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A Study on Improving the Blades of a Three-Blade Horizontal Axis Wind Turbine for Agricultural Areas Using a Laboratory Made Model

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INFO

ORIGINAL RESEARCH PAPER

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ABSTRACT

Since Iran is considered a windy country due to its proximity to the sea and the presence of the Alborz and Zagros plateaus. It is necessary to implement mechanisms to increase the production capacity of low-bladed wind turbines. The aim of this study was to determination the optimum parameters of the turbine including: angle of the blade, surface of the conical ratio of the blade and surface of the location of the maximum arc of the chord length. A 3-blade wind turbine was designed and built in a laboratory scale. The thickness of each blade was 20% of the chord length and a thickness of camber was 6% of the chord length. The results showed that the difference between the powers obtained from the experiment at different wind speeds, angles, the location of the maximum arc and the conical ratio of the blade has a significant difference. Results of Duncan's test presented that 15 degrees angle with the average power of 0.8612 W from five levels of blade attack angle, 100% level with the average power of 1.17 W from three levels of the conical ratio of the blade, 30% level with the average power of 0.8139 W from three levels of maximum arc location and 12 m/s with the average power of 1.078 W from three levels of wind speed have the highest productive power. In addition, the interaction of variables (blade attack angle, taper ratio, maximum arc location and speed) is significant and in the model with 15 degrees attack, 100% cone ratio, 30% maximum arc location and 12 m/s *wind speed was an optimal model for producing more power.*

INTRODUCTION

Wind energy is one of the renewable energies. This energy has been used and utilized due to universality and efficiency. Therefor this energy has a special position to research (Josimović and Pucar, 2010). Denmark is going to provide 50% of its electricity consumption by wind power by the year 2025 (Xu et al., 2009). Increasing the usage of wind energy could lead to lower dependence on fossil fuels, and it would gradually decrease global greenhouse gas emission(Wen *et al.*, 2021).

In Iran, the suitable platform of using of the wind turbines was provided with diverse climate with windy regions and the level of underground water resources, especially in locations far from the electricity grid. While in recent years, due to the government subsidies removal of fuel products, a significant financial burden is imposed on farmers to supply the fuel required of agricultural diesel generators annually (Krishnamoorthy et al., 2020). Therefore, investigation of wind turbines to irrigate agricultural farms in Iran is important. Based on the geography of Iran, this country has the possibility of maximum using of the wind energy in the different regions. Therefore, it is possible to use domestic wind turbines with different capacities and profit from its financial and economical (Grassi *et al.*, 2012).

Aerodynamic background

An aerodynamic force to oppose the weight can be generated by using specially shaped body called an airfoil. An airflow velocity over the top surface of an airfoil will be greater than that beneath, so the pressure differential that results will produce a force per unit area acting upwards (Satta et al., 2014). The larger the surface area, the bigger the force that can be generated. When the airflow passes above of the airfoil, a streamline flow of air accelerates, its kinetic energy will increase and its static pressure will decrease. When air decelerates at above of the airfoil, the kinetic energy will decrease and static pressure will increase again. An aerodynamic force is produced with integrating pressure. Therefor design of blades should be investigated.

Leading edge: The leading edge is the part of the wing that first contacts the air. Alternatively, it is the foremost edge of an airfoil section.

Trailing edge: The trailing edge of an aerodynamic surface such as a wing is its rear edge. Where the airflow separated by leading edge regions.

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Chord line: A straight line joining the centers of curvature of the leading and trailing edges of an airfoil.
Mean Line or Camber Line: A line joining the leading and trailing edges of an airfoil, equidistant from the upper and lower surfaces.

In aerodynamics and aeronautical engineering, camber is the asymmetry between the two acting surfaces of an airfoil, with the top surface of a wing (or correspondingly the front surface of a propeller blade) commonly being more convex (positive camber).

Angle of Attack: The angle between the chord line and the relative airflow. The angle between the chord line and the effective airflow is referred to as the effective angle of attack (Rasekh *et al.*, 2018).Angle of attack is shown in Fig. 1.

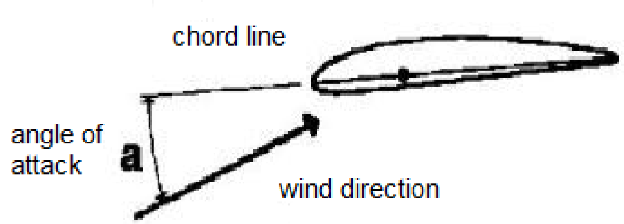

Fig 1. Blade attack angle

Thickness: The maximum thickness or depth of an airfoil section expressed as a percentage of the chord, with its location as a percentage of the chord aft of the leading edge. The thickness and thickness distribution of the airfoil section have a great influence on its airflow characteristics.

Taper ratio: The ratio of the chord length at the tip to the chord length at the blade root is called the taper ratio (λ) and this value is variable between ($0 \leq \lambda \leq 1$). As the taper ratio decreases, the blade weight decreases, so structural issues are less important and can play a role as a basic parameter in the amount of production power.

Maximum thickness: The maximum vertical distance between the upper and lower curves of the profile is called the maximum thickness. Depending on the design of the airfoil, the maximum thickness is usually between 20% and 30% of the length of the chord for wind turbine blades, and it makes the blade stable and firm.

Arc: The longest arc that intersects the chord line with the middle line is called an arc.

The collection of blades and hub in the middle is called a rotor. A horizontal axis wind turbine, consists of a number of blades that are installed radially around an axis, As such rotor rotates perpendicular to the direction of the wind(Howell *et al.*, 2010). The rotor is placed by a tower at a suitable height to the ground, and of course. In order to control of the turbine velocity, the axis is aligned with different wind directions and the absorbed power by the rotor is transferred to driven machine by a mechanical system. Blades may consist of a frame that is covered by a thin and suitable shell. The number of blades are between 2. To the chord length can be constant or variable. The characteristics of an airfoil are shown in Fig. 2.

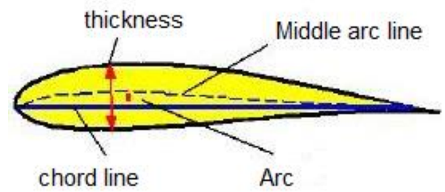

Fig 2. Specifications of an airfoil

In general, wind power is caused to rotate a wind energy generator and to transfer power to the outside by its rotor. Therefore, wind force creates lift and drag forces on the turbine. When airflow exit from top and bottom of the airfoil, airflow direction is changed and joined together. Depending on its shape, the air flow that passes over the turbine blade has traveled a longer path, as a result, it is diluted and sucks on the blades and on the contrary, the air flow that passes under the blade has a shorter path and as a result, it is thick and apply pressure on the blade. The lift force causes the rotation of the turbine blades and produces power, and the blades that hold the turbine neutralize the drag force. In the design of three-bladed turbines, the drag force is tried to be reduced (Fig. 3).

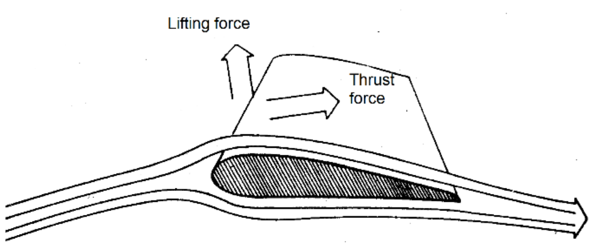

Fig 3. The forces acting on the wind turbine blades(Saghafi, 2009)

In general, the maximum wind power in a wind turbine that can be converted into mechanical energy is approximately 3.59% of the kinetic energy of the wind, which is called the maximum power factor. The practical power of a wind turbine is calculated from equation (1)(Ezatollahi et al., 2005).

$$P = \frac{1}{2}.e.\rho.A.v^3 \qquad (1)$$

Where, e is wind turbine efficiency, ρ is volumetric mass of air ($\frac{kg}{m^2}$), A is surface area swept by turbine blades (m^2), v is wind speed or air mass speed ($\frac{m}{s}$), P is actual wind power (W) (Schubel and Crossley, 2012).

MATERIALS AND METHODS

Model making

A picture of the built wind turbine model is shown in Fig. 4. This model includes blades, an electric generator, a hub, an axis or rotor, a rubber belt, a bearing, a chassis or tower, an electric circuit, speed increase system.

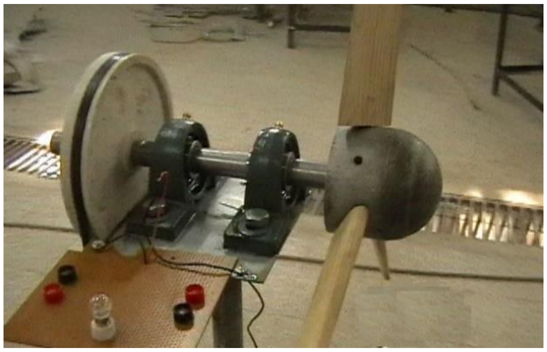

Fig 4. Different components of the constructed model

The anemometer was a digital propeller model (Lutron AM-4200) made in Taiwan with a measurement range of 8 to 30 m/s. The sensor in the anemometer was used to measure the wind speed. Fig. 5 shows this anemometer.

Fig 5. Digital butterfly anemometer

In this research, all blades, which are made of wood (Russian wood), have a maximum thickness of 20 % of the chord length, a maximum arc of 6 % of the chord length, a chord length of 5.5 cm, and a blade length of 30 cm. The reason for choosing these numbers is the ease of making blades. If smaller numbers were used, the manufacturing error in the blades would increase and the desired result would not be obtained. In Fig. 6, the blades with a cone ratio of 0%, 50%, and 100% of the chord length, and in Fig. 7, the blades with a maximum arc location of 30%, 40%, and 50% of the chord length, are shown. The three-bladed wind turbine, with 9 different blades and the total number of blades is 27, was made considering the mentioned parameters. As the cone ratio decreased, the weight of the blade and the structure reduced. It is possible to use more surfaces in the construction of blades, but due to the increase in the number of surfaces, the steps of experimenting became more complicated and it was simply not possible to investigate the interaction effect of the parameters.

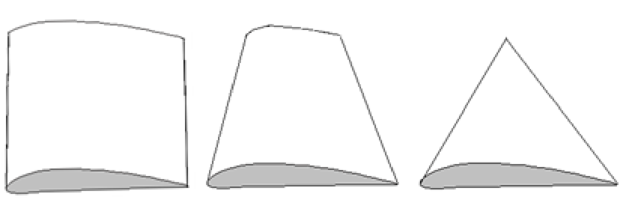

Fig 6. Blade with taper ratio of 0%, 50% and 100% of chord length (respectively from right to left)

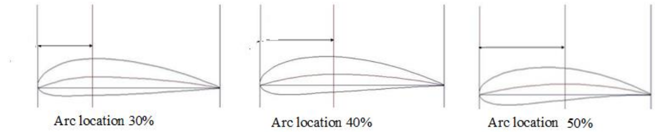

Fig 7. Blade with maximum arc location 30%, 40% and 50% of chord length (respectively from right to left)

In this research, a bicycle generator, dynamo (Kohestan, Iran), 6V was used. This system consists of two pulleys with diameters of 1 cm and 15 cm, the first one is connected to the head of the generator and the second one is connected to the end of the rotor axis, respectively.Thus the generator speed increases 15 times. Since the efficiency of the generator was a little low, it had to be increased to get enough light in the electric circuit of the 3V lamp. By making different pulleys with different diameters, the diameter of 15 cm was chosen for work, which is shown in Figs 4 and 9. In this research, a hub was made for a wind turbine model. The rotor was connected to the center of the hub through Allen bolts. On the hub, there are places to place the blade, which is installed with an angle of 120 degrees, and the hub was made of aluminum by casting. Considering that aluminum is a light metal, it was suitable for work. At first, a hub was made of Russian wood, but due to the opening and closing of the blades on it, the blade became loose and the quality of the work decreased Fig. 4). To obtain the output power, a simple circuit has been used, whose schematic is shown in Fig. 8. In this circuit, a 3-V lamp is used as a resistance, and the location of the ammeter and voltmeter, which are placed in the circuit in series and parallel, respectively, has been determined.

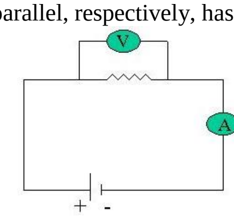

Fig 8. Electric circuit used in the model

In this research, a wind generation system was designed and built to achieve the 3 desired wind speeds. The purpose of this research was not to build a wind production mechanism system, but considering the wind conditions in a region, the aim was to design a wind source in a way that includes field conditions more than laboratory conditions. The This system includes an electric motor with specifications of 1 hp, 220 V, and single phase, a blower fan with a diameter of 75 cm, a wind flow equalizing network, and a chassis that holds the fan and network system (Fig. 9).

Fig 9- Wind production mechanism

By installing the wind flow paralleling and unifying network, it has been tried to achieve the wind speed almost the same at certain distances from the network. To determine the wind speed, the model was placed in three different positions in front of the wind speed mechanism. At a distance of 35 cm from the grid, the speed was 12 m/s, at a distance of 68 cm from the grid, the speed was 10 m/s and at a distance of 93 cm from the grid, it was 8 m/s.

Work method

The independent variables of this experiment are:

- Blade angle in five levels (5, 10, 15, 20, and 25 degrees)
- Location of the maximum arc in three levels (30%, 40%, and 50% of the chord length)
- Cone ratio in three levels (0%, 50% and 100% of chord length)
- Wind speed in three levels (8, 10, and 12 m/s)

To measure the output power of the model at different wind speeds, first, the mechanical power of the model was converted into electrical energy by the generator, and then the amount of energy received per unit of time (which is the same power) was measured by an electrical circuit. By rotating the rotor, direct current was taken from the two output wires of the dynamo. From the two ends of the electricity generator, the simple voltage was obtained by a voltmeter. To measure power, current or amperes must be measured, and by multiplying the current by the voltage, the power is obtained. The current is obtained if there is a consumer in the circuit. Therefore, a 3-volt lamp was used as a consumer. The voltage and current intensity were read and measured on the voltmeter and ammeter at different wind speeds, and the output power was obtained by the product of the two.

Statistical analyses

Based on the information obtained, the statistical design used is a four-factor complete randomized design in three replications. The results of average powers were compared and analyzed using Duncan's multi-range test at the 99% level. In this experiment, the wind turbine model was placed in the mechanism of the wind generation system. This experiment was performed in three repetitions and the voltage and current values were measured. With multiplying voltage and current intensity, the power output was calculated to four decimal places.

RESULTS AND DISCUSSION

All the data collected from this test were statistically analyzed by Duncan's test using Mstat-C, Excel, and SPSS software and it was clarified that the difference between the powers obtained from the test at different wind speeds, angles, the conical ratio of the blade and the location of the maximum arc is significant. In the analysis of variance, it can be seen that the calculated F value is much higher than the F value in the table, and it shows that the treatments have a significant difference this difference is not due to chance, but the treatments have a significant difference.

In the variance analysis table (Table 1), factor A is the blade angle, factor B is the location of the maximum arc, factor C is the conical ratio of the blade, and factor D is wind speed. Also, AB, the interaction effect of the blade angle and the location of the maximum arc, AC, the interaction effect of the blade angle and the cone ratio of the blade, BC, the interaction effect of the location of the maximum arc and the cone ratio, ABC, the interaction effect of the blade angle, the location of the maximum arc and the cone ratio, AD, the effect Interaction of blade angle and wind speed, BD, the interaction effect of maximum arc location and wind speed, CD, the interaction effect of blade cone ratio and wind speed, BCD, the interaction effect of maximum arc location, cone ratio and wind speed, and ABCD, the interaction effect of blade angle, The location of the maximum arc is the conical ratio and wind speed. As stated, the calculated F value is much higher than the F value of the statistical tables and indicates that the treatments have a significant difference and this difference was not due to chance. Therefore, it is necessary to compare the variables. Duncan's multi-range test was used to compare the variables. This test analyzes the trend of increasing or decreasing the average value of the variables or their mutual effects and determines to what extent the changes caused by the average value of the variables affect the production power of the built physical model.

Table 1 - Variance analysis table for three-bladed wind turbine

Source of changes	Degrees of freedom	sum of squares	average of squares	Value of F	Significance level
Repetition	2	0.045	0.022	65.6817	0.000
Factor A	4	5.277	1.319	3892.8236	0.000
Error	8	0.003	0.000	-	-
Factor B	2	4.284	2.142	2867.9834	0.000
AB	8	0.184	0.023	30.8667	0.000
Factor C	2	50.053	25.026	33506.0535	0.000
AC	8	1.406	0.176	235.2693	0.000
BC	4	1.239	0.310	414.7168	0.000
ABC	16	0.052	0.003	4.3107	0.000
Factor D	2	33.615	16.807	22502.2141	0.000
AD	8	0.957	0.120	160.0768	0.000
BD	4	0.480	0.120	160.8007	0.000
ABD	16	0.034	0.002	2.8338	0.0003
CD	4	11.453	2.863	3833.5605	0.000
ACD	16	0.358	0.022	29.9241	0.000
BCD	8	0.252	0.032	42.1821	0.000
ABCD	32	0.035	0.001	1.4715	0.0550
Error	260	0.194	0.001	-	-
Total	404	109.920	-	-	

The effect of variables on the amount of production power

By observing the results of the Duncan test at the 99% level, it was determined that the angle of attack of 15 degrees had the highest output power equal to 0.8612 W (Fig. 10). The main reason is the phenomenon of Separation. At angles of more than 15 degrees and less than 15 degrees, there is no airflow necessary to travel on the blade and it is removed from the blade, so the continuity of the flow on the blade is gradually lost. This discontinuity of the flow and the existence of a difference in the size of the movement of the flow in entering and exiting the blade follows. Therefore, the main force on the vanes, which is caused by the difference in the size of the airflow on the vanes, does not exist, as a result, increasing the vane angle by more than 15 degrees or less than 15 degrees is not recommended in any way.

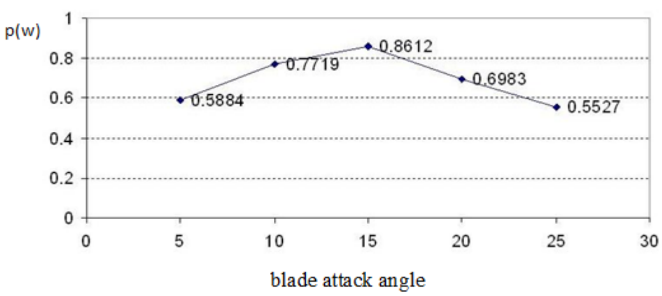

Fig 10. The effect of blade attack angle on output power

By observing the results of Duncan's test and Fig. 11 at the 99% level, it was determined that in the conical ratio at the level of 100% of the chord length, it had the highest output power equal to 1.17 W. The greater the ratio of the chord length at the tip to the chord length at the root of the blade, the weight of the blade will increase and its rigidity will also increase. Rigidity is the ratio of the surface of the blades to the swept surface of the blades, increasing the rigidity will have a direct effect on the power output. In three-bladed horizontal axis wind turbines with flat blades, increasing the rigidity will increase the amount of rotation of the blade, or in other words, increase the speed and also torque. Therefore, the higher the cone ratio, the more the effect of the wind on the vane will increase and it will cause the vane to rotate faster. Therefore, it is recommended that in low-bladed horizontal axis wind turbines with flat blades, a higher cone ratio will increase the production power. By observing the results of Duncan's test and (Fig. 14) at the 99% level, it was determined that the model had the highest output power of 0.8139 W at the maximum arc location of the 30% level, and this indicates that the maximum arc location More than 30% has never been desirable because by increasing the location of the maximum arc from 30% to higher, we saw a decrease in production power. In this location, it is possible to produce more power in less than 30%, which required the construction of a blade with the features of the maximum arc location of less than 30%. According to the construction of the blade and the aerodynamic characteristics of the blade airfoil, the maximum arc of the blade has the highest power at 30%, and the maximum arc of 30% has created a fundamental change in the airfoil of the blade and increased the lift force. By observing the results of Duncan's test and Fig. 15, it was determined that concerning the mutual effect of the carrying angle and the location of the maximum arc, the model had the highest output power equal to 1.015 W at the angle of attack of 15 degrees and the location of the maximum arc at the level of 30%.

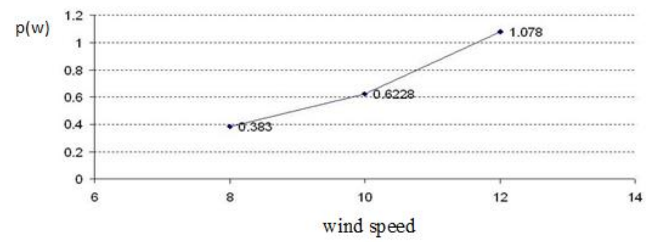

Fig 11. The effect of blade taper ratio on output power

By observing the results of the Duncan test and Fig. 12 at the 99% level, it was found that the wind speed of 12 m/s produced the highest output power equal to 1.078 watts. According to equation (1), the higher the wind speed, the higher the production power of the turbine because the power of a wind turbine is proportional to the third power of the wind speed. Therefore, it is recommended to use more wind speed to increase the power. Of course, the maximum wind speed for wind turbines is 25 m/s, and the turbine fails at speeds higher than that for its safety [6].

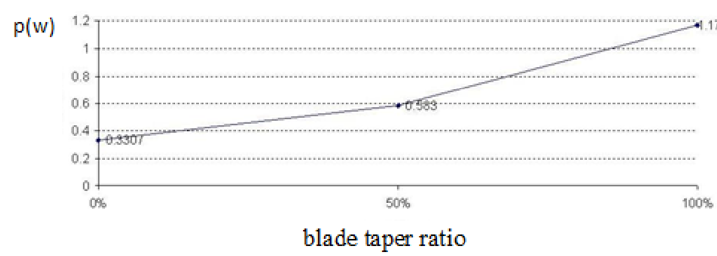

Fig 12. The effect of wind speed on output power

By observing the results of Duncan's test and Fig. 13, it was found that the model had the highest output power equal to 457.1 watts at the angle of attack of 15 degrees and the blade cone ratio at 100%. The combination of the angle and the cone ratio accurately describes the overlapping action without the slightest interaction. Angle and cone ratio as two parameters separately and in combination due to the independent effects of each variable indicates that the separation phenomenon is compatible with increasing the cone ratio. In Fig. 17, it was found that the model had the highest output power equal to 1.844 W at the cone ratio of 100% and the wind speed of 12 m/s. An increase in the cone ratio is associated with an increase in blade stiffness. Therefore, the increase in rigidity will produce more power at higher wind speeds. Therefore, it is recommended to increase the rigidity of the blade to create more power, and this can be done by increasing the cone ratio. Using the results of Duncan's test, it was determined that in the wind turbine model, among the five levels of blade attack angle, 15 degrees with an average power of 0.8612 W, among the three levels of conical ratio, the level of 100% with an average power of 1.17 W, among the three levels of wind speed, the level of 12 m/s with an average power of 1.078 W and of the three levels The location of the maximum arc, the level of 30% has the highest production power equal to 8139.0 W. It was also determined that the interaction effect between the variables (blade attack angle, maximum arc location, blade cone ratio, and wind speed) is significant according to the variance analysis table, and the model whose attack angle is 15 degrees, the maximum arc location is 30%, the ratio Cone is 100% and wind speed is 12 m/s, with a power equal to 2.304 watts, it was presented as the best model for producing more power among the selected levels. Concerning the effect of blade attack angle on output power, the best attack angle is 15 degrees and if more levels (more than five levels) were investigated in the experiment, it had no effect also 15 degrees angle was effective as the best angle in increasing production power. This action can also be related to the aerodynamic forces in front and behind the blade. Because the angle of attack of the blade is the angle that the chord line of the blade makes with the direction of the wind, therefore the aerodynamic force at a certain angle can produce the most lift force and this action occurred at an angle of 15 degrees, the reason for which is the separation phenomenon. Also, the effect of the blade taper cone ratio on production power showed that the blade cone ratio at 100% level showed the highest production power, and this shows that increasing the blade cone ratio from 0% to 100% has increased the production power, and never has the conic ratio below 100% been desirable. This can imply that the lower the cone ratio, the lower the weight of the blade and it cannot receive wind power well. Due to the decrease in the stiffness of the blades, the less lifting force is produced, therefore, the turbine will have less rotation at different wind speeds.

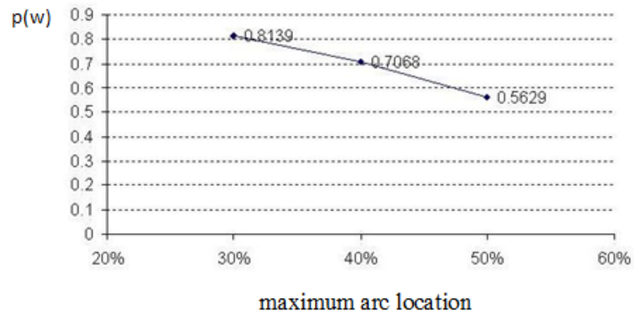

Fig 14. Effect of maximum arc location on output power

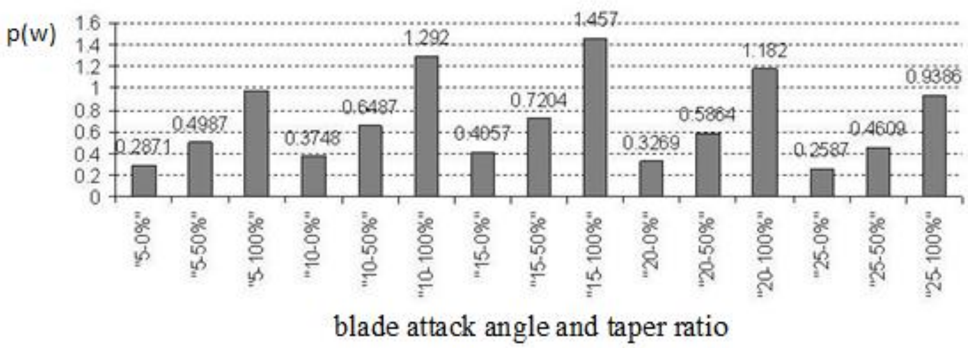

Fig 13. The mutual effect of blade attack angle and taper ratio on output power

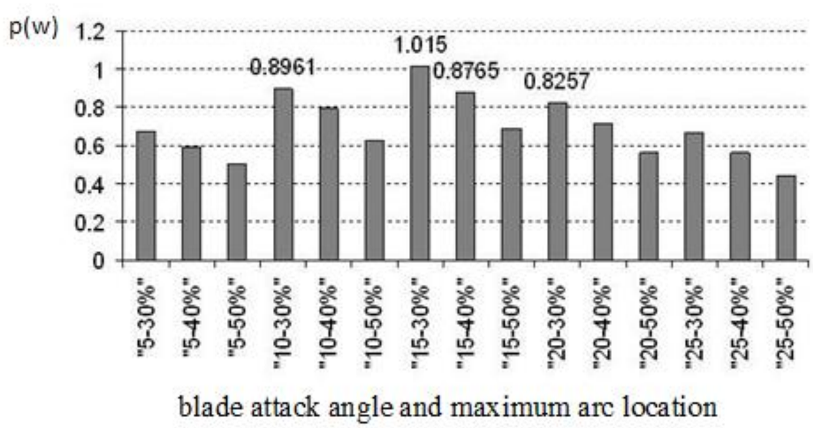

Fig 15. The mutual effect of blade attack angle and maximum arc location on output power

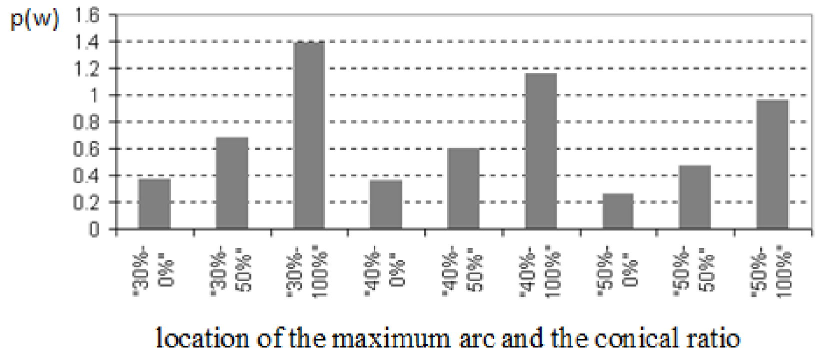

Fig 16. The mutual effect of the location of the maximum arc and the conical ratio on the output power

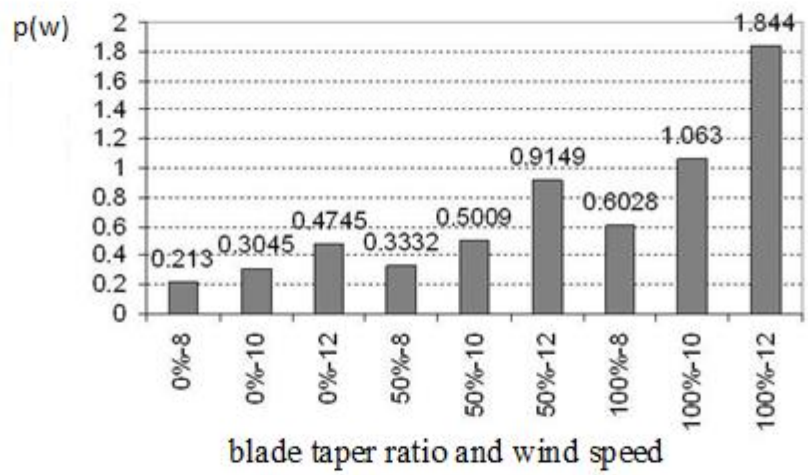

Fig 17. The mutual effect of blade taper ratio and wind speed on output power

Mathematical model parameters

Using SPSS software and Multiple Regression, the mathematical model of the production power for the wind turbine was determined and the coefficients are shown in table (2). In relation (2), X is the attack angle of the blade, Y is the location of the maximum arc of the blade, Z is the conical ratio of the blade, and W is the wind speed.

Table 2- Wind turbine model coefficients using SPSS software

Coefficients(a)						
Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig.
		B	Std. Error	Beta		
	(Constant)	0.545	0.0106		-5.143	.٠00
	(Cod-Angle) X	-0.14	0.015	-0.039	-0.937	.٠350
1	(Cod-Camber) Y	-0.126	0.027	-0. 197	-4.688	.٠000
	(Cod-Taper) Z	0.42	0.027	0. 658	15.674	.٠000
	(Cod-Speed) W	0.347	0.0277	0. 545	12.977	.٠000

The standard error is at a very low level and this indicates the significance of the independent parameters in relation (2). Of course, the computer has suggested the standardized coefficients, which are the constant coefficient is zero, the X coefficient is -0.039, the Y coefficient is -0.197, the Z coefficient is 0.658, and the W coefficient is 0.545. The noteworthy point is that in relation (2), the W coefficient is a positive number equal to 0.347. The positiveness of this number means that as the wind speed increases, the amount of production power will increase. Also, with the increasing conical ratio of the blade, the amount of production power increases with the positive coefficient of this variable. The reverse of this action is at the location of the maximum arc and the angle of attack. As the numerical value of the location of the maximum arc increases or the angle increases, due to the negative value of the coefficients of these two variables, the amount of production power will decrease.

$$P=-0.14X-0.12Y+0.42Z+0.347W-0.545 \quad (2)$$

CONCLUSIONS

Using the results of Duncan's test, it was determined that among the five levels of blade attack angle, the 15-degree angle with the average power of 0.8612 watts, among the three levels of the conical ratio of the blade, the 100% level with the average power of 1.17 watts, from Among the three levels of the maximum arc location, the 30% level with an average power of 0.8139 watts and among the three wind speed levels, the 12 m/s levels with an average power of 1.078 watts had the highest production power. It was also determined that the interaction effect between the variables (blade attack angle, cone ratio, maximum arc location, and speed) was significant and in the model with an attack angle of 15 degrees, cone ratio of 100%, maximum arc location of 30% and wind speed of 12 m/s. is presented as an optimal model for producing more power.

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