THEORETICAL STUDY FOR AERODYNAMIC PERFORMANCE OF HORIZONTAL AXIS WIND TURBINE [+]

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Abstract:

This work is based on theoretical mathematical model of aerodynamic forces acting on the blades of horizontal axis wind turbine and influence of different parameters on power efficiency and energy production has been investigated. It has been chosen an profile airfoil type NACA 2410 with different parameters (number of turbine blades (2–5), tip speed ratio (4–20) and ratio of coefficient forces (25–100)). Evaluation these parameters by using iterative solution and obtained a good results for turbine efficiency (0.45-0.51) when the number of blade is (3) and local tip speed ratio (5-7) with coefficient force (100) for chosen profile airfoil.

Key Word: Wind turbine, aerodynamics, rotor, blade profile

المستخلص:

هذا العمل يعتمد على النموذج الرياضي النظري لقوى الايروديناميك الهوائية التي تتصرف على ريشة توربين هوائي ذو المحور الافقي وتأثير العوامل المختلفة على كفاءة التوربين والطاقة المنتجة المتحققة . تم اختيار شكل لريشة انسيابية نوع NACA 2410 واخضاعها لعوامل مختلفة (عدد الريش التوربين (5-2) نسبة السرعة الرئسية للتوربين (20-4) نسبة معامل القوى الايروديناميك (100-25) . تم اجراء تقيم لهذة العوامل باستخدام طريقة الحل التكراري والحصول على نتائج جيدة لكفاءة التوربين (0.51-0.45) عندما يكون عدد ريش التوربين (3) و نسبة السرعة الرئسية (7-5) وبمعامل قوى ايروديناميكي (100) للشكل الذي تم اختيارة .

Nomenclatur:

Symbols	*Definition*
C_p	Power coefficient of wind turbine rotor
P	Power output from wind turbine rotor (W)
V_∞	Free stream velocity of wind (m/sec)
V_{rel}	Relative wind velocity (m/sec)
A	Area of wind turbine rotor (m^2)
R	Radius of wind turbine rotor (m)
r	Radial coordinate at rotor plane
T	Rotor thrust (N)
Q	Rotor torque (N.m)
D	Drag force on an annular blade element (N)
L	Lift force on an annular blade element (N)
C_D	Drag coefficient of an airfoil

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C_L	**Lift coefficient of an airfoil**
N	**Number of blade of a rotor**
S	**Number of blade element**
a	**Axial induction factor at rotor plane**
a'	**Rotational or tangential induction factor**
λ (TSR)	**Tip-speed ratio of rotor**
Ω	**Angular velocity of wind turbine rotor (rad/sec)**
α	**Angle of attack (degree)**
θ	**Pitch angle (degree)**
φ	**Angle of relative wind velocity with rotor plane (degree)**
Z	**Solidity ratio**
Π	**Constant ratio**
	Air density (Kg/m^3)ρ

Introduction

A wind turbine is a device for extracting kinetic energy from the wind. By removing some of its kinetic energy the wind must slow down but only that mass of air which passes through the rotor disc is affected. Assuming that the affected mass of air remains separate from the air which does not pass through the rotor disc and does not slow down a boundary surface can be drawn containing the affected air mass and this boundary can be extended upstream as well as downstream forming a long stream-tube of circular cross section. No air flows across the boundary and so the mass flow rate of the air flowing along the stream-tube will be the same for all stream-wise positions along the stream-tube. Because the air within the stream-tube slows down, but does not become compressed, the cross-sectional area of the stream-tube must expand to accommodate the slower moving air (Figure 1.1).

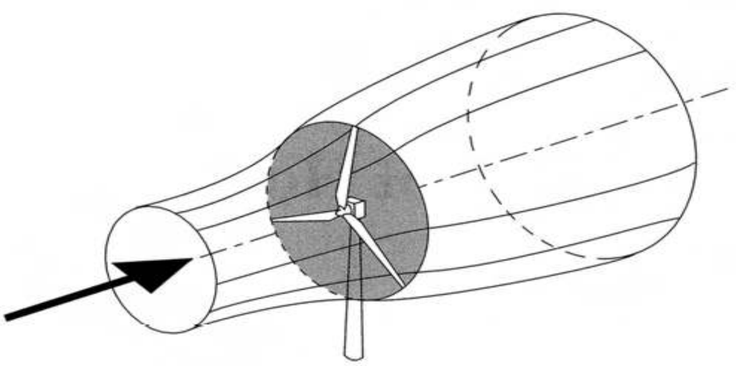

Figure 1.1 The Energy Extracting Stream-tube of a Wind Turbine

Although kinetic energy is extracted from the airflow, a sudden step change in velocity is neither possible nor desirable because of the enormous accelerations and forces this would require. Pressure energy can be extracted in a step-like manner, however, and all wind turbines, whatever their design, operate in this way. The presence of the turbine causes the approaching air, upstream, gradually to slow down such that when the air arrives at the rotor disc its velocity is already lower than the free-stream wind speed. The stream-tube expands as a result of the slowing down and, because no work has yet been done on, or by, the air its static pressure rises to absorb the decrease in kinetic energy. As the air passes through the rotor disc, by design, there is a drop in static pressure such that, on leaving, the air is below the atmospheric pressure level. The air then proceeds downstream with reduced speed and

static pressure – this region [1,2]
of the flow is called the wake. Eventually, far downstream, the static pressure in the wake must return to the atmospheric level for equilibrium to be achieved. The rise in static pressure is at the expense of the kinetic energy and so causes a further slowing down of the wind. Thus, between the far upstream and far wake conditions, no change in static pressure exists but there is a reduction in kinetic energy.

Several researchers have contributed to the insight into rotor design. Snel [1] describes wind turbine aerodynamics in general and gives an overview of the available methods to compute the aerodynamic rotor performance. Fuglsang [2] describes the methods needed in the rotor design process in terms of a guideline. Also, aerodynamic optimization of rotors are described by Fuglsang and Madsen [3].

In Fig.(1.2). The wind passes over both surfaces of the airfoil shaped are produced by air flow rapidly over the longer (upper) side of the airfoil, creating a lower- pressure area above the airfoil. The pressure different between top and bottom surfaces results in a force, called aerodynamic lift. In an aircraft wing, this forces causes the airfoil to "rise", lifting the aircraft off the ground. Since the blades of a wind turbine are constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub. In addition to lift force, a "drag" force perpendicular to the lift force impedes rotor rotation. A prime objective in wind turbine design is for the blade to have a relatively high lift-to drag ratio. Lift based designs can usually output much more power more efficiently. This ratio can be varied along the length of the blade to optimize the turbine's energy output at various wind speeds[5,6].

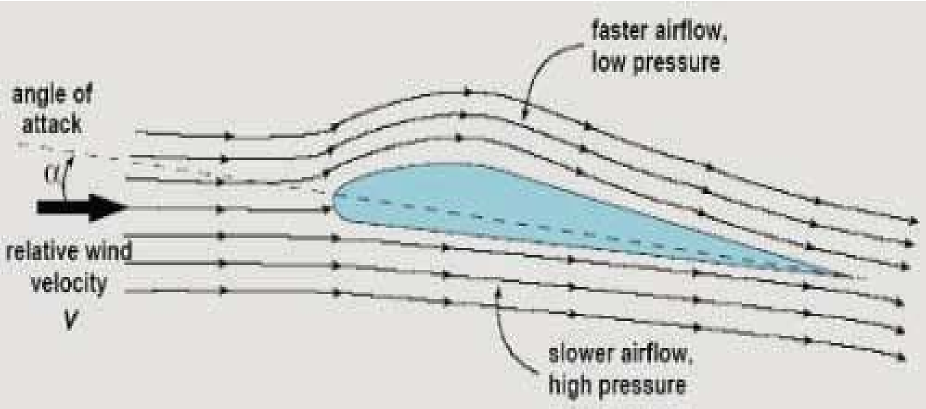

Figure (1.2) The air moving over the aerofoil [4].

Aerodynamic forces analyzing method:

Many similarities exist between wind rotor aerodynamics, and aero plane wing aerodynamics. In fact, the same two-dimensional air foil theory is applied to both, except that the rotational effects of the flow accounted for when considering a wind rotor. This section illustrates two of the fundamental concepts in rotor aerodynamics-one-dimensional momentum theory and blade element momentum theory this theories has wide application in wind turbine design [6,7].

Wind turbine aerodynamic analysis is mainly concerned with the prediction of rotor loads and power output. This analysis is one of the first and most critical steps in designing rotors and has, consequently, received a great deal of attention from a number of researchers.

Method of analyzing the behavior of blades due to their motion through air shown in Fig. (2.1), for this analysis , it is assumed that the blade is divided into S sections or elements and aerodynamic force acting on each blade element can be estimated as the force on suitable airfoil characteristics of the same cross-section adopted for the blade elements. Finally assuming that the behavior of each element is not affected by the adjacent elements of the same blade, the force on the whole blade can be derived by adding the contributions of all the elements along the blade [8,9].

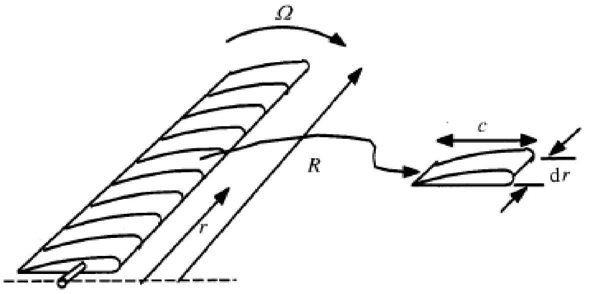

Figure (2.1) Schematic of blade elements.

A diagram showing the developed blade element at radius r and the velocities and forces acting on this element is given in Fig. (2.2) . The relative wind velocity $\mathbf{V}_{\mathbf{rel}}$ is the vector sum of the wind velocity at the rotor $\mathbf{V}_\infty$ **(1-a)** (the vector sum of the free-stream wind velocity, $\mathbf{V}_\infty$ and the induced axial velocity ($-aV_\infty$) and the wind velocity due to rotation of the blade. And this rotational component is the vector sum of the blade section velocity, Ωr and the induced angular velocity **áΩr**. Hence the relative wind velocity will be as shown on the velocity diagram in Fig.2.2. The minus sign in the term $V_\infty(1-a)$ is due to the retardation of flow while the air approaching the rotor and the plus sign in the term **Ωr (1+á)** as shown in Fig.2.2 is due to the flow of the air in the reverse direction of the blade rotation after air particles hit the blades and so give torque.

In the mean time let the existence of the axial and tangential induction factors assumed, their evaluation will be given in the subsequent section.

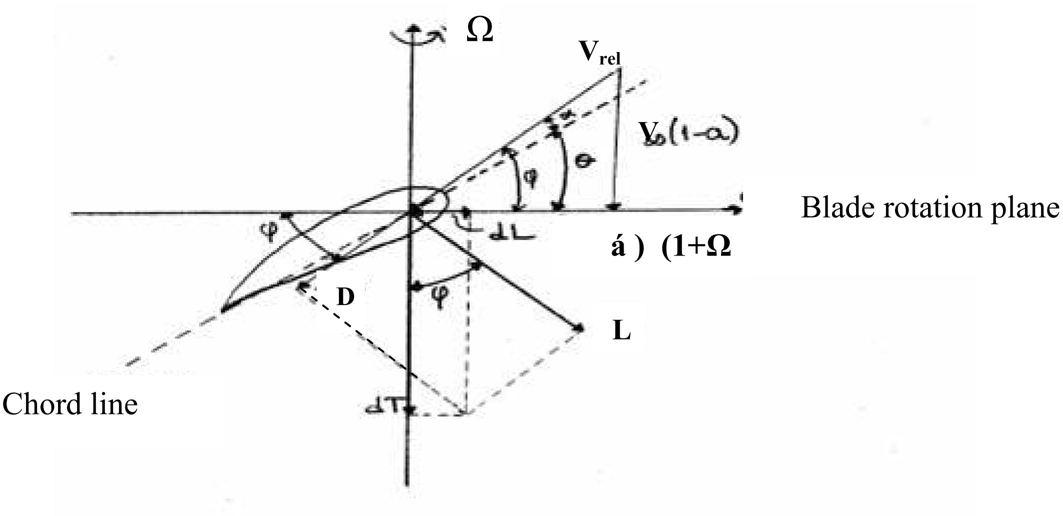

Figure (2.2) Blade Geometry for analysis of a HAW.

Blade element method relies on two key assumptions:

- There is no aerodynamic interaction between different blade elements

- The forces on the blade elements are solely determined by the lift and drag coefficients

In Figure (2,2) the airfoil profile at a cross-section of a wind turbine blade is displayed V_{rel} is the wind speed relative to the airfoil at a flow angle φ .Using the above Figure, it is possible to derive an expression for V_{rel} for substitution into equations (2.3) and (2.4) .

$$V_{rel}=\frac{V_\infty(1-a)}{Sin(\varphi)} \tag{2.1}$$

In Figure (2.2) it is possible to note the relation between the induced velocity and the components of the wind speed. V_{rel} is the relative velocity seen by the airfoil. This is a combination of the axial velocity and tangential velocity. The equation to estimate the flow angle is derived directly from Figure (2.2)

$$\tan(\varphi)=\frac{V_\infty(1-a)}{\Omega r(1+a^{/})}=\frac{(1-a)}{(1+a^{/})\lambda} \tag{2.2}$$

Lifting force L is perpendicular to V_{rel} and the drag force D is parallel. With the orientation and magnitude of the oncoming wind vector know, the coefficients of lift C_L and drag C_D can be calculated according to standard two-dimensional aerodynamic theory.

$$D=C_D\frac{1}{2}\rho V_{rel}^{\ 2}\,C\,dr \tag{2.3}$$

$$L=C_L\frac{1}{2}\rho V_{rel}^{\ 2}\,C\,dr \tag{2.4}$$

The lift and drag forces are projected onto the normal and tangential directions of the rotor plan to construct the normal and tangential components of the resultant aerodynamic forces

$$dT=L\cos\varphi+D\sin\varphi \tag{2.5}$$

$$dL=L\sin\varphi-D\cos\varphi \tag{2.6}$$

If the rotor has N number of blades, the total normal and tangential force on the element at a distance (r) by rearranging equation and with the use of equation 2.5 and 2.6 with the use of equation 2.1 , 2.3 , 2.4 ;

$$dT=N\frac{1}{2}\rho V_{rel}^{\ 2}(C_L\cos\varphi+C_D\sin\varphi)Cdr \tag{2.7}$$

$$dL=N\frac{1}{2}\rho V_{rel}^{\ 2}(C_L\sin\varphi-C_D\cos\varphi)Cdr \tag{2.8}$$

The elemental torque due to the tangential forces, (dL) operating at a distance (r) from the center is given by; [10].

$$dQ=rdL \tag{2.9}$$

Hence the elemental torque by inserting equation 2.8 into equations 3.9.

$$dQ = N\frac{1}{2}\rho V_{rel}^{\ 2}\,(C_L \sin\varphi - C_D \cos\varphi)\,Crdr \qquad (2.10)$$

And by defining solidity ratio, Z, [8] as following;

$$Z = \frac{NC}{2\Pi r} \qquad (2.11)$$

And inserting equations (2.11 & 2.12) into (2.7 & 2.10) the general form of elemental thrust and torque equations become;

$$dT = \mathrm{Z}\Pi\rho\frac{V_\infty^{\ 2}(1-a)^2}{\sin^2\varphi}(C_L \cos\varphi - C_D \sin\varphi)\,rdr \qquad (2.12)$$

$$dQ = \mathrm{Z}\Pi\rho\frac{V_\infty^{\ 2}(1-a)^2}{\sin^2\varphi}(C_L \sin\varphi - C_D \cos\varphi)\,r^2dr \qquad (2.13)$$

Thus, from blade element method, two equations (2.12 , 2.13) have been obtained.

They define the normal force (thrust) and the tangential force (torque) on an annular rotor section as a function of the flow angles at the blades and aerofoil characteristics , the solution of these equations depends on practical measures the lift and drag forces of blades in wind tunnel under non-rotating conditions with wind speed changes [13], so the determine the complete performance characteristic of rotor, the manner in which the power coefficient varies over a wind range of tip speed ratio , requires the iterative solution .

Power Output

The elemental power from each element was defined in equation

$$dP = \Omega\, dQ \qquad (3.1)$$

And the total power from the rotor is;

$$P = \int_0^R dP = \int_0^R \Omega\, dQ \qquad (3.2)$$

The ratio between power from rotor (P_{rotor}) and power from wind (P_{wind}) called *Power coefficient* C_p

$$C_p = \frac{P}{\frac{1}{2}\rho V_\infty^{\ 3} A} = \frac{\int_0^R \Omega\, dQ}{\frac{1}{2}\rho V_\infty^{\ 3}\Pi R^2} \qquad (3.3)$$

The rotor power coefficient is very important design factor, the maximum theoretical power that can extracted from the wind according to Beltz, only 59% of the wind power [9].

Calculation power coefficient depends on measures the lift and drag behaviors of aerofoil in wind tunnel under non-rotating conditions [13], so, the maximum achievable power coefficient for turbines with an optimum blade shape with finit number of blade and aerodynamic drag is given by an empirical formula [14,15] developed from experimental, data as follows:

$$C_p = (\frac{16}{27})\lambda \left[\lambda + \frac{1.32 + (\frac{\lambda - 8}{20})^2}{N^{2/3}} \right]^{-1} - \frac{0.57\lambda^2}{\frac{C_L}{C_D}(\lambda + \frac{1}{2N})} \qquad (3.4)$$

Where;

$$\frac{C_L}{C_D} = 25 - 100$$

N = 1-5

$$\lambda = \frac{\Omega R}{V_\infty} = 4 - 20\,\text{TSR=}$$

The total power output:

$$P = 0.5\, \rho V_\infty^3\, \Pi\, R^2\, C_p \qquad (3.5)$$

The calculation of power coefficient and power for wind turbine developed by a rotor requires a knowledge of the flow induction factors. The solution is usually carried out iteratively because the two-dimensional airfoil characteristics are non-linear functions of the angle of attack. To calculation the performance characteristic of a rotor, the manner in which the power coefficient varies over a wide range of tip speed ratio, requires the iterative solution. The iterative procedure is to assume (a) and (a') to be zero initially, determining φ , Cp on that basis, and from characteristic airfoil NACA 2410 the lift force coefficient =0.8 at angle of attack= 6deg.,and then to calculate new values of the flow factors. The iteration is repeated until convergence is achieved. The equation (3.4) also is used to determining Cp with different parameters.

Results and Discussion :

- Figure(4-1) shows the effect of the ratio lifting /drag coefficients forces on turbine efficiency with different tip speed ratio at blade number =3, the first point mention is that the maximum value of Cp is 0.51 achieved at the tip speed ratio of 6.5 while C_L / C_D =100 . And another side the maximum value of Cp is 0.42 achieved at the tip speed ratio =5 while C_L / C_D= 25, which is much less than the Betz limit 0.593. The decreasing is caused, in this cause, by drag and tip losses but the stall also reduces the Cp at low values of tip speed ratio. Also in this figure it mention is that the local speed ratio should be between 5 and 7 for air foil NACA 2410 with maximum C_L / C_D between 25 and 100, respectively, to obtain maximum local Cp .

- In figure (4.2) shows the effect of different number of blade 2,3,5 on turbine coefficient Cp and showed that with the assumption of constant maximum C_L/C_D =100 alone the entire blade , the point mention is that the maximum value of Cp is between 0.47 - 0.52 depending on the number of blade turbine . this figure mention is that the maximum value of Cp for the different number of blade approximately convergence, so for a design the wind turbine with three blade is a suitable for a good stability and a little noise at working.

- The investigation of Power from rotors the figure (4.3, 4.4) showed that with assumption of constant blade number is 3, tip speed ratio is 7 and turbine coefficient Cp with different radius rotor of turbine between 1m to 30m and wind velocity varied from 3m/s to 15m/s. The obtained results of power from rotors varied from 0.015Kw to 174.629Kw at Cp=0.30, while at Cp=0.55 the power from rotor is 0.028Kw to 3201.538Kw. Different range results depending on the airfoil performance and wind velocity.

- In figure (4.5, 4.6) showed that the generator speed and generator torque increasing Linearly and exponential respectively at designing tip speed ratio 6 and Cp=0.5. The principal use of this curve is for torque assessment purposes when the rotor is connected to a gear box and generator. For modern high-speed turbines for electricity generation as low a torque as possible is desirable in order to reduce gearbox costs.

Conclusion:

- In this work the influence of aerodynamic performance for airfoil NACA 2410 on the important design factor for power efficiency, Cp, The work was divided into an analysis of 2D airfoils/blade sections and of entire rotors. In the analysis of the 2D airfoils it was seen that there was a maximum of the local Cp for airfoils with CL/C_D values. The local speed ratio should be between 5 and 7 for airfoils with CL/C_D between 25 and 100, respectively, to obtain maximum local Cp.
- The investigation of Cp for rotors was made with three blades and showed that with the assumption of constant maximum C_L/C_D along the entire blade, the good design tip speed ratio changed from 5 to =7 for C_L/C_D = 25,100, respectively, with corresponding values of Cp=0.46 and Cp=0.525. It also showed that the design tip speed ratio and Cp are very dependent on airfoil performance and rotor size.
- Wind turbine must thus be designed to operate at their optimal wind tip speed ratio in order to extract as much power as possible from the wind and also, if the tip speed ratio is too high, the turbine will rotate very fast through turbulent air, and the power will not be only optimally extracted from the wind, but the turbine will be highly stressed at the risk of catastrophic failure.

Recommendations

From this work we can recommend to develop the better profile airfoil for turbine blade by using application nanotechnology to increasing power coefficient.

Table (4.1) Power Coefficient – Tip Speed Ratio Performance by using empirical formula Eq.(3.4)

TSR Tip speed ratio	Cp at C_L/C_D=25 N=3	Cp at C_L/C_D=100 N=3	Cp at C_L/C_D=100 N=5
3	0.420	o.470	0.490
5	0.415	0.500	0.510
10	0.325	0.490	0.500
15	0.220	0.480	0.490
20	0.120	0.440	0.450

Table (4.2) output power (watt) with different wind velocity and radius of blade at C_p=0.3

V / R m	٣ m/s	٥ m/s	١٠ m/s	١٥ m/s
١	١٥,٥	٧١,٩	٥٧٤,٩	١٩٤٠,٣
٣	١٣٩,٧	٦٤٦,٨	٥١٧٤,٢	١٧٤٦٢,٩
٥	٣٨٨,١	١٧٩٦,٦	١٤٣٧٢,٨	٤٨٥٠٨,٢
١٠	١٥٥٢,٣	٧١٨٦,٤	٥٧٤٩١,١	١٩٤٠٣٢,٦
٢٠	٦٢٠٩	٢٨٧٤٥,٦	٢٢٩٩٦٤,٦	٧٧٦١٣٠,٥
٣٠	١٣٩٧٠,٣	٦٤٦٧٧,٥	٥١٧٤٢٠,٣	١٧٤٦٢٩٣,٥

Table (4.3) output power (watt) with different wind velocity and radius of blade at C_p =0.55

V / R m	٣ m/s	٥ m/s	١٠ m/s	١٥ m/s
١	٢٨,٤١٠	١٣١,٨١٦	١٠٥٣,٩٨٣	٣٥٥٧,٢١٦
٣	٢٥٦,١١	١١٨٥,٨٠	٩٤٨٦,٠٣٣	٣٢٠١٥,٣١
٥	٧١١,٥١	٣٢٩٣,٧٦	٢٦٣٥٠,١٣	٨٨٩٣١,٧٠
١٠	٢٨٤٥,٨	١٣١٧٥,٦	١٠٥٤٠٠,٣	٣٥٥٧٢٦,٤
٢٠	١١٣٨٣,١	٥٢٧٠٠,٢	٤٢١٦٠١,٧	١٤٢٢٩٠٥,٩
٣٠	٢٥٦١٢,٢	١١٨٥٧٥,٤	٩٤٨٦٠٣,٨	٣٢٠١٥٣٨,٠٨

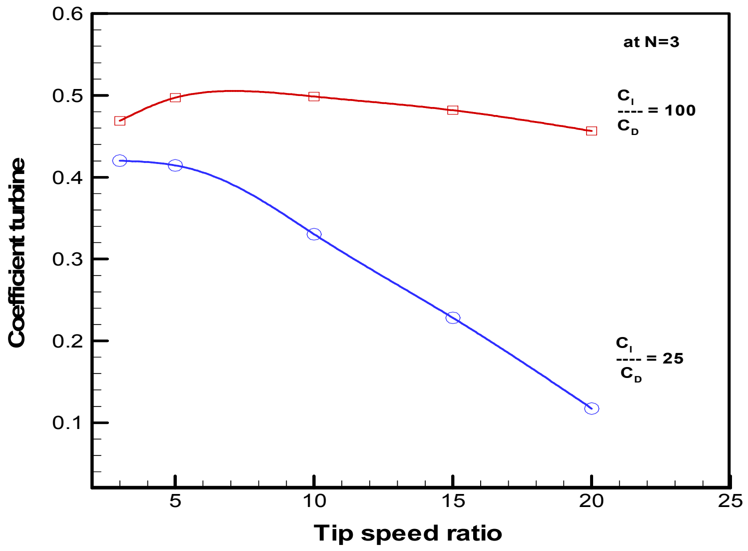

Figure (4.1) Effect of lift/drag ratio on coefficient performance of an Optimum three-bladed wind turbine.

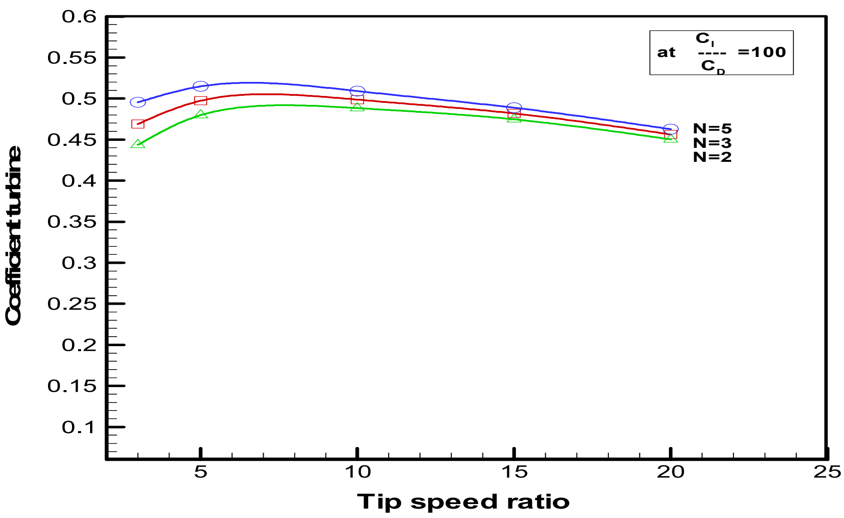

Figure (4.2) Effect number of blades on coefficient performance at   constant Lift/drag ratio coefficient.

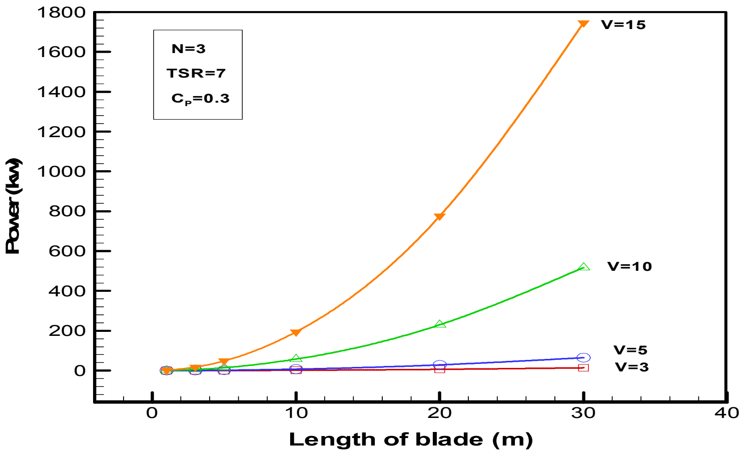

Figure (4.3) Effect radius rotor of blades on power performance with coefficient ower= 0.3.

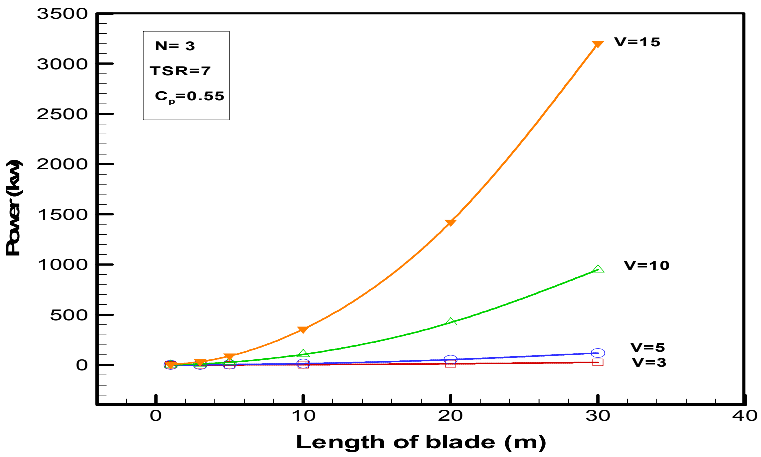

Figure (4.4) Effect radius rotor of blades on power performance with coefficient power =0.55.

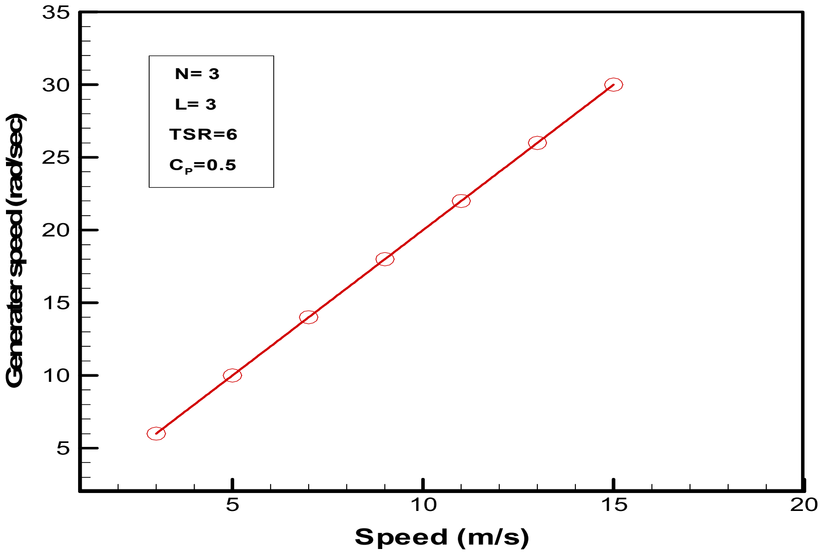

Figure (4.5) effect wind velocity on generates speed.

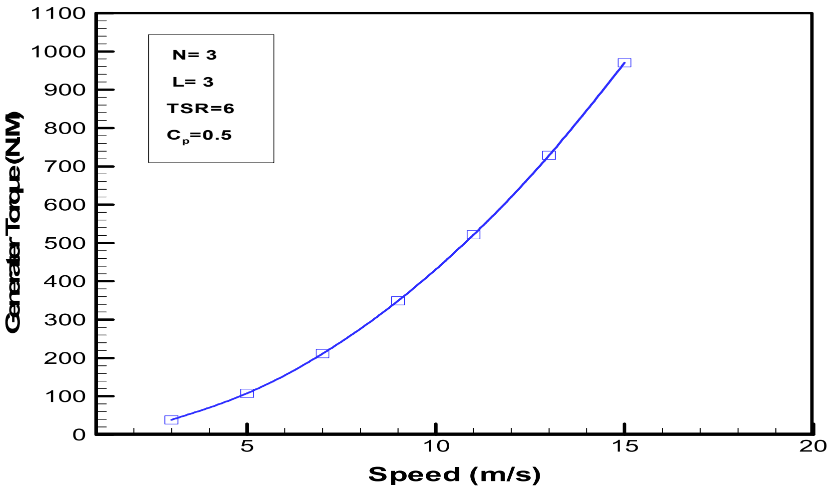

Figure (4.6) effect wind velocity on generates torque.

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