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A METHOD TO ANALYZE POWER OUTPUT OF VERTICAL-AXIS WIND TURBINES UNDER RAIN

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ABSTRACT

A method to analyze effect power output of a vertical axis wind turbine under rain is proposed. The rain had the effect of increasing the drag, slowing the rotational speed of the wind turbine and decreasing the power and performance. More and more ambitious projects for wind turbine production being set on many where on Vietnam, it is necessary to understand all the factors, especially by weather changes, that might affect wind power production. In this research, we lay out a model to estimate the effect of rainfall by simulating the actual physical processes of the rain drops forming on the surface of the blades of a vertical-axis wind turbine (VAWT), thereby determining optimal wetness, then power and performance respectively. This could have an effect on the control strategy necessary for designing and controlling wind turbine.

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

Classification numbers: 2.8.3; 3.4.1

1. INTRODUCTION

Worldwide development of wind power is raising with the increased demand for renewable energy. Rain is a widespread phenomenon in many parts of the world, and Vietnam is in a zone of high precipitation, so in order that more and more ambitious projects of wind turbine generation being set nowadays can be realized, it is necessary to understand the effect of rain and rainstorm on the power and performance of wind turbines. This will provide valuable insights into the design and control of a new wind tower.

The effect of rain on wind turbine power and performance has not been undergone any significant research. There have been several studies mainly on the simulation and analysis of aerodynamics and mechanics of rain on the shape of the blades [1, 2], to the structure of the horizontal-axis [3] and the vertical-axis [4] turbine tower. However, no studies have shown the optimal results related to wind velocity, droplet size, and surface wetness that affects the power and performance of the turbine.

VAWT is almost domestic production and has a capacity factor of the order of 1-2%, much less than a wind farm (HAWT installed) in the order 25-30%. In general, domestic wind-turbines have simpler power control systems and are more prone to the variability of the wind in the turbulent boundary layer closer to the ground, making them less efficient compared to large turbines. Reductions in power output due to rain would have a larger financial impact on owners of these VAWT turbines and could go some way to explaining the lower than predicted power output from these systems, particularly for certain power optimization strategies.

It is suspected that, as for results from the aircraft industry and airfoil research airfoils, the effect on power output and performance will depend on the velocity, size and density of the raindrops. This means that a significantly decrease of power output since large rain droplets will have a different effect to small raindrops at the same rainfall rate, a drizzle might be different to a shower. Since the average annual amount in Vietnam is above 150 days, this might have an impact.

Another problem, during heavy rain, the rain direction has sudden changes during its approach because of strong turbulent movement or local topographic effects, the loads on wind turbines are significantly larger than conventional design loads. The rain is given a cross-ward velocity component by the wind, aggravating the vibration of the wind turbine blades, affecting the power output as well as performance.

We focus mainly in this paper on physical modeling and simulating the effect of rainfall and wind parameters on blades of a vertical-axis turbine under rainy weather and extends the assessment in case of heavy rain. The model is built based on the form of turbine blades and the characteristics of rainfall. The simulation results give the characteristic curve of wind turbine power in rainfall conditions, and then evaluate the design and safety of wind turbines.

The paper is organized as follows. Section 2 is the main body of the work, in which we will systematically build a physical model that describes the effect of rain on turbine output from: (i) the impact force of rainfall, (ii) wetness on the turbine blades, (iii) power loss of wind turbine. Then, the results of simulating this model are showed in Sec. 3. Finally, the conclusions and discussions will be addressed in Sec. 4.

2. PHYSICAL MODEL

2.1. The impact force of rainfall

When it rains there is always a wind associated. Along the wind, the raindrops impact against the wind turbine’s blades, which affects on power and performance of the wind turbine. The energy that wind turbine’s blades receive from raindrop depends on the diameter and impact speed of the raindrop [5]. The raindrop’s velocity downs to zero very quickly just after it impacts on the turbine blades. We can, thus, write down the impact force of a single raindrop on the wind turbine in a very short time interval τ based on the Newton’s second law [6]:

$$F(\tau) = \frac{1}{\tau}\int_0^\tau f(t)\mathrm{d}t = \frac{mv}{\tau} = \frac{1}{6\tau}\rho\pi d^3 v.$$

where, $f(t)$ is the impact force of a raindrop at the time t; v is the velocity of a raindrop; ρ is the raindrop density; d is the raindrop diameter; m is the mass of the raindrop, $m = (1/6)\rho\pi d^3$, if the shape of the raindrop is assumed to be spherical in the descent process.

The impact force of a raindrop can be converted into a uniformly distributed load as follows:

$$F_d = F(\tau)\frac{\alpha W}{S} = \frac{2}{9}N\rho\pi d^3 v^2 W. \quad (1)$$

where, we use the actuation duration $\tau = vd/2$; the action area of a raindrop is $S = \pi d^2/4$; the volume occupancy of each category of raindrops $\alpha = (1/6)\pi d^3 N$; the width of the structure against the rain, equivalent to wetness W which is found in the next subsection; 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 [7]. $n(d)$ the raindrop size distributions for various rainfall intensities (referred to as Marshall-Palmer spectrum [8, 9]); n_0 = 0,08 cm^{-4} for any rainfall intensity; $\Lambda = 4.1\ I^{-0.21}$ cm^{-1} the slope factor; I the rainfall intensity in mm/h taken as the rain grading standard, as classified in Table 1.

Table 1. The levels of rain intensity.

Classification	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

Rain and wind often occur simultaneously, and the strength of the wind and the rain are also random. Sometimes the strength of the rain is very large, but the strength of the wind is not significant, and vice versa. Studies on distribution of the intensity, frequency and density of the wind and rainfall in different regional meteorology relating to complex mechanism are beyond the scope of this paper. For a simply and feasible analysis, in this paper, we regard that the wind is the main design load of the wind turbine, and the rain only impacts as an additional load. By this way, the effects of wind and rain together are considered, in which the impact of wind generates power output, whereas the impact of rain is a factor that affects that power. The simulation of this physical model not only can address the nature of the problem but also simplifies the calculation.

2.2. Wetness on turbine blades

Assumed that rain is falling uniformly with constant velocity (no gusts) $\boldsymbol{v}_r$, whose vertical component is negative. The key idea is this: focus on the region occupied by all the raindrops that will strike the turbine blades during their rotating. We call this the rain region (swept space of blades in three dimensions) which is easily determined from Figure 1.

The amount of water striking the turbine blades will be in proportion to the measure of the rain region. Accordingly, we adopt this geometric measure as a total wetness.

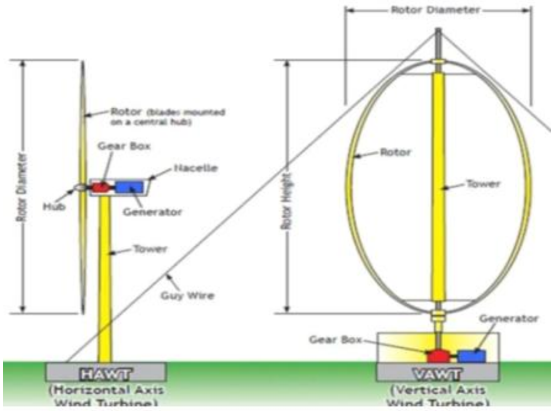

Figure 1. Two typical types of wind turbines, from which the rain regions (swept spaces of blades) can be easily determined.

Now we assume that the turbine blade rotates at constant speed by receiving a useful amount of wind velocity at constant speed along a horizontal line. We orient a Cartesian coordinate system in such a way that a reference point on the base of turbine tower at the origin and moves relatively in the positive *x* direction. Thus, the wind velocity vector is $\boldsymbol{v}_m = \{s, 0,0\}$. The blades were exposed to droplets for a finite amount of time, specifically $1/s$. The rain region consists of all initial locations from which a raindrop can land on the blades. Let *Q* be such a location, corresponding to a raindrop that will land at time *t*. Then it will strike the swept region at the point *Q* + $\boldsymbol{v}_r t$. That point in turn has traveled relatively with the turbine from its original location *P* = *Q* + $\boldsymbol{v}_r t - \boldsymbol{v}_m t$. Thus, for every exposed point *P* on the turbine blades at time 0, the point *P* + $(\boldsymbol{v}_r - \boldsymbol{v}_m)t$ is in the rain region for $0 \le t \le 1/s$. This shows that the rain region is made up of line segments parallel to the apparent rain vector $\boldsymbol{v} = \boldsymbol{v}_r - \boldsymbol{v}_m$, each terminating at an exposed point on the blades at time 0, and each of length $\|\boldsymbol{v}\|/s$. Hence, total wetness *W* is swept space of turbine blades times the magnitude of the vector $\boldsymbol{v}/s$. To measure the swept space of blades, regard that total wetness *W* as a function of *s* is the volume of the rain region, that is, the volume of the region containing the rain that will strike swept space of blades in the course of their rotating. For a horizontal-axis wind turbine, the swept space is approximately considered as a vertical oblate spheroid (flattened). For a vertical-axis wind turbine, the swept space is approximately considered as a prolate spheroid (elongated). Take the rain vector $\boldsymbol{v}_r = \{v_t, v_c, -k\}$, so that a tail-wind is represented by a positive value for v_t, the cross-wind is represented by v_c, and represents the downward speed of the rain $k > 0$. Then, $\boldsymbol{v}/s = \{v_t - s, v_c, -k\}/s$. Thus, the total wetness function *W* is written as follows [10]:

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

for VAWT with the swept space is prolate spheroid, and

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

for HAWT with the swept space is vertical oblate spheroid.

Here, z and r are half of rotor height and rotor radius for VAWT, respectively; a and R are half of thickness and rotor radius for HAWT.

It is readily verified that this total wetness function W has a limiting value of πrz for VAWT and πR^2 for HAWT as $s \to \infty$, is strictly decreasing on $(0, \infty)$ when $v_t \leq 0$ (tail-wind absent), and that it has an absolute minimum at its lone critical point

$$s_{opt} = \frac{z^2 v_t^2 + z^2 v_c^2 + r^2 k^2}{z^2 v_t},$$

for VAWT, and

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

for HAWT, when $v_t > 0$ (tail-wind present). This optimal speed is strictly greater than the speed v_t of the tail-wind for both cases.

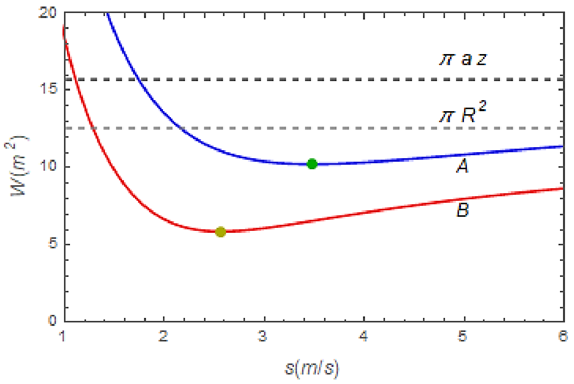

Figure 2. The total wetness on turbine blades for VAWT (curve A) compared with HAWT (curve B). The total wetness has a limit value of πaz for VAWT and πR^2 for HAWT as $s \to \infty$.

For example, consider two swept spaces figured out by spinning of turbine blades with the following dimensions: a = 0.3 m, R = 2 m for HAWT, and z = 5 m, r = 1 m for VAWT. And imagine rain conditions where the vertical downward rainfall speed is k = 5 m/s, with a tail-wind v_t = 2 m/s and a cross-wind v_c = 1 m/s. In this case, the total wetness $W(s)$ is minimized at a useful wind speed $s \approx$ 2.6 m/s for HAWT, or $s \approx$ 3.5 m/s for VAWT well above the speed of the tail-wind. (See the Figure 2, where the wetness at speeds s = 2.6 and 3.5 m/s are highlighted).

2.3. Power loss of wind turbine

The output power of a wind turbine can be expressed by using a Weibull cumulative distribution to the useful wind speed s as follows

$$P(s) = \int_0^s P(u) f(u) \mathrm{d}u, \tag{3}$$

where,

$$P(u) = \frac{1}{2}\rho A u^3, \tag{4}$$

A is the swept area of rotor, and

$$f(u) = \frac{\kappa}{\lambda}\left(\frac{u}{\lambda}\right)^{\kappa-1} e^{-\left(\frac{u}{\lambda}\right)^{\kappa}}, \tag{5}$$

with $\kappa \geq 1$, is Weibull probability density function. Here, κ is shape parameter and λ is scale factor. Taking the integral (3), we obtain:

$$P(s) = \frac{1}{2}\rho A s^3 \left\{ \frac{3\lambda^3\left[\Gamma\left(\frac{3}{\kappa}\right) - \Gamma\left(\frac{3}{\kappa}, \frac{s^{\kappa}}{\lambda^{\kappa}}\right)\right]}{\kappa s^3} - e^{-\left(\frac{s}{\lambda}\right)^{\kappa}} \right\}. \tag{6}$$

Hence, the coefficients can be found as

$$C_p \eta = \frac{3\lambda^3\left[\Gamma\left(\frac{3}{\kappa}\right) - \Gamma\left(\frac{3}{\kappa}, \frac{s^{\kappa}}{\lambda^{\kappa}}\right)\right]}{\kappa s^3} - e^{-\left(\frac{s}{\lambda}\right)^{\kappa}}, \tag{7}$$

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

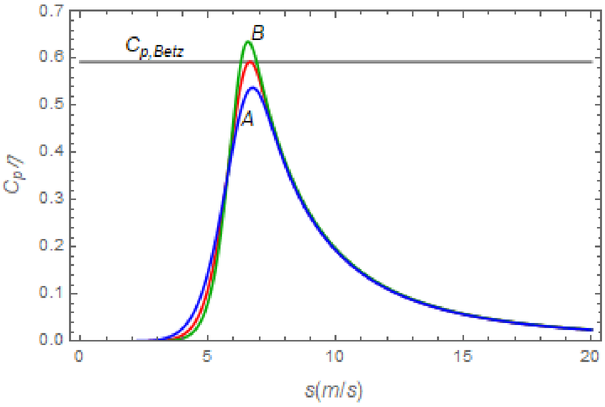

Figure 3. The power coefficients depend on the wind speed corresponding to three different shape parameters (κ = 8, 10, 12 for the lines from A to B) with λ = 6 m/s.

Since $\eta \leq 1$, $C_p \leq C_{p,Betz}$ ($C_{p,Betz}$ = 16/27, is the Betz limit), Eq. (7) leads to

$$\frac{3\lambda^3\left[\Gamma\left(\frac{3}{\kappa}\right) - \Gamma\left(\frac{3}{\kappa}, \frac{s^{\kappa}}{\lambda^{\kappa}}\right)\right]}{\kappa s^3} - e^{-\left(\frac{s}{\lambda}\right)^{\kappa}} \leq C_{p,Betz}. \tag{8}$$

Equation (8) is solved by animation simulation (see Figure 3) and gives $\kappa \leq 10$, with every value of λ.

Taking into account the effect of rain, the power is reduced a quantity $F_d s$,

$$P_d(s) = P(s) - F_d s, \tag{9}$$

with F_d from the expression (1) and the wetness W from (2a) or (2b).

3. SIMULATION RESULTS

The model is simulated by Wolfram Mathematica [11]. Input parameters included:

1. Swept shape of turbine blades:
   - Half of rotor height *z*, surveyed from 2 to 7 m;
   - Radius of the rotor *a*, surveyed from 1 to 5 m;
2. Rain and air components:
   - Air density, surveyed from 0.1 to 1.5 kg/m^3;
   - Density of raindrop, from 800 to 1000 kg/m^3;
   - Diameter of raindrop, from 0.1 to 0.6 cm;
   - Rainfall intensity, from 1 to 200 mm/h;
   - Tail-wind speed of rain, from -5 to 14 m/s;
   - Cross-wind speed of rain, from 0 to 30 m/s;
   - Vertical downward rainfall speed, from 5 to 15 m/s;
3. The parameters of the wind turbine:
   - Shape parameters, surveyed from 1 to 10;
   - Scale factor, measured from 0.1 to 20 m/s;

The simulation steps are as follows:

- First, select the geometry of swept space of the turbine blades, then the shape parameter and wind scale factor. Rain and wind parameters selected for medium and low wind conditions.
- Equations including equation of rainfall, expressions of wetness, impact force of raindrops, turbine power under the effect of rain, and their optimal values are evaluated and graphically depicted.
- The parameters can be changed according to the specific case, and the results are illustrated respectively on the figures.

With this method, it is possible to assess the effect of rain on wind turbine power, thus offering solutions for turbine blade design or optimal speed for wind turbines in order to use wind energy in rainstorm conditions. The simulation results are given in Table 2a and 2b, Figure 4 and Figure 5. The power loss of wind turbine is affected by the size of the raindrop, and by the increase of cross-wind speed of rainfall.

Table 2a. Some simulation results for operation parameters of HAWT.

Turbine type	Raindrop diameter	Cross-rain speed	Optimal wind speed	Minimum wetness	Power coefficient	Idealized power (MW)	Power loss (MW)
HAWT	0.2 cm	0 m/s	5 m/s	3 m^2	0.297	1.09	1.06
	0.2 cm	7 m/s	5 m/s	3 m^2	0.297	1.09	1.05
	0.3 cm	0 m/s	5 m/s	3 m^2	0.297	1.09	0.94
	0.3 cm	7 m/s	5 m/s	3 m^2	0.297	1.09	0.89
	0.4 cm	0 m/s	5 m/s	3 m^2	0.297	1.09	0.58
	0.4 cm	7 m/s	5 m/s	3 m^2	0.297	1.09	0.37

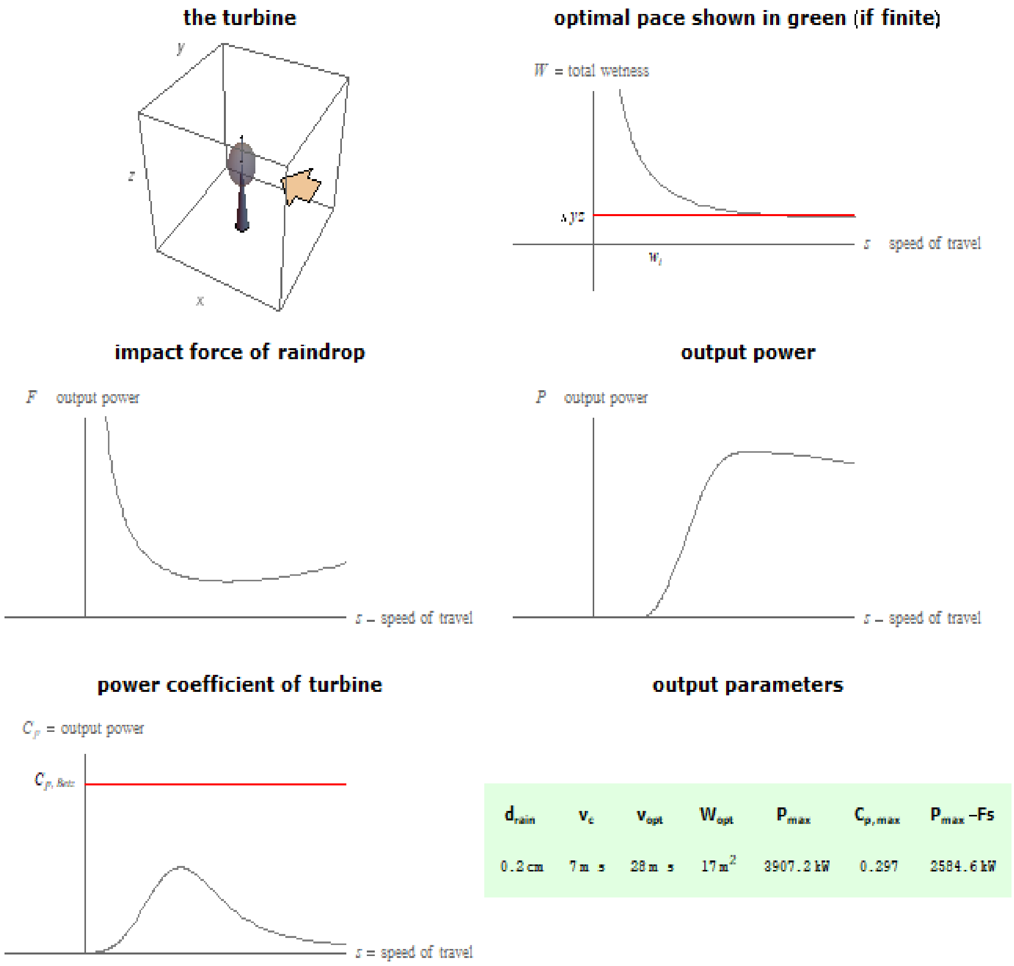

Figure 4. Simulation results for VAWT with r = 2 m, z = 3 m.

Table 2b. Some simulation results for operation parameters of VAWT

Turbine type	Raindrop diameter	Cross-rain speed	Optimal wind speed	Minimum wetness	Power coefficient	Idealized power (MW)	Power loss (MW)
VAWT	0.2 cm	0 m/s	18 m/s	16 m^2	0.297	3.91	2.59
	0.2 cm	7 m/s	28 m/s	17 m^2	0.297	3.91	2.58
	0.3 cm	0 m/s	18 m/s	16 m^2	0.297	3.91	2.52
	0.3 cm	7 m/s	28 m/s	17 m^2	0.297	3.91	2.48
	0.4 cm	0 m/s	18 m/s	16 m^2	0.297	3.91	2.32
	0.4 cm	7 m/s	28 m/s	17 m^2	0.297	3.91	2.17

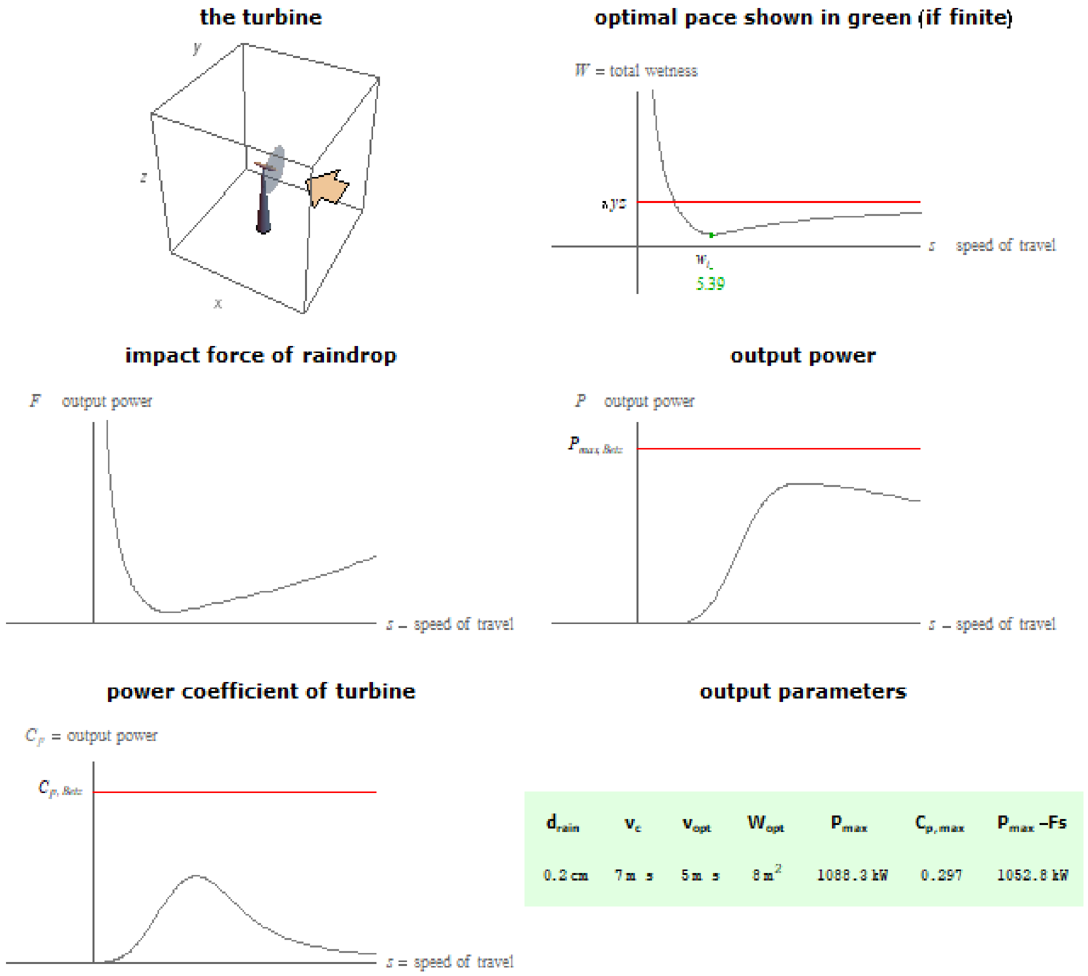

Figure 5. Simulation results for HAWT with a = 0.3 m, R = 3 m.

4. DISCUSSIONS AND CONCLUSIONS

With the development of wind power as well as an increase of extremely wind and rain events, wind turbines can be affected by wind and rain. In this study, a method of analyzing generated power of wind turbines under the conditions of rain and rainstorm is proposed. The main conclusions are as follows.

1) This article is the first study to investigate the effects of rain on wind turbine power.
2) The wetness of the turbine blades is closely related to the impact force of the rain. The results show that there is minimum wetness, as the impact force of the rain on the turbine blades is also minimal, and therefore the power loss due to rainfall is also minimal.
3) The characteristic curve of the power calculated according to the statistical analysis is quite consistent with the actual measured characteristic curve, only by selecting the appropriate shape parameter and scale factor.
4) The power loss in rainfall is significant when the size of raindrop increases. That's easy to understand, because the heavier the rains, the more likely they are to affect the speed of rotation of the turbine blades. The power loss is also strongly influenced by rain. Power is also slightly reduced when other parameters such as downward rainfall, tail-wind and cross-wind speeds increase. However, the best power can be found, depending on the case, for optimal wind speed and minimum wetness, or the impact force of the rain is minimal.
5) In comparing with HAWT, VAWT operates for better power output at higher optimal wind speeds (no twist). It looks like VAWT is quite suitable in case of heavy rain and wind. However, during heavy rain and strong wind, the structure of VAWT will be difficult to maintain, which has not been evaluated in the studies here. Therefore, VAWT will not be suitable for installation in rainy regions.

Economic capability requires optimal configurations of the components of the wind turbine. To develop an optimal system, it is necessary to have a viable model. Although there have been previous studies, mainly for mechanical oscillations in large wind conditions or heavy rainstorms, it has not yet shown the effect of rain on power with specific predictions, in different weather conditions. The model is simulated here to predict the properties of the wind turbine with the different geometries of swept space of turbine blades and the different conditions of the rain. Simulation results of wetness, impact force of rainfall and power output, and power coefficient are visually illustrated by interacting and adjusting the animation according to the purpose of the survey. The model is relatively simple but still produces fairly accurate results.

This subject is in the field of research and implementation of distributed and renewable energy solutions. Therefore, this topic is necessary for Vietnam's high-tech and sustainable economic development strategy.

REFERENCES

1. Wang Z., Zhao Y., Li F., and Jiang J. - Extreme Dynamic Responses of MW-Level Wind Turbine Tower in the Strong Typhoon Considering Wind-Rain Loads. Hindawi Publishing Corporation, Mathematical Problems in Engineering **2013** (2013) Article ID 512530.

2. Wan T. and Pan S.-P. - Aerodynamic Efficiency Study under The Influence of Heavy Rain via Two-Phase Flow Approach, 27th International Congress of The Aeronautical Sciences, ICAS, (2010).
3. Cohana A. C. and Arastoopoura H. - Numerical simulation and analysis of the effect of rain and surface property on wind-turbine airfoil performance. International Journal of Multiphase Flow **81** (2016) 46-53.
4. Al B. C., Klumpner C. and Hann D. B. - Effect of Rain on Vertical Axis Wind Turbines. International Conference on Renewable Energies and Power Quality, ICREPQ'11, Las Palmas de Gran Canaria, Spain. Proceeding **1** (9) (2011) 1263-1268.
5. Abuku M., Janssen H., Poesen J., and Roels S. - Impact, absorption and evaporation of raindrops on building facades. Building and Environment **44** (1) (2009) 113–124.
6. Li H.N., Ren Y.M., and Bai H. F. - Rain-wind-induced dynamic model for transmission tower system. Proceedings of the CSEE **27** (30) (2007) 43–48.
7. Chen W. L. and Wang Z. L. - The trial research on the behaviours of artificial rainfall by simulation. Bulletin of Soil and Water Conservation **11** (2) (1991) 55–62.
8. Marshall J. and Palmer W. - The distribution of raindrops with size. Journal of Meteorology **5** (1948) 165–166.
9. Villermaux E. and Bossa B. - Single-drop fragmentation determines size distribution of raindrops. Nature Physics **5** (9) (2009) 697–702.
10. Seongtaek Seo - Run or walk in the rain? (orthogonal projected area of ellipsoid). IOSR Journal of Applied Physics (IOSR-JAP) **7** (2) (2015) 139-150.
11. Wellin P. R. - Programming with Mathematica. Cambridge Publishing, (2013).