Effect Analysis of Performance and Pitch Controller Operation for Wind Turbine under Rain

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ABSTRACT

More and more wind power projects are being built in Vietnam, while Vietnam located in a tropical rainy area, so studying the effects of the weather on the generated powers of wind turbines will give contributions to optimizing operational processes and designing new turbines. Therefore, an analytical method is proposed in this paper to study the generated powers of a horizontal-axis wind turbine (HAWT) as well as the operation of the pitch control system during rains, heavy rains, and rainstorms with wind load and rain load. The model is simulated along the actual physics process of the raindrops falling on the blades' surface, thereby determining optimal wetness depending on the shape of swept area, then generated power and performance under the rain respectively. Analytical results point out that pitch angles should decrease when wind turbine operates during the wind speed exceeds the rate value in case of rain.

1. INTRODUCTION

In Vietnam, more and more wind power projects are being built. Offshore wind farms in Vietnam have been planned up to 10 GW in next coming years. However, Vietnam is located in a tropical rainy area. It is therefore necessary to investigate performance of wind farms during rains. With clear understating operation of wind farms under rain, it could contribute to the optimal operation process and as a result more generated power output can be achieved.

Recently, the study of the effects of rain has not been mentioned much yet, only some studies in the world mainly on analysis or simulation of aerodynamics of rain falling on the blades [1, 2, 3], or mechanical force of impact to the turbine tower [4, 5]. However, there are a few articles that mention a little about the effect of rainfall on the generated powers of wind turbines. [6] suggested a decrease of 27% in power output under rain, other study [7] reported results similar to [6] but another work [8] supposed that the power outputs could increase 3% for different types of rain. Therefore, further research in this area should be studied to understand the operational performance of wind turbines in offshore as well as wetter climates.

Some results from other field - the aircraft and airfoil research - showed that a decrease of lift and an increase of drag are dependent on the rainfall rate and the rain type. Hence, with the same rainfall rate the loss of generated power is significantly affected by raindrops. When the blades of wind turbine were feathering in heavy rains, they are impacted larger. A similar situation when the rain direction is changed suddenly. In short, because of sudden changes in wind velocity and rain direction in bad weather conditions as well as the complex factors related to the wind turbine control, the blades' surface is attacked by wind along with the rain loads, decreasing the generated power, thus reducing the performance of wind turbine.

Normally, the operation performance of a wind turbine is decided by the specific characteristics of the wind turbine and its control systems as well as requirement of the grid codes [9, 10, 11]. Specific characteristic data of a wind turbine is provided by the manufacturer but it is only available with normal weather conditions without rain. Additionally, the operation of the control system is still not investigated under rain conditions in detail. Hence, two essential questions for the operation of a wind turbine during rain are raised as follows:

(1) The first question is how the performance changes of a wind turbine under rain?

(2) The second question is whether the operation of the control system, namely the pitch control system needs to adaptive adjust to achieve the maximum performance of a wind turbine under rain?

Therefore, the effects of rain on operating conditions of wind turbines under rain should be further studied. Analyzing effects of extreme weather conditions on wind turbines will give contributions to enhancing the optimization of operation processes.

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Extending our previous study [12], this paper focuses mainly on analyzing and evaluating the performance and pitch controller operation of HAWT under rain. Key contribution of this study is to propose a physical based model describing the operation of a wind turbine including a pitch controller. This model is hereafter used to quantitatively analyze effects of rain on performance of wind turbine and pitch controller operation. The analytical results help to clarify effects of the pitch controller operation of wind turbine during rains, and thus evaluate the optimal operation as well as the safety of wind turbines.

This article is organized as follows. A physics-based model is proposed to know how the raindrops impact against the blades of wind turbine in Section 2. Section 3 is analysis of the generated power and operation of pitch controller within the affection of rain. The generated power is considered corresponding to changes of some parameters. Finally, conclusions are drawn in Section 4.

2. AN ANALYTICAL MODEL OF WIND TURBINE UNDER RAIN

2.1 Modelling the Impact Force of Raindrops

There is always rain associated with wind in rainfall. The mechanical and electrical generated power of a wind turbine will change when the blades of wind tower is affected by raindrops. Two parameters of a raindrop are its diameter and impact speed, that effect to the force of a raindrop on the wind turbine's blades [13].

The velocity of the raindrop decreases to zero in a flash as landing on blades of wind turbines. This interaction process obeys Newton's second law [14],

$$\int_0^\tau \vec{f}(t)\mathrm{d}t + \int_{v_r}^0 m\mathrm{d}\vec{v} = 0 \tag{1}$$

where $\vec{f}(t)$ and m are the force vector and the mass of a raindrop; v_r is the velocity of raindrop before acting on the blade; τ is the time interval for the raindrop speed change from v_r to zero.

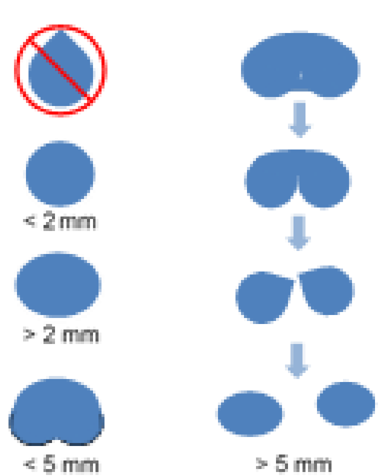

Fig. 1. The Shapes of the Raindrop as Falling [15].

Assuming that in the descent process of the raindrop, its shape is spherical (Fig. 1). Then, m = (1/6) $\varrho\pi d^3$, and $\tau = d/2v_r$, with d the raindrop diameter and ϱ the water density. Thus, a uniform-distributed load can be used to describe the raindrop' impact force landing to the blades as below:

$$F_d = F(\tau)\frac{\alpha W}{S} \tag{2}$$

where,

$$F(\tau) = \frac{1}{\tau}\int_0^\tau f(t)\mathrm{d}t = \frac{m v_r}{\tau} = \frac{1}{3}\varrho\pi d^2 v_r^2 \tag{3}$$

is the force of a single raindrop impacted on the blade in a very short time interval τ. Here, $S = \pi d^2/4$ is the action area of a raindrop; W is the structure's width against the rain; and α is the volume occupancy of each category of raindrops,

$$\alpha = \frac{1}{6}\pi d^3 N \tag{4}$$

where, N is the number of raindrops, whose diameters are between [d_1, d_2] in a unit volume of the air. It can be calculated by:

$$N = \int_{d_1}^{d_2} n(d)\mathrm{d}d \tag{5}$$

Here, d_1 = 0.1 mm, d_2 = 6 mm, and $n(d)$ is the distribution on the raindrop size. Many observations showed that the size of raindrop obeys a negative exponential distribution, referred to as the Marshall-Palmer (M-P) spectrum, and used widely [16, 17] as follows:

$$n(d) = n_0 e^{-\Lambda d} \tag{6}$$

where, n_0 = 0,08 cm^{-3} for any rainfall intensity and $\Lambda = 4.1\, I^{-0.21}$ cm^{-1} as the slope factor, with I is the rainfall intensity as listed in Table 1. The raindrop distributions vs the size of raindrop corresponding to various intensity are showed in Figure 2.

Table 1. Intensity Classification of Rain

Classification	Light rain	Moderate rain	Heavy rain	Rainstorm
Rain intensity (mm/h)	2,5	8	16	32
Classification	Heavy rainstorm (weak)	Heavy rainstorm (moderate)	Heavy rainstorm (strong)	Heavy rainstorm (extreme)
Rain intensity (mm/h)	64	100	200	709,2

Substituting $F(\tau)$, S, α into (6) yields:

$$F_d = \frac{2}{9}N\varrho\pi d^3 v_r^2 W, \tag{7}$$

as the rainfall's impact force on the blade. It could be described by using three components in tail-wind, cross-wind and downward directions. Here, only W is unknown and it is considered in the next subsection.

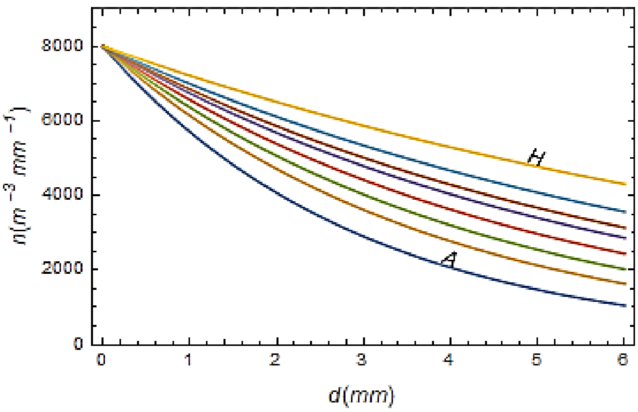

Fig. 2. Raindrops Distribution vs Raindrop Diameter for Various Rainfall Intensities 2,5; 8; 16; 32; 64; 100; 200; and 709,2 mm/h from A to H, respectively, referred to as M-P Spectrum.

For a simplified and feasible analysis, in present article, the wind is considered as the key load and rain is seen as an additional factor of a wind turbine. Thus, the generated power output of the wind turbine will rely on the velocity of wind and rain. This analytical methodology can help to see the nature of the problem as well as reduce complicates when calculating.

2.2 Modelling the Wetness on Turbine Blades

The key idea to consider W is this: a rainy zone is considered as the area covered by all the raindrops hitting the rotating blades. Figure 3 describes swept zone of the blades. It is clear that the swept space of the turbine blades is proportional to the amount of water falling into rotating blades. As a result, the geometric measure is used as an index of the total wetness.

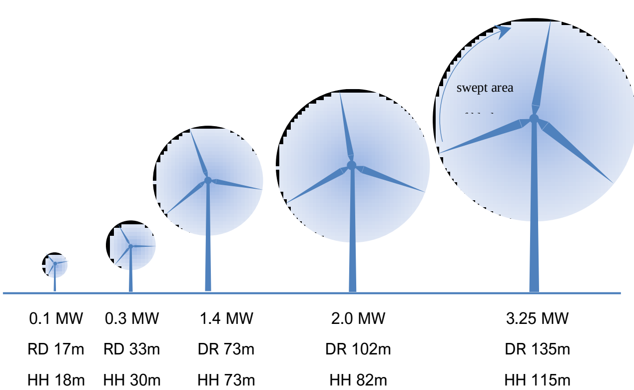

Fig. 3. The Swept Area of Blades and Size of Wind Turbines [18].

In this our study, it is supposed that the falling of rain is uniformed and the velocity of raindrop is assumed as a constant value (no gusts), $\vec{v}_r = \{v_t, v_c, -k\}$, so that the components of the tail-wind v_t, the cross-wind v_c, and the downward rain k are represented by the positive values. And supposing that the horizontal wind velocity $\vec{v}_w = \{s, 0, 0\}$ determines a constant speed of the rotating blades. Additionally, assuming droplets will hit to blades with a time as $1/s$. The rainy area of the blades is composed of all areas that a raindrop can land on. Called Q as a such area that a raindrop will land on at time t. Thus, it will reach the swept space at the point $Q + v_r t$. Then that point in turn has travelled relatively with the turbine from its initial location $P = Q + v_r t - v_w t$. Therefore, for every exposed point P on the turbine blades at time 0, the point $P + (v_r - v_w)t$ is in the rain region for $0 \le t \le 1/s$. It means that the rain region is made up of line segments parallel to the apparent rain vector $\vec{v} = \vec{v}_r - \vec{v}_w$, each of length $\|\vec{v}\|/s$, terminating at an exposed point on the blades at time 0. Hence, the total wetness W equals to swept space of turbine blades multiplied by the magnitude of the vector $\vec{v}/s$. For a HAWT, the swept space is considered approximately as an oblate spheroid or a bi-cone. And, $\vec{v}/s = \{v_t - s, v_c, -k\}/s$. Thus, the total wetness function W obtain as [19]:

$$W(s) = \frac{\pi R\sqrt{R^2(v_t - s)^2 + a^2 v_c^2 + a^2 k^2}}{s}, \qquad (8)$$

for the swept space of an oblate spheroid with radius of rotor disc R and half of thickness of swept a.

It is easily realized that the wetness function tends to a limiting value of πR^2 (the area of the projection of the spheroid onto the y-z plane) as $s \to \infty$. It is precisely reducing on $(0, \infty)$ for $v_t < 0$ (tail-wind absent), and gets an absolute minimum at its lone critical point

$$s_{opt} = \frac{R^2 v_t^2 + a^2 v_c^2 + a^2 k^2}{R^2 v_t}, \qquad (9)$$

for $v_t > 0$ (tail-wind present). Again, the optimal speed is greater strictly than the tail-wind speed v_t.

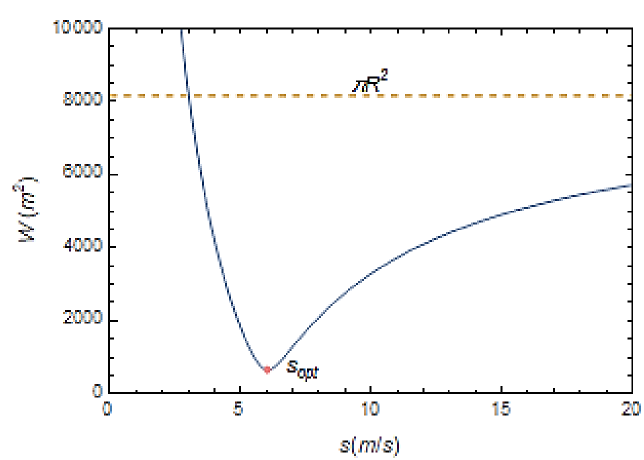

Fig. 4. The Total Wetness Function vs wind speed corresponding to Swept Space of Oblate Spheroid.

In order to illustrate a swept space derived from a spheroid with following dimension: a = 2 m (half of blade's width), R = 51 m (length of blade). And imagine rain conditions where v_t = 6 m/s for a tail-wind, v_c = 10 m/s for a cross-wind, and k = 7 m/s for a vertical downward rainfall. The total wetness function $W(s)$ then gets a minimum at a useful wind speed s = 6.1 m/s well above a bit the tail-wind speed (as highlighted in Figure 4).

Note that, there are here three worthy speeds: of the tail-wind v_t, of the optimum s_{opt}, and of the wind's top obtained by turbine, which we note by s_{max}. Supposing that conditions are such that $0 < v_t < s_{max}$, we now inspect how much wetter a swept space of blades could possible obtain the less-than-ideal speeds v_t or s_{max} than it would have by continuing at the optimal pace, i.e. consider the ratio

$$\chi = \frac{W(s_{max})}{W(s_{opt})} = \frac{\sqrt{(a^2k^2+R^2v_t^2)[a^2k^2+R^2(s_{max}-v_t)^2]}}{a\,R\,k\,s_{max}}, \quad (10)$$

in the case that the swept space of blades has the shape of an oblate spheroid.

It is easily to realize that this ratio reaches to maximum

$$\chi_{max} = \frac{a\,k}{R\,s_{max}} + \frac{R\,s_{max}}{4\,a\,k}, \quad (11)$$

when, $v_t = s_{max}/2$ and the cross-wind $v_c = 0$, i.e. the rain is precisely moving in the direction of the wind and the tail-wind is a half of the top-wind.

If one then substitutes the values a = 2 m, R = 51 m, and uses a top speed s_{max} = 15 m/s and a vertical rainfall velocity k = 7 m/s, then in the worst case (a 6 m/s tail-wind), χ is approximately 13.68. That is, at the top wind speed turbine blades get more than 13 times wetter when they rotate to receiving at the optimum pace. Thus, rotating at the optimum pace, blades can be kept much driest. Noting that χ is sensitive to changes in both s_{max} and k (see Figure 5).

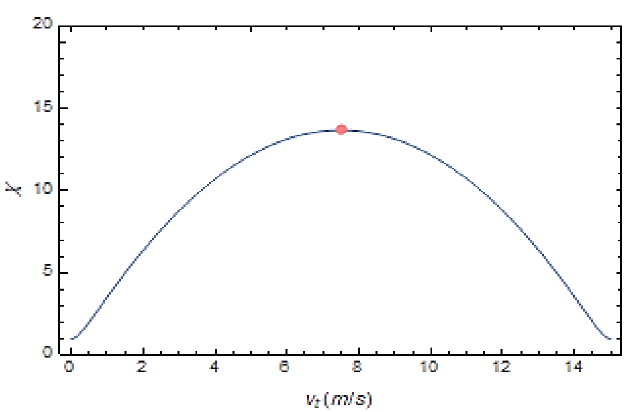

Fig. 5. The Ratio of Wetness on the Turbine Blades at the Top Speed and the Optimal Pace.

3. ANALYZING THE PERFORMANCE OF WIND TURBINES OPERATION DURING RAIN

The characteristic performance curve of a wind power can be deployed to calculate the power generation of a wind turbine without considering its various technical components in detail [20]. A function of the hub-height wind can be used to described as below:

$$P(s) = \frac{1}{2}\rho A C_p s^3, \quad (12)$$

where, $A = \pi R^2$ is the rotor disc area, ρ is the air density. Power generation curves for present wind turbines can be derived from field tests, using standardized testing methods by the manufacturer. The data is stored in the memory of the turbine controller and is used as a look-up table, and the turbine output is controlled for each speed of wind, not to exceed the value indicated on the curve.

As known, C_p is the coefficient of the wind power. It can be described by using a function of the pitch angle θ and the tip-speed ratio λ . λ is the ratio of the speed of the tip of the blades to the wind speed s at hub height upstream of the rotor. In almost cases, types of wind turbines with fixed-speed are stall controlled, θ does not change and hence C_p is only a function of λ .

It is realized that power-characteristic curves from many wind turbines are quite similar, thus it could use a general approximation for the C_p to describe both types of wind turbines with the variable-speed and constant-speed as follows:

$$C_p(\lambda,\theta) = c_1(c_2 y - c_3\theta - c_4\theta^{c_5} - c_6)e^{-c_7 y}, \quad (13)$$

where,

$$y = \frac{1}{\lambda + c_8\theta} - \frac{c_9}{\theta^3+1}, \quad (14)$$

This equation initiates from [21], however here, the values of the parameters c_1 to c_9 are adjusted a little bit meet the manufacturing data as listed in Table 2.

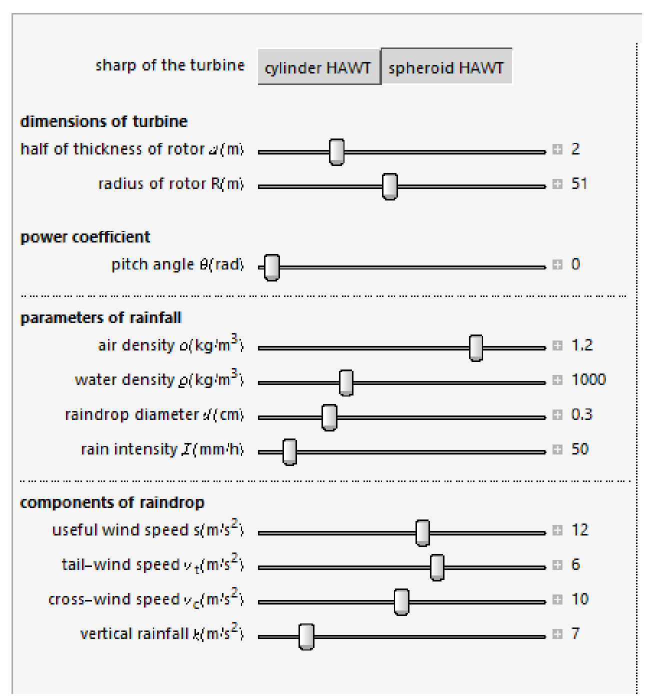

Fig. 6. The Inputted Parameters of the Model as starting Values for Analyzing.

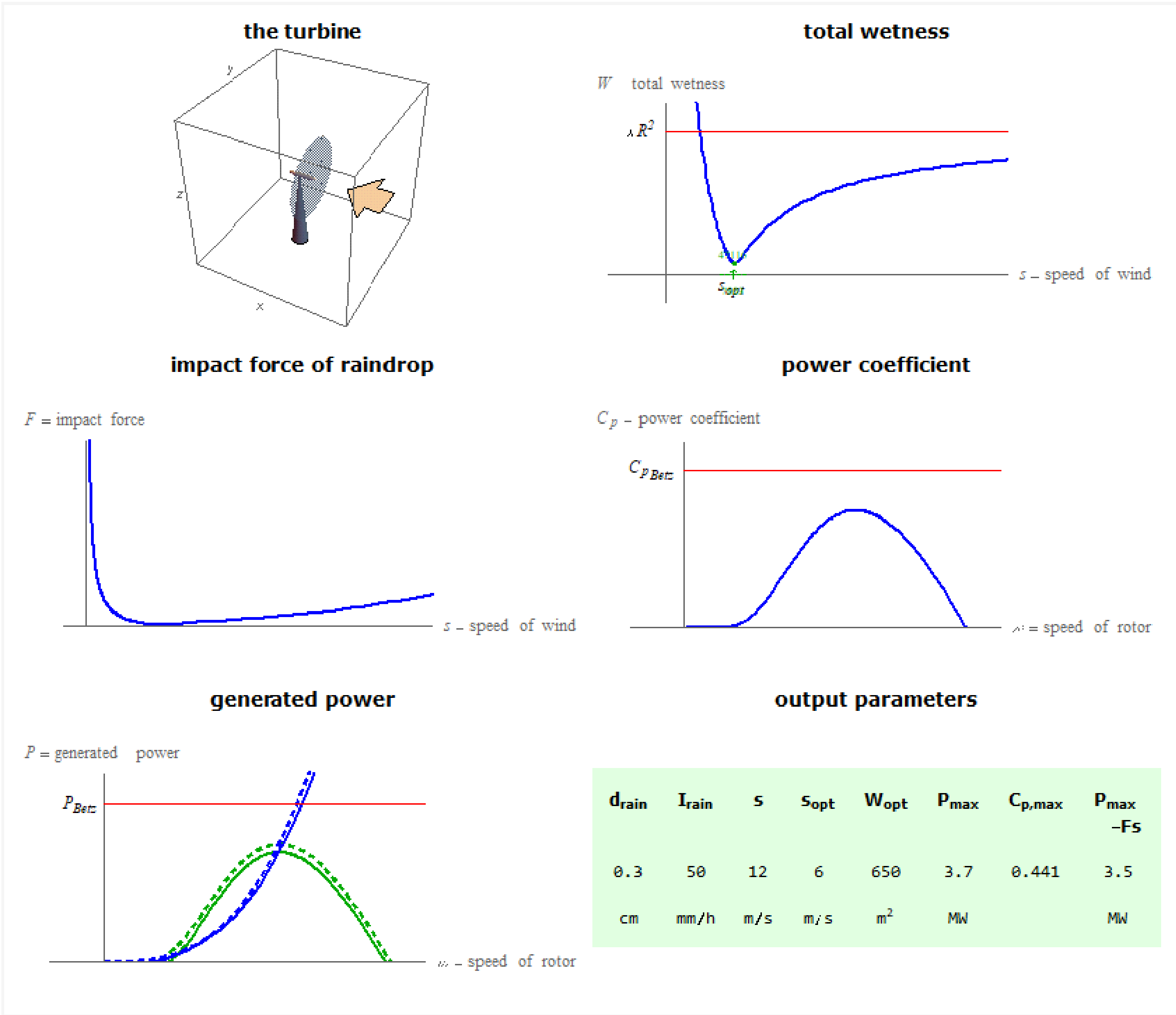

Fig. 7. The Analytical Results of the Model with a Sample Set of Inputted Parameters.

Hereafter we consider the effect of rain on the generated power by using the set of parameters for power coefficient of variable-speed wind turbines (other cases can be considered similarly),

$$P_d(s) = P(s) - F_d s, \tag{15}$$

with F_d from the expression (7) and the wetness W from (8).

We use a set of parameters listed in Table 3 as inputs to evaluate the generated power under rain. These parameters then can change or run (Fig. 6), and thus we obtain the changeable analysing the coefficient of the power, the raindrop' impact force as well as the wetness the generated power, and their values listed finally as shown in Fig. 7.

Table 2. Sets of parameters used for power coefficient

Parameters	[22]	Wind turbines with constant-speed	Wind turbines with variable-speed
c_1	0.5	0.44	0.73
c_2	116	125	151
c_3	0.4	0	0.58
c_4	0	0	0.002
c_5	-	0	2.14
c_6	5	6.94	16.5
c_7	21	16.5	18.4
c_8	0.08	0	-0.02
c_9	0.035	-0.002	-0.003

The results show that there are the optimal values of wetness as well as the impact force of rainfall, the curves of the power coefficient and the generated output are affected significantly under rain. The values listed in Fig. 7 show that the generated power gains 2 MW under rain, lower 7% as the case without rain (2.16 MW) when the parameters of the turbine and rainfall given in Table 3. Other values of generated power are compared in Table 4.

Table 3. Input parameters used for evaluating the generated power

Parameters	R (m)	a (m)	ρ (kg/m^3)	θ (rad)	ϱ (kg/m^3)	d (cm)
Values	51	2	1.2	0	10^3	0.3
Parameters	s (m/s)	v_t (m/s)	v_c (m/s)	k (m/s)	n_o (cm^{-3})	I (mm/h)
Values	12	6	10	7	0.08	50

The results are investigated more detail given in Figures 8-13. The powers as functions depending on the wind speed and the rotor speed given in Figs. 8 and 9. The dependence of the powers vs the rotor speed corresponding to different pitch angles, different raindrop diameters, different cross-wind speeds, and different rainfalls as seen in Figs 10, 11, 12 and 13 respectively while values of other parameters are fixed in Table 3.

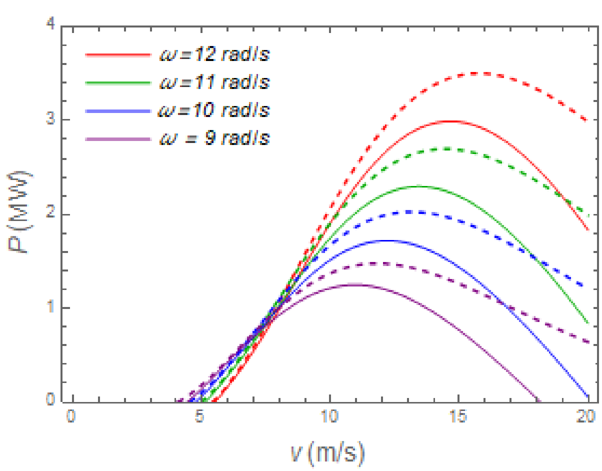

Fig. 8. The Power Curves vs Wind Speed Corresponding to Different Rotor Speeds at Zero Pitch Angle under Rain (solid lines) and No Rain (dashed lines).

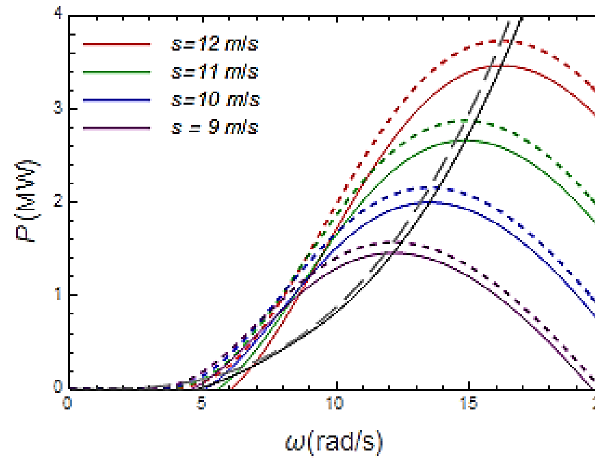

Fig. 9. The Powers (color lines) and Generated Powers (black lines) vs the Rotor Speed Corresponding to Different Wind Speeds at Zero Pitch Angle under Rain (solid lines) and No Rain (dashed lines).

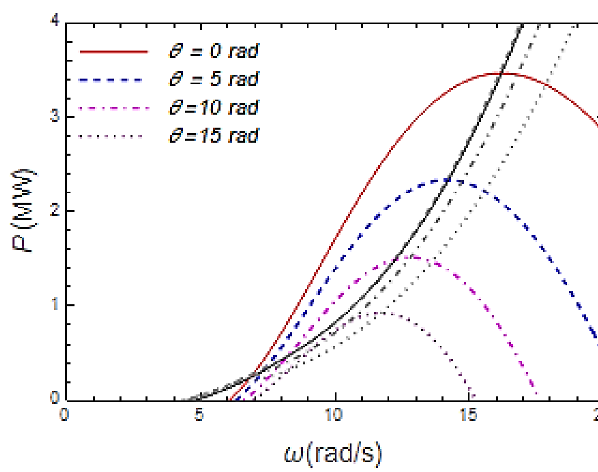

Fig. 10. The Powers (color lines) and Generated Powers (black lines) vs the Rotor Speed Corresponding to Different Pitch Angles at the Wind Speeds 12m/s.

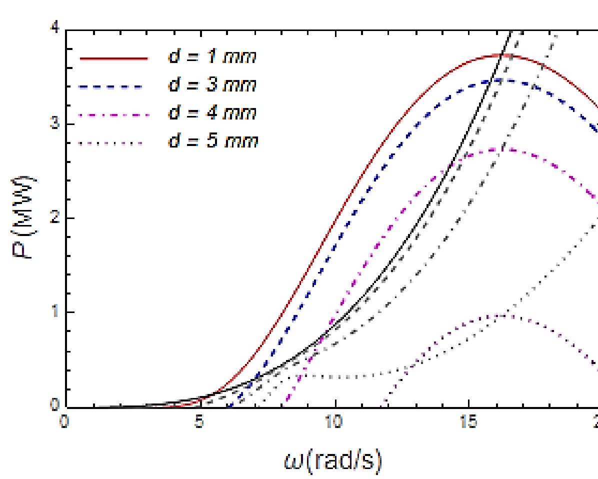

Fig. 11. The Powers (color lines) and Generated Powers (black lines) vs the Rotor Speed Corresponding to Different Raindrop Diameters at the Wind Speeds 12m/s.

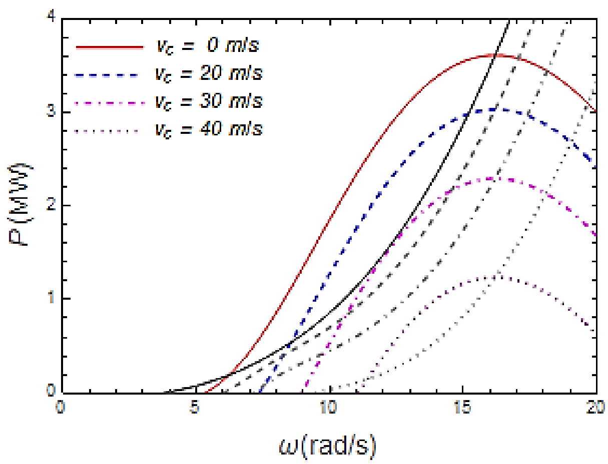

Fig.12. The Powers (color lines) and Generated Powers (black lines) vs the Rotor Speed Corresponding to Different Cross-Wind Speeds at the Wind Speeds 12m/s.

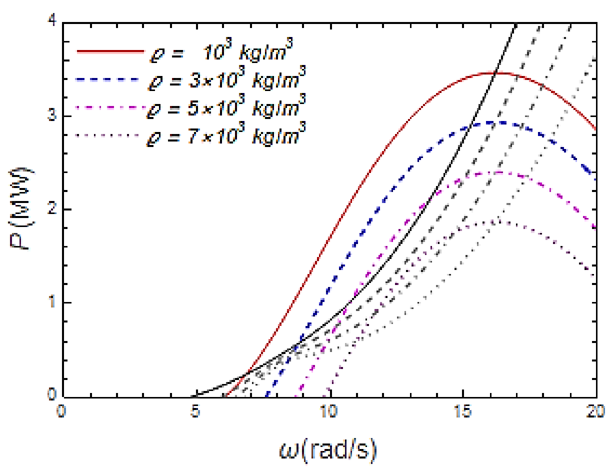

Fig. 13. The Powers (color lines) and Generated Powers (black lines) vs the Rotor Speed Corresponding to Different Raindrop Densities at the Wind Speeds 12m/s.

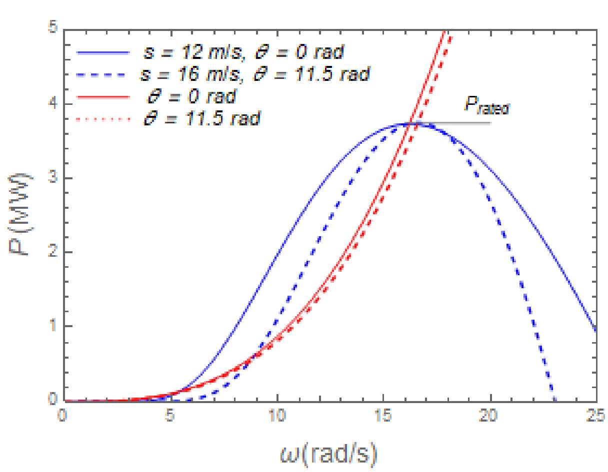

Fig. 14. The Powers (blue lines) and Generated Powers (red lines) vs the Rotor Speed Without Rain. When Wind Speed increases from 12 m/s to 16 m/s, the Pitch Angle is adjusted to 11.5 rad in order to remain the Rated Power 3.75 MW.

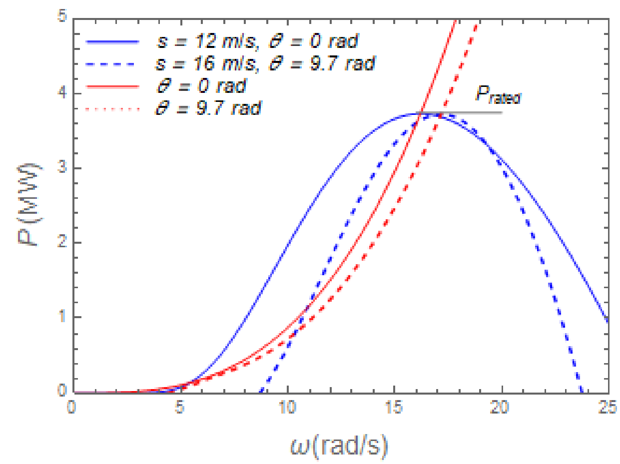

Fig. 15. The Powers (blue lines) and Generated powers (red lines) vs the Rotor Speed under Rain. When Wind Speed increases from 12 m/s to 16 m/s, the Pitch Angle is adjusted to 9.7 rad in order to remain the Rated Power 3.75 MW.

Table 4. Output Values of Generated Power

Wind speed	8	9	10	11	12
No rain (MW)	1.11	1.58	2.16	2.88	3.74
Under rain (MW)	1.03	1.46	2.00	2.67	3.47
Reduced (MW)	0.08	0.11	0.16	0.21	0.27
Reduced rate (%)	6.8%	7.3%	7.4%	7.3%	7.1%

Fig. 8 describes effects of power outputs of the wind turbine under rain (solid lines) in comparison to the case without rain (dashed lines) vs wind speed at different rotor speeds as the pitch angle is zero. Fig. 9 shows relationship between the rotor speed and generated powers of the wind turbine at zero pitch angle and different wind speeds under rain (solid lines) and without rain (dashed lines). These results show that the effect of rain is apparent. It is realized that the power is significantly reduced under rain. Fig. 10 shows a suggestion that since wind speeds are higher than the nominated wind speed, the pitch angle should increase so that the turbine runs at the rated power. Namely, for example, in order to maintain the rated power with respect to the nominated wind speed value of 12 m/s, if the wind speed increases to 16 m/s and wind power exceeds the rated power we should adjust the pitch angle about 11.5 rad (without rain) or 9.7 rad (under rain) to reduce the power equal to the desired average value (see Fig. 14 and 15). The pitch angle is adjusted less in the case of rain.

The reduction of the generated power also is realized clearly as some parameters of rainfall change. Fig. 11 shows the relationship between generated powers and the rotor speed corresponding to different raindrop diameters at the wind speed 12m/s. Fig. 12 and 13 describe dependency of power outputs on the rotor speeds with different cross-wind speeds as well as different raindrop densities. From Figs. 11, 12 and 13, it is realized that the significant influence of the raindrop size, the cross-rain velocity, and the raindrop density on the wind turbine power. As shown, the generated power decreases significantly when rain is heavier as well as the cross-wind component is larger. In more severe weather conditions, the power will sharply decrease and then even disappear.

4. CONCLUSIONS

The wind power is one of main resources of renewable energy, so studying on the generated powers of wind turbines under the effects of the climate will give contributions to designing new turbines and optimizing the operation processes. In this paper, a physics-based analytical method is proposed to study the performance of wind turbines including the operation of pitch controller under the rainfall conditions. Follow is some main conclusions.

1. A physics-based model is firstly investigated to study influence of rain on generated power outputs of different wind turbine.
2. It is drawn that the loss power due to rainfall is minimum corresponding to the minimal impact force of the rainfall on the turbines' blades.
3. The power characteristic curves of wind turbines are considered with different parameters. It shows the decrease of the power output under different rainy conditions.
4. The decrease of generated power under rain is proportion to the size of raindrop. It is clearly seen that the speed of rotating blades will be affected by heavy raining. Other investigates show that the loss of generated power is also significantly determined by other parameters during rain. As increasing tail-wind, cross-wind, downward rainfall, or raindrop density, the power is also slightly reduced. Of course, the best power can be attended at the optimal wind speed as well as the minimum wetness, or since the impact force of the rain is minimal.
5. From results as seen in Fig. 8, Fig. 10, Fig. 14 and Fig. 15, it is realized that operation of the pitch controller will be significantly influenced under rain. The pitch angle should be will be slightly reduced during rain in comparison with a case of no rain when wind velocity exceeds rated wind speed.

This model and its method can be utilized to analyse and predict the characteristic operation of a horizon wind turbine including the performance of its pitch controller under different rainy conditions as well as several geometries of swept area of rotating turbine blades. Merits of this model are that the operation analysis of a wind turbine is performed by investigating and changing parameters for visual animation. Additionally, although the simple mathematics description, the model still generates enough-accurate analysing results. This model is able to extended to consider the drive train system and the generator system, similar to [9], or controller [10, 11]. These are issues for our research in future.

This paper is in our direction of research on the optimal operations and controls of wind turbines in rainy weather conditions in Vietnam. This topic is therefore essential for Vietnam's offshore as well as onshore wind farms development plan near future.

LIST OF SYMBOLS

$\vec{f}(t)$	force vector of a raindrop
v_r	velocity of raindrop before acting on the blade
τ	time interval for the raindrop speed change from v_r to zero
m	mass of a raindrop
d	raindrop diameter
ϱ	raindrop density
F_d	impact force of a raindrop
S	action area of a raindrop
α	volume occupancy of each category of raindrops
W	width of the structure against the rain = the wetness
N	number of raindrops with diameters between $[d_1, d_2]$
n	distribution on the size of the raindrop
Λ	slope factor
I	rainfall intensity
v_t	tail-wind component of rain
v_c	cross-wind component of rain
k	downward speed of the rain
s	horizontal wind speed
a	half of thickness of swept space
R	radius of rotor disc
A	rotor disc area
ρ	air density
P	wind power
C_p	power coefficient
λ	tip-speed ratio

θ pitch angle

P_d wind power under rain

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