Vietnam Journal of Science and Technology ***57*** *(3) (2019) 356-365*

doi:10.15625/2525-2518/57/3/12721

A STUDY ON POWER OUTPUT OF HORIZONTAL-AXIS WIND TURBINES UNDER RAIN

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Received: 4 July 2018, Accepted for publication: 20 March 2019

ABSTRACT

The generated power of the wind turbine is significantly affected by the air conditions of the operating environment. Rain is a widespread phenomenon in many parts of the world especially in Vietnam, so studying the generated power of wind towers during rain will make a contribution to designing new wind turbines. In this paper, an analytical method and a model are developed to estimate the effect of precipitation by simulating the actual physical processes of the rain drops forming on the surface of the blades of horizontal-axis wind turbines (HAWT), thereby determining optimal wetness, then power and performance respectively. Consequently, it gives a contribution to operation and control strategies for horizontal-axis wind turbines.

Keywords: power reduction; effect of rain; horizontal-axis wind turbine.

Classification numbers: 2.8.3, 3.4.1

1. INTRODUCTION

The demand for renewable energy has strongly increased with the rapid development of wind power generation. In order for wind power production can be met the more ambitious targets around the world, it is necessary to understand all the factors that might affect wind power production. Once a significant portion of the power is derived from intermittent sources it becomes increasingly important to be able to predict how production will vary with the weather so that back-up power can be ramped up in time.

The effect of rain on wind turbine performance is the one of areas that have not undergone by any significant research. There have been several reports in recent literature mainly on impacts of rain on structure and shape of turbine blades [1, 2] and wind towers [3, 4]. However, the optimal problems related to parameters of rain such as droplet size, velocity, and output power and performance of wind turbines are so far not deal with.

There have been several contradictory reports [5] reported a 27 % decrease in power output in rain, but there have been few follows on studies to investigate this and only one for vertical-axis wind turbines (VAWT) has done by our group [6]. Other work [7] noted similar results to [5] while another study [8] showed that power output could increase 3 % for a different type of rain. This is a confusing state of affairs and more work needs to be carried out in this area if wind turbines are installed offshore or in wetter climates.

Results from airfoil researches and the aircraft industry show that an increase of drag and a decrease of lift is dependent on the rain type and rainfall rate. This loss can lead to a significantly reduction of generated power due to different rain-drops. .

During heavy rain, the blades of wind turbine suffered larger when they were feathering. Another unfavorable wind regime occurs when the rain direction has sudden changes during its approach because of strong turbulent movement or local topographic effects. In short, because of the complex factors related to sudden changes in rain direction and wind velocity as well as wind turbine control in typhoon conditions, the loads on wind turbines are significantly larger than conventional design loads. Furthermore, when a typhoon lands, it always brings a heavy rain. The rain gives a horizontal velocity component along with the wind, striking the wind turbines blades' surface along with the wind load, affecting the power output as well as performance, aggravating the vibration of the wind turbines.

Light to moderate rains may not impact on structures of the turbine, but they also affect the power output and performance. Therefore, the effects of power outputs of operating in the rainy weather should be paid more attention. After studying and understanding the effects of extreme conditions on wind turbines, the design and analysis of the reduction of wind turbine power needs to be further developed.

Continuing our previous investigation [6], this paper focuses mainly on analysis impacts of rain on blades of horizontal-axis wind towers, afterwards evaluation the problem with condition of heavy rain. Wind turbine is modeled and simulated based on the characteristics of rainfall and the swept of turbine blades. As a result, the characteristic curves of the output in rainy weather are clarified, and thus support for design process of horizontal-axis wind turbines.

The paper includes four sections. Section 2 introduces a physical model that describes the impact force of rain, wetness on the turbine blades, power loss of turbine, and then the impacts of rain on power output. Using this model in Section 2, a simulation is realized in Section 3. Finally, Section 4 presents discussion and conclusions.

2. PHYSICAL MODEL

2.1. The impact force of rainfall

Similar to our previous paper [6], the impact force of a raindrop can be expressed as follows [9, 10]:

$$F_d = \frac{2}{9} N\rho\pi d^3 v^2 W. \qquad (1)$$

where ρ is the density, d is the diameter, v is the velocity of a raindrop; the width of the structure against the rain considered as the wetness W that will be found in the next section; and N is the number of raindrops with diameters between [d_1, d_2] in a unit volume of air calculated as follows:

$$N = \int_{d_1}^{d_2} n(d)\mathrm{d}d = \int_{d_1}^{d_2} n_0 e^{-\Lambda d}\mathrm{d}d$$

with d_1 = 0.01 cm and d_2 = 0.6 cm [11]. $n(d)$ the raindrop distributions for various rainfall intensities (known as Marshall-Palmer spectrum [12, 13]); n_0 = 0,08 cm^{-4} for any rainfall intensity; the slope factor $\Lambda = 4.1\, I^{-0.21}$ cm^{-1}; I the rainfall intensity is classified in Table 1.

Table 1. Intensities of rain.

Intensities	Light rain	Moderate rain	Heavy rain	Rainstorm	Heavy rainstorm (weak)	Heavy rainstorm (moderate)	Heavy rainstorm (strong)
Rain intensity (mm/h)	2,5	8	16	32	64	100	200

It is noticed that rain along with wind is not always occurring at the same time. Similarly, the intensities of the rain and wind load are also random. Occasionally the intensities of the wind load is not significant, but the strength of the rain is very large, and vice versa.. In this study, the main design load of the wind turbine is the wind load and adjunct load is the rain. Therefore, both rain and wind are together taken into account, in which wind produces power while rain affects power output. By using a simulation method, the nature of the problem can be deal with as well as the calculation is easier. .

2.2. Wetness on turbine blades

Different to our previous paper [6] for the vertical-axis turbine, here the swept space for the horizonal-axis turbine has a shape of vertical oblate spheroid (see Figure 1).

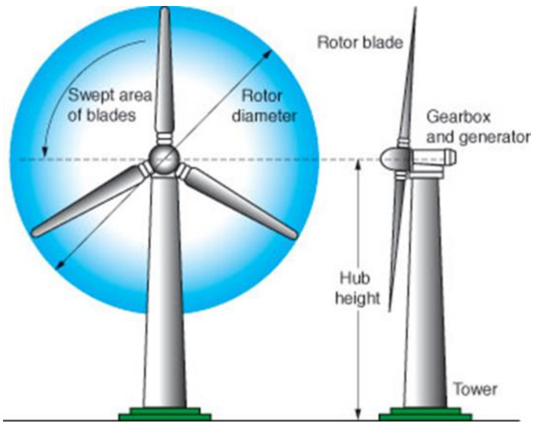


Figure 1. The swept area of blades.

In general, we consider two kinds of swept space: a horizontal cylinder and a vertical oblate spheroid. Take the rain vector $\boldsymbol{v_r} = \{v_t, v_c, -k\}$, so that v_t represents a tail-wind, v_c the cross-wind, and the downward rainfall speed $k > 0$. Then, $\boldsymbol{v}/s = \{v_t - s, v_c, -k\}/s$. Thus, the total wetness function W leads to [14]:

$$W(s) = \frac{\pi R^2|v_t - s| + 2aR\sqrt{v_c^2 + k^2}}{s}, \tag{2a}$$

for swept space of a horizontal cylinder, and

$$W(s) = \frac{\pi R\sqrt{R^2(v_t - s)^2 + a^2v_c^2 + a^2k^2}}{s}, \tag{2b}$$

for swept space of a vertical oblate spheroid.

Here, a is half of thickness and R is large radius of swept space.

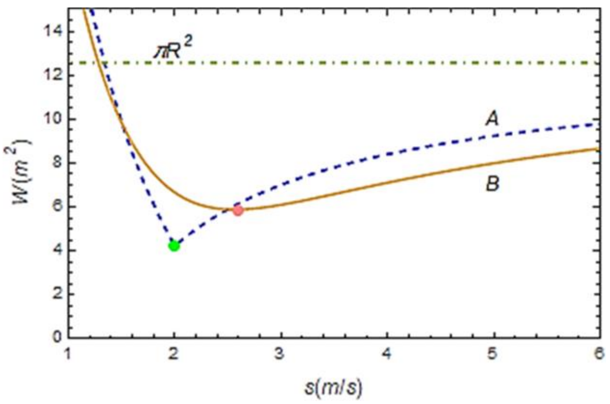


Figure 2. The s dependence of the total wetness on turbine blades in case of swept space in cylindrical (curve A with dashed line) and ellipsoid shape (curve B with solid line).

Consider an example with a swept space figured out a horizontal cylinder or a vertical oblate spheroid by spinning of turbine blades with a = 0.3 m, R = 2 m. And suppose a tail-wind v_t = 2 m/s, a cross-wind v_c = 1 m/s, and a vertical downward speed k = 5 m/s. In consequence, the total wetness $W(s)$ gains a minimum at a useful wind speed s = 2 m/s (in case the swept space as a horizontal cylinder), or s = 2.6 m/s (in case the swept space as a vertical oblate spheroid) well above the speed of the tail-wind (see Figure 2, s = 2 and 2.6 m/s are highlighted).

2.3. Power loss of wind turbine

Similar to our previous paper [6], the power of a wind turbine as a Weibull cumulative distribution to the useful wind speed s with the shape parameter $\kappa \geq 1$ and the scale factor $\lambda > 0$, and can be expressed

$$P(s) = \frac{1}{2}\rho A s^3 \eta C_p. \tag{3}$$

Here, the coefficients satisfies

$$\eta C_p = \frac{3\lambda^3\left[\Gamma\left(\frac{3}{\kappa}\right) - \Gamma\left(\frac{3}{\kappa}, \frac{s^\kappa}{\lambda^\kappa}\right)\right]}{\kappa s^3} - e^{-\left(\frac{s}{\lambda}\right)^\kappa} \leq C_{p,Betz}, \tag{4}$$

where, η is the drive train efficiency and C_p is the rotor power coefficient.

Since $\eta \leq 1$, $C_p \leq C_{p,Betz}$ ($C_{p,Betz}$ = 16/27, the Betz limit), it is solved by figure (see Figure 3) and the solution is $\kappa \leq 10$, with every value of λ.

The power under rain is reduced by a quantity F_ds,

$$P_d(s) = P(s) - F_d s, \tag{5}$$

with F_d from the expression (1).

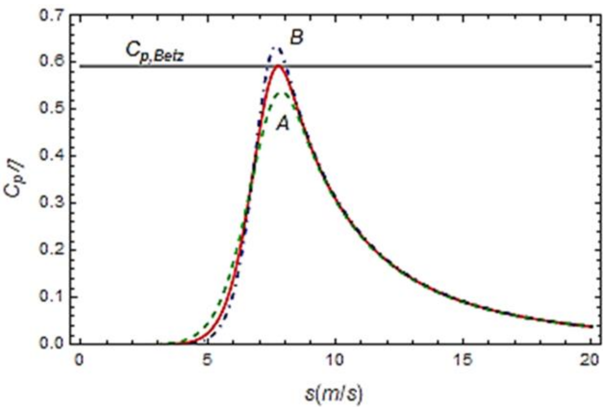


Figure 3. The *s* dependence of power coefficients is plotted with λ = 7 m/s and three different values of shape parameters: κ = 8 (dashed line), 10 (solid), and 12 (dot-dashed) for the lines from A to B.

3. SIMULATION RESULTS

Using Wolfram Mathematica [15] the model is simulated with the following input parameters and simulation steps:

1. The input parameters: Input parameters of the case study are shown in Table 2.

Table 2. Input parameters of the case study.

Name of parameters	Surveyed values	Name of parameters	Surveyed values
Half of thickness of swept space	0.2 to 0.5 m	Vertical downward speed	5 to 20 m/s
Radius of the rotor disc of area	1 to 5 m	Tail-wind speed	-5 to 20 m/s
Density of air	0.1 to 1.5 kg/m^3	Cross-wind speed	0 to 30 m/s
Density of raindrop	0.1 to 0.6 cm	Shape parameter	1 to 10
Rainfall intensity	1 to 200 mm/h	Scale factor	0.1 to 20 m/s
Diameter of raindrop	0.1 to 0.6 cm		

2. The case study is simulated following these steps:

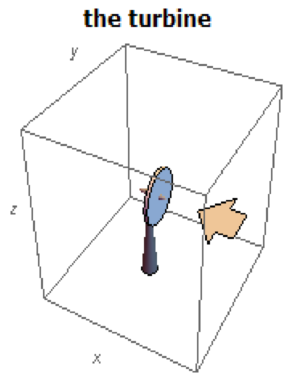
a) First, a geometry shape of swept space is selected, then wind scale factor and the shape parameter. Parameters of rain and wind are chosen in case of low and medium wind.
b) Then, we solve and investigate by simulating the equations of rainfall, impact force, total wetness, and turbine power under rain. Set of optimal values are automatically determined and graphically figured after that.
c) According to the specific cases, the parameters can be changed and the simulation results are respectively depicted on the figures.

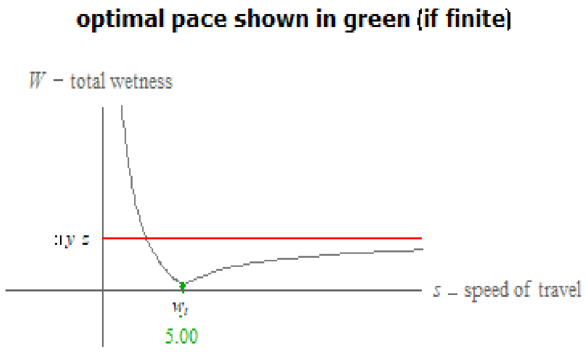
Using this methodology, power output of horizontal-axis wind turbines under rain can be assessed, therefrom offering solutions for designing blades' wind turbines as well as optimizing rotating speed in a great effort to harvest effectively wind energy in rainy weather conditions.

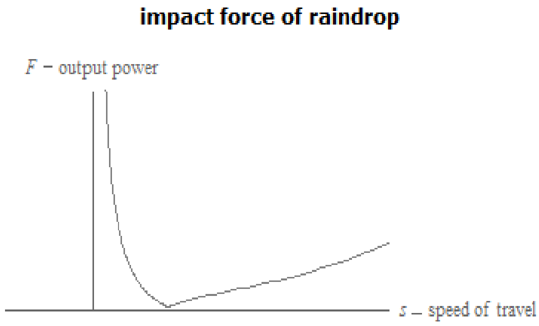
Several typical results of the simulation are listed in Table 3 and plotted in Figure 4. The results show that the power loss of the turbine is increased by the raindrop size, and by cross-wind speed.

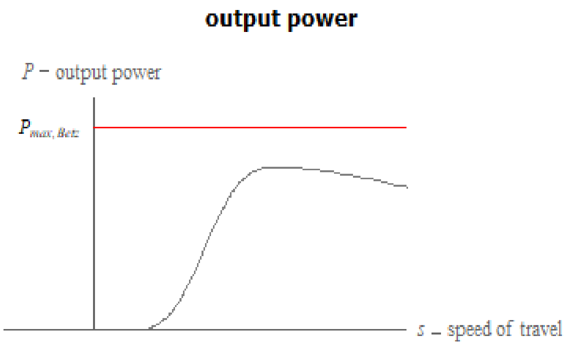
Table 3. Several simulation results for wind turbine in rainy weather condition.

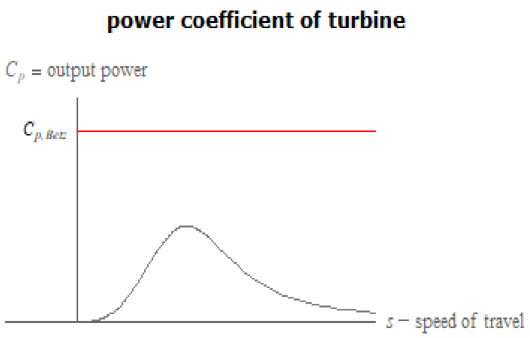
Swept space	Raindrop diameter	Cross-wind speed	Optimal wind speed	Minimum wetness	Power coefficient	Idealized power (MW)	Power loss (MW)
Cylinder	0.2 cm	0 m/s	5 m/s	3 m^2	0.297	1.08	1.06
	0.2 cm	8 m/s	5 m/s	3 m^2	0.297	1.08	1.05
	0.3 cm	0 m/s	5 m/s	3 m^2	0.297	1.08	0.94
	0.3 cm	8 m/s	5 m/s	3 m^2	0.297	1.08	0.87
	0.4 cm	0 m/s	5 m/s	3 m^2	0.297	1.08	0.58
	0.4 cm	8 m/s	5 m/s	3 m^2	0.297	1.08	0.30
Spheroid	0.2 cm	0 m/s	5 m/s	4 m^2	0.297	1.08	.,07
	0.2 cm	8 m/s	5 m/s	4 m^2	0.297	1.08	1.06
	0.3 cm	0 m/s	5 m/s	4 m^2	0.297	1.08	0.97
	0.3 cm	8 m/s	5 m/s	4 m^2	0.297	1.08	0.90
	0.4 cm	0 m/s	5 m/s	4 m^2	0.297	1.08	0,66
	0.4 cm	8 m/s	5 m/s	4 m^2	0.297	1.08	0.41







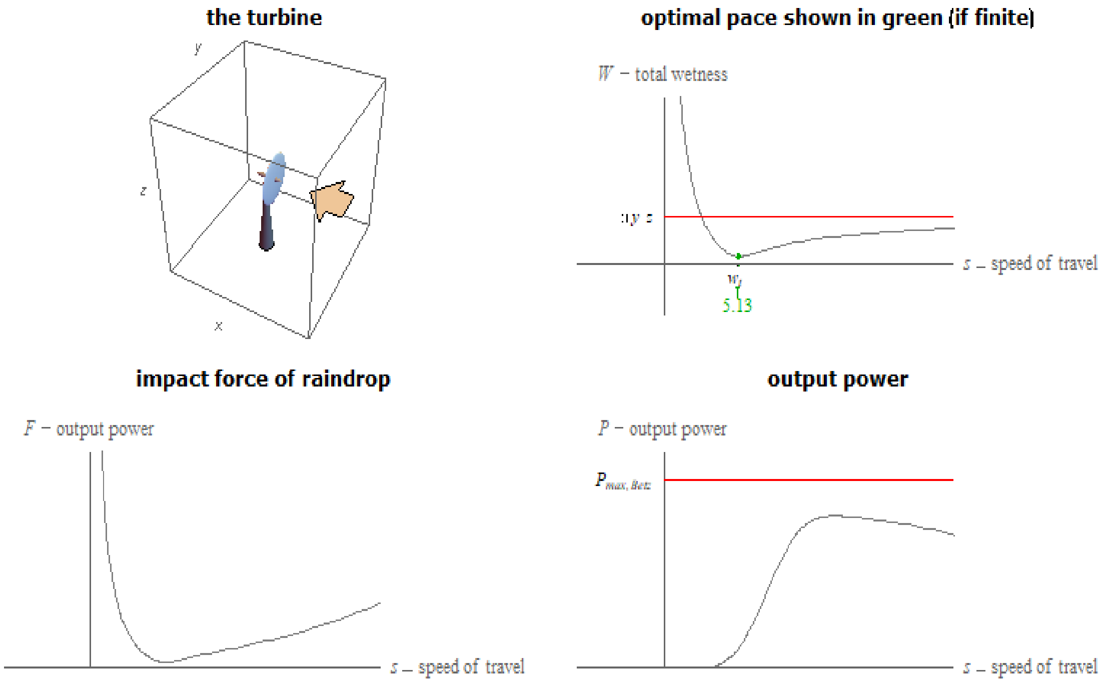


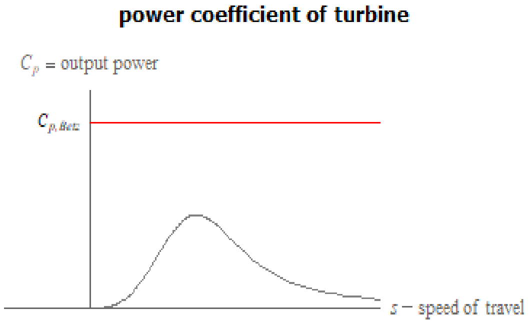


output parameters

d_{rain}	v_c	v_{opt}	W_{opt}	P_{max}	$C_{p,max}$	P_{max}–Fs
0.2 cm	0	5 m/s	3 m^2	1088.3 kW	0.297	1064.9 kW

Figure 4a. Simulation results when the swept space is cylinder. In the first row, the left figure shows an image of a turbine tower, the right one shows the total wetness as a function of wind speed. In the second row, the left figure shows the impact force of rain on the blades, the right one shows the power output reduced by effect of rain. In the last row, the left figure shows the curve of power coefficient vs speed of wind, the right table shows parameters of rain, wetness, power and performance.





output parameters

d_{rain}	v_c	v_{opt}	W_{opt}	P_{max}	$C_{p,max}$	P_{max}–Fs
0.2 cm	0	5 m/s	4 m^2	1088.3 kW	0.297	1068.5 kW

Figure 4b. Simulation results when the swept space is ellipsoid. In the first row, the left figure shows an image of a turbine tower, the right one shows the total wetness as a function of wind speed. In the second row, the left figure shows the impact force of rain on the blades, the right one shows the power output reduced by effect of rain. In the last row, the left figure shows the curve of power coefficient vs speed of wind, the right table shows parameters of rain, wetness, power and performance.

4. DISCUSSIONS AND CONCLUSIONS

With strong growth of wind farms as well as increase of extremely weather events, operation and control of wind turbines can be affected during raining. In this paper, a methodology based on physics model and simulation is proposed in order to analyze and simulate the power of horizontal-axis wind turbines under rain. Main ideas are concluded as follows.

1) This paper is the one of few studies in order to analyze impacts of rain on the power and performance of a horizontal-axis wind turbine.

2) It is found that the wetness on the turbine blades is related to the impact force of the rain, and there is a minimum wetness corresponding to an optimal wind speed. Then at that speed, the impact force of the rain is minimal, the power loss therefore due to rainfall is also minimal.

3) Only by selecting appropriate scale factor and shape parameter, the characteristic curves of the power evaluated based on the statistical analysis is quite consistent with the one measured by experiment.

4) The reduction of the power output is significant with an increase of the raindrop size. This can be understood as follows, the heavier the rain, the more likely it is to affect the rotation speed of the turbine blades. The power reduction is also influenced strongly by rain speed. The output is also slightly reduced when the other parameters such as tail-wind, cross-wind and downward rainfall speeds increase. However, the best output can be found, depending on the typical cases, corresponding to an optimal wind speed, a minimum wetness, and a minimum impact force of the rain.

In order to achieve economic and feasible capacity of the horizontal-axis wind turbine, an optimal configuration of the wind turbine should have been designed. A physics model is developed and simulated in order to predict the properties of the wind turbine under the different rainy weather conditions with the different swept geometrical shapes of turbine blades. Depending on the different purposes of survey, the simulation results such as impact force of rain, wetness, power and output coefficient are visually illustrated by adjusting and animating. One of the merits of this method is that achieving results are fairly accurate although only simple model is required.

This study is follows to optimal operation and design problems of wind turbines under random weather conditions. This topic is therefore important for Vietnam's renewable energy development strategies.

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