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A Comparison of a Three Blade and Five Blade Wind Turbine in Terms of the Mechanical Properties Using the Q-Blade Software

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Abstract

Wind turbines deployed in utility-scale wind farms can support and meet future energy desires and also decrease carbon dioxide emissions by reducing energy requirements from fossil fuels. As the air heats up throughout the day, the wind velocity increases due to temperature gradients. This in turn produces a density pressure gradient, inducing air movement that a wind turbine encounters. Depending on ground topography, the wind can encounter and be directed in valleys and between and over hills as it flows and follows the curves of the earth. These topographies produce an increase in wind velocity at summits and ridges. In the current study, a small horizontal wind turbine rotor blade is designed to operate under low wind speed, by using the Q-Blade software. Based on the Blade Element Momentum method (BEM) and airfoil NACA3712, a three-blade rotor and a five-blade rotor are used based on turbine type and rotor size to generate mechanical power from wind power. A comparison and analysis of turbine power, power coefficient, and torque coefficient are carried out at low wind speed 1m/s-8m/s and highly accurate results are obtained. It is found that the best performance is gained when a three-bladed turbine rotor can work with a turbine power of 582W. As for the five-blade rotor, the turbine power obtained is (955W). It is also found that the design of a small horizontal wind turbine with five blades is more efficient than a turbine with three blades, suitable for working in areas with low wind speed and is of high efficiency compared to the size of the turbine.

Keywords: Low wind speed, Power Coefficient, Torque Coefficient, Wind Turbine Blade, Wind Energy.

Introduction

A great effort continues by researchers who are focusing on using alternative energy generation resources to replace fossil fuels to meet energy needs, thus reducing carbon dioxide (CO2) emissions. One of the best options, due to its sustainable and renewable nature, is wind energy[1-3]. An illustration of a horizontal axis wind turbine (HAWT) is given in Fig. 1, showing the blades and the rotor[2]diameter. Although the distribution of wind speed varies with location and time, wind energy is the best source of renewable energy, being one of the most efficient energy sources that reduce the energy deficit and are more suitable for reducing gas emissions. In addition, it is of good cost compared to other energy sources in such locations where wind resources are well available[4,5]. New and effective airfoils are developed for small-sized horizontal axis wind turbine rotor blades using the Blade Element Momentum method. Calculations are carried out using the Q-Blade software reaching a power of 1KW at a wind speed of 8.4 m/s [6]. Helical blades of horizontal wind turbines are designed for urban electric power generation and it is concluded that such turbines produce (RPM) at wind speed 5 m/s. To obtain the best power output, the wind speed should be 18-25 m/s. This design also withstands wind disturbances and enjoys a high efficiency of up to 80% of the energy available in the wind at low altitudes[7]. Eight different types of airfoils with varying thicknesses are designed for two groups of the National Aeronautics and Space Administration (NASA). The first group is (55xx) and the second group (00xx). These have used the Q-Blade simulation program to design a blade length 25 m and simulate the two groups at various angles to obtain the highest power that the turbine rotor can pick up from the wind. They have come to the conclusion that the best design is (55xx). It is detected that altering the chord length and twist angle only little alters the power output at a wind turbine. Additionally, it is found that at a wind speed of 18 m/s with a change in the twist angle and the chord's length results in a minor variation in power production[8].

An experimental study is conducted to develop wind turbines and generate more energy. In this case, a horizontal turbine is designed by changing the number of blades and the diameter of the rotor. It is concluded that the rotor with a 90 cm diameter of five blades can produce a power of 40W at a wind speed of 10 m/s. The power produced can be increased to 60 W at the same wind speed, by increasing the diameter of the rotor to 1.20 m and increasing the number of blades to eight[9]. A wind turbine blade is designed consisting of airfoils (S1223) and (S1210) to increase the power coefficient through blade optimizations employing (MATLAB) simulation software and (Q-Blade) software. A rotary turbine of 4 m in diameter with three blades is gained. Also, a spindle radius of 20 cm and a power coefficient of 0.42 are obtained with a turbine power ranging from 650 W-1.18 KW having a tip speed ratio of 6.5 at a wind speed of 5.5 m/s-7 m/s[10]. This horizontal wind turbine is designed using the Blade Element Momentum method (BEM).At a wind speed of 5 m/s, the Q-Blade analysis of a wind turbine with a 3 m diameter is performed. The findings of the analysis indicate a maximum torque of 15 Nm and a maximum annual energy output (AEP) of 538 kWh. This method can be successfully used for the design and analysis of HAWTS blades that operate in stronger winds[11].

This small horizontal-axis wind turbine is designed as a clean source of energy, with no hazards to electricity production in this wind turbine. These turbines neither emit toxicity nor have any specific productivity time, making them a superior alternative to fossil fuels and solar power. The wind turbine is analytically designed and the results are verified using the simulation Q-blade Software. A theoretical efficiency of 38.25% is obtained as the simulation results determined power of 750-800 W at an average wind speed 4 m/s-8.5 m/s[12]. A (HAWT) blade with three configurations (spar, no spar, and solid) is examined using modal analysis. The configurations responses to forces and aerodynamic loads are also examined. It is concluded that a blade constructed of aluminum class 6000 which reduces extra weight, is superior in its resistance to bending at all speeds and has a longer life, especially in places with high wind speed[13]. Wind speed data have been statistically analyzed for 4 regions in Iraq (Sinjar, Al- Qa'im, Salah Al-Din-Bayji, and Al-Rutba) over one year (2018-2019) at heights 10 and 50 meters above the ground. The monthly, seasonal, and yearly power wind potentials are determined. It is found that the months that had the maximum power density values were October and July, while November and February had the lowest wind power potential, respectively. The annual power density in all four regions is between 200 W/m^2 and 500 W/m^2. It is thus shown that wind turbines can be installed to generate electricity now and in the future for almost all specified locations[14].

Since most of the studies discuss wind turbines at high speeds, this does not apply to the geographical location of the current study (Iraq- Salah Al-Din-Bayji). The project aims to design a small-sized horizontal wind turbine rotor blade with three and five blades using the same airfoil. This is conducted to determine which is superior, in terms of the number of blades needed to harness the greatest amount of mechanical power from low wind, and solve the problem of power outages in rural areas or areas with low wind speed.

Theoretical Formulation

Wind energy (P_o), free-flowing at a given speed through the rotor blades can be expressed by Eq. 1[15]:

$$P_o = \frac{1}{2}\rho\, V_1^3 A \qquad 1$$

ρ Air density (1.225 kg/m^3).

A Area of the turbine rotor.

V_1 Wind speed before the turbine.

The mechanical energy of the wind turbine (P_T), which represents the wind energy converted into rotational energy by the turbine rotor, can also be expressed by Eq. 2[15]:

$$P_T = \frac{1}{4}\rho A(V_1^2 - V_2^2)(V_1 + V_2) \qquad 2$$

Where (V_2) represents the wind speed flowing after the turbine through the rotor blades as in Fig. 1.

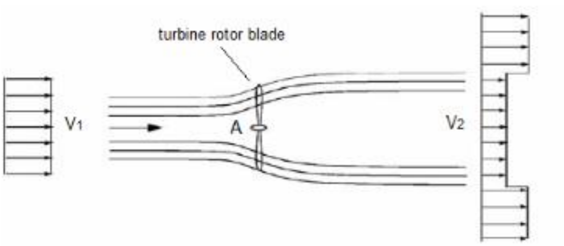


Figure 1. Wind flowing through the rotor of a wind turbine.

The maximum efficiency that a wind turbine can produce from free wind energy is 0.59, and this is known as the (Betz limit) set by the German scientist Albert Betz, meaning that the value of the power coefficient (C_P) of the wind turbine must be less than the Betz limit. This depends on wind turbine durability and surrounding conditions such as turbulence and wind intensity[16]. As for (C_P), it can be defined as the ratio of the power produced from the turbine to the free wind power and is given by Eq. 3[17].

$$C_P = \frac{P_T}{P_o} = \frac{\frac{1}{4}\rho A(V_1^2 - V_2^2)(V_1+V_2)}{\frac{1}{2}\rho\, V_1^3 A} \qquad 3$$

That is, no ideal turbine rotor can produce (C_P) more than the (Betz limit). The (C_P) relationship can also be written in another form as in Eq. 4[17]:

$$C_P = 4a(1-a)^2 \qquad 4$$

Where (a) the coefficient of axial induction, is given by Eq. 5[18]:

$$a = \frac{V_1 - V_2}{V_1} \qquad 5$$

The torque (T) of the wind turbine in terms of (a) is shown by Eq. 6[18]:

$$T = 2\rho A V_1^2 a\,(1-a) \qquad 6$$

The torque coefficient (C_T) can be written in a similar way to (C_P) and is given by Eqs. 7 and 8[18]:

$$C_T = \frac{T}{\frac{1}{2}\rho V_1^2 A} \qquad 7$$

$$C_T = 4a(1-a) \qquad 8$$

Rotor Design

The first step in designing a wind turbine is to choose the most suitable airfoil for the turbine rotor blade. Here, a high-lift coefficient and low-drag flap is chosen at low wind speeds to achieve the best power coefficient (C_P) and obtain an effective and intuitive design for the turbine rotor. A (Q-Blade) software is used to design the blade and make certain engineering improvements to the shape of the blade by distributing the airfoils along the blade and controlling the airfoil chord length and twist angle using the Blade Element Momentum method (BEM). The selection of the airfoil is based on the type of turbine and the size of the rotor to generate mechanical energy from wind energy. the airfoil (NACA 3712) which is chosen reaches a maximum thickness 29.10% of the airfoil to 11% at the end of the airfoil. The shape of the airfoil is concave from the bottom and convex from the top in order to obtain an appropriate lifting force that works to rotate the rotor blade as can be shown in Fig. 2.

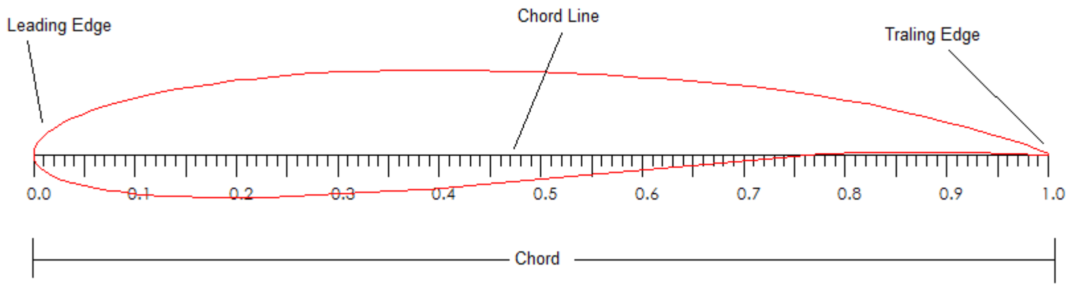
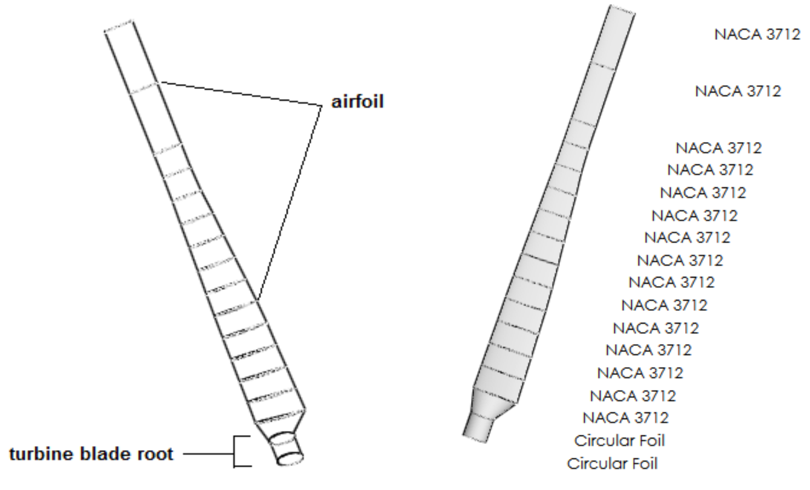


Figure 2. Airfoil shape chosen for the rotor blade design

In the second step of the design, several attempts were made to choose the appropriate length of the rotor blade and divide the blade into several sections in order to distribute the airfoils on it so that the shape of the blade is streamlined to suit the low wind speed. It is concluded that the length of the airfoil should reach 190 cm, divide the blade into 17 sections, use the first and second sections as the root of the blade, and the other 15 sections of the airfoils (NACA 3712) are distributed on it. Table 1 show the distribution of the ailerons with their different lengths for each section over the length of the rotor blade. It can be seen that the airfoil is larger in the parts close to the root and smaller in the outer sections of the blade, where the length of the airfoil (NACA 3712) near the root of the third section is 19.77 cm. It gradually decreases down to section 13 with a length of 11.45 cm, then the length of the airfoil from section 14 to the end of the blade is 10 cm long. The twist angle is distributed starting from the third section at an angle of 20.3^o to 2.4^o at the tip of the blade. Fig. 3a show how the airfoils along the blade are distributed. Here, each section of the blade faces the direction of the wind to obtain a high coefficient of lift.

Table 1. Horizontal axis wind turbine rotor specifications

Sr No:	Position (cm)	Chord (cm)	Twist-angle (deg)	Foil
1	0	10	0	Circular foil
2	10	10	0	Circular foil
3	20	19.77	20.3	NACA7611
4	30	19.13	16.6	NACA7611
5	40	18.65	13.9	NACA7611
6	50	18.11	11.9	NACA7611
7	60	17.76	10.2	NACA7611
8	70	16.99	8.9	NACA7611
9	80	15.99	7.8	NACA7611
10	90	14.85	6.9	NACA7611
11	100	13.75	6.2	NACA7611
12	110	12.79	5.5	NACA7611
13	120	11.45	4.9	NACA7611
14	130	10	4.4	NACA7611
15	140	10	4	NACA7611
16	165	10	3.1	NACA7611
17	190	10	2.4	NACA7611



a **b**

Figure 3. The design of the blade, (a) distribution of the ailerons along the length of the blade. (b) final blade shape.

After completing the blade design process, the required number of blades is entered into the software, after which a wind turbine rotor is constructed, and then the rotor axis is determined and designed with a diameter of 28 cm to install the rotor blades with three and five blades. The diameter of the entire rotor 4.8 m is at tip speed ratio TSR=7 and design rotational speed 250rpm. Fig. 4 show the final shape of the rotor design. The selection of the number of blades should be reached according to the required (C_p) value resulting from the wind turbine, which may increase or decrease by increasing the number of blades depending on the height and decrease in wind speed. Thus, it is necessary to determine the number of rotor blades suitable for generating good energy that can be used in practical applications. This is to be discussed in the results.

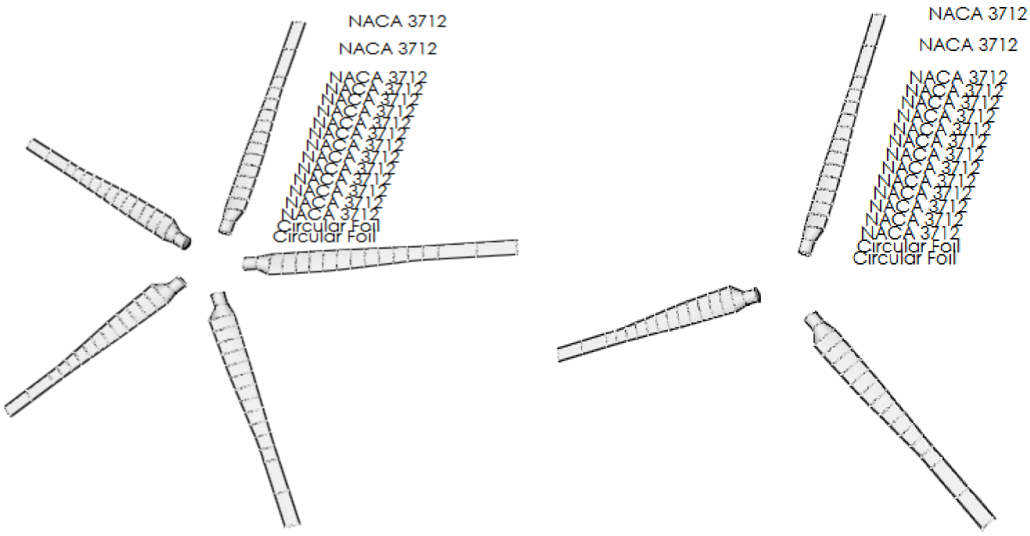
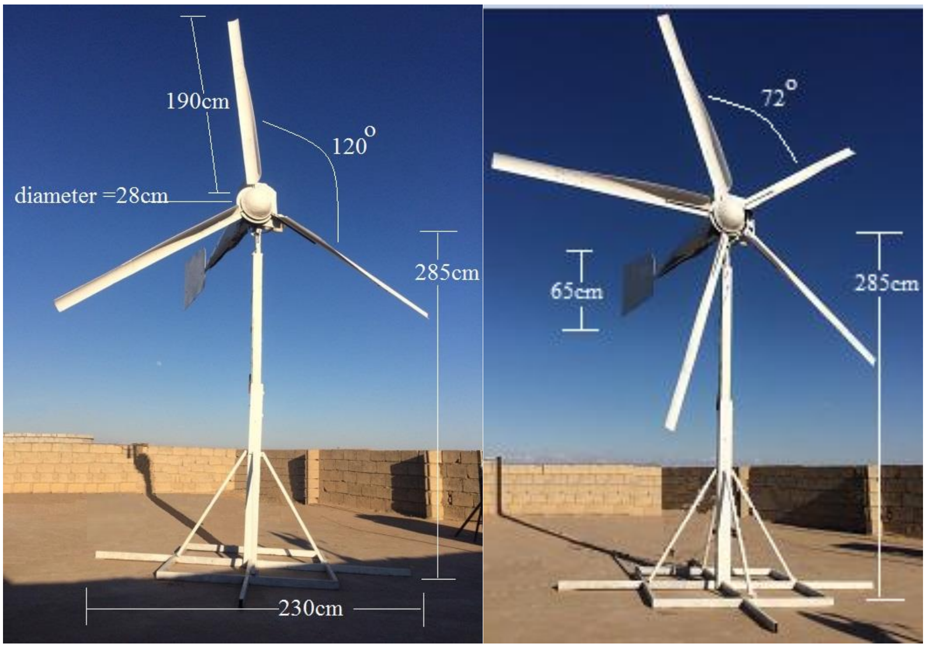


Figure 4. The shape of the rotor after completing the blade design processes.

Practical Part

Based on the measurements shown in Table 1 and the shapes shown above by (Q-blade) software, the rotor blades are made of plastic in order to obtain a blade that has good strength compared to its weight of 4.5 kg and is also water resistant and resistant to breakage at high wind speeds. These blades are installed on the axis of rotation, which has a diameter of 28 cm. The turbine is directed towards the wind by the tail, which is made of aluminum with a thickness of 3 mm, which is light in weight and resistant to rust. These parts are installed in the highest tower which is made of iron to hold the weight of the rotor and the tail and resist the vibrations that occur during the rotation of the rotor. The tower is installed from the bottom on a base of different dimensions which stabilizes and supports the tower, and the base itself is installed on the roof of the house. Fig. 5 show certain turbine designs with their dimensions.



a b

Figure 5. Turbine design: (a) three-blade rotor (b) five-blade rotor.

Results and Discussion

After completing the design and manufacturing process and making some appropriate modifications to the shape of the blade, a simulation is conducted to find out the mechanical properties (turbine power, power coefficient, torque coefficient), to perform the rotor blades, whether the design can be used in practical applications or not, where an analysis of the turbine rotor was conducted wind, with three blades, and five blades, to find out which one is better for producing power and which works to generate mechanical power at a wind speed rate of 1m/s-8m/s. The wind turbine is installed on the roof of a house at a height of 9 m, at a low wind speed, and using Eq. 2. It is found that the power of a five-bladed turbine increases with the increase in wind speed with greater power than a three-blade turbine. Where the power of the turbine with three blades 582W and five blades 955W Fig. 6 show the difference of increase in the mechanical power of the turbine which is gained from the wind. Thus, it can be said that the power of a small wind turbine can be increased by increasing the number of blades, without the need to change the diameter of the rotor to capture wind energy. The performance of the wind turbine is more sensitive to changes in wind speed whenever the number of blades is increased, in a way that suits the size of the turbine, through which it is coincident with[19].

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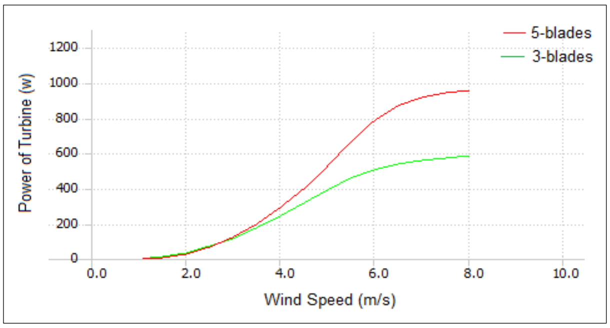

Figure 6. Power of the turbine with wind speed.

The choice of the number of blades is important as it directly affects the speed and efficiency of the wind turbine. The energy gained by the turbine from the wind is proportional to the area swept by the turbine rotor blades. Thus, the number of blades affects power generation, and the greater the number of blades, the greater the torque of the turbine rotor. In addition to easier rotation at low wind speeds, the number of blades is also appropriate to the size of the turbine. By comparing the three-blade turbine with the five-blade turbine, it is noted that the five-blade turbine improves performance significantly in areas where the wind speed does not exceed 8m/s when compared to the traditional three-blade turbine. On the other hand, in addition to the turbine's self-operating, the turbine rotor blade has an unbalanced torsional force acting on the shaft and this undesired deflection may reduce the energy produced and may lead to vibrations. The fact is that the three-blade turbine has minimal vibration. To explain this, when one of the blades is horizontal it is balanced by the other two blades, and to reduce this torsion, the load is either reduced from the effect of unbalanced wind loads on the three-blade rotor or the number of blades is increased. Using Eq. 4, it is noted that the increase in the power coefficient (C_P) of a five-bladed turbine rotor is more than that of a three-bladed rotor with the increase in wind speed as shown in Fig. 7. The value of (C_P) does not exceed the Betz limit 0.59, as the power coefficients of the three-blade rotor 0.46 and the five-blade rotor 0.49 were obtained. Thus, it can be said that the value of (C_P) is typical and its high value in the five-blade rotor is due to the use of an ideal design such as the improving of the profile of the blade and adjusting the twist angle created for each section of the blade. In addition, the lift coefficient for each blade is increased more than the drag coefficient with an increase in the number of blades. For this, it can be said that this design supports small wind turbines, and its power coefficient can be increased by increasing the number of blades, which is coincident with[20]. This represents the ideal curve shape for the results of the wind turbine.

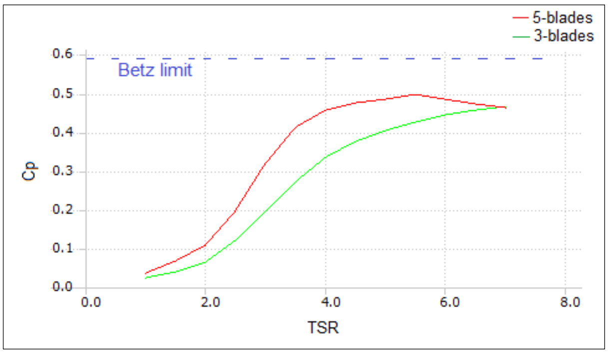

Figure 7. Power coefficient curve with Tip Speed Ratio (TSR).

Using Eq. 8, it is also noted that the torque coefficient (C_T) increases with the tip speed ratio (TSR) as the wind speed increases. That is, increasing the tip speed ratio increases the productivity of the turbine as a result of increasing the torque of the turbine rotor. Thus, this should be studied with the power factor and torque coefficient to increase its value in order to obtain more cycles and more turbine productivity. However, it is clear that the (C_T) of five blades is very large compared to that of the three blades. As a result of doubling the turbine torque due to the increased number of blades, this indicates that five blades can ensure stable operation of the wind turbine. Fig. 8 show a comparison between a three-bladed and five-bladed turbine with (TSR), in which it is coincident with[21]. This represents the best curve shape for the wind turbine findings.

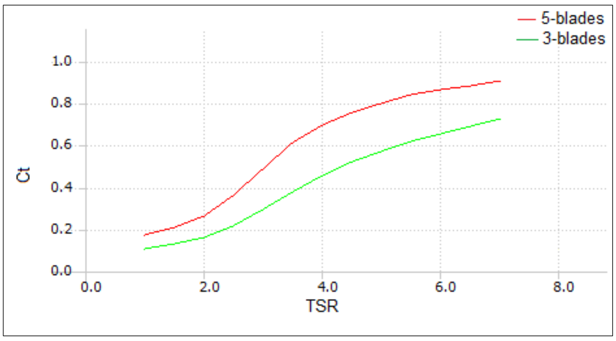

Figure 8. Torque coefficient curve with Tip Speed Ratio (TSR).

Conclusion

In this study, a horizontal axis wind turbine is designed with a rotor consisting of three blades and five blades. A comparison is made to find out which of the two turbines is better at average wind speed 1m/s-8m/s and at a height 9m to generate mechanical energy from wind energy based on the (BEM) method using the (Q-blade) design software. The results of the study show:

- That the use of an airfoil (NASA 3712) curved for the central geometric line in the middle line, is better for the blade of a small wind turbine to achieve a lifting force that rotates the turbine rotor.
- Increasing the number of blades using the same airfoil is appropriate in order to increase the torque and power of the turbine, provided that the number of blades is appropriate for a small-sized wind turbine.
- The percentage of improvement of the power coefficient after adding five blades is more than three 6.5%.
- The use of small-sized systems with a five-blade rotor is appropriate in areas with low wind speed to raise water in rural areas or invest in homes for the purpose of generating electrical power or using street light.

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Authors' Declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for re-publication, which is attached to the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Tikrit.

Authors' Contribution Statement

O. K. Z. He wrote the manuscript, corrected the errors, and conducted the present work by mastering the program used and interpreting the data. Supervisor Y. H. M. In the current study, he set the mechanism of action and refined the research from errors. The authors read the manuscript carefully. They approved the final version of this research.

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مقارنة بين توربينات الرياح ذات ثلاثة شفرات وخمسة شفرات من حيث الخصائص الميكانيكية باستخدام برنامج Q-Blade

عثمان خلف زيدان، ياسين حميد محمود

قسم الفيزياء، كلية العلوم، جامعة تكريت، صلاح الدين، العراق

الخلاصة

يمكن لتوربينات الرياح المنتشرة في مزارع الرياح على نطاق المرافق أن تدعم تلبية رغبات الطاقة المستقبلية وتقليل انبعاثات ثاني أكسيد الكربون عن طريق تقليل متطلبات الطاقة من الوقود الأحفوري. مع ارتفاع درجة حرارة الهواء على مدار اليوم، تزداد سرعة الرياح بسبب تدرجات درجة الحرارة، والتي تنتج تدرجًا في الكثافة / الضغط، مما يؤدي إلى حركة الهواء التي تواجهها توربينات الرياح. اعتمادًا على تضاريس الأرض، يمكن أن تواجه الرياح وتوجه في الوديان بين التلال وفوقها حيث تتدفق وتتبع منحنيات الأرض. تنتج هذه التضاريس زيادة في سرعة الرياح في القمم والتلال. في هذا العمل، تم تصميم شفرة دوار توربينات الرياح الأفقية الصغيرة للعمل في ظل سرعة الرياح المنخفضة، باستخدام برنامج (Q-Blade). استنادًا إلى نظرية عنصر الشفرة (BEM). مع الجنيح NACA3712. تم استخدام دوار ثلاثي الشفرات ودوار بخمس شفرات بناءً على نوع التوربين وحجم الدوار لتوليد الطاقة الميكانيكية من طاقة الرياح. تم إجراء مقارنة وتحليل قوة التوربين ومعامل القدرة ومعامل عزم الدوران عند سرعة رياح منخفضة ((m/s-8m/s1 وتم الحصول على نتائج دقيقة للغاية. وجد أن أفضل أداء يمكن أن يعمل فيه دوار توربيني ثلاثي الشفرات بقدرة توربينية تبلغ (W955) كما تم الحصول على قدرة التوربين ((W582 للدوار خماسي الشفرات. وجد أن تصميم توربينة رياح أفقية صغيرة بخمس ريش أفضل من التوربين بثلاث ريش ومناسب للعمل في المناطق ذات سرعة الرياح المنخفضة وبكفاءة عالية مقارنة بحجم التوربين.

الكلمات المفتاحية: سرعة الرياح المنخفضة, معامل القدرة, معامل عزم الدوران, شفرة توربين الرياح, , طاقة الرياح.