Effect of rotor length on generating power in horizontal axis wind turbines

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Abstract. The benefits of the rotor design are optimizing power generation and reducing cost of build in wind turbines. In this study, a performance comparison of horizontal axis wind turbines in terms of their rotor diameter is made using Qblade software. The airfoil selected is the National Advisory Committee for Aeronautics (NACA 0012) for all models, and the wind turbines have three blades. From simulations, the optimal rpm for each rotor diameter was calculated, and the generated power for different wind speeds. The results found show that the operation of wind turbines consider need operated with tip speed ratios of between 4 to 7 to give optimal power output. Maximum power was produced for a blade diameter of 170 metres and the highest power coefficient found was for a diameter of 30 metres and for this case also had the highest tip speed ratio of 6.68. Overall results can suggest which diameter range is used for choosing a rotor size that is the most cost-effective.

1. Introduction
Renewable energy is seen as the only solution in order to solve a developing energy crisis [1]. Two factors have been the key causes. The first is global warming attributed to carbon dioxide (CO₂) emission from the combustion of fossil fuels, there has been a rising trend since the industrial revolution. [2]. The second is the increase of energy demand in recent years where the oil supply-demand gap which has started from 2000 and will become very great by 2040 [2]. Wind turbines play an important role in reducing dependence on fossil fuels in many countries. Research assessment carried by Evans et al. [3] claims that wind has the minimum greenhouse emission and water wasting and the most beneficial social effects compared to other energy sources. Wind turbines can rotate about either a horizontal (HAWT) or a vertical axis(VAWT). However, Vertical axis wind turbines generate less power and thus are less common. Sources of energy which are renewable, such as wind can be to be used for solving the massive demand for energy and reduce the use of fossil fuels. In the available literature, the effect of configuration parameters on the performance of horizontal axis wind turbines has been investigated. However, there has been little research on performance if wind turbines are compared in terms of power generation. The advantages of this comparison might be predictable energy generation, increased energy density of array, and cost-effectiveness design.
This research aims to redress this shortage of research by carrying out a detailed numerical study. A thorough and comprehensive numerical simulation and modelling will be performed using QBlade. The outcome of the research is to consideration of rotor length parameter in design of Horizontal axis wind turbines for power generation.

2. Theoretical Background

The actual power produced by a wind turbine is the power generated by the wind which is multiplied by the power coefficient $C_P$ of the turbine given in equation (1) [4].

$$P_T = \frac{1}{2} \cdot \rho \cdot TSA \cdot V^3 \cdot C_P$$

where $V$ is wind velocity (m/s) and $\rho$ is the density of air (kg/m$^3$) and TSA is the turbine swept area (m$^2$).

The area sweeping by blades or TSA is a function of rotor radius $R$ (m) and is given in equation (2)[5]:

$$TSA = \pi R^2$$

The power coefficient is dependant on the tip speed ratio (TSR or $\lambda$), where $\lambda$ is defined as the ratio of rotational velocity of blades to wind velocity and one of the main parameters in design of wind turbines.

In design of rotors, low solidity and high tip speed ratio are favourable parameters. However, in case of a three blade HAWT, TSR is 5 and it is aerodynamically stable. In horizontal axis wind turbine, rotor moves perpendicular to the wind direction shown in figure 1.

![Horizontal axis wind turbine - general view (left image) and components (right image)](image)

Figure 1 Horizontal axis wind turbine - general view (left image) and components (right image)

The advantages of HAWT turbine is its high efficiency and its low cut-in speed[6]. Its disadvantage are the high cost of building tower and difficulty of maintenance at the top of tower. In their design, considering two other systems are necessary : yaw system for changing the rotor direction to the wind and brake system working for rotor speeds more than wind speed called run-away condition [7]. Airfoils are cross-sectional shape of blades which when exposed to wind stream results lift and drag forces.

3. Wind turbine simulation

The selected air foil for simulation with QBlade of HAWT is the NACA (National Advisory Committee for Aeronautics) 0012. The reason of selecting this airfoil is its widespread usage in industry such as B-17 Flying Fortress and Cessna 152, the helicopter Sikorsky S-61 SH-3 Sea King as well as horizontal and vertical axis wind turbines [8]. A Reynolds value of 100000 was used. As B (number of blades) is 3, tip speed ratio will be 5.1 according to
The chord length is calculated with respect to below formula [9]:

$$\lambda = \sqrt{\frac{80}{B}}$$  

$$C = \frac{4D}{\lambda^2 B}$$  

As maximum rotor diameter in HAWT is 170 m, turbines from 10 m to 170 m diameters is modelled and for them chord length separately is calculated. If we assume wind speed is at least 3 m/s, we can find optimized rpm for different kind of turbine diametrical. The chord length and optimized rpm in each case is tabulated in table 1.

Table 1. Optimized rpms for different rotor diameters.

| Diameter (m) | Chord length | rpm  |
|--------------|--------------|------|
| 10           | 0.5          | 36   |
| 20           | 1            | 26   |
| 30           | 1.5          | 21   |
| 40           | 2            | 13   |
| 50           | 2.5          | 11   |
| 60           | 3            | 9    |
| 70           | 3.5          | 7    |
| 80           | 4            | 6    |
| 90           | 4.5          | 5    |
| 100          | 5            | 5    |
| 110          | 5.5          | 5    |
| 120          | 6            | 4    |
| 130          | 6.5          | 4    |
| 140          | 7            | 3.5  |
| 150          | 7.5          | 3.5  |
| 160          | 8            | 3    |
| 170          | 8.5          | 3    |

The model in case of 10m diameter is shown in figure 2.

Figure 2. Three-bladed Horizontal Axis Wind Turbine design module.

The simulation in this case is shown in figure 3.
Figure 3. 3-bladed Horizontal Axis Wind Turbine Simulation in QBlade.

Rotor blades have optimal tip speed ratio designed, at which they will produce maximum power. Generated power of a wind turbine corresponds to the air mass lifted/raised by the rotor blades in given time. An increase in tip speed ratio results in decrease in the mass being lifted and affects the power output. The power curve in the figure 4 shows the correlation between power output and TSR and power output reaches its maximum values for tip speed ratios of 4 to 7. It is intended that wind turbine be operated in that range of tip speed ratios for maintaining high power output. The corresponding results of tip speed ratio for maximum powers verify it as tabulated in table 2.

Figure 4. Power Vs Tip Speed Ratio in HAWTs.

Table 2. Corresponding tip speed ratios for maximum powers.

| Diameter(m) | Pmax(W)  | TSR     |
|------------|----------|---------|
| 10         | 660.789  | 4.90088 |
| 20         | 6800.67  | 6.17148 |
| 30         | 24170.6  | 6.68531 |
| 40         | 26687    | 6.11098 |
| 50         | 46500    | 6.45    |
| 60         | 67300    | 5.69    |
| 70         | 68528.2  | 5.73399 |
| 80         | 79000    | 5.61    |
| 90         | 91300    | 5.92    |
| 100        | 152000   | 5.84    |
| 110        | 255247   | 5.78053 |
The maximum power coefficient can be found 0.43 for a 3 blade HAWT with \( D = 30 \, \text{m} \) for a tip speed ratio of 6.69 as shown in figure 5.

![Power Coefficient Vs Tip Speed Ratio in HAWTs](image)

**Figure 5.** Power Coefficient Vs Tip Speed Ratio in HAWTs.

| Diameter (m) | Power (W) | Coefficient |
|-------------|-----------|-------------|
| 120         | 172598    | 5.60367     |
| 130         | 280000    | 6.07        |
| 140         | 272000    | 5.72        |
| 150         | 371064    | 6.12494     |
| 160         | 305689    | 5.59902     |
| 170         | 459483    | 5.94808     |

The power generated for different configuration of HAWT is shown in figure 6.

![Output power Vs Wind Speed in HAWTs](image)

**Figure 6.** Output power Vs Wind Speed in HAWTs.

From figure 6 can be understood that in all cases \((D = 10 \, \text{to} \, 170 \, \text{m})\) maximum power generates in wind speed range of 4 to 5 m/s. To make trend clearer, maximum power values for each diameter imported and shown in figure 7.
Figure 7. Maximum power Vs Rotor Diameter in HAWTs.

From figure 7, trend is rising except rotor diameters 120, 140 and 160 m which in case of D=140 m is a slight fall.

4. Conclusions

In this study, different turbines in terms of rotor diameter is compared. Choosing a proper length for rotors is important for two aspects; cost-effectiveness and power generation. In terms of power generation, the maximum power achieves respectively from diameter:

\[170, 150, 160, 140, 110, 120, 100, \ldots\]

However, maximum power coefficient of 0.43 achieves for \(D=30\) m and in this case also highest tip speed ratio of 6.68 happens. Changing rotor diameter from 10 m to 20m increases power generation 10 times. Generated power of diameter 170 is 1.5 times of 160 m. Changing diameter from 90 to 110 m, increases power 164 kW. Also, it can be concluded if we want to design a turbine in range of rotor diameters 90 to 140 m(in term of cost-effectiveness), the best options are 130 and 110 m respectively and again for range of 130 to 160 m, the best options are 150 and 130 m respectively.

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