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An Investigation of Design and Simulation of Horizontal Axis Wind Turbine Using QBlade

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Abstract: The wind turbine blade design is important in obtaining an effective wind turbine. In the field of wind energy, it is essential to understand the design and parameters affecting the blades of the wind turbine in order to obtain a successful design. However, most of the parameters are dependent on each other and this makes the design of wind turbines a challenging task. This research paper used the QBlade software to analyze and optimize the behavior of the small horizontal axis wind turbine. The software applies the Blade Element Momentum Theory (BEM) to study the wind turbine blades by calculating the drag and lift coefficients which were achieved by dividing the blades into 10 ascending segments. The twist angle and chord length of the blade are optimized to get the highest performance. Among the various airfoil types, the SG-6041 airfoil type was selected to build the blade structure. The calculated power coefficient was almost 0.4, which is considered high given that it was calculated under 10 m/s average wind speed and 1-meter length blade conditions. Where all the results are logical and reasonable, the software is proven to be reliable. The paper also evaluates the wind characteristics in different locations in Iraq in order to find the most optimal promising locations in Iraq.

Keywords: horizontal axis wind turbine, power generation, aerodynamic analysis, QBlade, wind data analysis.

1. INTRODUCTION

Wind energy is one of the most important renewable resources that are used widely in the world. Wind energy plays a key element in the energy industry in terms of wind turbines. Many researchers from the industry sectors are working to develop the wind turbine design in order to enhance efficiency and performance. On the other hand, pollution is considered a major problem, and most of the pollutants are produced when converting fossil fuels to energy. So, the utilization of renewable energy sources has a promising future to reduce the level of pollution. As a result, to meet the growing energy demands, it is necessary to involve a clean and efficient energy source in the process.

The design of a wind turbine blade has a significant impact on its ability to generate the highest level of power. Wind energy is considered a clean energy source, where it is considered as a competitive type of energy production facility. The analysis and optimization of the wind turbine blade is a necessary element in producing an efficient energy source. QBlade software is used to build a wind turbine with variable wind speeds. [1]. Many studies have been carried out to optimize the wind turbine performance using the QBlade software. A new model of a five-bladed wind turbine was developed and then investigated under the effect of low-speed wind turbine (2, 3, 4, 5 and 6 m/s). In addition, the blade element momentum method (BEM) was used to achieve the theoretical analysis using NACA 4412 airfoil type. The results showed that when the wind speed increased, the power increased proportionally [1]. Hani et al. [2] designed and optimized the output of a small horizontal axis wind turbine with a power coefficient (*Cp*) greater than 40 % at a low wind speed of 5 m/s. In order to obtain the final optimized airfoil, they combined two symmetric airfoils of different shapes and improved the design using the blade element momentum theory. They finally obtained the rotor design with a power coefficient of 0.445 (44.5 %), which was higher than 40 % of the oldest model [2]. The performance of small horizontal axis wind turbine blades with power output of less than 1 kW was studied [7]. The wind turbine blade is stimulated during operation using the QBlade software based on the blade element momentum theory (BEM). The SG6043 airfoil type was used, where the effect of twist angle and chord length on

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wind turbine behavior and performance were investigated. It was discovered that when the angle of attack is 2 degrees, the highest value of (*CL*/*CD*) is obtained and it was revealed that when the tip speed ratio is equal to 8, the rotor performance is optimal [7]. For the Jamshoro wind corridor in Pakistan, a wind blade design was created and optimized using the QBlade software. We studied theoretically a 43 m blade in order to find the optimum design. Also, we optimized the twist angle by combining different NACA profiles and using an exhaustive iterative process [3]. A rotor blade for a wind turbine is designed for a particular wind corridor in which the basic set of airfoil output for the wind conditions at the turbine site is the first step in the rotor blade design process. Following the findings of various simulations using the QBlade software, it was determined that the 5 blade was the best rotor blade configuration for the specified location [4]. Raut et al. [5] designed a micro turbine which is less than 1 kw using the QBlade software. They tested various airfoil types and observed the behavior of wind turbine after and before optimization. Ponakala et al. [6] simulated the wind turbine rotor blades in order to enhance the performance to utilize the small wind turbine systems. They used the QBlade software to build the geometry of rotor blades and then examined it. The airfoil type used in their design was NACA 0018, based on the optimization results.

Also, there are many other researchers that used the QBlade software to optimize the design of HAWT blades to obtain high performance blades and high-power generation [7]-[10]. The main aim of this research paper is to analyze and optimize the wind turbine blade (horizontal axis) using airfoil (SG-6041). This type of airfoil was selected because all its data are available and the results of the developed model can be verified. This analysis was achieved according to the design and operational parameters such as the variation of lift and drag coefficients with angle of attack, and power. All results were validated with theoretical results that were obtained using the developed Matlab code.

2. THEORETICAL FORMULATION

The blade element momentum method (BEM) is considered as the key to investigating the aerodynamic characteristics of wind turbine blades. The typical cross-sectional airfoil of the blade is shown in Fig.1., which describes the aerodynamic forces that act on the blade section and the aerodynamic angles. The design parameters for the HAWT that has been specified will be defined in details. The aerodynamic lift and drag forces can be determined as follows

$$cl = \frac{l}{0.5*\rho\infty*V\infty^2*A} \quad (1)$$

$$cD = \frac{D}{0.5*\rho\infty*V\infty^2*A} \quad (2)$$

$\rho\infty$ (kg/m^3) is the air density, $V\infty$ (m/s) is wind speed, L is lift force (N), D is the drag force (N), and A (m^2) is the cross-section area. The power coefficient, which is defined as the efficiency of a wind turbine, is therefore defined as output power divided by wind power. The power coefficient is affected by a number of factors, including turbine efficiency, which affects rotor and blade efficiencies, mechanical efficiency, gearbox efficiency, and electrical efficiency. The power coefficient is

$$Cp = \frac{P_{generated}}{\rho*V\infty^3*Ad} \quad (3)$$

where

$$P_{generated} = 2\,\rho\,A_d\,V\infty^3\,a\,(1-a)^2 \quad (4)$$

where a is defined as the axial induction factor [7]. It is the fractional decrease in wind velocity between the freestream and the turbine rotor [6]. Thus, the power coefficient equation can be rewritten in terms of the axial induction factor (a) as follows

$$Cp = 4\,a\,(1-a)^2 \quad (5)$$

After that the thrust coefficient can be calculated in terms of axial induction factor as follows

$$Ct = 4\,a\,(1-a) \quad (6)$$

The next step is simulation and optimization the performance and behavior of the small horizontal axis wind turbine using the QBlade software.

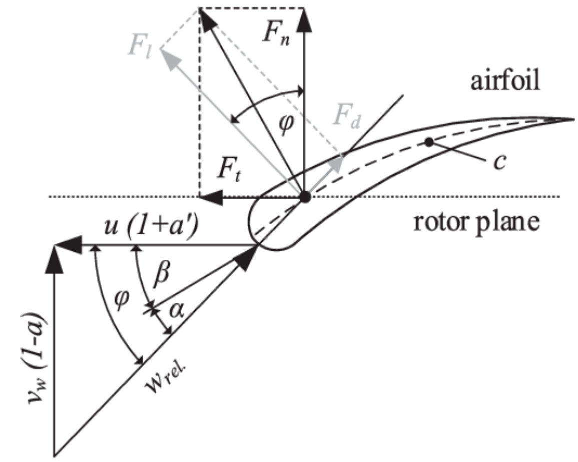


Fig.1. Airfoil sectional aerodynamic forces and angles [10].

3. ANALYSIS AND OPTIMIZATION OF BLADE USING QBLADE

The first step is to import the selected airfoil (SG-6041) as a data file from the website (airfoiltools.com) in order to use it. Fig.2. illustrates the overview of the facilities of the QBlade software. The spline, circular, and SG-6041 airfoils are generated as shown in Fig.3. Also, the standard thickness percentage of each airfoil type (spline, circular, and SG6041) is shown in Fig.3. The simulated blade is divided into 10 sections in equal and ascending sections which gives approximately 1 m as illustrated in Fig.3. Fig.4. shows the 3-blade design with position, chord, and twist angle before the optimization process.

Owing to short length of the blade and the low level of wind velocity, the value of the Reynold number will be considered 100,000. The next step is simulated using Xfoil direct analysis to create a new polar extrapolation. Then we choose a starting and ending angle of attack -5 to 25 degrees.

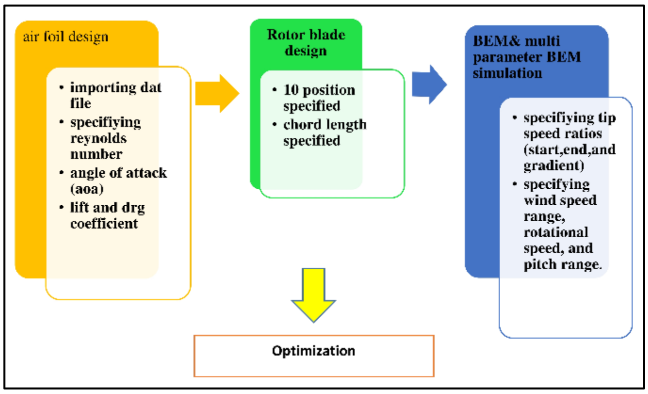


Fig.2. The main sections of the QBlade software.

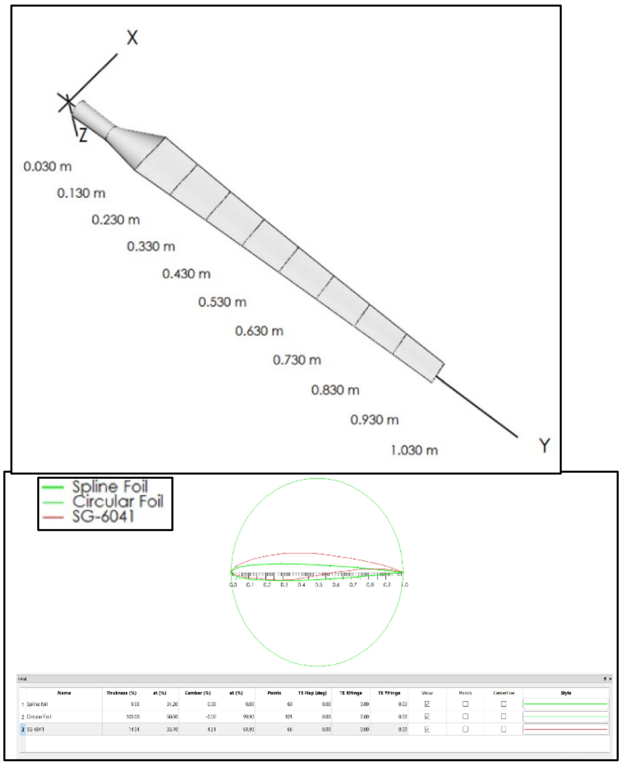


Fig.3. Details of selected airfoils.

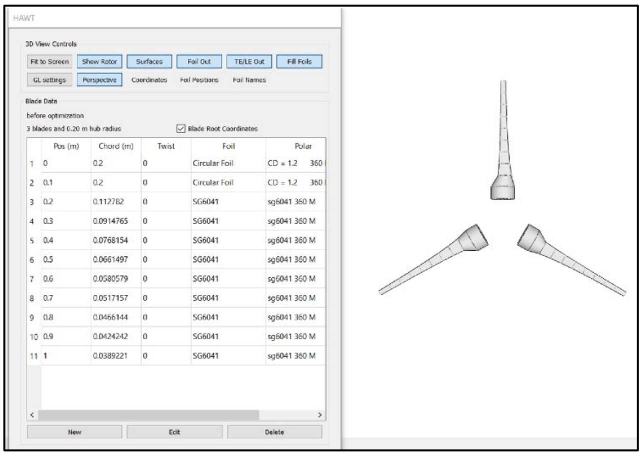


Fig.4. Generating the 3-blade design with position, chord, and twist angle before optimization.

4. RESULTS AND DISCUSSIONS

This research focused on the importance of analyzing and optimizing the aerodynamic characteristics of the turbine blade (horizontal axis) using QBlade. Full details and deep investigation were achieved to find the optimal operational and design parameters for the wind turbine blade.

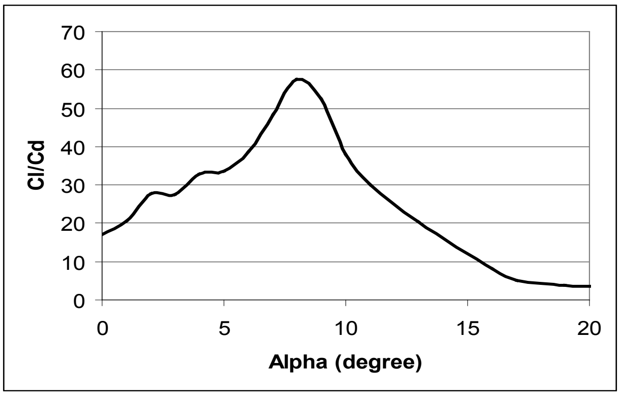


Fig.5. Variation of Cl/Cd with angle of attack.

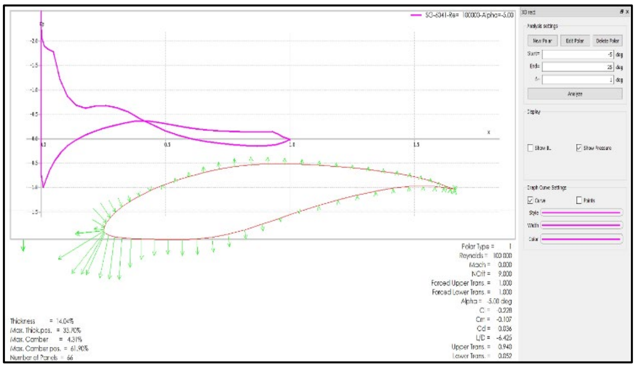
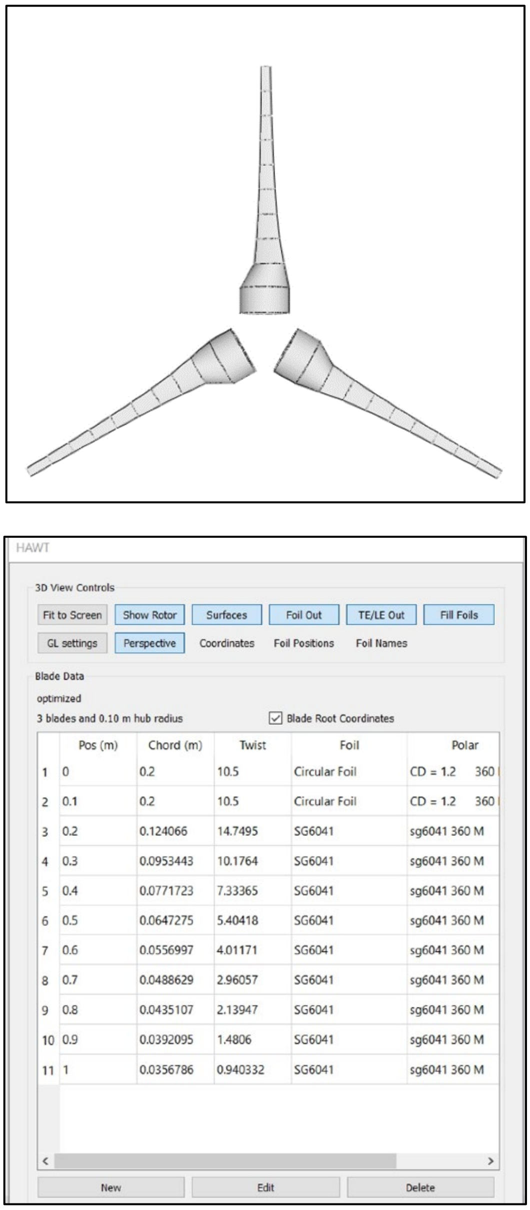


Fig.6. visualization of boundary layer and pressure produced on the airfoil.

Later on, the ratio of *CL*/*Cd* versus angle of attack (alpha) is illustrated in Fig.5. Fig.6. shows the operation point view used to envision the pressure (indicated in arrows) and boundary layers produced on the chosen airfoil type. A circle was extrapolated using 360-degree polar extrapolation to get a circle having a similar diameter as the airfoil chord. Extrapolation is extremely necessary, otherwise the simulation of turbine or rotor cannot be done [11]. By optimizing the generated blades (Fig.3.), new chord lengths and twist angles for each segment were obtained as shown in Fig.7. This is done by obtaining the maximum angle of attack at the maximum *CL*/*Cd* which is approximately equal to 8 degrees. The reason behind these results is the optimum performance of the wind turbine blades obtained at the maximum angle of attack. The BEM method in this research has two tasks which are *CD* (drag coefficient) and *CL* (lift coefficient), and then the drag and lift forces can be determined, respectively [8]. Based on the Betz method that was used to obtain the maximum power from the wind turbine [7], the optimization can be accomplished. The rotor BEM simulation gives the ratio of power coefficient versus tip speed ratio (*CP*/*TSR*) as shown in Fig.8. A comparison between the blades before and after the optimization is made. Fig.9. exhibits the variation of thrust coefficients before and after the optimization.



	Pos (m)	Chord (m)	Twist	Foil	Polar
1	0	0.2	10.5	Circular Foil	CD = 1.2 360
2	0.1	0.2	10.5	Circular Foil	CD = 1.2 360
3	0.2	0.124066	14.7495	SG6041	sg6041 360 M
4	0.3	0.0953443	10.1764	SG6041	sg6041 360 M
5	0.4	0.0771723	7.33365	SG6041	sg6041 360 M
6	0.5	0.0647275	5.40418	SG6041	sg6041 360 M
7	0.6	0.0556997	4.01171	SG6041	sg6041 360 M
8	0.7	0.0488629	2.96057	SG6041	sg6041 360 M
9	0.8	0.0435107	2.13947	SG6041	sg6041 360 M
10	0.9	0.0392095	1.4806	SG6041	sg6041 360 M
11	1	0.0356786	0.940332	SG6041	sg6041 360 M

Fig.7. The optimized twist angle of the wind turbine.

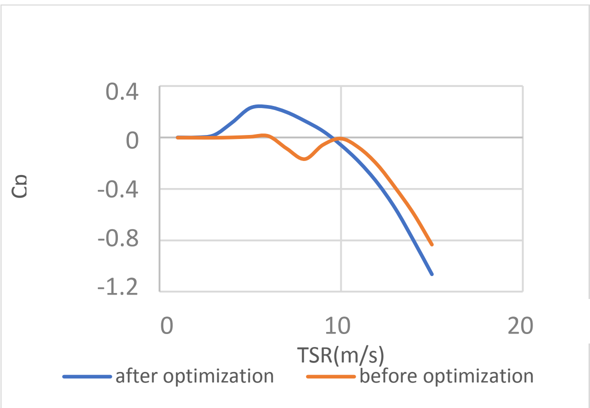


Fig.8. Power coefficient versus tip speed ration in MS Excel.

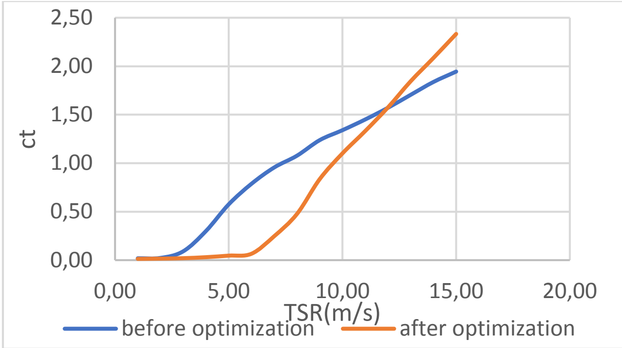
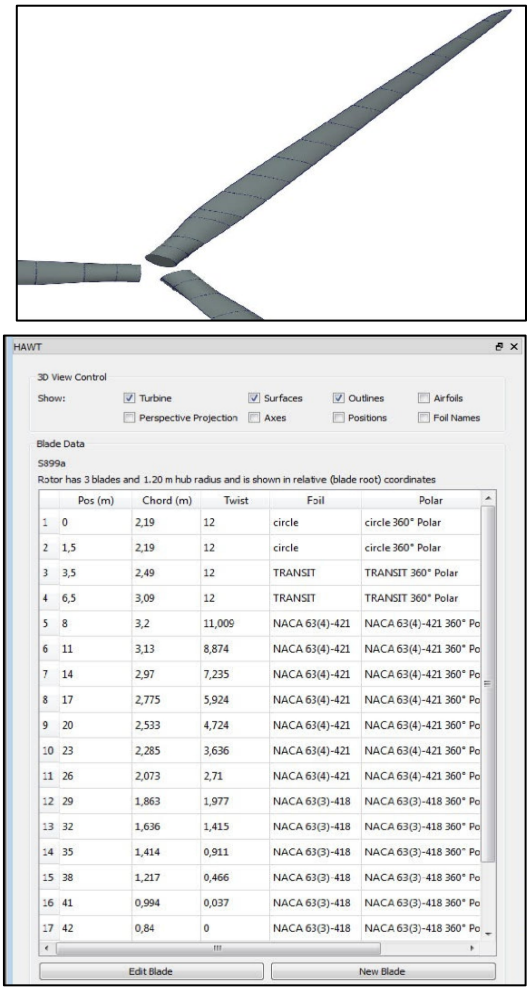


Fig.9. Variation of thrust coefficient with tip speed ratio before and after optimization.



	Pos (m)	Chord (m)	Twist	Foil	Polar
1	0	2,19	12	circle	circle 360° Polar
2	1,5	2,19	12	circle	circle 360° Polar
3	3,5	2,49	12	TRANSIT	TRANSIT 360° Polar
4	6,5	3,09	12	TRANSIT	TRANSIT 360° Polar
5	8	3,2	11,009	NACA 63(4)-421	NACA 63(4)-421 360° Po
6	11	3,13	8,874	NACA 63(4)-421	NACA 63(4)-421 360° Po
7	14	2,97	7,235	NACA 63(4)-421	NACA 63(4)-421 360° Po
8	17	2,775	5,924	NACA 63(4)-421	NACA 63(4)-421 360° Po
9	20	2,533	4,724	NACA 63(4)-421	NACA 63(4)-421 360° Po
10	23	2,285	3,636	NACA 63(4)-421	NACA 63(4)-421 360° Po
11	26	2,073	2,71	NACA 63(4)-421	NACA 63(4)-421 360° Po
12	29	1,863	1,977	NACA 63(3)-418	NACA 63(3)-418 360° Po
13	32	1,636	1,415	NACA 63(3)-418	NACA 63(3)-418 360° Po
14	35	1,414	0,911	NACA 63(3)-418	NACA 63(3)-418 360° Po
15	38	1,217	0,466	NACA 63(3)-418	NACA 63(3)-418 360° Po
16	41	0,994	0,037	NACA 63(3)-418	NACA 63(3)-418 360° Po
17	42	0,84	0	NACA 63(3)-418	NACA 63(3)-418 360° Po

Fig.10. The simulation of airfoils using QBlade.

The optimization process is covered by a wide range of wind speed (1-20 m/s), rotational speed (200-500 rpm), and pitch range (0-10 degrees), respectively. It can be seen from Fig.8., the *cp* increased to almost 0.35 after optimization, which is high compared to the low wind speed and the blade size of 1 m. Fig.9. shows the variation of thrust coefficients with tip speed ratio before and after optimization.

It can be seen that the unoptimized Ct was higher than the optimized one, but this behavior changed completely when TSR reached value 12 and after that. So, it is clear that the maximum Ct for the TSR > 12 can be obtained.

Fig.10. shows the simulation of optimized airfoils using QBlade. The variation of lift coefficient with angle of attack is shown in Fig.11., where the maximum values of the lift coefficient (1.4) occurred at angle of attack (8 and 13 degrees). Fig.12. presents the variation of moment coefficient with angle of attack.

Fig.13. illustrates the variation of lift coefficient with transition point (xtr). It can be noticed that the values of *Cl* are approximately steady from the root of the blade until the mid-point of the blade. After that fast degradation occurs in the values of *Cl* until reaching the minimum value near the tip of the blade.

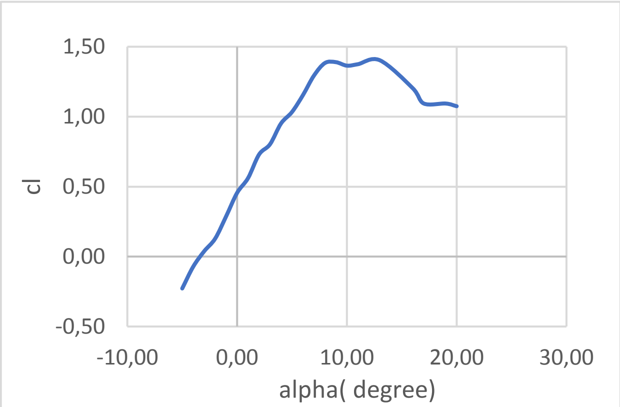


Fig.11. Variation of lift coefficient with angle of attack.

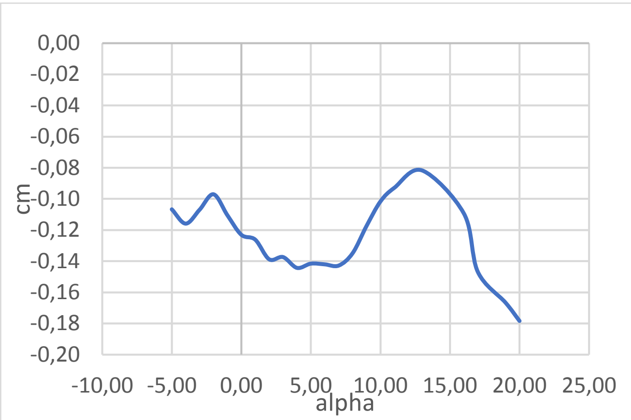


Fig.12. Variation of moment coefficient with angle of attack.

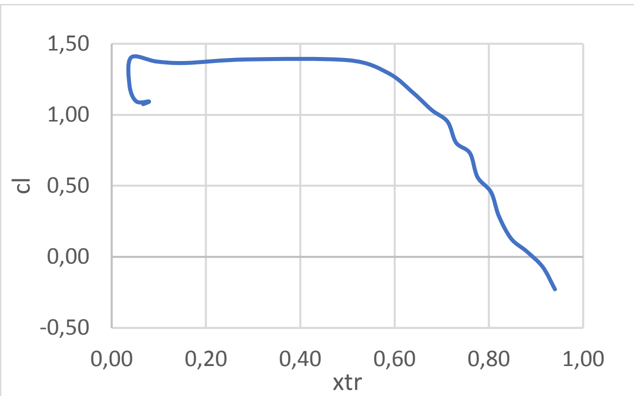


Fig.13. Variation of lift coefficient with transition point (xtr).

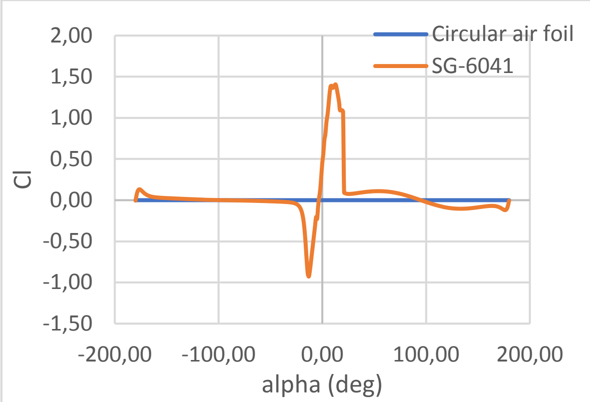


Fig.14. Variation of lift coefficient with angle of attack with 360 - degree extrapolation.

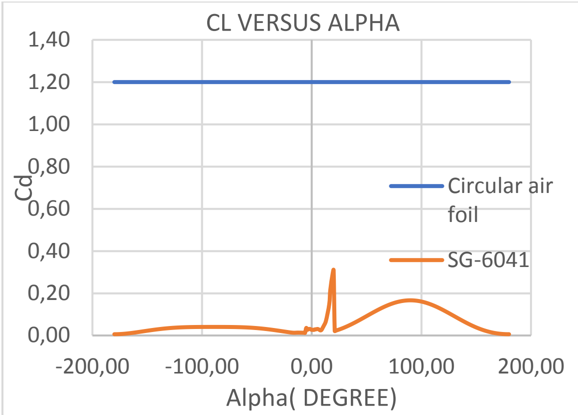


Fig.15. Variation of drag coefficient with angle of attack with 360 - degree extrapolation.

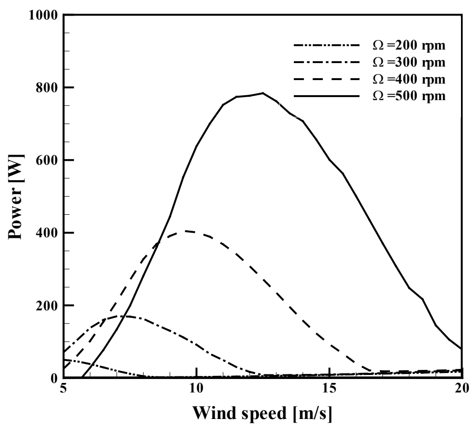


Fig.16. Variation of output power with wind speed at different rotational speeds of rotor.

A comparison was made between the variation of lift and drag coefficients of circular and SG-6041 airfoils with the angle of attack as shown in Fig.14. and Fig.15. It can be noticed that values of the cl for the circular airfoil are steady and almost equal to zero, while the values of Cd for the circular airfoil are steady and almost equal to 1.2.

Fig.16. shows the variation of output power with wind speed at different rotational speeds of the rotor. We can see a dramatic increase in the output power when the with rotational speed is applied. Approximately, all cases have the same behavior, where the output power increased from the minimum value to the peak value and then decreased to the final value. But there is a significant point that should be mentioned, which is the peak point shifted to the right side (with wind speed) when the rotational speed of the rotor increases. Fig.17. and Fig.18. show the variations of power and torque with the tip speed ratio at various wind speeds.

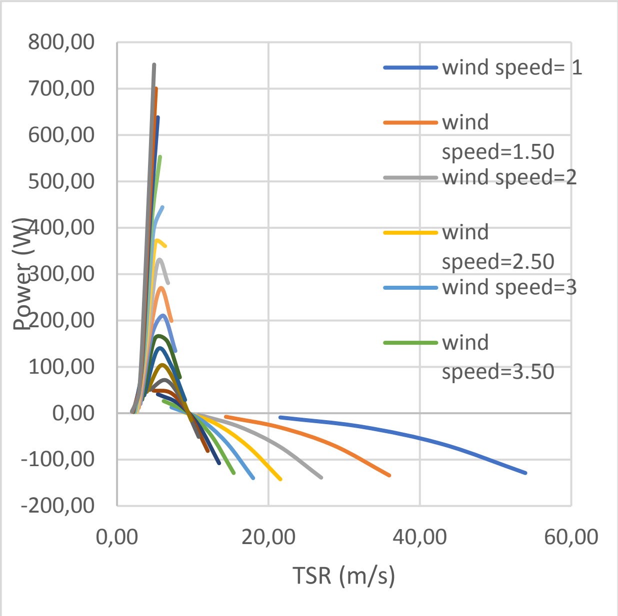


Fig.17. Variations of power with tip speed ratio at various wind speeds.

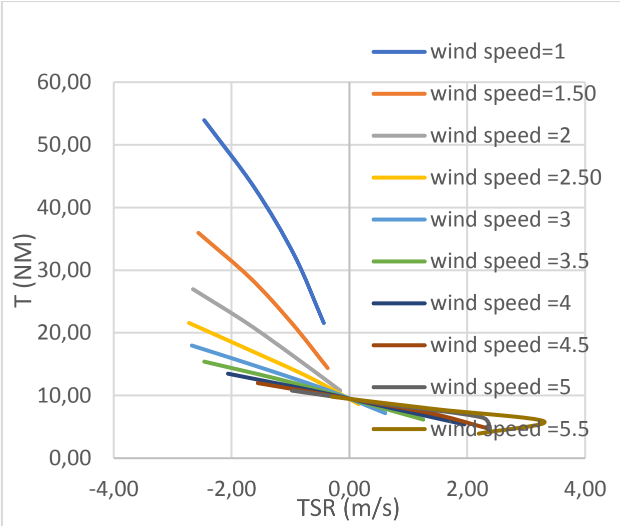


Fig.18. Variation of torque with tip speed ratio at various wind speeds.

5. INVESTIGATION OF THE PROMISING SITES IN IRAQ

In the second part of this research paper, we achieved a deep investigation of the wind characteristics in Iraq to find the most promising sites that can be selected to install the wind turbines in the near future.

Iraq is generally characterized by a low wind speed due to the presence of the subtropical high semi-permanent at an altitude of 5600 m, as this elevation is found permanently in the summer season in the form of a wide center, so it works through its low current effect on the occurrence of a state of atmospheric stability, despite that, there are a number of cases recorded that there is a high wind speed in Iraq during the retreat of this height from its atmosphere.

Table 1. The wind speed at 50 m for different locations in Iraq.

No.	Station	Wind Speed at 50 m	WP [w/m^2]	Direction	Prevailing Wind Direction %
1	Dealaa (Khalis)	2.736	391.72	NW	78 %
2	Mayssan (Ekhala)	3.691	1003.60	W	67 %
3	Muthna (Khader)	4.880	1667.30	WNW	65 %
4	Babel (Kifli)	2.629	307.34	NW	56 %
5	The-Qar (Shatrah)	2.783	397.82	WNW	87 %
6	Anbar (Aldawar)	3.601	749.35	WNW	80 %
7	Wasat (Essaouira)	4.270	1243.40	NW	86 %
8	Salahaldeen (Tikrit)	3.821	872.16	SW	34 %
9	Qadisiyah (Dewaneia)	3.080	546.75	NW	77 %
10	Mosul (Bashiqah)	2.243	169.33	NW	41 %
11	Najaf (Mashkhab)	2.299	254.46	WNW	45 %
12	Basrah (Albrjsuh)	5.298	2355.00	NW	54 %
13	Karbla (Lake Razzaza)	2.014	164.41	NW	67 %
14	Baghdad (Abughraib)	2.541	272.99	NW	52 %
15	Kirkuk (Daquq)	3.705	782.72	NE	11 %

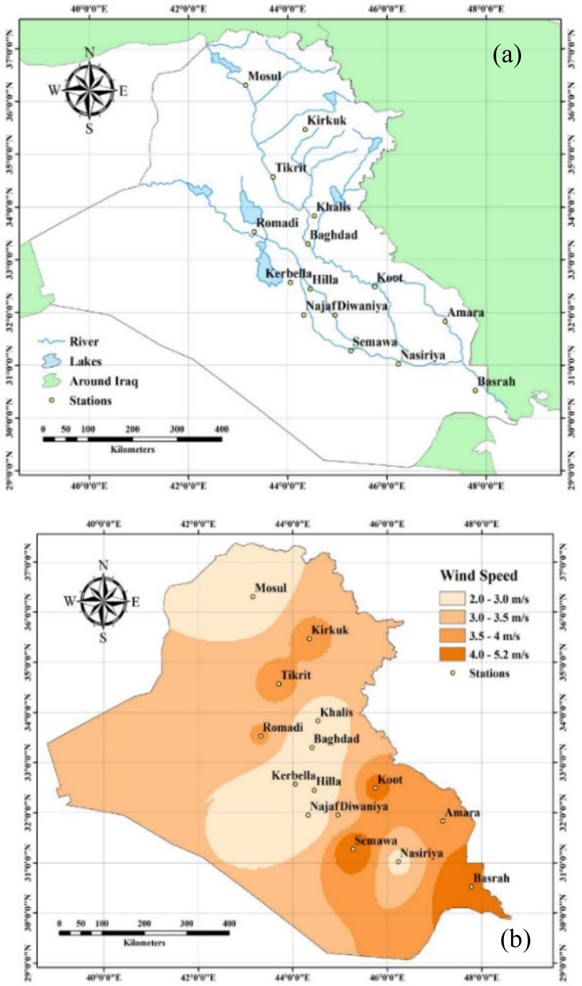


Fig.19. The map of Iraq; a) geographic map b) Wind Distribution Map at station.

The highest frequency of strong wind blowing over all regions of Iraq occurs in the warm half of the year, the process of mixing the turbulence of the surface air with the upper layers of the air column during the high hours of the sun. Also, strong wind may arise with the arrival of cold weather that affects Iraq in the winter season, in addition to its emergence with the warm western furrows that reach up to Iraq sometimes in winter and spring.

Table 1. shows the values of the monthly wind speed based on the average daily values of wind speed at 50 m. The data was collected in cooperation with the ministry of agriculture for locations distributed in different regions in Iraq. It was found that the highest wind speed occurred in the southern regions station After analyzing the data, it was found that the wind speed decreases moving northwards due to the influence of the mountains, while the wind speed increases towards the south due to the flatness of the earth, as well as the effects of the temperature factor that rises in half the southern and central parts of Iraq compared to its northern half, which made their air more turbulent.

The annual average wind speed in Iraq is about 2.9 m/s, and the highest average wind speed occurs in the warm half of the year, especially in the months of March, June, and July, which recorded the highest frequency of dust storms, rising dust and suspended dust. The lower average of wind speed happens in the cold half of the year, particularly in the months of November, December, and January.

Fig.19. shows the Iraqi geographic map and wind distribution map at the selected stations, while Fig.20. shows the wind distribution map of Iraq at 50 m and 100 m.

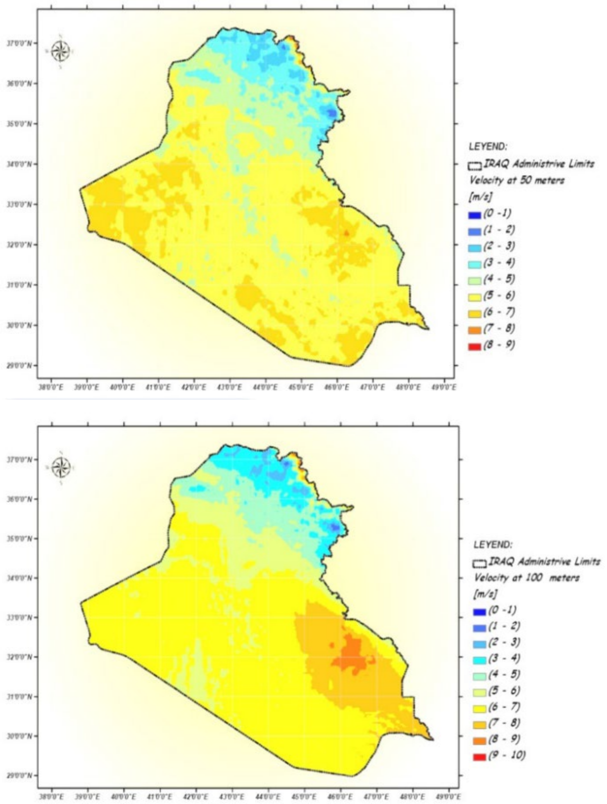


Fig.20. The Wind Distribution Map of Iraq at 50 m and 100 m.

6. CONCLUSIONS AND REMARKS

The first part of this research presents a comprehensive study and analysis of the aerodynamic characteristics of horizontal axis wind turbine blades using the QBlade software. The results were theoretically validated and developed in Matlab code. The main goal of this part was to obtain the optimum wind turbine blade under low-wind conditions. The SG-6041 airfoil blade was chosen, and it was split into ten equal parts. When the blade was tuned, the graphs revealed good results. Based on the results, a promising enhancement for the power coefficient by approximately 90 % was found after the optimization process. The main recommendation for future work is to increase the number of sections in order to obtain more accurate results.

The second part of this work, the analysis of wind data in Iraq, has been highlighted because of its great importance for the future use of wind energy to generate electrical power. Based on the results of wind data analysis for the recent years, the most promising sites in Iraq were identified which are eligible for the installation of the wind turbines .

LIST OF SYMBOLS AND ABBREVIATIONS.

Symbol	Description	Unit
Cp	Power coefficient	-
CL	Lift coefficient	-
CD	Drag coefficient	-
V_w	Wind speed	m/s
P	Mechanical power	W
F_l	Lift force	N
F_d	Drag force	N
F_t	Tangential force	N
F_n	Normal force	N
c	Chord length	m
a	Axial induction factor	-
a'	Radial induction factor	-
u	Circumferential speed	m/s
W_{rel}	Relative speed	m/s
β	Pitch angle	degree
α	Angle of attack	degree
Φ	Angle of relative wind	degree

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