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Investigation on the impact of design wind speed and control strategy on the performance of fixed-pitch variable-speed wind turbines

X. Liu[1], L. Wang[2] and X. Tang[1]

[1] School of Computing, Engineering and Physical Sciences, University of Central Lancashire
Preston, PR1 2HE (UK)
Phone/Fax number: +0044 895177, 892915, e-mail: xliu9@uclan.ac.uk, xtang4@uclan.ac.uk

[2] School of Mechanical Engineering, Xiangtan University, Xiangtan
Xiangtan, Hunan Province, 410005 (PR China)
Phone/Fax number: +0086 15200335173, e-mail: sanshenwl@126.com

Abstract. Wind turbine blade design optimization remains one of the fundamental research areas for modern wind turbine technology. The general design process for fixed-pitch variable-speed wind turbine blades assumes the rated wind speed as the design wind speed. However, for a fixed-pitch wind turbine with fixed rotor diameter and rated power at rated speed, we do not know the optimum design wind speed, which should be used for the calculation of the wind turbine blade parameters based on a particular aerofoil for a specific site with low annual mean wind speed.

This paper investigates the impact of design wind speed and control strategy on the performance of fixed-pitch wind turbines through a set of design case studies. The design wind speeds are considered at the more prevalent wind speeds than the rated wind speed. Three different control strategies are addressed, i.e. maximum power point tracking, mixture of variable-speed and fixed-speed, and over-speeding. Annual energy production, blade manufacturing cost, aerodynamic load performance and cost of energy are analyzed and compared using the design case studies. The results reveal a clear picture in determining the optimum design wind speed and control strategy for both maximizing annual energy production and minimizing cost of energy.

Key words

Design wind speed, blade design optimization, fixed-pitch, variable speed, wind turbine control.

1. Introduction

Wind energy is one of the most popular sources of renewable energy in today’s society and is under rapid development. However, from every point of view, wind energy is not a mature industry sector, such as the automotive and aerospace industries. The most important aspects people care about are the wind turbine performance and the associated cost of energy (CoE).

Wind power is proportional to the cube of the wind speed that comes through the wind turbine rotor - higher wind speed means more power. For a fixed-pitch wind turbine, the power performance is determined dominantly by the wind turbine blade design, as expensive blade pitch control is omitted. In other words, the wind power conversion efficiency depends greatly on the blade geometry and parameters. Generally, the calculation of a fixed-pitch variable-speed wind turbine blade parameters is based on the rated wind speed at which the power output of the wind turbine generator reaches its rated power or nominated power output[1,2].

To maximize energy capture of fixed-pitch wind turbines, variable-speed operation is a good choice. Variable speed control generates 20 to 30% more energy than constant speed control. It also minimizes power oscillation and improves reactive power injection[3].

For a specifically rated power wind turbine, higher rated wind speed means smaller rotor diameter. However, for a fixed-pitch wind turbine with fixed rotor diameter and rated power, we basically do not know, what is the optimum design wind speed, which should be used for the calculation of the wind turbine blade parameters. And more, if a lower design wind speed is selected, what control strategy should be used to improve the turbine’s performance. This paper will address these issues.

As a rule, rated wind speed is generally higher than the prevailing wind speed. With different optimum design methodologies available in the research domain, the authors argued that a lower design wind speed could perhaps generate more power for a fixed-pitch wind turbine with fixed rotor diameter and rated power, due to better power performance at prevailing wind speed.

Design wind speed based on a more prevalent wind speed than rated wind speed could make it possible for the wind turbine to operate at constant speed (rated speed) between design wind speed and the rated wind speed.

Alternatively, if the generator could accommodate over-speeding, say 10% above its rated speed, the wind turbine could even operate over-speeding with maximum power point tracking above design wind speed until the generator power output reaches its rated power output or its speed reaches its up-limited value. With this control strategy, the wind turbine will operate with the optimum tip speed ratio until the generator power output reaches its rated power or its speed reaches the allowed over-speeding limit, whichever applies first. Thereafter the turbine operates with either constant power control or constant speed control strategy until the generator power output reaches its rated power.

In this paper, based on the framework of a 10kW fixed-pitch wind turbine, we put together different design cases of the wind turbine blade using different design wind speeds based on the same airfoil, and then analyze their performance in terms of annual energy production (AEP), manufacturing cost and aerodynamic loads. The major criterion for the optimization is the highest AEP based on a particular wind speed Weibull distribution. For a comprehensive understanding of the methodology, we briefly give the AEP calculation in the next section.

2. Annual Energy Production Calculation[4]

A. Wind turbine generator power

The power output of a wind turbine generator can be expressed as

$$P = \frac{1}{2}\eta C_{\mathrm{PR}} \rho A v^3 \tag{1}$$

where η is the transmission efficiency of the wind turbine, including both mechanical and electrical efficiency, C_{PR} is the rotor power coefficient of the wind turbine, $C_P = \eta C_{\mathrm{PR}}$ is the power coefficient of the wind turbine, ρ is the air density, $A = \pi R^2$ is the rotor swept area, and v is the wind velocity.

B. Wind speed Weibull distribution

The wind power density is given by

$$p_w = \frac{1}{2}\rho v^3 \tag{2}$$

The annual mean wind power density can be expressed as

$$\bar{p}_w = \frac{1}{2}\rho \times \frac{1}{8760} \times \int_{year} v^3 \mathrm{dt} \tag{3}$$

Considering the natural wind speed frequency distribution throughout the year, i.e. Weibull distribution:

$$f_{\mathrm{Weibull}}(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} \exp\left(-\left(\frac{v}{a}\right)^{k}\right) \tag{4}$$

where k is the shape parameter and a is the scale parameter, which depend on the wind resource of the site. The characteristics of wind resources differ from site to site.

Then we have the annual mean wind power density

$$\bar{P}_w = \frac{1}{2}\rho v^3 f_{\mathrm{Weibull}}(v) \tag{5}$$

If the shape parameter is unknown, the calculation of the AEP for a wind turbine should be based on Rayleigh distribution, which assumes a shape parameter of $k = 2$ in Weibull distribution.

$$f_{\mathrm{Rayleigh}}(v) = \frac{\pi}{2}\frac{v}{\bar{v}^2} \exp\left(-\frac{\pi}{4}\frac{v^2}{\bar{v}^2}\right) \tag{6}$$

here, $\bar{v}$ is the annual mean wind speed (AMWS):

$$\bar{v} = \frac{1}{8760}\int_0^\infty f_{\mathrm{Weibull}}(v) dv \tag{7}$$

C. Annual energy production

The AEP for a wind turbine for a specific site can be expressed as

$$E = 8760 \times \frac{1}{2}\rho A \int_{\text{cut in}}^{\text{cut out}} v^3 \eta(v) C_{\mathrm{PR}}(v) \times f_{\mathrm{Rayleigh}}(v) dv \tag{8}$$

where $C_{\mathrm{PR}}(v)$ is the rotor power coefficient of the turbine, which is a complex function of the wind speed (or tip speed ratio) and greatly affected by the control strategy. Generally there is no simple way to express it exactly in a mathematical expression for different rotors.

For the framework of our wind turbine design, in the first instance, we assume a constant power coefficient between cut-in wind speed and design wind speed, a constant rotor speed between design wind speed and the rated wind speed until rated power output is achieved, and a constant rated power output thereafter until cut-out wind speed. Therefore we can rewrite equation (8) as

$$\begin{aligned} E = 8760 \times (&\frac{1}{2}\rho A C_{PR} \int_{\text{cut}-\text{in}}^{\text{design}} v^3 \eta(v) f_{\mathrm{Rayleigh}}(v) dv \\ &+ \frac{1}{2}\eta\rho A \int_{\text{design}}^{\text{rated}} v^3 C_{\mathrm{PR}}(v) f_{\mathrm{Rayleigh}}(v) dv \\ &+ P_{\text{rated}} \int_{\text{rated}}^{\text{cut}-\text{out}} f_{\mathrm{Rayleigh}}(v) dv) \end{aligned} \tag{9}$$

Please note in the equation:

1) We define the rated wind speed as the wind speed at which generator output reaches rated power output.

2) We assume a linear relationship between the transmission efficiency of the wind turbine and the rotor speed, which is the case for the synchronous permanent management generator[5].

3) We assume a 100% availability of the wind turbine. For comparison purpose, this is acceptable.

In the second instance, we assume a constant power coefficient between the cut-in wind speed and the transition wind speed, at which the generator reaches its rated power or the rotor speed reaches the allowed over-speeding limit, such as 110% of the rated speed, whichever applies first. Thereafter we assume a constant rotor speed between the transition wind speed and the rated wind speed (in the case of reaching over-speeding limit first) until rated power output is achieved, then followed by a constant rated power output until the cut-out wind speed. In this case we can rewrite equation (8) as

$$E = 8760 \times (\frac{1}{2}\rho A C_{\text{PR}} \int_{\text{cut-in}}^{\text{transition}} v^3 \eta(v) f_{\text{Rayleigh}}(v)dv$$
$$+ \frac{1}{2}\eta\rho A \int_{\text{transition}}^{\text{rated}} v^3 C_{\text{PR}}(v) f_{\text{Rayleigh}}(v)dv$$
$$+ P_{\text{rated}} \int_{\text{rated}}^{\text{cut-out}} f_{\text{Rayleigh}}(v)dv) \qquad (10)$$

Please note: If the transition wind speed is equal to the rated wind speed, the second part of the formula should be omitted. The other assumptions remain the same as equation (9).

3. Design case studies and analysis

A. *Base-line wind turbine*

The design case studies used here are based on a fixed-pitch 10kW wind turbine with a direct-driven permanent magnet synchronous generator. The basic parameters of the wind turbine, which are initially determined with a rated design wind speed 9m/s, are listed in Table 1:

Table 1: Basic parameters of the 10kW wind turbine

Expected rated power output at the inverter output point	kW	10
Transmission efficiency η		0.82
Transmission cable and power electronics efficiency		0.94
Rated rotor speed	rpm	150
Rotor diameter	m	9.0
Number of blades		3
Blade tip speed at rated rotor speed	m/s	70.7
Cut-in wind speed	m/s	3
Cut-out wind speed	m/s	20.5

Please note:

1) Transmission efficiency includes mechanical and electrical efficiency of the wind turbine generator, but does not include the loss of the transmission cable and power electronics.

2) We assume a linear relationship between the transmission efficiency and the rotor speed, which is the case for the permanent management synchronous generator[3]. At the rated rotor speed 150rpm, $\eta = 0.82$; at 50rpm, $\eta = 0.7$.

3) We define the rated wind speed is the wind speed at which generator output reaches rated power output.

4) The aerofoil used for the wind turbine blade design is DU93W210 with a lift coefficient $C_l = 1.336$ at the attack angle $\alpha_0 = 7.71°$, where $C_l / C_d = 118$ achieves its maximum value[6].

B. *Design case studies*

We consider the design wind speeds 9m/s, 8.5m/s and 8m/s, i.e. the rated rotor speed reaches 150rpm at these three wind speeds respectively. Using the design theory summarized in Reference [1] and GH-Bladed, we have their calculated wind turbine fundamental parameters listed in Table 2, and their wind turbine blade chord and twist angle distributions depicted in Figures 1 and 2, and their $C_{\text{PR}} - \lambda$ curves illustrated in Figure 3.

Table 2: Calculated parameters of the three designs of the 10kW wind turbine

Design wind speed	8m/s	8.5m/s	9m/s
Design tip speed ratio	8.836	8.316	7.854
Rotor power coefficient	0.47386	0.47397	0.4738
Rotor power output (W)	9454	11342	13459
Generator power output (W)	7752	9300	11036
Inverter power output	7287	8742	10374

Table 2 shows that we can define the power output at design wind speed 9m/s as the rated power output of the wind turbine, and 9m/s as the initial rated wind speed.

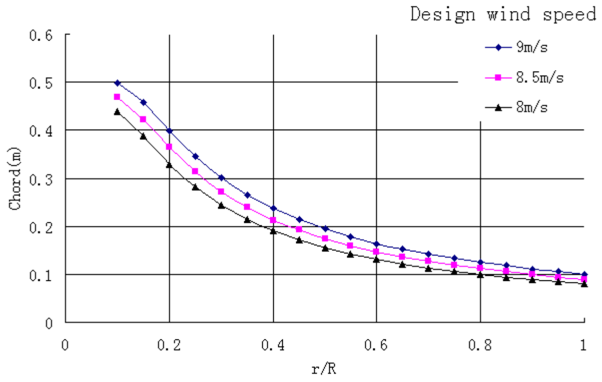

Fig. 1. Blade chord distributions of the three designs

Figure 1 demonstrates that the average blade chord with 8.5m/s design wind speed is 9.2% smaller than the one with 9m/s design wind speed, and the value with 8m/s design wind speed is 18.2% smaller than the one with 9m/s design wind speed.

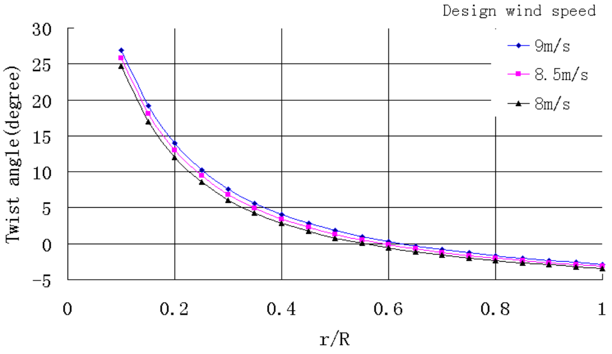

Fig. 2. Blade twist angle distributions of the three designs

Figure 2 reveals that the blade twist angle with 8.5m/s design wind speed is 2.7% smaller than the one with 9m/s design wind speed, and the value with 8m/s design wind speed is 5.6% smaller than the one with 9m/s design wind speed.

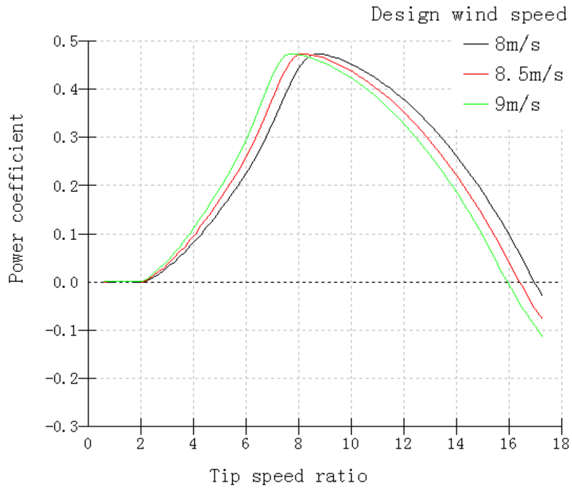

Fig. 3. $C_{PR} - \lambda$ curve of the three designs (GH-Bladed)

Figure 3 (along with Table 2) indicates that the three designs have almost the same maximum rotor power coefficient C_{PR} , and lower design wind speed results in higher optimum tip speed ratio.

C. *Constant speed control above design wind speed until rated power output achieved*

For the cases of design wind speed 8.5m/s and 8m/s, we assume a constant speed control (CSC) above the design wind speed, i.e. the rotor speed keeps constant at rated speed 150rpm, until rated power output is achieved. Thereafter, we assume a constant power output control. We calculate and depict the rotor power curve (rotor power vs wind speed), the rotor torque curve (rotor torque vs wind speed) , and the rotor thrust curve (rotor thrust force vs wind speed) of the three designs, as illustrated in Figures 4 to 6. Then we calculate and list the annual energy production (AEP) of the three designs in Table 3 based on annual mean wind speed (AMWS) 3.5m/s, 4m/s, 4.5m/s, 5m/s, 5.5m/s and 6m/s respectively.

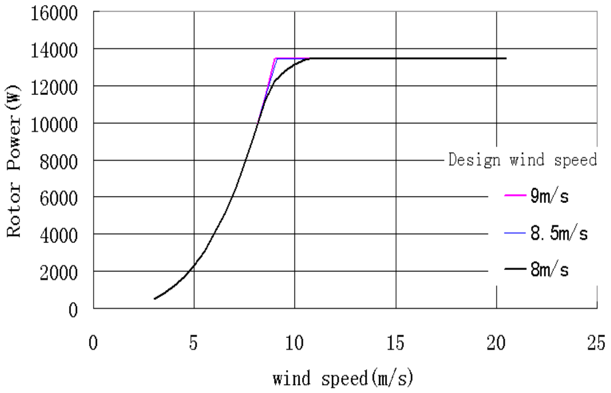

Fig. 4. Rotor power output of the three designs based on CSC

Figure 4 shows that the rotor power output with 8m/s design wind speed has a significant drop between wind speed from 8m/s to 10.7m/s due to lower tip speed ratio with constant speed control.

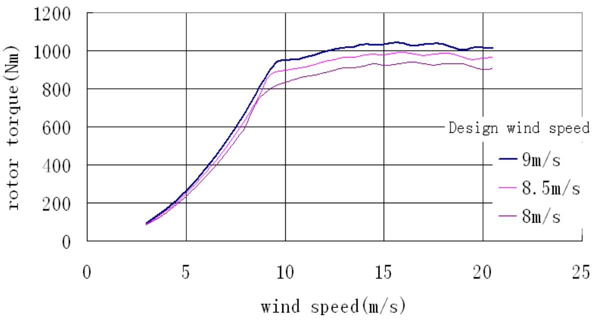

Fig. 5. Rotor torque of the three designs based on CSC

Figure 5 reveals that the rotor torque of 8.5m/s design wind speed is 5% (average between cut-in and cut-out wind speed) lower than 9m/s design wind speed; for 8m/s design wind speed, it is 10.4% lower than 9m/s design wind speed.

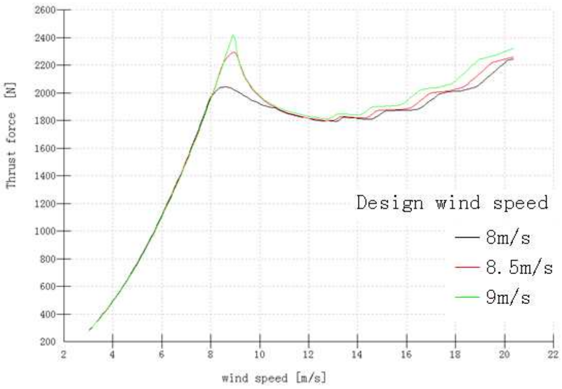

Fig. 6. Rotor thrust force of the three designs based on CSC (GH-Bladed)

Figure 6 demonstrates that the rotor thrust force of 8.5m/s design wind speed is 1.96% (average between 8m/s and cut-out wind speed) lower than 9m/s design wind speed; for 8m/s design wind speed, it is 4.1% lower than 9m/s design wind speed.

Table 3: AEP of the three designs based on CSC

AMWS (m/s)	8m/s AEP (kWh)	Increase rate over 9m/s	8.5m/s AEP (kWh)	Increase rate over 9m/s	9m/s AEP (kWh)
3.5	8895	0.67%	8907	0.81%	8836
4.0	13232	-0.18%	13352	0.73%	13255
4.5	18105	-0.92%	18389	0.64%	18273
5.0	23232	-1.44%	23699	0.54%	23571
5.5	28365	-1.76%	29005	0.46%	28872
6.0	33324	-1.91%	34107	0.39%	33974

As indicated in Figure 4, between wind speed 8m/s~10.7m/s, the rotor power output of design wind speed 8m/s is lower than that of 8.5m/s or 9m/s design wind speed (please refer to Figure 4). This outcome results in a lower AEP of 8m/s design wind speed than other two designs with higher design wind speed, as listed in Table 3 for the whole range of AMWS from 3.5m/s to 6.0m/s.

The lower static driving torque and thrust forces of the design cases with 8.5m/s and 8m/s design wind speeds are very desirable for the wind turbine. We also expect much lower static driving torque and thrust forces for these two designs at higher wind speed than cut-out wind speed when the turbine is braked.

As to determine which design is the best, obviously the one with 8.5m/s design wind speed exhibits better performance in all the aspects for all the AMWS than the 9m/s design wind speed. As for the design with 8m/s design wind speed, we need to understand the criteria for the design optimization. If the AEP is the sole parameter for design optimization, on a site with 3.5m/s AMWS, 8.0m/s design wind speed is the best solution. On a site with higher than 3.5m/s AMWS, 8.5m/s design wind speed is the best solution. However the design with 8.0m/s design wind speed exhibits better aerodynamic performance and lower manufacturing cost than the one with 8.5m/s design wind speed.

C. *Maximum power point tracking above design wind speed until rated power output achieved or over-speeding limit achieved*

The above design cases are based on constant speed control above design wind speed until rated power output is achieved. If the wind turbine generator can operate at a higher speed than the rated speed with a lower load than rated power, then it is possible to adopt the maximum power tracking (MPT) control strategy above lower than 9m/s design wind speed, if a proper generator controller is integrated into the wind turbine system.

For the cases of 8.5m/s and 8m/s design wind speed, let’s assume a constant power coefficient (or maximum power tracking with the design tip speed ratio $\lambda_0 = 8.316$ for design wind speed 8.5m/s and $\lambda_0 = 8.836$ for design wind speed 8m/s) between the cut-in wind speed and the transition wind speed, at which the generator reaches its rated power output or the rotor speed reaches the allowed over-speeding limit, say 165rpm or 110% of the rated speed, whichever applies first. Thereafter we assume a constant rotor speed above the transition wind speed, for the case of transition wind speed equals to 165rpm, until rated power output is achieved, then followed by a constant rated power output until cut-out wind speed. Along with 9m/s design wind speed, we calculate and depict the rotor power curve, the rotor torque curve, the rotor thrust curve of the three designs, as illustrated in Figures 7 to 9.

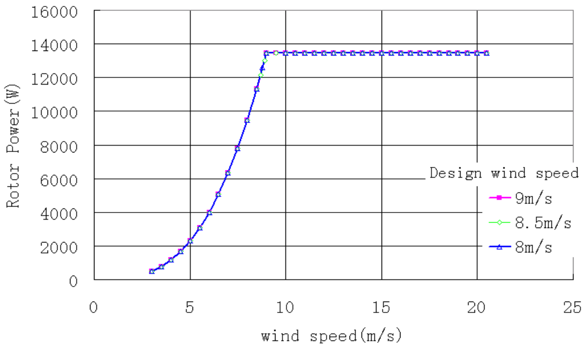

Fig. 7. Rotor power of the three designs based on MPT and over-speeding

Figure 7 reveals that all the three designs have very close rotor power output performance.

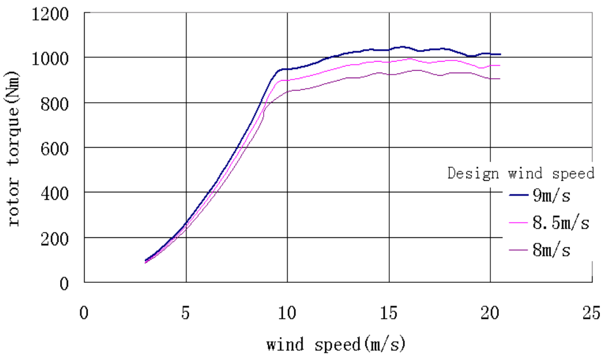

Fig. 8. Rotor torque of the three designs based on MPT and over-speeding

Figure 8 shows that the rotor torque of 8.5m/s design wind speed is 5.1% (average between cut-in and cut-out wind speed) lower than 9m/s design wind speed; for 8m/s design wind speed, it is 10.5% lower than 9m/s design wind speed. The performance is very similar to the one in Figure 5.

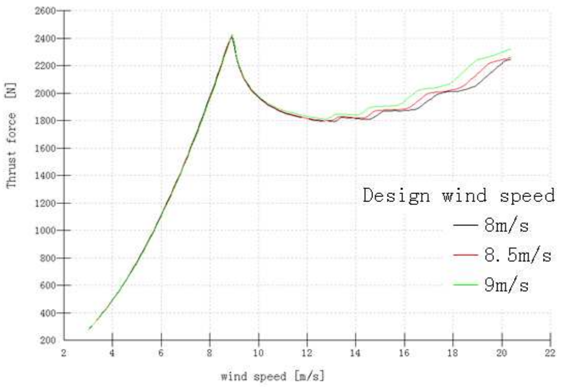

Fig. 9. Rotor thrust force of the three designs based on MPT and over-speeding (GH-Bladed)

Figure 9 shows that at higher than 10m/s wind speed, the rotor thrust force of lower design wind speed (than 9m/s) exhibits lower values than 9m/s design wind speed. For 8.5m/s design wind speed, average 2.03% lower than 9m/s design wind speed; for 8m/s design wind speed, it is 3.09% lower than 9m/s design wind speed.

Then we calculate and list their annual energy production (AEP) in Table 4 based on annual mean wind speed (AMWS) 3.5m/s, 4m/s, 4.5m/s, 5m/s, 5.5m/s and 6m/s respectively.

Table 4: AEP of the three designs based on MPT and over-speeding

AMWS (m/s)	8m/s AEP (kWh)	Increase rate over 9m/s	8.5m/s AEP (kWh)	Increase rate over 9m/s	9m/s AEP (kWh)
3.5	8990	1.74%	8913	0.87%	8836
4.0	13469	1.61%	13365	0.83%	13255
4.5	18539	1.45%	18412	0.76%	18273
5.0	23874	1.28%	23732	0.68%	23571
5.5	29197	1.13%	29047	0.61%	28872
6.0	34309	0.99%	34157	0.54%	33974

Table 4 indicates that the design cases with lower design wind speed produce more energy than the design case with rated wind speed, and 8m/s design wind speed exhibits highest AEP for the whole range of AMWS.

Design wind speed 8m/s demonstrates the lowest static driving torque and thrust force, which is very desirable, as shown in Figures 8 and 9. However, if the wind turbine is going to be sited very close to residential properties, there is a need to analyze the noise of the design cases. Generally speaking, the noise has a very close relationship with the blade tip speed, higher blade tip speed, higher noise level[7]. However, smaller chord generally exhibits lower noise.

The two design cases with 8.5m/s and 8m/s design wind speed have a higher blade tip speed but smaller chord than that of 9m/s design wind speed. In the design case of 8m/s design wind speed with maximum power tracking control strategy, the blade tip speed top limit is 77.75m/s, which is 110% of its rated value of the wind turbine, as stated in Table 1. Generally, we expect a higher noise than that of 9m/s design wind speed. However, the design case of 8m/s design wind speed has a blade chord, which is 18.2% smaller than that one of 9m/s design wind speed. Therefore, at this stage, we do not know which case exhibits the highest noise, and further analysis is to be undertaken.

4. Conclusions and Recommendations

This study demonstrates a comprehensive methodology for determining the optimized design wind speed and control strategy for a fixed-pitch wind turbine design, with the following conclusions and recommendations.

1) For direct-driven low speed permanent magnet synchronous generator, we can expect to have a slightly higher annual energy production with a slightly lower design wind speed than the rated wind speed (in a general sense), with either constant speed control or maximum power tracking control strategies when the wind speed is above the design wind speed. This is mainly due to higher generator transmission efficiency at rated speed than at low speed, and also slightly higher rotor power coefficient when the design wind speed is slightly lower than the rated wind speed.

2) With fixed rated power and rotor diameter, the wind turbine has a lighter rotor with lower design wind speed than rated wind speed due to smaller blade chord, which generally results in lower blade manufacturing cost, particularly with smaller twist angle.

3) With fixed rated power and rotor diameter, the wind turbine experiences lower driving torque and lower thrust force with slightly lower design wind speed than rated wind speed, even with constant speed control strategy when the wind speed is higher than the design wind speed. This performance improvement is very desirable. We can expect the wind turbine to experience the same performance improvement at higher wind speed than cut-out wind speed when the turbine is braked, due to smaller blade chord.

4) For a wind turbine with fixed rated power and rotor diameter, if the generator can operate at higher speed than rated speed but with a lower than rated power output, then we can use a further lowered design wind speed along with the maximum power tracking control strategy above the design wind speed. Doing so can further improve the power performance and reduce the blade chord, and at the same time lower the driving torque and thrust force experienced by the rotor. However in this case, we should consider carefully the maximum blade tip speed and assess the acceptable noise level of the wind turbine.

5) The methodology presented in this paper could be used as a guide for refurbishment of established fixed-pitch wind turbines, so as to improve the power performance and reduce the blade chord, and at the same time lower the driving torque and thrust force experienced by the rotor. Ultimately this will increase the life span and reduce the cost of energy of the wind energy system.

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