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# Suggestions for improving wind turbines power curves

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**Abstract**

The question is usually not whether a wind turbine can be designed to optimise the power production at the site, but rather whether an existing wind turbines with a certain rotor can be modified in order to improve the power production. In this paper the various methods for improving the wind turbines power output were investigated experimentally and theoretically. The effect of changing the rotational rotor speed on the power performance of Nordtank 300 kW stall-regulated, horizontal axis wind turbine was investigated experimentally. This was performed by changing the setting program for operating the wind turbine. The variation in the aerodynamic performance of the wind turbine rotor due to changing the pitch angle was investigated experimentally in Hurghada wind farm. The manufacture setting tip angle for Nordtank 300 kW wind turbine is (–1.8°). In this study, the angle was changed to two values (–2.8°) and (–0.8°). Also, to improve the blade performance of a wind turbine operating in low wind speed ranges; the vortex generators may be used. These vortex generators were placed over low-pressure surface of blade or tip blade part. In this study, two types of vortex generators, rectangle and triangle shapes were investigated.

*Keywords:* Wind turbine; Performance upgrading; Pitch regulated; Stall regulated; Vortex generators

## 1. Introduction

Once a wind turbine is installed and passed its operational checkouts, it is put in regular operating mode. As a piece of machinery, it can then be evaluated on its performance, reliability and maintenance costs and compared with other similar machinery on an economic basis. The performance of the wind turbine is an important measurement because the economy is to a large extent based on the ability of the turbine to produce power. For the power performance analysis, the wind speed is characterized by their velocity distributions over the time. These analyses of wind turbine performance were carried out in the case of steady state of wind flow only. Because, the real conditions of unsteady flow are not well understood, particular difficulty is encountered in characterizing the

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amplitudes and frequencies of the aerodynamic forces whenever the flow is not well defined, such as in stall regime. The main factor which affects the wind turbine sales is its power curve, which defined as a table of data, consisting of connected values of net electric power from the wind turbine and the wind speed [1].

The potential of wind available for power production varies greatly over Egypt. It also varies considerably from region to region and within regions. When a site is selected and a proper sitting accomplished resulting in a Weibull distribution function for the wind speed, the next step, to decide upon is the appropriate wind turbines. Due to the large variations in wind climate, one should ensure that the chosen wind turbine design is the best possible for the particular locations. The traditional procedure is to calculate the mean production from one or more available turbines. This, however, does not ensure that the selected turbine gives optimum production at the site as the turbine may have been designed for another wind regime. The objective of the work is to study the various possible methods to improve the power curve of stall-regulated, horizontal axis wind turbines which are operating in low regimes of wind speed sites. The annual mean wind speed in Hurghada site was greatly lowered recently due to change of site surface roughness. The study was performed in Wind Energy Technology Centre, in Hurghada wind farm, at 12.5 km north of Hurghada city. The site area is about 2.5 km times 1 km with the length parallel to the coastline. The prevailing wind was westerly coming from the north.

## 2. Wind turbines power curve analysis

### *2.1. Wind turbine efficiency effect*

The overall efficiency of a wind turbine is defined as, the ratio of the actual power output at a given wind speed to the total available power which passes through the swept area of wind turbine rotor. It is evident that, the best utilization of the energy in the wind can be obtained when the turbine efficiency reaches its highest value at a point close to the maximum of the power density function of the wind. Thus, the aerodynamic efficiency curve of the wind turbine should be matched to the wind speed distribution [2]. By assuming the wind turbine with a simple linear power curve as shown in Fig. 1, the efficiency curve becomes

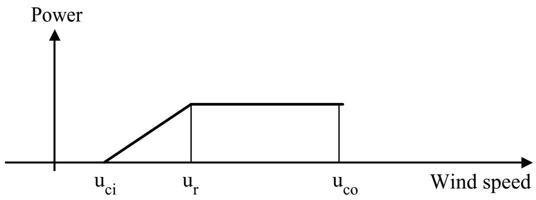


Fig. 1. Simple linear wind turbine power curve.

$$C_P(u) = \frac{P(u)}{E(u)\,A_R} = \frac{S\,(u-u_{ci})}{1/2\,\rho\,u^3\,A_R}, \quad u_{ci} \le u \le u_r \tag{1}$$

and

$$S = \frac{P_{max}}{u_r - u_{ci}} \tag{2}$$

The maximum efficiency for any wind turbine takes place at a certain wind speed, $u_m$, which can be determined by differentiating Eq. (1), leading to $u_m$ = 3/2 $u_{ci}$, then, the power output can be written as

$$P(u) = 3/2\; C_P\rho(u_m)\, A_R u^2{}_m (u - 2/3\; u_m) \tag{3}$$

By using the approximated piecewise linear function with few nodes as shown in Fig. 2. The power of the wind turbine can be written as

$$P(u) = P_i + \left(\frac{P_{i+1} - P_i}{u_{i+1} - u_i}\right)(u - u_i) \quad \text{for } u_i \le u \le u_{i+1} \tag{4}$$

The analytical solution of this equation is

$$P = \sum_i \frac{P_{i+1} - P_i}{\alpha_{i+1} - \alpha_i}\left[G_K\left(\alpha_{i+1}\right) - G_K\left(\alpha_i\right)\right], \tag{5}$$

where $\alpha_i = u_i/A$.

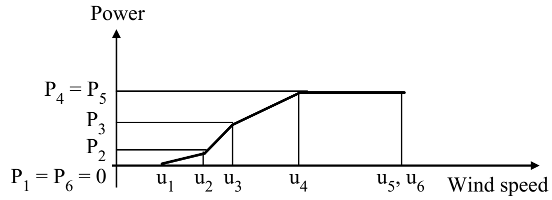


Fig. 2. Power curve approximated by a piecewise linear function.

The function $G_k(\alpha)$ is $1/k$ times the arguments $(1/k)$ and $\alpha^k$. This function can be solved and tabulated for a range of $(k)$ values [3]. In some situations a discontinuity can be found in the power curve at $(u_5 = u_6)$. In the case of a jump in power from $(P_i)$ to $(P_{i+1})$ at $(u_i = u_{i+1})$, the contribution to the sum from this interval becomes

$$(\mathrm{P}_{i+1} - \mathrm{P}_i)\cdot \exp\,(-\alpha_i^k) \tag{6}$$

By using Eqs. (5) and (6), the mean power can be theoretically calculated for any power curve simply by dividing it into a sufficient number of linear sections. In practice, this method will only be useful if the power curve can be approximated by a small number of linear sections. For many wind turbines the power curve is reasonably well approximated by simple shape as shown in Fig. 1. Then Eqs. (5) and (6) give:

$$P = \frac{P_{\max}}{\alpha_{\mathrm{r}} - \alpha_{\mathrm{ci}}}\left[G_K\left(\alpha_{\mathrm{r}}\right) - G_K\left(\alpha_{\mathrm{ci}}\right) - \exp\left(-\alpha_{\mathrm{co}}^K\right)\right] \tag{7}$$

In practice, the last term can often be neglected especially at very high wind speed sites, because the wind turbine must be stopped at very high wind speeds (>25 m/s). For a wind turbine with a power curve close to linear approximation, Eq. (7) provides a rapid method for calculating the power production. A more accurate procedure is to use the wind speed $(u_{\mathrm{m}})$ at which the efficiency of the wind turbine is the highest value [4]. Substituting by this expression in Eq. (7) yields to this result:

$$P = 1/2\,\rho\, C_P\, u_{\mathrm{m}}\, A_{\mathrm{R}}\, A^3 \times\left[3(u_{\mathrm{m}}/A)^2\left[G_k\left(u_{\mathrm{r}}/A\right) - G_k\left(2u_{\mathrm{m}}/3A\right)\right]\right] \tag{8}$$

This expression contains parameters, which describe the main characteristics of the wind turbine. The value of $(u_{\mathrm{m}})$ which optimises the mean power production $(P)$, can be approximated with the sufficient accuracy by this expression:

$$u_{\mathrm{m}} = A\left[\left(\frac{k+2}{k}\right)^{1/k} - 0.15\right] \tag{9}$$

The first term in the parenthesis gives the wind speed scaled with $A$ at which there is a maximum power density function for the wind speed. The expression thus shows that, the maximum efficiency should be chosen at a wind speed somewhat lower than that corresponding to the maximum in the power density function of the wind [5].

### *2.2. Lift function effect*

Wind turbines operate by the action of the relative wind speed, which is the resultant of the stream wind speed, blade section speed and rotor induced flow. The relative flow creates aerodynamic forces on the rotating blades. These can normally be grouped into lift force and drag force. Lift force is the main force which responsible about the operating of the wind turbine to produce useful power.

As shown in Fig. 3, the lift on the blade element per unit length of span can be stated as

$$L = 1/2\,\rho W^2 \sin\alpha\; c\; C_{\mathrm{L}} \tag{10}$$

For finite element of blade, $\alpha$ is very small, and it can be assumed that $\alpha \approx \sin\alpha$

$\alpha = \tan^{-1}(\Phi - \theta) \approx \Phi - \theta$, and $U_{\mathrm{p}} << U_{\mathrm{t}}$ so, $\Phi \approx U_p/U_t$, then

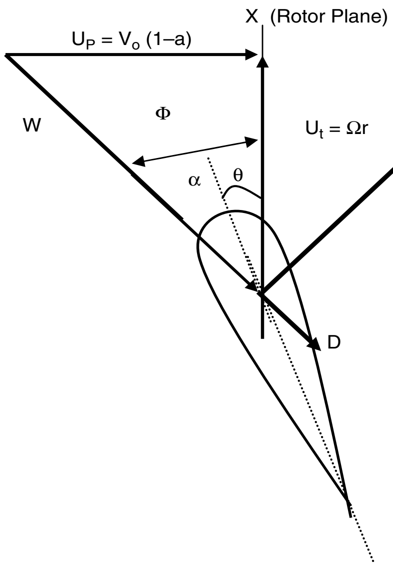


Fig. 3. Blade element velocity diagram.

$$\alpha = U_p/U_t - \theta \tag{11}$$

$$W = \sqrt{(U_t^2 + U_p^2} \tag{12}$$

and,

$$U_t = \Omega r \tag{13}$$

$$U_p = V_o(1-a) \tag{14}$$

By substituting in Eq. (10), then:

$$L = 1/2\rho\ C_L c\ \left[U_t^2\theta + U_p\ U_t\right]$$
$$= 1/2\rho\ C_L c\ \left[(\Omega r)^2\theta + V_o\ (1-a)\Omega r\right] \tag{15}$$

## 3. Experimental set-up

### *3.1. Wind turbine specifications*

The investigated wind turbine has three-bladed upwind turbine rotor with fixed cantilevered blades on the hub. The main specifications are listed in Table 1. The cut-in and cut-out wind speed are 4, 25 m/s respectively.

Table 1
Main technical data of Nordtank 300 kW wind turbine

| | |
|---|---|
| Nominal rating | 300 kW |
| Swept area | 755 $m^2$ |
| Hub height | 30.5 m |
| Diameter | 31 m |
| Rotor speed (synchronous) | 34 RPM |
| Blade length | 14.2 m, NACA 63200 |

### *3.2. Instrumentation of measurements*

The measuring sensors were mounted at the different locations on the nacelle of turbine. The main shaft instrumentation contained some strain gauges to measure the shaft torque, and inductive sensors to measure the rotor speed. For measuring the rotational speed of the rotor, the disc with a certain numbers of holes was used, it was mounted behind the wind turbine generator with inductive sensors to count the frequency of the disc holes. The measurement of the electrical power output by the turbine was carried out by three-current transformers, one for each phase. The current is measured with separate current converters, which were positioned on each phases. The electrical power sensor measures the true RMS value of the active power. This sensor was mounted on the electric grid side of the wind turbine, so that it is only the net power of the wind turbine that is measured. Power consumption by the turbine equipment in that connection was estimated. The wind speed was measured with a cup anemometer with three cups, it was mounted at 1 m above hub height of the wind turbine [6]. Also the wind direction was measured with a wind vane system. At the beginning of the measuring, all sensors were checked and calibrated. All of the amount of the stored data was averaged over 10 consecutive minutes. Data-link system applied for the measurements are shown in Fig. 4.

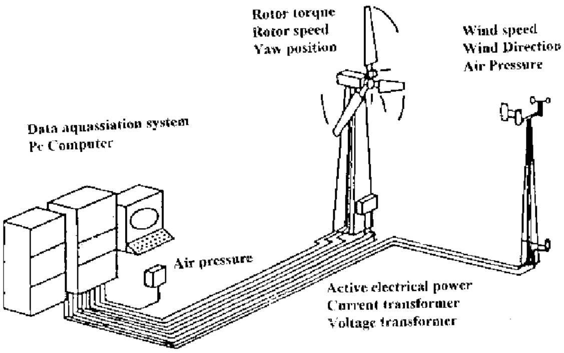


Fig. 4. Data-link measurement system.

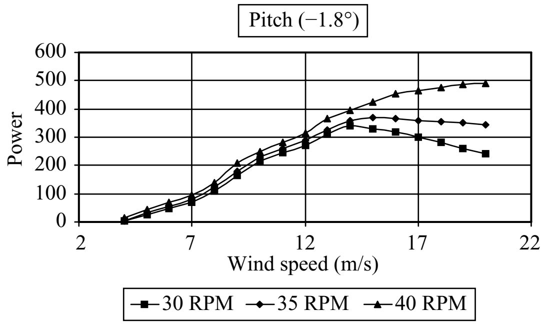


Fig. 6. Effect of rotor RPM on the rotor power (kW).

Vortex generators were used to suppress or delay separation in aircraft wings. It should be noted that by erecting an energetic vortex, vortex generators necessarily incur a drag penalty when separation is not imminent. The improvement in the wind turbines performance by installing vortex generators depends on vortex generators shape and place of installation on the blade surface. In the present study, two types of vortex generators were used, rectangle and triangle shapes. Fig. 5 shows the geometry of the two designed types of VGs fins on surface of blade of the wind turbine.

## 4. Results and discussion

As shown in Eq. (15), air density, element blade radius and chord, and interference factor, are constant parameters. But element blade lift coefficient, pitch angle, rotor rotational speed, can be changed and could be optimized to improve the lift force. Generally, for stall-regulated, horizontal axis wind turbines with a given rotor and operating in the below annual average wind speed sites, the simplest modifications which can be carried out to improve the wind turbine performance are changing rotor rotational speed, changing pitch angle and installing vortex generators on the blade surface.

### *4.1. Rotor rotational speed (RPM) effect*

The first modification which may be carried out on the wind turbines of Nordtank 300 kW is variation the rotor rotational speed (RPM). The changing of the rotor rotational speed on the power performance Nordtank 300 wind turbine

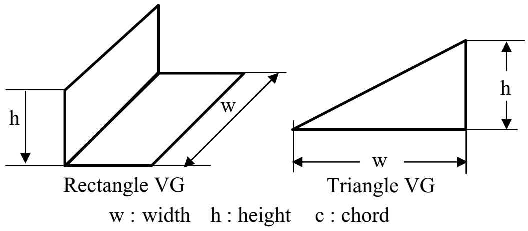


Fig. 5. Typical vortex generators dimensions ($w = c/40$, $h = w/4$).

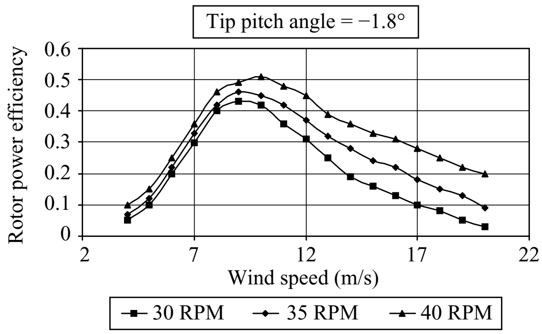


Fig. 7. Effect of RPM on the rotor efficiency ($C_P$) of wind turbine.

was investigated experimentally. Figs. 6 and 7 show the effect of the rotor speed RPM on the rotor aerodynamics performance. The RPM of wind turbine rotor is increased and decreased by 5 RPM about design one. The performance of Nordtank wind turbine was measured at three cases, (30, 35, and 40 RPM). As shown in the Figures, if the rotor RPM increases, the rotor aerodynamic power increases also and visa versa. It is clear that, the cut-in speed does not affected by the changing of the rotational speed of the wind turbine rotor. The aerodynamic efficiency ($C_p$), is improved by increasing the rotational rotor speed of the wind turbine (RPM). This modification may be used to improve the performance of the wind turbines operating in sites, which have low wind speed conditions and has high variability.

### *4.2. Blade pitch angle effect*

The second modification, is changing the pitch angle of aerofoil, this angle is normally fixed during the operation of the stall-regulated wind turbines. The change of pitch angle leads to change the attack angle, and then the behavior of aerodynamics is changed too. The variation in the aerodynamic performance of the wind turbine rotor due to changing the pitch angle was investigated experimentally. The manufacturer setting tip angle for Nordtank 300 kW wind turbine is (–1.8°). The angle was changed into two values, (–2.8°) and (–0.8°). The results are shown in Figs. 8 and 9, where it is seen that, there is sensible gain in the energy produced by rotor of wind turbine, which is remarkable for the low wind regime. Whereas for high wind regime, the improvement in rotor power is very high.

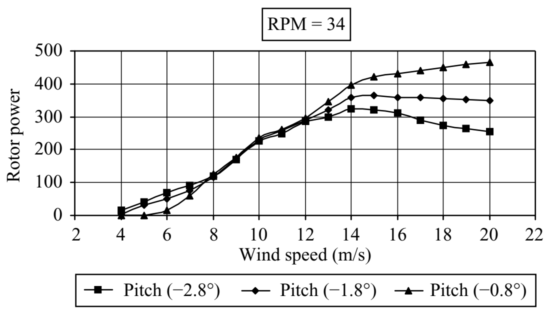


Fig. 8. Effect of pitch angle on the rotor power (kW) of wind turbine.

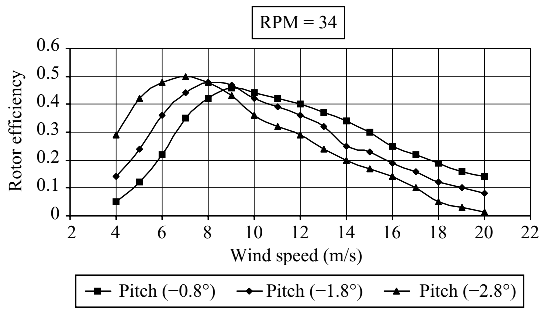


Fig. 9. Effect of pitch angle on the rotor efficiency ($C_p$) of wind turbine.

Increasing the blade pitch angle leads to increasing the cut-in speed from the design one. Also, the power produced by the turbine rotor decreased compared to the design power especially in low wind speed regimes, and after that it became near to the design power in medium wind speeds, but for the strong wind speed conditions (>12 m/s), the rate of increasing rotor power is very high. The rotor power produced for the case of decreasing pitch angle by (1°) compared to design setting on is shown in Fig. 8. It is shown that, cut-in speed decreased compared to design one. And the rotor power production is improved especially at low wind speed conditions. But in medium ranges of wind speed the improvement in power is not high. However, after 12 m/s wind speed, the rotor power decreased by a high degree compared to the design value. Fig. 9 shows the rotor power efficiency $C_p$, in three previous cases of pitch angles (–2.8°, –1.8° and –0.8°), while the rotational rotor speed is constant at, 34 RPM. It is noted that, the rotor efficiency of wind turbine at case of decreasing pitch angle is higher than other two cases especially in low wind ranges. As shown, after (8 m/s) wind speed, the efficiency of rotor decreased compared to the other two cases, so the decrease of the pitch angle below design setting one (–1.8°), in Nordtank 300 kW wind turbine, may be useful especially in low wind speed sites.

The result from the previous discussion is that changing of pitch angle of the Nordtank 300 kW wind turbine, which operates in low and average wind speed conditions, is very required to improve the performance of the turbine. But this change is limited due to the effect of post-stall conditions and the wind turbine availability. Also, it depends on the capacity of the generator and the stability of the wind turbine. So, the blade pitch angle of Nordtank 300 wind turbine may need to reset and optimize to compensate the reduction of annual wind speed.

### 4.3. Installing vortex generators effect

*I. Rectangle VGs Fins.* Fig. 10 shows the effect of installing rectangle VGs on Nordtank 300 wind turbine. Two types of rectangle vortex generators were installed on blade and tip parts of wind turbine to investigate their effect on the power output. When the rectangular VGs is placed on blade part, the rated power is produced at 10 m/s wind speed approximately, so

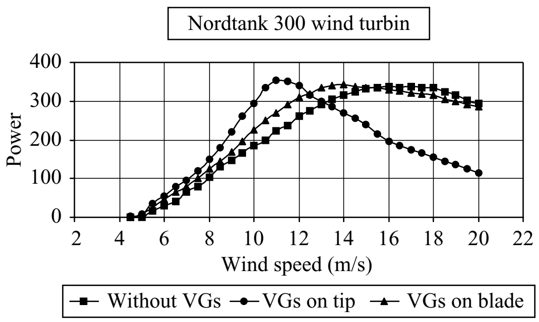


Fig. 10. Effect of rectangular VGs on the turbine power output (kW).

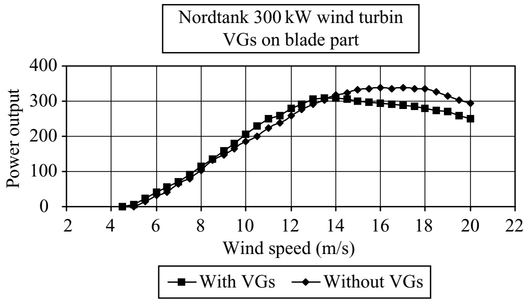


Fig. 11. Effect of triangle VGs type on turbine power output (kW).

there is 3.5 m/s approximately reduction in rated wind speed. The rate of improvement in power at lower wind speed sites is very high. This power improvement reached to 35% at 11 m/s wind speed. The maximum value of power output, 355 kW is obtained at 11 m/s wind speed. But the power output decreased very fast with VGs from the other at wind speed higher than 13 m/s. When using rectangle vortex generators, the power output of turbine was improved up to 10–35%. So, the use of rectangle vortex generators introduces an important method to improve aerodynamics performance of the wind turbines. In sites of low annual wind speed rates, (less than 7 m/s), as in Hurghada wind farm, it is recommended to use rectangle vortex generators on blade surface only. Because, the total improvement in wind turbine power performance is better than other cases. Also, the power performance with tip VGs decreases by very fast rates when, the wind turbines were operating at higher wind speeds.

*II: Triangle VGs Fins.* A typical triangle shape vortex generators fins was tested in Nordtank 300 kW, stall-regulated, wind turbines. Also, the VGs were painted by same roughness material in rectangle shape. The performance was investigated only with VGs on blade surface. Fig. 11 shows the effect of installing triangle surface blade VGs fins on the turbine power output. The rated power is reached at 13 m/s

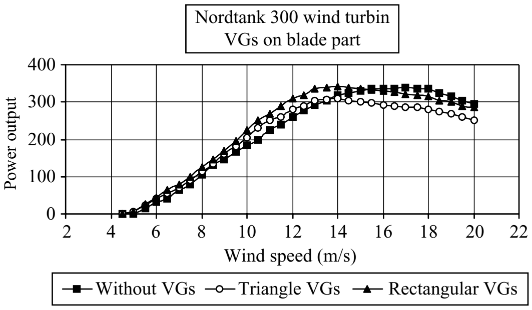


Fig. 12. Effect of two types vortex generators on the power output (kW).

with vortex generators. This value is near to the normal measured rated one without VGs. Also, there is a little improvement in power output, about 5–8% only. Fig. 12 shows the difference in improvement of Nordtank 300 kW wind turbine when installing two types of VGs on blade surface. The performance in rectangle type is better than triangle VGs. This occurred due to the increasing of vortex flow in case of rectangle type compared to the triangle shape VG. Rectangle type accelerates the air motion on the surface blade higher than other type. So, it is recommended to install rectangle vortex generators on surface of wind turbine rotor blades, to upgrade performance in low wind speed sites. Fig. 13 shows the effect of installing rectangle VGs on tip, and triangle types on blade surface on the power output from turbine. As discussed above the improvement in power with rectangle VGs is better than installing triangle fins on blade surface especially at low wind speed conditions only.

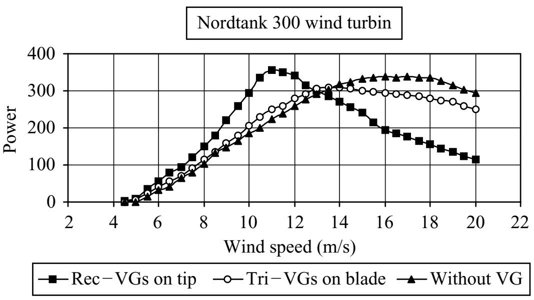


Fig. 13. Effect of blade triangle and tip rectangular VGs on the power output.

## 5. Conclusion

(1) To design a wind turbine for a specific wind condition, that should involve not only the location of the maximum efficiency, but also the detailed shape of the efficiency curve (efficiency as a function of the wind speed). The question is usually not whether a wind turbine can be designed to optimise the power production at the site, but rather whether an existing wind turbines types with a certain rotor can be modified in order to improve the power production.

(2) If the rotor RPM increases, the rotor aerodynamic power increases also and vice versa. Also, the cut-in speed may not be affected by the changing of the rotational speed of the wind turbine rotor. The aerodynamic efficiency ($C_p$), is improved by increasing the rotational rotor speed of the wind turbine (RPM). This modification can be used to improve the performance of the wind turbines operating in sites, which have low wind speed conditions and high variability.

(3) Putting vortex generators on the rotor blades surface leads to delaying stall and increasing the lift coefficient of the moderately-thick airfoils, also it improves the power output from the stall-regulated horizontal axis wind turbines, which operates in low annual average wind speed sites.

(4) The improvement in power output of wind turbine with installing rectangle VGs fins is better than triangle VGs on the blade surface due to the increasing of vortex flow with rectangle type which accelerates the air motion on the surface blade higher than other type. So, in low annual average wind speed sites, vortex generators may be added to the

tip sections to improve the wind turbine power output. The VGs on tip parts lead to increase the maximum power (peak) produced by wind turbine in low wind speed sites, but the power output is reduced in high wind sites due to the effect of additional drag due to installing the vortex generators.

## Nomenclature

| | |
|---|---|
| $P(u)$ | power output from turbine at wind speed, u |
| $E(u)$ | total available power (energy) passing through swept area |
| $A_R$ | swept area |
| $u$ | wind peed |
| $u_{ci}$ | cut-in wind speed. |
| $u_{co}$ | cut-out wind speed |
| $u_r$ | rated wind speed |
| $S$ | slope of the power curve |
| $A$, $k$ | Weibull distribution parameters (scale & shape factors) |
| $P$ | mean power produced from the wind Turbine |
| $W$ | relative (effective) velocity |
| $c$ | element local chord |
| $C_L$ | element lift coefficient |
| $L$ | lift force |
| $D$ | drag force |
| $U_t$ | velocity tangential to blade element due to rotor rotation |
| $U_p$ | velocity perpendicular to the rotor plane |
| $r$ | blade element radius |
| $a$ | interference factor |
| $h$ | height of vortex generator |
| $w$ | width of vortex generator |
| $V_o$ | free stream wind velocity |
| RPM | revolution per minute |
| $C_P$ | turbine power coefficient |

*Greek symbols*

| | |
|---|---|
| $\rho$ | air density |
| $\alpha$ | element attack angle |
| $\Phi$ | (flow relative velocity) angle |
| $\theta$ | element pitch angle |
| $\Omega$ | rotor rotational speed |

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