MATEC Web of Conferences **70**, 03002 (2016) DOI: 10.1051/matecconf/20167003002
ICMIT 2016

The Performance Evaluation of Horizontal Axis Wind Turbine Torque and Mechanical Power Generation Affected by the Number of Blade

Rodney H.G. Tan[1] and Matthew Y.W. Teow[2]

[1]*UCSI University, Faculty of Engineering, Technology and Built Environment, 56000 Kuala Lumpur, Malaysia*
[2]*KDU University College, School of Engineering, 40150 Shah Alam, Malaysia*

Abstract. This paper presents the evaluation of horizontal axis wind turbine torque and mechanical power generation and its relation to the number of blades at a given wind speed. The relationship of wind turbine rotational frequency, tip speed, minimum wind speed, mechanical power and torque related to the number of blades are derived. The purpose of this study is to determine the wind energy extraction efficiency achieved for every increment of blade number. Effective factor is introduced to interpret the effectiveness of the wind turbine extracting wind energy below and above the minimum wind speed for a given number of blades. Improve factor is introduced to indicate the improvement achieved for every increment of blades. The evaluation was performance with wind turbine from 1 to 6 blades. The evaluation results shows that the higher the number of blades the lower the minimum wind speed to achieve unity effective factor. High improve factors are achieved between 1 to 2 and 2 to 3 blades increment. It contributes to better understanding and determination for the choice of the number of blades for wind turbine design.

1 Introduction

Wind energy is one of the top choices of renewable energy resources widely harvest by many countries around the world particularly China, Germany, UK and USA. According to Global Wind Energy Council 2014 statistics report [1], wind energy in the past decade has recorded an average growth rate of 21% and global total installed capacity of 318105MW as end of year 2013. Wind turbines are used to harvest wind energy. It has the advantage over others renewable energy resources harvesting method in term of smaller footprint per MW making it possible to install on uneven land terrain and offshore. If the installed location is strategically favor to wind meteorology, wind energy allows continuous harvesting day and night throughout the years.

Wind energy is extracted using either horizontal or vertical axis wind turbine configuration. Wind turbine relies on its rotating blades to convert wind energy into mechanical energy. There are many literatures on how wind turbine performance affected by the blade efficiency and aerodynamic design [2], [3]. However, there is not many literature reported on how the number of blades affect the performance of a given wind turbine. Even it does, there is no evaluation on the mechanical power and torque generation with respect to the number of blades [4]. This paper presents the evaluation of horizontal axis wind turbine affected by the number of blades in terms of mechanical power and torque output at a given wind speed.

2 Wind turbine model

Wind turbine extracts wind energy when wind flows through the blades perpendicularly resulting in mechanical rotational motion due to aerodynamic force. The blade rotational motion that sweeps across its area converts into mechanical energy which in turn drives the generator to generate electricity. The mechanical energy in watt of a given wind turbine can be modeled using Eq. (1), where ρ is the air density of 1.225 kg/m^3, v is the wind speed in m/s, A is the wind turbine sweep area of πr^2 where r is the blade radius. 2 x 252 mm.

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{1}$$

The power coefficient C_p is the function of wind turbine tip speed ratio λ and the blade pitch angle β. The tip speed ratio λ is defined in Eq. (2) as the ratio of the turbine blade tip speed Ts in m/s to the wind speed v in m/s.

$$\lambda = \frac{Ts}{v} \tag{2}$$

The generic wind turbine power coefficient [5] can be modeled using Eq. (3) and Eq. (4), where c_1=0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21, c_6=0.0068.

$$C_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^2 + 1} \tag{4}$$

The power coefficient performance with respect with tip speed ratio for a fixed pitch wind turbine of blade pitch angle β=0 is shown in Figure 1. For this generic wind turbine model, it can be clearly see that the highest power coefficient of 0.4798 can be achieved at tip speed ratio of 8.

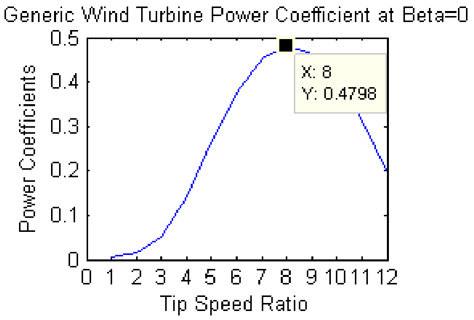

Figure 1. Power coefficient of generic wind turbine model.

The wind turbine torque in newton-meters can be determined using Eq. (5), where P_m is the wind turbine mechanical power in watts, rpm is the wind turbine angular velocity in revolution per minute.

$$P_t = \frac{P_m \cdot 60}{2\pi \cdot rpm} \tag{5}$$

3 Blade wind energy extraction

The basic principle for a wind turbine to effectively extract wind energy is to complete the sweep area with its blades in one second. With refers to Figure 2, for a single blade B1 wind turbine to effectively extract wind energy passing through its sweep area A1 is to complete one revolution in one second. Therefore, the frequency must not be less than 1Hz to effectively extract wind energy without losses. The wind turbine tip speed in m/s is defined in Eq. (6) where ω is the angular velocity of $2\pi f$ and r is the blade radius in meter. Thus, the tip speed require is proportional to the length or radius of the blade.

$$Ts = \omega \cdot r \tag{6}$$

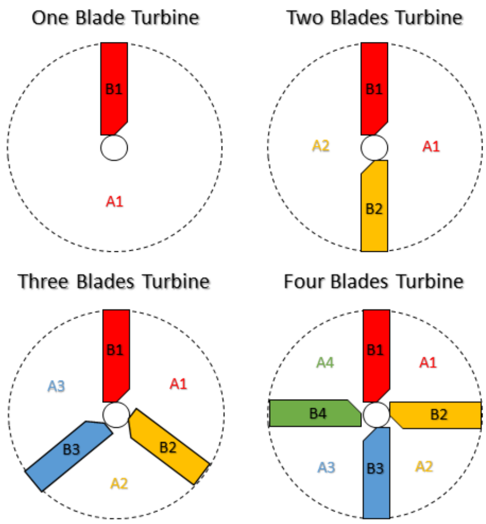

Figure 2. One, two, three and four blades wind turbine and its sweep area.

Since the frequency require to complete one revolution is 1Hz, tip speed became the circumference of the wind turbine in meter, which can be directly translated to the minimum tip speed in m/s to effectively extracts the wind energy.

For two blades wind turbine, the frequency needed to complete the sweep area is half or 0.5Hz, simply because when the first blade B1 sweep the first half area A1 of the wind turbine, at the same time the second blade B2 at its opposite direction sweep the second half area A2 of the wind turbine. Thus, the frequency needed to complete the sweep area is half. For three blades wind turbine, blade B1 sweep area A1, blade B2 sweep area A2 and blade B3 sweep area A3 at the same time, therefore it require only one third of the frequency 0.33Hz to complete the turbine sweep area. The same principle applies to any number of blade as defined in Eq. (7), where f is the frequency needed to complete the turbine sweep area and n is the number of blade.

$$f = \frac{1}{n} \tag{7}$$

In practice, the wind turbine rotational speed is expressed in revolution per minute (rpm), as it is used in relation to drive the electric generator. Eq. (8) shows the wind turbine *rpm* required to complete the sweep area in relation to the number of blade n.

$$rpm = \frac{60}{n} \tag{8}$$

In summary the wind turbine rotational frequency and rpm is the reciprocal function of the number of blades. The higher the number of blades and slower the tip speed required to complete the wind turbine sweep area. With Eq. (6) and Eq. (7) in place, we can rearrange Eq. (2) to determine the minimum wind speed Eq. (9) required for the wind turbine to complete the wind turbine sweep area and effectively extract wind energy.

$$v_{\min} = \frac{2\pi fr}{\lambda n} \tag{9}$$

If the wind speed v experienced by a wind turbine for a given n number of blades is greater than the minimum wind speed $v_{\min}$, then the wind turbine effective factor η is 1. On the other hand, if the wind speed v experienced by the wind turbine is less than $v_{\min}$, then the wind turbine effective factor can be determined in Eq. (10). The reduction of effective factor is simply due to the turbine tip speed drive by the wind speed is not fast enough to complete the sweep area.

$$\eta = \frac{v}{v_{\min}} \qquad \eta = 1 : v \geq v_{\min} \tag{10}$$

In the general wind turbine mechanical power equation the effective factor η is 1. Therefore effective factor η can be neglected in Eq. (1). However, with the wind turbine effective factor η taken into account, the wind turbine mechanical power can now be determined in Eq. (11).

$$P_m = \frac{1}{2}\rho A v^3 Cp\eta \tag{11}$$

4 Results and discussion

To demonstrate how the wind turbine mechanical power affected by the number of blades and wind speed. A commercial wind turbine EWT500kW was chosen as reference. The EWT500kW is a three blades wind turbine with blade radius of 26 meter, cut-in speed of 2.5m/s and rated wind speed of 10m/s. The tip speed ratio is assumed to be maintained at 8 from cut-in to rated wind speed based on the generic wind turbine model.

Table 1 shows the Wind turbine mechanical power generation with respect to the number of blades, wind speed and tip speed. It is arranged in such a way that the wind turbine mechanical power highlighted in bold refers to the minimum wind speed for a given number of blades. For example, the minimum wind speed for the reference three blades wind turbine is 6.8 [m/s] and produces mechanical power of 196.9 [kW] in bold. At the wind speed of 10.2 [m/s], the turbine produces 664.6 [kW] mechanical power, which is above the rated 500 [kW] electrical power rating for the turbine. This indicates that the turbine generates more than enough mechanical power to drive the rated 500 [kW] electrical power generation conversion.

At the wind speed of 6.8 [m/s] for every additional increment of blade from 3, 4, 5 and 6 blades to the same turbine, the mechanical power produce is the same, this is because the minimum wind speed for 4, 5 and 6 blades are lower than 6.8 [m/s], therefore the effective factor is 1. On the other hand, at wind speed 6.8 [m/s], if the blades is reduce from 3, 2 and 1 blade, the effective factor less than 1 is taken into effect and the turbine mechanical power reduces from 196.9 [kW] to 131 [kW] and 65.6 [kW] respectively. Figure 3 illustrate Table 1 in graphical plot. The similar characteristics apply to wind turbine torque generation with respect to the number of blades, wind speed and revolution per minute as shown in Table 2.

Table 1. Wind turbine mechanical power generated with respect to wind speed, tip speed and number of blades.

Wind Speed [m/s]	Turbine Blade Tip Speed [m/s]	Number of Blades					
		1	2	3	4	5	6
		Wind Turbine Mechanical Power [kW]					
20.4	163.4	**5295.4**	5295.4	5295.4	5295.4	5295.4	5295.4
10.2	81.7	331	**661.9**	661.9	661.9	661.9	661.9
6.8	54.5	65.4	130.8	**196.1**	196.1	196.1	196.1
5.1	40.8	20.7	41.4	62.1	**82.7**	82.7	82.7
4.1	32.7	8.6	17.3	25.9	34.6	**43**	43
3.4	27.2	4.1	8.2	12.3	16.3	20.4	**24.5**

Table 2. Wind turbine torque generated with respect to wind speed, rpm and number of blades

Wind Speed [m/s]	Turbine Rotational Speed [rpm]	Number of Blades					
		1	2	3	4	5	6
		Wind Turbine Torque [kNm]					
20.4	60	**843.6**	843.6	843.6	843.6	843.6	843.6
10.2	30	105.5	**210.9**	210.9	210.9	210.9	210.9
6.8	20	31.2	62.5	**93.7**	93.7	93.7	93.7
5.1	15	13.2	26.4	39.5	**52.7**	52.7	52.7
4.1	12	6.8	13.7	20.5	27.4	**34.1**	34.1
3.4	10	3.9	7.8	11.7	15.6	19.5	**23.4**

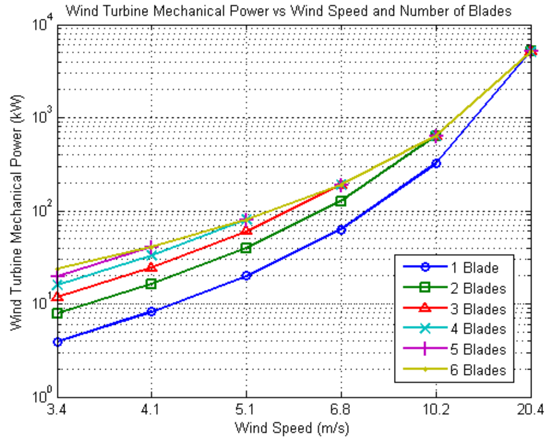

Figure 3. Wind turbine mechanical power vs wind speed and blades.

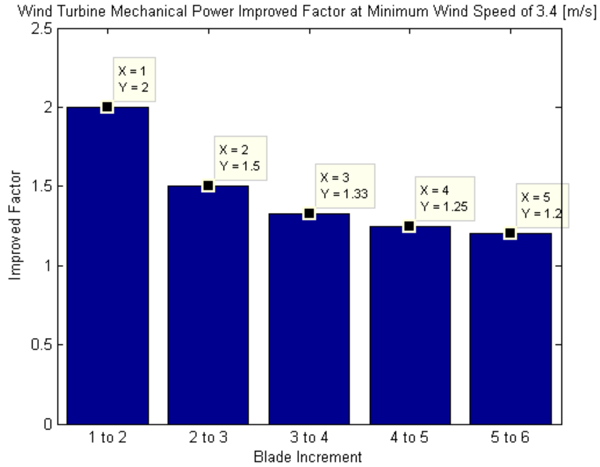

Figure 4. Improve factor for each blade increment.

The improve factor for every incremental number of blades shows in Figure 4 is fundamentally governed by Eq. (12), where n_{ref} is the reference number of blades.

$$\frac{n_{ref}+1}{n_{ref}} \tag{12}$$

In summary, the higher the number of blades, the lower the minimum wind speed and tip speed require to achieve unity effective factor. The improve factor decreases as the number of blades increases. It is observed in Figure 4 that the improve factor from 3 to 4 blades onward is significantly lower as compared to 1 to 2 and 2 to 3 blades increment. This is the main reason why modern large scale wind turbines are designed with only three blades. Secondly, three blades design is more optimum design in term of cost per blade and electric power generation aspect. This leads to modern large scale horizontal axis wind turbine to have three blades standard design. However, for micro scale turbine operates at low wind speed maybe more feasible in term of cost per blade to have more than three blades design to achieve unity effective factor at lower minimum wind speed.

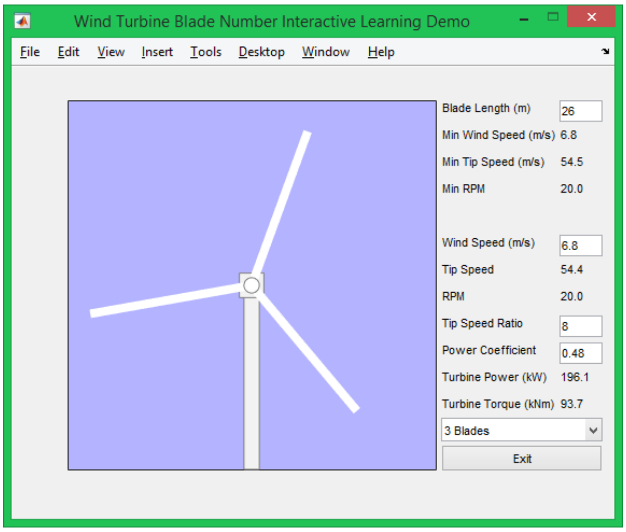

Figure 5. Wind turbine blade number interactive learning demo.

A Wind Turbine Blade Number Interactive Learning Demo was developed in MATLAB as shown in Figure 5. It provides interactive demonstration on how the blade number affect the turbine torque and mechanical power which allows the reader to reproduce the results shown in Table 1 and 2. This interactive demo is made available for reader to download at Mathworks official MATLAB Central File Exchange link below http://www.mathworks.com/matlabcentral/fileexchange/55536-wind-turbine-blade-number-interactive-learning-demo

5 Conclusion

The relationship of the wind turbine mechanical power, torque, wind speed and the number of blades are presented. The evaluation results shows that the higher the number of blades the more effective the wind turbine extracts wind energy at low wind speed. However, high improve factor can only achieve at 1 to 2 and 2 to 3 blades increment. This paper contributes to better understanding and determination for the choice of the number of blades for wind turbine design.

References

1. Global Wind Statistic 2013, Global Wind Energy Council, (2014)
2. A. Sarkar, D. Kumar Behera, International Journal of Scientific and Research Publications, **2**, (2012)
3. P. J. Schubel, R. J. Crossley, Energies, **5**, 3425, (2012)
4. M. Predescu, A. Bejinariu, O.Mitroi, A. Nedelcu, International Conference on Renewable Energies and Power Quality, (2009)
5. A. W. Manyonsge, R. M. Ochieng, F. N. Onyango, Applied Mathematical Sciences, **6**, 4527-4536 (2012)