine. The power coefficient of the turbine depends on important variables, such as the profile of the rotor blades, the configuration and setting of the blade, etc... The designer must attempt to set these parameters at their optimal level in order to reach maximum Cp at a large range of wind velocities. The force of propulsion encountered by the rotor (F) can be expressed as:

$$F = \frac{1}{2}\rho_a A_T V^2 \quad (3)$$

While the rotor torque (T) can therefore be expressed as:

$$T = \frac{1}{2}\rho_a A_T V^2 R \quad (4)$$

Where R is the radius of the turbine rotor. In fact, a rotor shaft will only develop a fraction of this torque. The ratio of the actual torque produced by the rotor to the ideal torque is referred as the torque coefficient (C_T) [15] that can be given by,

$$C_T = \frac{2T_T}{\rho_a A_T V^2 R} \quad (5)$$

Where T_T is the actual torque produced by the rotor.

The major non-dimensional parameter is called tip speed ration, TSR or (λ) that is used to explain the variables impacting Savonius rotor performance. It is defined as ratio of the rotor's tip speed (u_t) to the wind velocity (V) as given by Eq. (6):

$$\lambda = \frac{R\omega}{V} = \frac{2\pi NR}{V} \quad (6)$$

Where ω is the angular velocity and N is the rotational speed of the rotor. A rotor's power coefficient and torque coefficient vary with the tip speed ratio. For a given rotor, there is an optimum (λ) at which the energy transfer is most effective and the power coefficient is the maximum (CP max). Thus, to find the relationship between the power coefficient and the tip speed ratio, Eqn. (7) can be used as,

$$C_P = \frac{2P_T}{\rho_a A_T V^3} = \frac{2T_T\omega}{\rho_a A_T V^3} \quad (7)$$

By dividing the equation (7) and equation (6), the tip speed ratio can be given by [17]:

$$\frac{C_P}{C_T} = \frac{R\omega}{V} = \lambda \quad (8)$$

3. Experimental work

The experiment was conducted in the laboratories of the University of Babylon/College of Engineering/Department of Mechanical Engineering. To test the model, the wind rotor model was placed in the direction of a fan, where the air fan was turned on for variable wind speeds. The wind speed was measured by means of a device (Vane Anemometer) that was placed in front of the rotor blade as in Fig (3). Three wind speeds were considered in this work (1.5 m/s, 2.5 m/s and 3 m/s). The experimental work was achieved for different directions of the rotor blades at different angles with each wind speed (40˚, 45˚, 60˚, 90˚, 120˚ and 135˚) with respect to the x-axis as shown in Fig. (5).

Three values of the radius of the rotor (30 cm, 40 cm and 50 cm) were considered in the work as well. The rotational speed of the turbine, voltage and the current generated by the turbine were measured by the device three in one as in Fig (4).

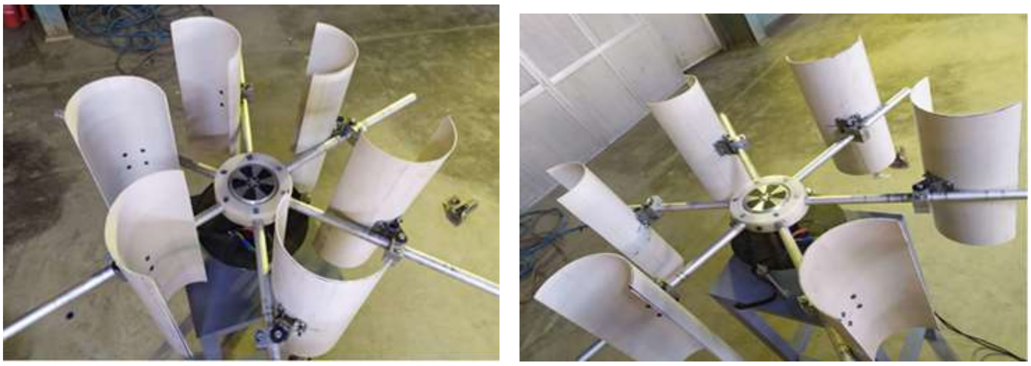


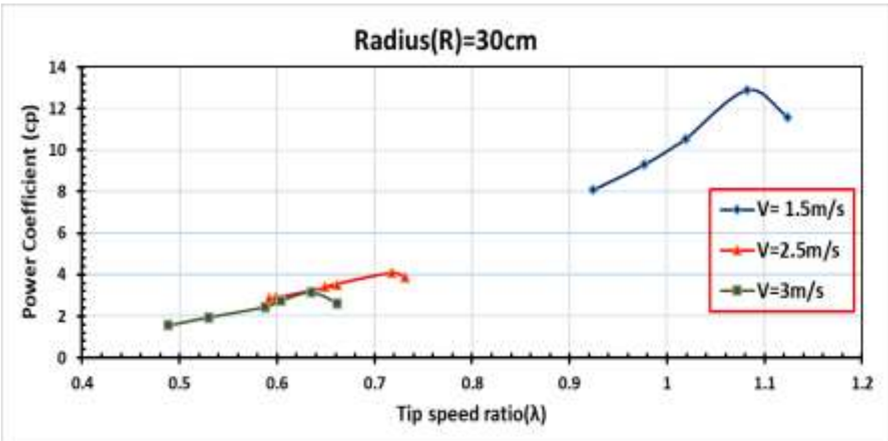
Figure (5) Changing the direction of the rotor blades at different angles.

4. Results and Discussion

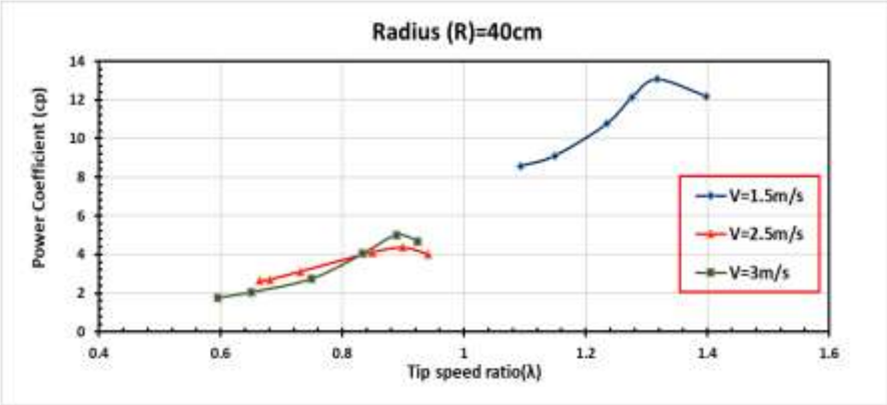
To evaluate the performance of a wind rotors, the power and torque coefficients were obtained. As a result, the power production and the rotational speed (rpm) at a specific wind speed were determined. The dynamic torque, on the other hand, was determined mathematically from the relationship between power production and measurable torque values. After acquiring the data, the mathematical formulations described above were applied to determine the rotor's performance parameters.

4.1. Effect of tip speed ratio on the turbine performance

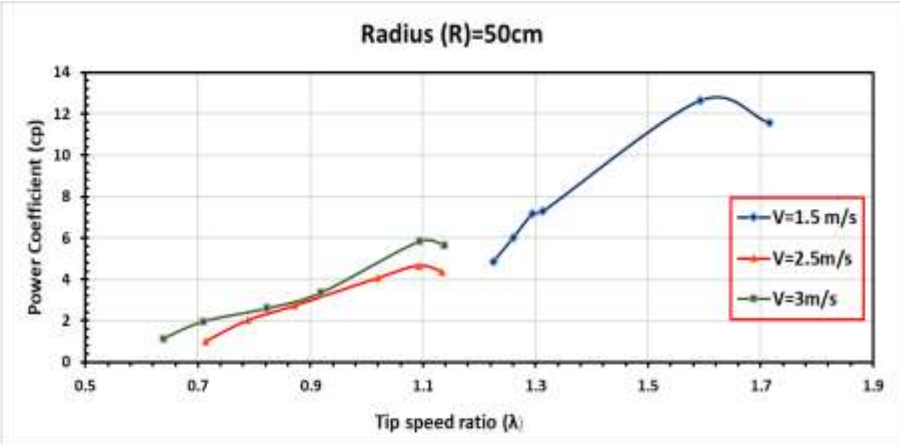
Figure (6) shows the variations of the power coefficients due to variations of the tip speed ratio for different values of radius and wind speed. Figure (6-a) shows power coefficients when the radius (R) = 30 cm. The main characteristics of the subfigures is the nonlinear behavior of the power coefficients due to changes in TSR. In other words, a critical value for a specific wind speed is noticed. This behavior is noticed for all values of radius and wind velocities. On the other hand, it is noted that a turbine that operates at the lower values of the tip speed ratio (corresponding to higher wind speed) shows smaller values of the power coefficients. That means the turbine operate under what called by stall mode condition during turbine blades rotation, leading in reducing the power generated by the turbine. In addition, at higher tip speed ratio, the turbine spins faster. However, the fast spinning modify the aerodynamic behavior of the stream around the blades and develops incoming flow blockage. This blockage might enforce the streamlines for bypassing the rotors. Similar behavior can be noticed for the other values of the blades location (the radius increases). The main behavior of plots in Fig. 6 is attributed to the inverse relationship between the wind speed and power coefficients as noticed by Eqn.s (2) and (7), respectively. It is worthy to mention that the highest value of power coefficient is (Cp=13.05 at TSR=1.3) for wind speed V= 1.5 m/s and the rotor radius R=40 cm.



(a)



(b)

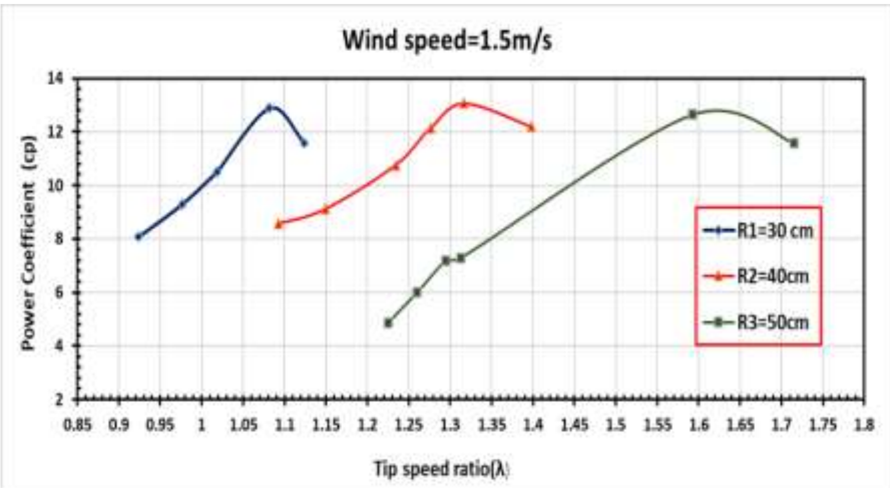


(c)

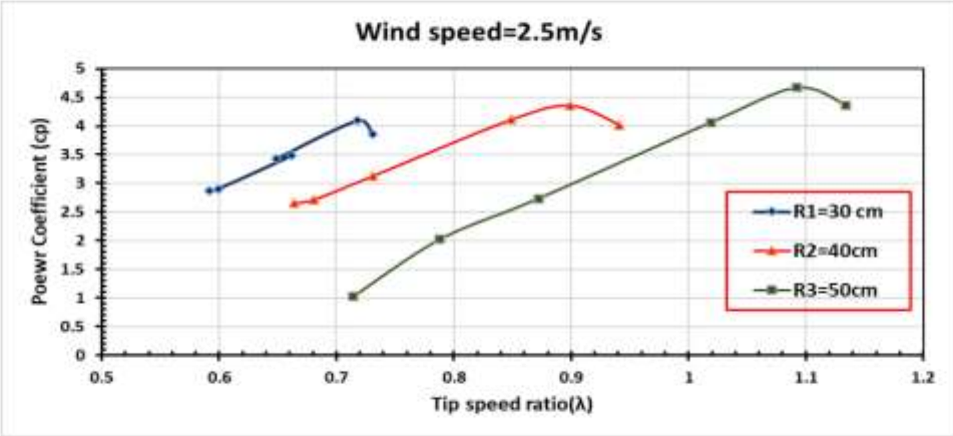
Fig. 6. Power coefficient of the wind turbine for different radius and wind speeds.

For more convenient, the relationship between power coefficient and the tip speed ratio, when the wind speed is fixed while the blade locations or blade radius is variable, is presented in Fig.7. The critical value of the tip speed ratio is higher for the turbine blades farthest in the design (R=50 cm).Similar behavior for the subfigures of the turbine in this Figure is noticed. However, the maximum value of the power coefficients is noticed in Fig.7a where the smaller wind speed and maximum blade radius.

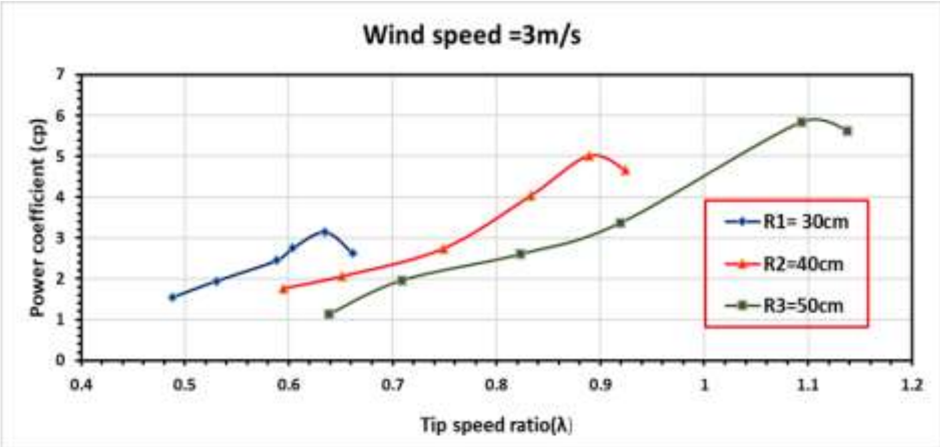
To sum up with, when the value of the rotor radius is constant with the change in wind speed, or the rotor radius changes with the wind speed remaining constant, and according to equation (6) we noted that TSR depends on the rotor radius and wind speed, as it is directly proportional to the rotor radius and inversely with wind speed. When the radius of the rotor is increased with constant wind speed, TSR increases, and when the wind speed increases with the radius of the rotor held constant, the TSR decreases.



(a)



(b)

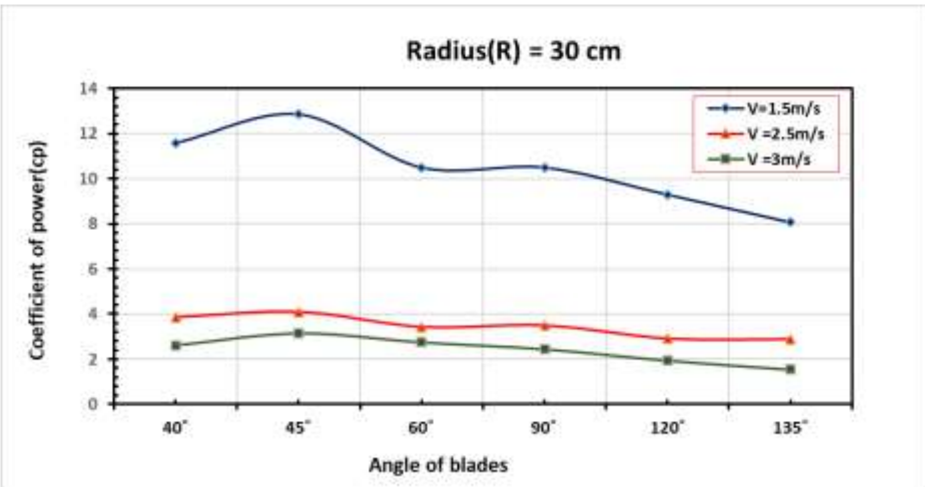


(c)

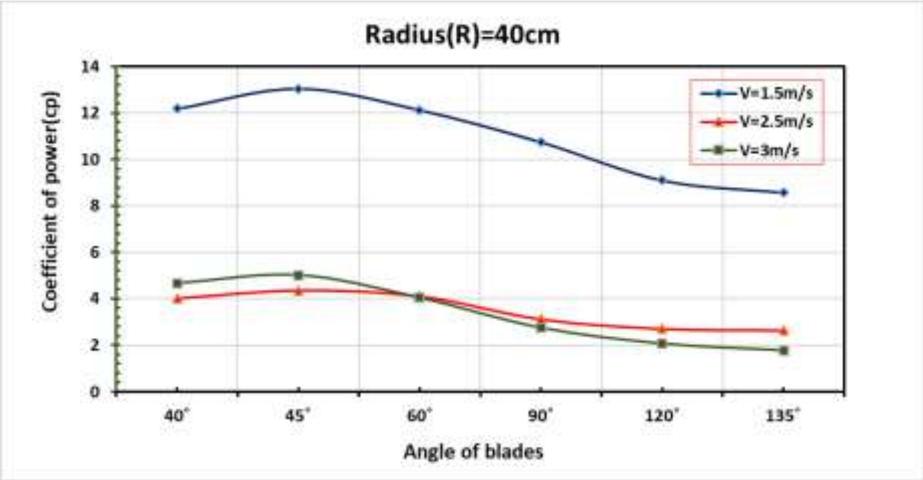
Fig.7. Coefficient of power versus (TSR) for different radius of the rotor (R) and wind speed (V)

4.2. Effect of blade angle on the wind performance

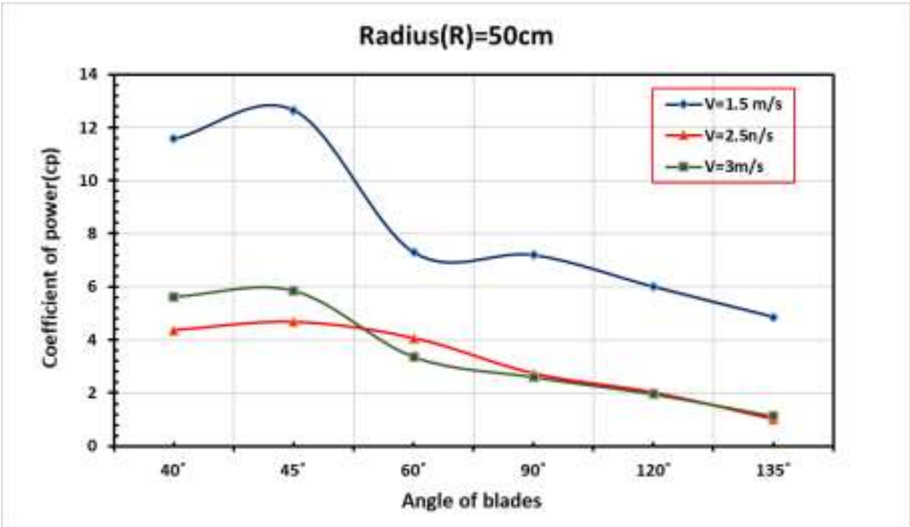
Power coefficients for different values of blades angle, blade location, and wind speed are calculated and presented in Fig. (8) in order to investigate effect of all of these parameters on the turbine performance. Several values of blade locations (R=30, 40 and 50) cm and wind speeds (V=1.5, 2.5, 3) m/s are used. It is noticed that the critical values (maximum value) of the power coefficients for all subfigures of Fog. 8 are located at 45o blades angles. However, their values vary with both of blade location and wind speed. Effect of blade angles is significant when the blade located at the maximum distance from the rotational center with smaller values of the wind speed as shown in Fig 8c. This explains how power coefficients is sensitive to wind speed and blade locations.



(a)



(b)



(c)

Figure (8) Power coefficient versus the angle of blades for a different radius of the rotor (R) and wind speed (V).

All numerical values of the power coefficients are presented in Table 1 for more clarifications. The maximum absolute values of tip speed ratio is noticed at the maximum blade radius for and lower wind speed.

Table (1) represents the results of the experimental work.

Wind Speed (V) m/s	Radius of Rotor (R) cm	Blade Angle (˚)	Power coefficient(Cp)	Tip Speed Ratio (λ)
1.5	30	40˚	11.593	1.124
		45˚	12.876	1.082
		60˚	10.509	1.019
		90˚	10.509	1.019
		120˚	9.301	0.977
		135˚	8.067	0.924
	40	40˚	12.189	1.398
		45˚	13.056	1.317
		60˚	12.135	1.276
		90˚	10.756	1.234
		120˚	9.111	1.149
		135˚	8.58	1.093

	50	40˚	11.569	1.715
		45˚	12.64	1.593
		60˚	7.293	1.313
		90˚	7.194	1.295
		120˚	6	1.26
		135˚	4.861	1.225
2.5	30	40˚	3.854	0.731
		45˚	4.095	0.718
		60˚	3.422	0.649
		90˚	3.489	0.662
		120˚	2.901	0.599
		135˚	2.869	0.592
	40	40˚	4.022	0.941
		45˚	4.361	0.899
		60˚	4.112	0.849
		90˚	3.125	0.731
		120˚	2.716	0.681
		135˚	2.649	0.664
	50	40˚	4.364	1.134
		45˚	4.669	1.092
		60˚	4.065	1.019
		90˚	2.733	0.872
		120˚	2.021	0.788
		135˚	1.018	0.714
3	30	40˚	2.618	0.662
		45˚	3.143	0.635
		60˚	2.748	0.604
		90˚	2.444	0.588
		120˚	1.941	0.53
		135˚	1.546	0.488
	40	40˚	4.663	0.924
		45˚	5.014	0.889
		60˚	4.039	0.833
		90˚	2.742	0.749
		120˚	2.061	0.651
		135˚	1.766	0.595
	50	40˚	5.627	1.138
		45˚	5.844	1.094
		60˚	3.367	0.919
		90˚	2.604	0.823
		120˚	1.964	0.709
		135˚	1.137	0.639

5. Conclusion

In this paper, the underlying concepts in the method of conversion of wind energy is presented. Thus, the rotor's actual power output is determined by the system performance with which energy is transported from the winds to the rotor; this performance (Cp) is frequently referred to as the power coefficient. Additionally, examined the effect of turbines design on mechanical power generated at low wind speeds. Wind speed and rotor diameter are assumed as the independent variables. The wind speeds varied between 1.5 m/s, 2.5 m/s, and 3 m/s. The rotor's radius varied between (30 cm, 40 cm, and 50 cm), respectively. The blades are constructed entirely of PVC material. All testing are achieved indoors to exclude the influence of wind and other environmental factors. The main conclusions of this paper are:

1- Wind turbine performance is dependent on wind speed, blades locations, and blade design.
2- The maximum power coefficients (C_p =13.056%) is obtained at 40cm and 1.5 m/s for blade radius and wind speed, respectively. specifically at TSR=1.3 and 45^o blade angle.
3- The maximum values of the C_p for all values of the effective parameters are noticed at 45^o blade angle.
4- Higher Cp are achieved at lower wind speeds and high blade radius and that corresponds to higher TSR.
5- VAWT is able to generate electricity for local use even at low wind speeds.

6. References

[1] A. M. Abdelsalam, M. A. Kotb, K. Yousef, and I. M. Sakr, “Performance study on a modified hybrid wind turbine with twisted Savonius blades,” *Energy Convers. Manag.*, vol. 241, no. March, p. 114317, 2021, doi: 10.1016/j.enconman.2021.114317.

[2] H. A. D. Hdom, “Examining carbon dioxide emissions, fossil & renewable electricity generation and economic growth: Evidence from a panel of South American countries,” Renew. Energy, vol. 139, pp. 186–197, 2019, doi: 10.1016/j.renene.2019.02.062.

[3] Global Wind Energy Council (GWEC). Global wind report 2019; April 2020.

[4] Karimian SMH, Abdolahifar Abolfazl. Performance investigation of a new Darrieus Vertical Axis Wind Turbine. Energy 2020;191:116551. https://doi.org/10.1016/j. energy.2019.116551.

[5] Naseem Ammar, Uddin Emad, Ali Zaib, Aslam Jawad, Shah Samiur Rehman, Sajid Muhammad, et al. Effect of vortices on power output of vertical axis wind turbine (VAWT). Sustain Energy Technol Assess 2020;37:100586. https://doi.org/10.1016/j. seta.2019.100586.

[6] Chen Liu, Chen Jian, Zhang Zhouzhou. Review of the Savonius rotor’s blade profile and its performance. J Renew Sustain Energy 2018; 10(1):013306. https://doi.org/10.1063/1.5012024.

[7] Montelpare S, D’Alessandro V, Zoppi A, Ricci R. Experimental study on a modified Savonius wind rotor for street lighting systems. Analysis of external appendages and elements. Energy. 2018 Feb; 1(144):146–58.

[8] Rezaeiha Abdolrahim, Kalkman Ivo, Blocken Bert. Effect of pitch angle on power performance and aerodynamics of a vertical axis wind turbine.Appl Energy 2017;197:132 50.

[9] Zhao D, Han N. Optimizing overall energy harvesting performances of miniature Savonius-like wind harvesters. Energy Conv Manage 2018; 178 (October):311–21.

[10] Govind B. Increasing the operational capability of a horizontal axis wind turbine by nits integration with a vertical axis wind turbine. Appl Energy 2017 Aug; 1(199): 479–94.

[11] Akwa Jo˜ao Vicente, Vielmo Hor´acio Antonio, Petry Adriane Prisco. A review on the performance of Savonius wind turbines. Renew Sustain Energy Rev. 2012; 16(5): 3054–64.

[12] A. El-Ghazali,"The influence of turbine geometry on the performance of c- section vertical axis wind turbine athesis submitted to the graduate school of applied sciences of by Abdalla El-Ghazali In Partial Fulfillment of the Requirements for the Degree of Master of Scie,” 2016.

[13] Mathew S 2006 Wind energy: fundamentals, resource analysis and economics Springer.

[14] El-Askary WA, Saad AS, AbdelSalam AM, Sakr IM. Investigating the performance of a twisted modified Savonius rotor. J Wind Eng Ind Aerodyn. 2018 Nov; 1:(182) 344–55.

[15] El-Askary WA, Saad AS, AbdelSalam AM, Sakr IM. Experimental and theoretical studies for improving the performance of a modified shape Savonius wind turbine. J Energy Resour Technol. 2020 Dec 1;142(12).

[16] Y. Jiang, P. Zhao, T. Stoesser, K. Wang, and L. Zou, “Experimental and numerical investigation of twin vertical axis wind turbines with a deflector,” Energy Convers. Manag., vol. 209, no. November 2019, p. 112588, 2020, doi: 10.1016/j.enconman.2020.112588.

[17] A. S. Saad, A. Elwardany, I. I. El-Sharkawy, S. Ookawara, and M. Ahmed, “Performance evaluation of a novel vertical axis wind turbine using twisted blades in multi-stage Savonius rotors,” Energy Convers. Manag., vol. 235, no. November 2020, p. 114013, 2021, doi: 10.1016/j.enconman.2021.114013.