Small Horizontal Wind Turbine Design and Aerodynamic Analysis Using Q-Blade Software

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Abstract:

Wind energy is one of the most common and natural resources that play a huge role in energy sector, and due to the increasing demand to improve the efficiency of wind turbines and the development of the energy field, improvements have been made to design a suitable wind turbine and obtain the most energy efficiency possible from wind. In this paper, a horizontal wind turbine blade operating under low wind speed was designed using the (BEM) theory, where the design of the turbine rotor blade is a difficult task due to the calculations involved in the design process. To understand the behavior of the turbine blade, the QBlade program was used to design and simulate the turbine rotor blade during working conditions. The design variables such as (chord length and torsion angle) affecting the performance of wind turbines were studied. Aileron (NACA4711) was selected for sixteen different sections of the blade with a length of (155 cm) both (power factor, torque coefficient, lift coefficient, drag coefficient, lift-to-drag coefficient ratio) where high-accuracy results were obtained and it was found that the best performance in which the turbine rotor can operate is when the tip speed ratio is equal to (7). In addition, a power factor was obtained (Cp = 0.4742), not exceeding the Betz limit (0.59%). It is good efficiency for a small wind turbine, and it turns out that the design of a small horizontal wind turbine with three blades is suitable for working in areas with low wind speed.

Key words: Blade Shape, Power Coefficient, Twist Angle, Torque Coefficient, Wind Energy.

Introduction:

Many technological challenges stem from the need for renewable energy to reduce environmental pollution, and wind energy is one of the solutions. The recent development in wind energy technology has raised hopes for providing electrical energy in many countries, and investments have increased to enable countries to produce electrical energy from wind energy [1,2]. To reduce the effects of carbon dioxide emissions, which leads to global warming, and although the distribution of wind speed varies in place and time, wind energy is the best option for renewable energy [3,4]. When studying or designing wind turbines, the aerodynamics of the airfoils used in the design of the wind turbine rotor must be described. Based on BEM, the aerodynamic data is among the inputs required when conducting the simulation [5]. Gray and others compared a group of airfoils designs for the National Renewable Energy Laboratory (NREL) and National Advisory

Committee for Aeronautics (NACA) series of ailerons to design a model that works in areas with low wind speeds using the QBlade program to increase aerodynamic performance and they came up with an airfoil design (G4510) that works within a wind speed (2m/s - 6m/s). It was found that the value of (CL/CD) has increased in comparison with other airfoils that were studied to become the efficiency of G4510 by (52.2%) [6]. Mujahid and others designed eight types of airfoils with different thicknesses for two groups of (NACA) the first group was (55xx) and the second group (00xx) to design a blade length (25 m) using QBlade simulation program and simulate the two groups at different angles to obtain the highest power that the turbine rotor can pick up from wind and they concluded that the optimal design is (55xx), as this design can capture energy from wind at a rate of (4 m/s) and give energy of (500 kw) at a wind speed (9

m/s), and this characteristic is desirable. It was also found that the change in the twist angle and the length of the chord leads to a small change in the power output at a wind speed of (18 m/s) [7]. Modal analysis was studied on a horizontal axis wind turbine (HAWT) blade with three configurations (solid, no spar and spar) and the analysis of the blade configurations (bending stress, blade edge, and frequencies) and their response to forces and aerodynamic loads. They concluded that the blade made of aluminum class (6000) to reduce the additional weight is better for its resistance to bending at all speeds and has a longer life, especially in areas with high wind speed [8]. Some new designs were presented including (slotted blades and tuber or convex design models) and some experiments were conducted to verify the validity of numerical studies and obtain more detailed and understandable results. It was found that the slotted blade design is more energy-producing than the straight blade design at low wind speed. As for the tuber blades, it was found that its performance is better for producing power at high wind speeds and its behavior is more stable at unstable and harsh wind speeds, due to its tuber design, which prevents disturbances [9]. Shah and Barve designed and modeled a vertical wind turbine type (Darrieus) where the ailerons were designed using QBlade software, turbine modeling using Solidworks software, and aerodynamic analysis using ANSYS Workbench software and with the help of QBlade, a highly efficient airfoil design has been obtained that can be used to capture energy from the wind [10]. Gulve and Barve designed two types of small turbines with a hybrid system with solar cells, where they came up with the design of a compact system consisting of (VAWT) that is installed above (HAWT) to generate electric power The results were efficient and useful for rural areas, homes and most cities, and at a lower cost. They can also be installed for bridges that need continuous lighting [11]. A new concept has been studied for the design of the Darrieus wind turbine blade for the J-shaped vertical wind turbine that can benefit from the force of lift and drag at the same time, and these forces help the turbines to have a faster rotation process in low wind speed, which leads to the termination of the autorun problem and the improvement of power parameters, especially in the low and moderate TSR. The results obtained indicate that the J-shaped profile improves the intrinsic ability to initiate the rotor rotation process and helps to escape from the area called the dead zone because of its ability to harness the kinetic energy of the wind. This type of design is superior to traditional blades in taking advantage of the

forces of lifting and pulling at the same time [12]. Muhsen and others designed and improved the (HAWT) blade using the BEM theory, where the QBlade program was used to perform the optimization and the MATLAB program was used for the input parameters and a high power coefficient was obtained by designing the airfoils S1223 and S1210 with a rotor diameter of 4 m with three blades, and a power coefficient of (0.40%) was obtained at a wind speed of (7 m/s) and the power of the wind turbine was (1.18 kw) [13]. The horizontal axis (1MW) wind turbine is designed using the (BEM) theory in order to obtain the maximum power coefficient and lower the manufacturing cost of the blade It also made the manufacturing process easier and more accurate by developing linear chord distributions and also to cross the tangent line through different points on the chord the results determined that the best point along the chord has the highest total energy parameter and is close to the results of (BEM). It was also observed that the optimal location is approximately (60-64%) and (30-37%) of the blade length, for the chord and twist [14]. The horizontal axis wind turbine model was studied at variable wind speed and it was found that the change of blade angle is important to control the values of power factor Cp and TSR at variable wind speed to obtain efficiency within a specified range [15].The aim of the study is to design a small three-bladed horizontal wind turbine 'rotor blade' and make some engineering modifications to the blade in terms of shape and torsion angle in order to obtain the maximum amount of energy gained from the wind and then study the mechanical properties of the wind turbine.

Theoretical Formulation:

The power coefficient (Cp) is the most important parameter for choosing a suitable wind turbine, which is defined as the ratio of the power obtained by turbine rotor (P_T) to the total wind energy (P_o) flowing through the blades of the turbine rotor at a certain speed, Fig.1.
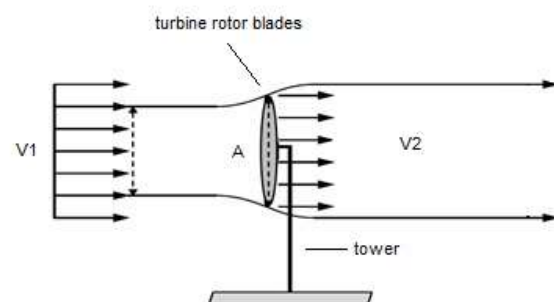

Figure 1. Shows the wind flow through the turbine rotor blades.

Many factors are included in the power coefficient such as the efficiency (gearbox, shaft bearings, power electronics, generators). The value of (Cp) is affected by operating conditions such as wind speed, blade angle, rotation speed, etc... The power coefficient (Cp) can be expressed by equation No. 1.

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

Where, V1 is the upstream wind speed and V2 is the wind speed flowing through the rotor blades, ρ air density (1.225 kg/m3) A is the rotor diameter. Therefore, the power coefficient can be written in another form in terms of the axial induction factor (a).

$$C_P = 4a(1-a)^2 \text{------------ 2}$$

The axial induction coefficient (a) represents the partial drop in wind speed between (the turbine rotor and the free wind speed upstream), and is given by equation 3:-

$$a = \frac{V1 - V2}{V1} \text{----------- 3}$$

The axial torque on the wind turbine rotor can also be expressed by equation 4:-

$$T = 2\rho A V_1^2 a (1-a) \text{----- ------ 4}$$

So the torque coefficient can be written in Equation 5:-

$$C_T = \frac{T}{\frac{1}{2}\rho V_1^2 A} \text{----------- 5}$$

It can also be written (CT) in terms of the coefficient of axial induction (a) in Equation 6:-

$$C_T = 4a(1-a) \text{-------- 6}$$

The lift and drag coefficients are important for wind turbine design, which are given by equations 7 and 8:-

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \text{------------ 7}$$

$$C_D = \frac{D}{\frac{1}{2}\rho A V^2} \text{------------ 8}$$

Where (CL) represents the lift coefficient, (CD) the drag coefficient, (L) represents the lift force due to the uneven pressure on the lower and upper surface of the airfoil, which is perpendicular to the wind direction. And (D) represents the drag force that is parallel to the wind direction due to the unequal pressure of the airfoil surfaces facing the wind [16,17].

Rotor Design:

The blade is the most important element in wind turbine design. Using the BEM method, some of the inputs shown in Table 1 should be considered to improve the wind turbine blade (HAWT) using airfoil (NACA 4711). Airfoil analysis was performed in QBlade for different wind speeds and record the ideal values for (CL/CD, CL, CD). Then the blade element was divided into (N=16) elements and then determine the shape of the blade suitable for the design of the rotary with a diameter of (170 cm) was determined, works with good efficiency Fig.2. With the application of some modifications to engineer the shape of the blade so that each section of the blade could face the wind direction to achieve the best tip speed (TSR) for optimum power generation. The aim of this research is to design a horizontal wind turbine with a factor of (CP), greater than (0.40) and it works in areas with low wind speed (0.5 m/s – 7 m/s) not exceeding the value of the Betz limit (0.59), which states that wind turbines cannot convert more than (59.3%) of the kinetic energy of the wind into mechanical energy.

Table 1. Horizontal Axis Wind Turbine Specifications.

Sr No:	Position (cm)	Chord (cm)	Twist-angle (deg)	Foil
1	0	10	0	Circular foil
2	5	10	0	Circular foil
3	10	10	0	Circular foil
4	15	10	0	Circular foil
5	45	17.17	11.1	NACA4711
6	55	14.85	9.02	NACA4711
7	65	13.07	7.44	NACA4711
8	75	11.67	6.19	NACA4711
9	85	10.53	5.19	NACA4711
10	95	9.60	4.37	NACA4711
11	105	8.81	3.68	NACA4711
12	115	8.14	3.09	NACA4711
13	125	7.57	2.59	NACA4711
14	135	7.07	2.16	NACA4711
15	145	6.63	1.77	NACA4711
16	155	6.25	1.44	NACA4711

(a)   **(b)**
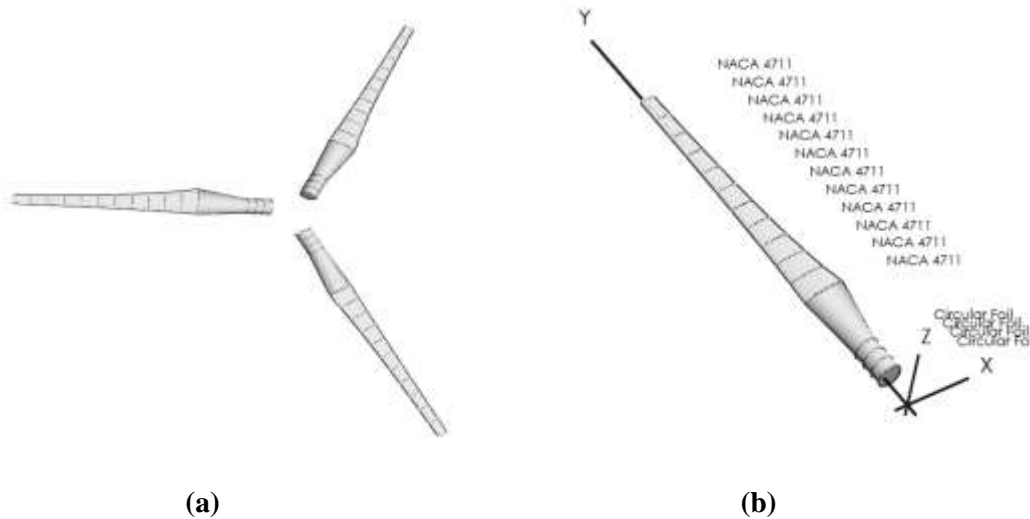**Figure 2. (a) shows the design of the blade. (b) shows the design of a three-blade turbine rotor.**

We note from Figure 2, that the blade sections from 1 to 4 are the root of the blade and the angle at that is (zero), as for the rest of the other sections, the angle is gradually changed from (11.101°) to (1.440°) so that each section could face the wind direction to achieve the best lifting force, and obtain an optimum tip velocity ratio (TSR) for the blade. The blade sections from 5 to 16 are the parts that interact with the wind to capture energy from the wind and convert it into mechanical energy.

Results and Discussion:

In this paper, the chord optimization was carried out in addition to the torsion angle of an airfoil (NACA4711) to obtain a high power wind turbine. The turbine rotor blade consists of sixteen different sections, so that the shape of the airfoil can be curvilinear for the central geometric line (the middle line) of the airfoil section, as well as the distribution of airfoil thickness. As the shape of the airfoil is streamlined, the wind can flow through it. Thus, it can be said that the airfoil is the first step in designing the turbine rotor blade. Fig.3 shows how the aileron (NACA4711) was created.
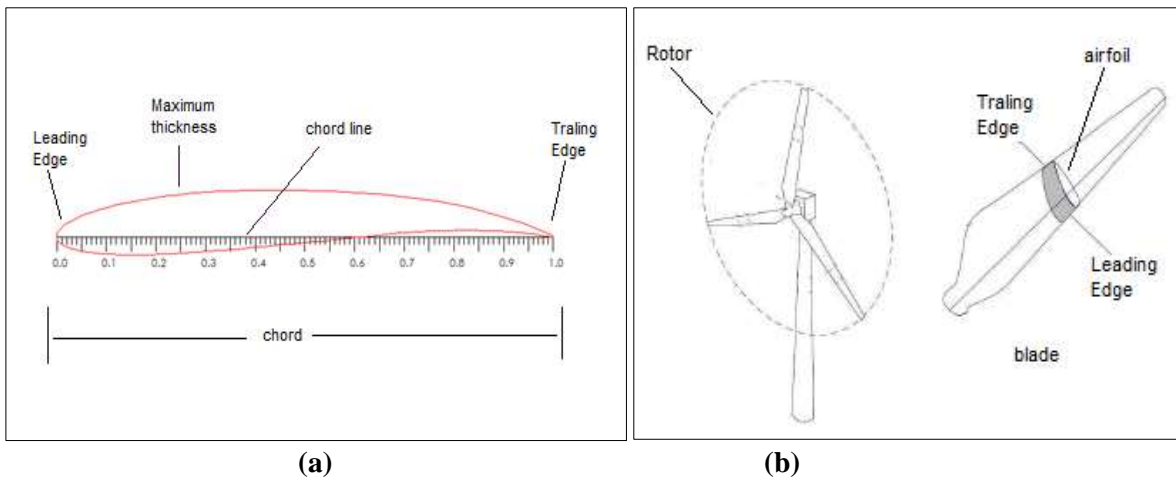

(a)   **(b)**
Figure 3. (a) The design of the airfoil of the blade, the rotor of the turbine. (b) b Describes the blade design and final shape of the turbine.

After designing the aileron and determining the appropriate blade shape using the Q-Blade program, a simulation was carried out to calculate the lift and drag coefficients by using both equation (7 and 8) to find out the best angle at which the rotor blades can

be placed, and obtaining a high lift coefficient and a low drag coefficient to rotate the rotor and capture wind energy and then convert it into mechanical energy that can be used. Fig.4 shows the lift and drag coefficients.
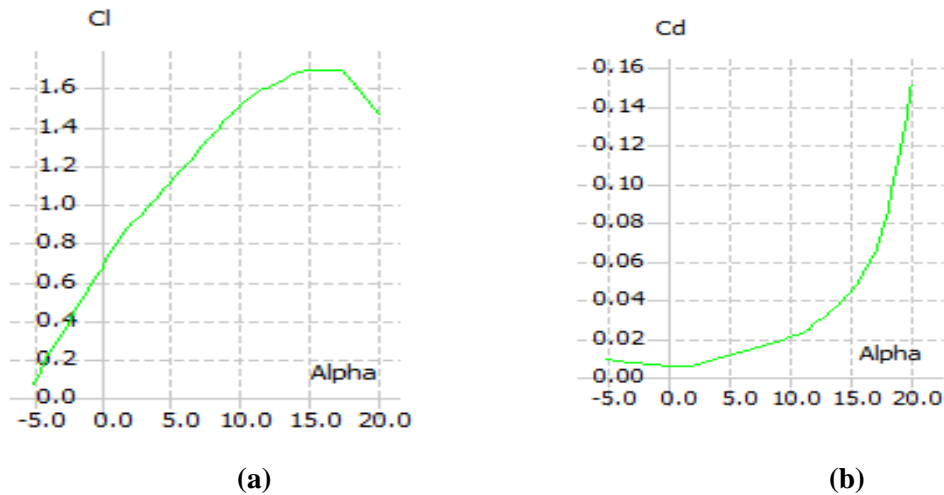
(a) (b)

Figure 4. (a) Shows the lift coefficient (Cl) with the angle (Alpha), (b) Shows the drag coefficient (Cd) with the angle (Alpha).

We notice from Fig.4a that the lift coefficient (Cl) increases as the angle (Alpha) increases, with a slight increase in the drag coefficient, so that the lift coefficient can reach a maximum value at an angle of (16º) degrees. Then it starts decreasing, and thus the drag coefficient (Cd) increases to reach its maximum value at an angle (20º) Fig.4b. In order to find out the pitch angle to complete the blade optimization process, the ratio of the lift-to-drag coefficient (Cl/Cd) with the angle (Alpha) was calculated from Fig.5, it was found that the pitch angle value is equal to (2º) degrees, Similar to what was found in the study [18-20].
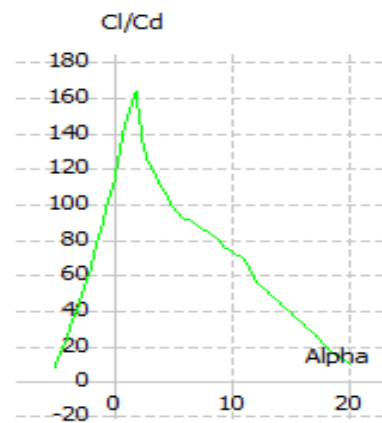

Figure 5. Ratio of the lift-to-drag coefficient (Cl/Cd) with the angle (Alpha).

The power coefficient (Cp) and thrust coefficient (CT) by using equations (2 and 6), with tip velocity ratio (TSR) are also simulated. To achieve the blade element theory (BEM), and that the value of (Cp) does not exceed the Betz limit (0.59), and through the simulation process, it was found that the data are typical, as Fig.6a indicates that the wind turbine operates at optimum tip speed ratios. The high Cp value is due to the ideal design of the rotor blade, such as improving the twist angle and profile of the blade. We also notice from Fig.6b that the torque coefficient (CT) increases with the increase in tip speed ratio (TSR), Similar to what was found in the study [21,22].
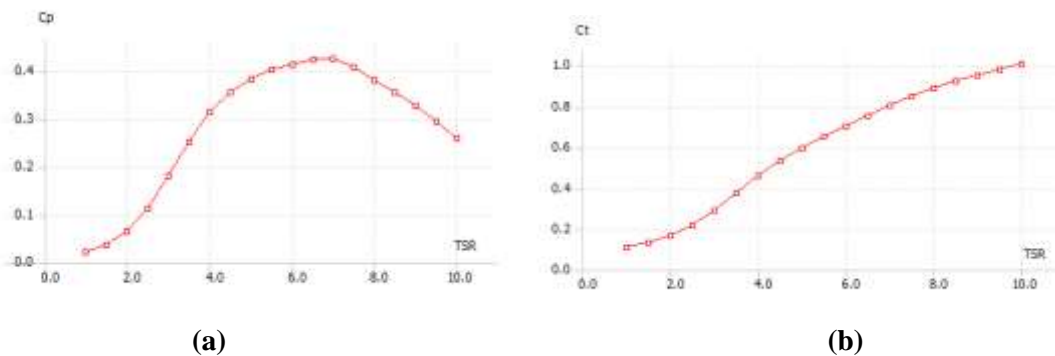
(a)   (b)
Figure 6. Shows the (Cp) and (CT) curves with the tip velocity ratio (TSR) values.

Conclusions:

In this paper a horizontal axis wind turbine, optimizing the rotor blade is designed to operate at low wind speeds, based on BEM theory using Q-blade design software. It has been concluded that the shape of the rotor blade improves the performance of the turbine. Any mistake in the design of the blade such as the torsion angle or the aileron curvature will negatively affect the performance of the turbine, and the selection of the NACA4711 airfoil is very appropriate. Through the results obtained, it is found that the highest value of (Cl/Cd) when (Alpha) is equal to (2º) degree. And the use of small-sized turbines is suitable in areas with low wind speed, to raise water in rural areas or use it to generate electric power for street lighting or invest it by homes.

Authors' declaration:

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

Authors' contributions statement:

O. Kh. wrote the manuscript, corrected the errors, and conducted the study used in the present work by mastering the program used and interpreting the data. Supervisor Y.H. On the study used, setting the mechanism of action, and refining the research from errors everyone The authors read the manuscript carefully.
They approved the final version of this research.

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تصميم توربين رياح أفقي صغير والتحليل الأيروديناميكي باستخدام برنامج Q-Blade

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الخلاصة:

طاقة الرياح واحده من الموارد الطبيعية والاكثر شيوعاً حيث تلعب دوراً هائلاً في قطاع الطاقة وبسبب الطلب المتزايد لتحسين كفاءة توربينات الرياح وبسبب تطور مجال الطاقة تم اجراء تحسينات لتصميم توربين رياح مناسب والحصول على اكثر قدر ممكن من كفاءة الطاقة من الرياح. في هذه الورقة تم تصميم شفرة توربين رياح افقي يعمل ضمن سرعة الرياح المنخفضة وباستخدام نظرية (BEM), حيث يعد تصميم شفرة دوار التوربين مهمه صعبة بسبب العمليات الحسابية المتضمنة في عملية التصميم. ولفهم سلوك شفرة التوربين تم استخدام برنامج Q-Blade لتصميم ومحاكاة شفرة دوار التوربين حيث تم دراسة متغيرات التصميم مثل (طول الوتر وزاوية الالتواء) المؤثرة على اداء توربينات الرياح تم اختيار جنيح (NACA4711) لستة عشر قسم مختلفة للشفرة بطول (155cm) . تم تحليل (معامل القدرة, معامل العزم, معامل الرفع, معامل السحب, نسبة معامل الرفع الى السحب) حيث تم الحصول على نتائج ذات دقة عالية وتبين ان افضل اداء يمكن ان يعمل فيه دوار التوربين عندما تكون نسبة سرعة الطرف تساوي (7) بالإضافة الى ذلك تم الحصول على معامل قدرة (Cp = 0.4742) لا يتجاوز حد بيتزا (0.59 %) وهي كفاءة جيدة بالنسبة لتوربين رياح صغير وتبين ان تصميم توربين رياح افقي صغير ذو ثلاث شفرات مناسب للعمل ضمن المناطق ذات سرعة رياح منخفضة.

الكلمات المفتاحية: شكل الشفرة، معامل القدرة، زاوية الالتواء, معامل العزم، طاقة الرياح.