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Comparative Critique on Power Generation in Wind Turbines

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In this study, the performance of different wind turbines is compared using Qblade software. Typically wind turbines are categorized as Horizontal Axis Wind Turbine (HAWT), and Vertical axis wind turbine (VAWT) which in this paper Darrieus type as a VAWT is discussed with HAWT. The airfoil selected for this study is NACA 0012, and from simulations, it can be seen in which wind speed range, each type has higher efficiency. Then, the parameters involved in their performance is discussed, and suggestions are made on how to modify them to have a higher output power. Qblade contains the XFOIL airfoil analysis functionalities which make a software a single tool which comprises all functionality needed for the design and simulation of vertical and horizontal axis wind turbines. The benefits of the proper airfoil design optimal are increasing the efficiency of wind turbines and maximization of the power produced.

1. Introduction

Globally electricity demand is provided from different sources such as fossil fuels, i.e. coal, oil and natural gas. The issues with fossil fuels are that they have a limited resource and cause pollution. Other sources of electrical energy which are economically viable are renewable energies from solar, wind and hydro, and can be used for commercial purposes to solve the vast demand for electrical energy (Mathew 2006). The penetration of wind power in some European countries has reached values of around 20 %, as in the case of Denmark (24 %) (Díaz-González, et al. 2012). Wind turbines are classified into two aspects; based on their size and electrical output power. Their electrical power is categorized as follows: (a) Small with output power less than 25 kW, (b) Medium with 25-100 kW, (c) Large with 100 – 1,000 kW and (d) Very Large with more than 1 MW (Mathew 2006). But in terms of their rotor direction to the wind, there are two primary types (a) Horizontal Axis Wind Turbine (HAWT) and (b) Vertical Axis Wind Turbine (VAWT). This paper researches the parameters of wind turbines that need to be considered for electrical power from vertical and horizontal axis wind turbines.

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 Eq(1). According to Betz theory, the maximum theoretical power coefficient is 0.593 (Menet 2004).

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

where V is wind velocity (m/s) and ρ is the density of air (kg/m^3), and TSA is the turbine swept area (m^2).
The TSA is the area swept by the rotating blades and is dependent on rotor radius R (m) and is given in Eq(2) (Kamarudin, et al. 2015):

$$TSR = \pi R^2 \tag{2}$$

The value of C_P is a function of the tip speed ratio (TSR or λ), shown in Figure 1, where λ is calculated by dividing the tip speed of the turbine blades by the speed of the wind. This is an essential parameter for designing a wind turbine.

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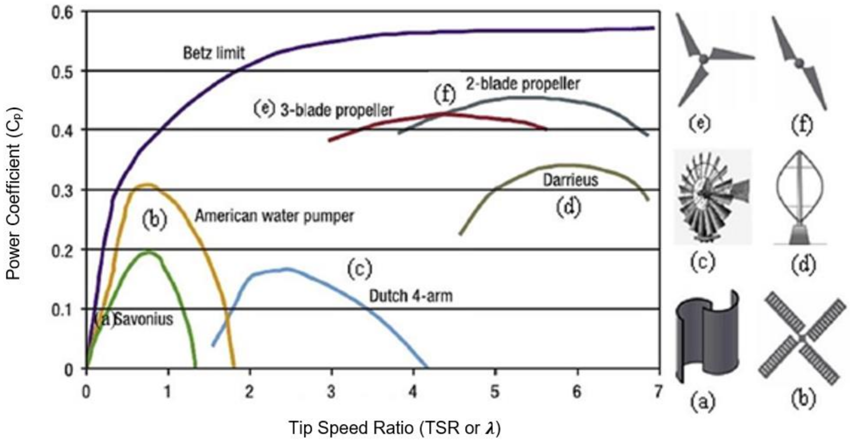

Figure 1: Performance curves of wind turbines (Al-Kayiem, et al. 2016)

For wind turbines, there are two other parameters that are important. They are:

1. Cut-in speed or the speed turbines begin to turn, i.e. where is not sufficient torque, this is a value between 3 and 4 m/s.
2. Solidity or the ratio of the actual blade area to its swept area. So by increasing the number of blades, the solidity will also increase.

There is a need to design a rotor with low solidity working at a high TSA and with the minimum number of blades. A three-bladed rotor is stable aerodynamically with TSA value of 5.

2.1 Horizontal Axis Wind Turbine (HAWT)

In a horizontal axis wind turbine, the rotor moves perpendicular to the wind direction shown in Figure 2.

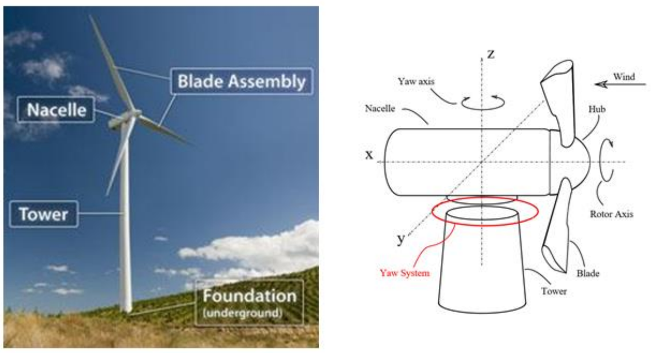

Figure 2: Horizontal axis wind turbine - general view (left image) and components (right image)

The advantages of a HAWT turbine is its high efficiency and its low cut-in speed (Mathew 2006). Its disadvantage is the high cost of building the tower and difficulties of maintaining the rotor, generator and gearbox, which are located at a height and above the tower. They also need a tail or yaw system for turning the rotor to the wind direction and engage an over-speed protection system or brake work for when the velocity is faster than wind system, which is called the run-away condition (Laín, et al. 2007).

The blade's shape is usually an airfoil section which when exposed to wind stream results, lift and drag forces. The lift (*L*) and drag (*D*) forces are given by Eq(3) and Eq(4):

$$L = \frac{1}{2} C_L \cdot \rho \cdot A \cdot V^2 \tag{3}$$

$$D = \frac{1}{2} C_D \cdot \rho \cdot A \cdot V^2 \tag{4}$$

where C_L and C_D are lift and drag coefficients for the blade’s airfoil shape.

So there is a need to identify the angle of attack α when C_D/C_L amount is minimum by plotting a tangential curve of them. To maintain this minimum value and reach the optimum angle, the blade needs to be twisted along its length. Another factor affecting lift and drag forces is Reynolds (Re) number given by Eq(5):

$$Re = \frac{V \cdot C}{\gamma} \tag{5}$$

where C is chord length (m), V is wind velocity (m/s), and γ is the kinematic viscosity for air is 15×10^{-6} m^2/s at 20°C. By increasing the angle of attack, the drag force increases and stalling of the blades will occur, or if there was a decrease in angle, the induced drag also decreases and furling happens.

2.2 Vertical Axis Wind Turbine (VAWT)-Darrieus

This type of turbine has curve bladed rotors. The rotating axes of blades are perpendicular to the wind direction, and as they rotate with lift force generated from them as shown in Figure 3, they can capture wind from all directions (Paraschivoiu 2002).

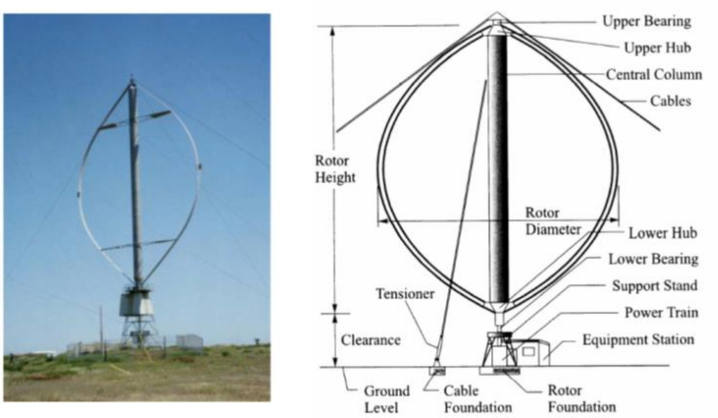

Figure 3: Vertical Axis Wind Turbine - general view (left image) and components (right image)

An advantage for the Darrieus design is that it is possible to obtain wind from all directions and the shape of the blades minimizes bending stress exposure by the blades. Its TSR is high, and the cable is twisted to the vertical shaft, and the load is on the ground level, so no brushes are needed for large twisting angles. But Darrieus has several disadvantages. Its C_P is low, and while aerodynamic theory used for the design is complicated, the vibration of blades is high. Designing TSR is limited between 4 to 7, which in the case of lower range stalling happens, and in the higher range, C_P is not acceptable. To have adequate C_P, this turbine needs to work at low wind speeds. So, the chord width and Reynolds number need to be small. If the cord width is high, higher minimum C_D/C_L results in an unacceptable C_P. In high stream wind, safety systems cannot protect it, and it needs significant guidelines at the top of the shaft to protect it from bending moments (Mathew 2006).
There is a parameter called tangential velocity in the range of 30 to 40 m/s or more used for the design of the geometry of Darrieus rotor, which is given by Eq(6).

$$V_T = \frac{\pi n R}{30} \tag{6}$$

For a constant V_T, if rotational velocity changes from n_1 to n_2, according to $n_1/n_2 = D_2/D_1$, the rotor diameter varies from D_1 to D_2. To keep the diameter to height ratio (β) constant, the height of the rotor needs to be changed (Paraschivoiu 2002).
The base of the theoretical analysis presented in sections 3 and 4 are related to Eq(1). In this equation, ρ and C_P are constant parameters in getting power generation. So, in section 3, effect of V on output power and in section 4, the impact of TSA with using rotor radius is examined. In both sections' rotor speed is 150 rpm, which is applicable for many generators, and rotor diameter is 7 m. Table 1 shows the parameters used in this paper for HAWT and VAWT turbines.

Table 1: Wind turbines parameters

Parameters	HAWT	VAWT
Airfoil Type	0012	0012
Air Density	1.225 kg/m^3	1.225 kg/m^3
Re	100,000	100,000
Number of Blades	3	3
rpm	150	150
Rotor Diameter	7 m	7 m
TSR or λ	5.1	5.1
Chord Length	0.35 m	0.35 m

3. The effect of wind velocity on output power

To find which type turbine mentioned have a better performance, energy generated in the range of 5 to 15 is calculated. Here, ρ is the density (kg/m^3) of air which is 1.225 kg/m^{3}and TSA is πR^2. As R = 3.5m, TSA is 38.45 m^2. Just C_P remained which is dependent on λ or tip speed ratio, and it changes with changing λ. λ can be calculated for any of wind speeds with:

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed} = \frac{\frac{rpm \times \pi \times D}{60}}{wind\ speed} \tag{7}$$

After calculating λ, from C_P- λ diagram, C_P can be achieved and by putting it in Eq(1), the output power results as shown in Figure 4.

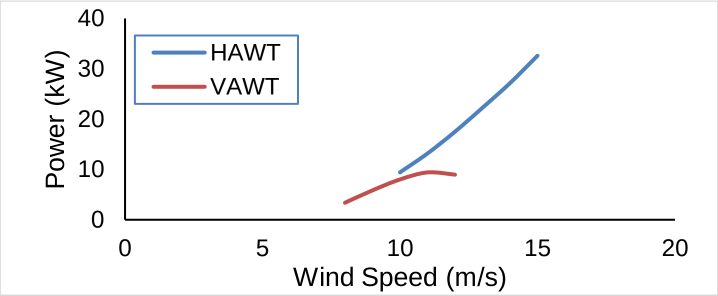

Figure 4: The effect of wind speed on the output power of wind turbines

Figure 4 shows the VAWT type, and HAWT cannot work for wind speeds less than 8 and 10 m/s. The Maximum power for VAWT generates in 11 m/s wind speed, which is 9.4 kW and for HAWT in 15 m/s with 32.58 kW.

4. The effect of rotor radius on output power

The power generated in the rotor radius range of 6 to 13 m is calculated. The reason for the chosen mentioned range is that TSR range or our model as shown in Figure 1. Here different rotor radius results in different TSA or πR^2 in Eq(1). Wind speed is assumed to be 15 m/s and rotational speed to be 150 rpm. So, like section 3, calculating λ yields C_P and after that, power can be calculated for any rotor radius as shown in Figure 5.

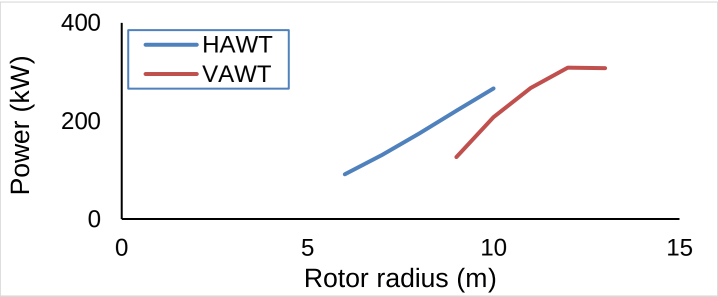

Figure 5: The effect of rotor radius on the output power of wind turbines

As can be seen, different radius generates different powers. However, in radius 8 and 9 m, when overlap happens, HAWT is superior.

5. Wind turbine simulation

The selected airfoil for simulation with QBlade of VAWT and HAWT is the NACA (National Advisory Committee for Aeronautics) 0012. A Reynolds value of 100,000 was used for a rotor diameter(D) of 7 m with rotational speed is 150 rpm which is the optimized rotational speed for normal wind speed conditions (5 - 6 m/s) according to simulations done in different rpms with QBlade. As B (number of blades) in both calculations are 3, tip speed ratio will be 5.1 according to

$$\lambda = \sqrt{\frac{80}{B}} \tag{8}$$

So, the chord length is 0.35 m with respect to below formula (Izli, et al. (2007):

$$C = \frac{4D}{\lambda^2 B} \tag{9}$$

The maximum power for VAWT is reached at wind speed 4.5 m/s which is P = 68.3 W. While it is 332 W for HWAT at wind speed 6.1 m/s, as shown in Figure 6.

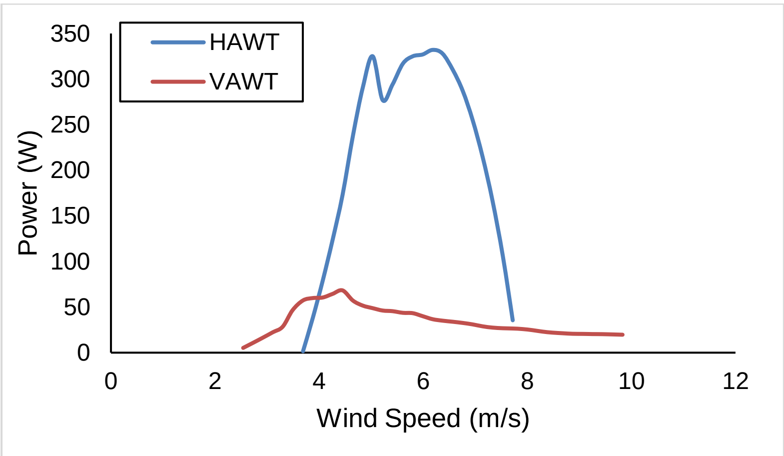

Figure 6: Power versus wind velocity

In both cases, the blade has a Cl/Cd maximum at the angle of attack 5 or the optimized angle of attack is 5, as shown in Figure 7.

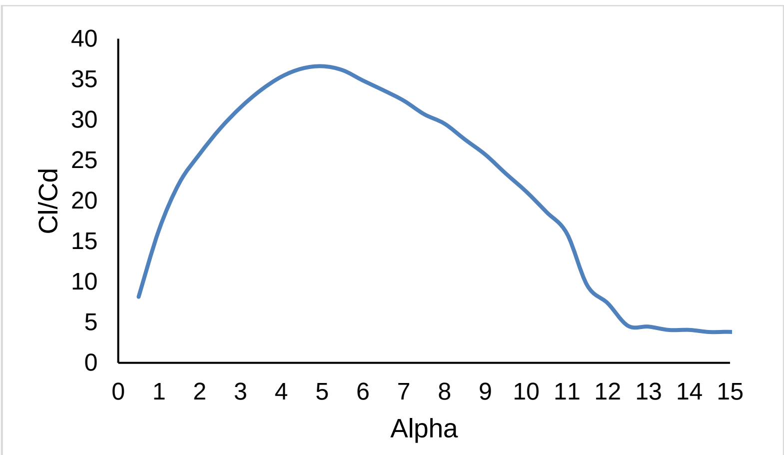

Figure 7: Cl/Cd for different angle of attacks

The maximum power coefficient for VAWT was found 0.44 and for HAWT 0.25, as shown in Figure 8.

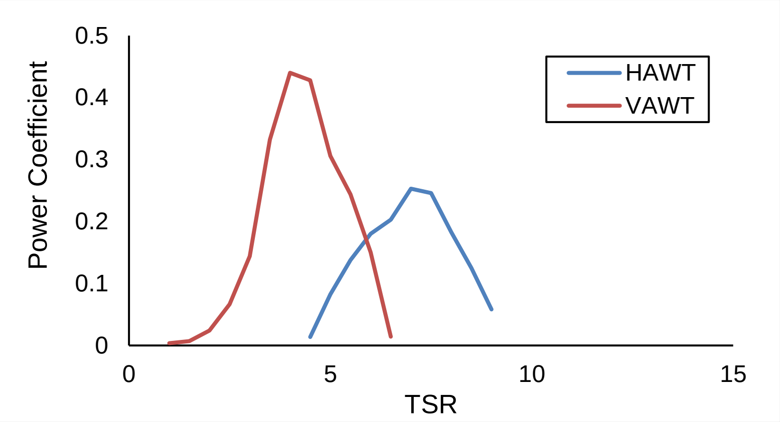

Figure 8: C_P vs TSR rotor simulation

6. Conclusions

With respect to considering all parameters involved in this research, it can be recommended that using HAWT can produce much more electricity to VAWT. To reach this conclusion, the power generation of both turbines in different wind speeds calculated and Qblade results also showed higher power for HAWT. Changing rotor radius also verify that in the same rotor radius, HAWT can get more power rather than VAWT.

The optimized angle of attack for both cases is 5, and best performance for HAWT is in wind speed of 15 m/s while it is for VAWT in 11 m/s.

The results of this study can be useful for the design and application of wind turbines for different weather conditions.

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