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Effect of Rain on Vertical Axis Wind Turbines

B. C. Al[1], Dr C. Klumpner[2] and Dr D. B. Hann[1]

[1]Energy and Sustainability Division, and
[2]Electrical Systems and Optics Division, University of Nottingham, Nottingham, NG7 2RD, UK
Tel: ++44(0)115 951 4153
Contact e-mail: david.hann AT nottingham.ac.uk

Abstract

Results are presented that demonstrate that rain will have a significant effect on the output of a vertical axis wind turbine. The experiments were carried out in the climatic wind tunnel at the University of Nottingham where water was sprayed into the wind tunnel to simulate several rainfall rates. The rain had the effect of increasing the drag, slowing the rotational speed of the wind turbine and decreasing the Power for the equivalent wind speed. The increasing in the drag has the additional effect of decreasing the optimal coefficient of performance as the rainfall rate is increased. Similar studies in airfoil performance in the rain have shown that the increase in drag and decrease in lift is related to the chord length of the airfoil and so could potentially be larger for larger turbine blades. This could have an effect on the control strategy necessary for controlling wind turbine performance and will need to be studied further.

Keywords: renewable energy, Wind power, optimal tip speed ratio, precipitation.

Introduction

In order that the more ambitious targets being set around the world for wind power production can be met, 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 be able to predict how production will vary with the weather so that back-up power can be ramped up in time [1].

One area that has not undergone any significant research is the effect of rain on wind turbine performance. There have been several contradictory reports in recent literature. One paper suggests that the power increases after rain, and this has been attributed to the cleaning of soiled blades [2]. Other work has suggested that the increased mass density during rain will improve the performance of the turbine due to changes in humidity despite the fact that humidity decreases the density of air.

Corrigan and Demiglio [3] reported a 27% decrease in power output in rain in the 80's, but there have been few follow on studies to investigate this and none for VAWT. Nebel and Molly [4] noted similar results to [3] while another study showed that for a different type of rain and turbine there could be a 3% power output increase [5]. This is a confusing state of affairs and more work needs to be carried out in this area if wind power is to achieve its goal especially offshore or in wetter climates.

Figure 1: Image of the Ropatec (150W) [6] wind turbine used in this study.

Domestic production of wind energy is not as cost effective as large wind farm production and typically has a capacity factor of the order of 1-2% compared to a wind farm which has a capacity factor of 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. Recent studies suggest that most of these turbines do not produce the power output that the manufacturers have suggested based on their tests in dry wind tunnels and therefore are less economically viable than initial studies suggested [7]. Reductions in power output due to rain would have a larger financial impact on owners of these turbines and could go some way to explaining the lower than predicted power output from these systems, particularly for certain power optimisation strategies.

Expected effect on VAWT

Results from the aircraft industry and airfoil research show that a decrease of lift and an increase of Drag is dependent on the rain type and rainfall rate. This loss can lead to a significantly increased stall angle from dry but is very complex since large rain droplets will have a different effect to small raindrops at the same rainfall rate.

There have been a number of studies in this area and this will be summarised here.

- Rain will decrease the Coefficient of Lift C_L of the airfoil at low angles of attack, but increase it at higher angles of attack [9].

- A laminar airfoil undergoes a larger decrease in C_L in the rain than a turbulent airfoil. It can lose up to 75% lift in the rain. The wetability of the surface also has a dramatic effect for laminar wings as the flow will be triggered to turbulence differently for different flow patterns of the rain over the wing[10].

- As the rain impacts the airfoil, the spray of the fine droplets that are splashed back will slow down the boundary layer and this can change the flow of air over the wing, decreasing the Lift and increasing drag [11]

- The wing will have higher lift at higher angle of attack when wet [12]. Roughening the wing at the leading edge can have the effect of increasing or decreasing the lift dependant on the method used.

A wing will have increased drag in the rain, although roughening the leading edge can decrease the drag at high angles of attack.

The result of this is that it is expected that the drag should increase and the Lift should decrease, with laminar airfoils having the biggest difference between dry and wet conditions. It is suspected that, as for airfoils, the effect will depend on the raindrop size and velocity and the density of the raindrops. This means that a light drizzle might be different to a light shower. Since the UK in particular has regions where there are 240 days of rain each year, this might have an impact.

Experimental Procedure

An experiment was performed using a 150 W Ropatec VAWT in the climatic wind tunnel at the University of Nottingham (Figure 1). This tunnel-simulated rain by the use of spray nozzles mounted in the ceiling of the tunnel at several points in the working section. The rainfall rates used in this experiment are 10, 15 and 20 mm/hr, which corresponds to a light shower with increasing density of droplet impacts.

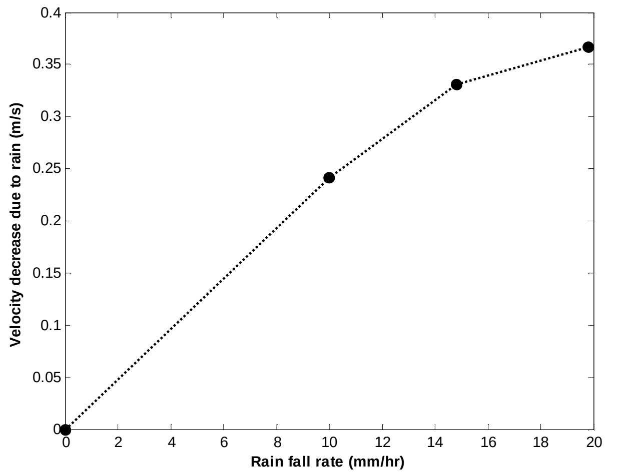

Figure 2: This graph shows that the velocity in the wind tunnel decreases slightly when rain is introduced. This is averaged for each rainfall rate.

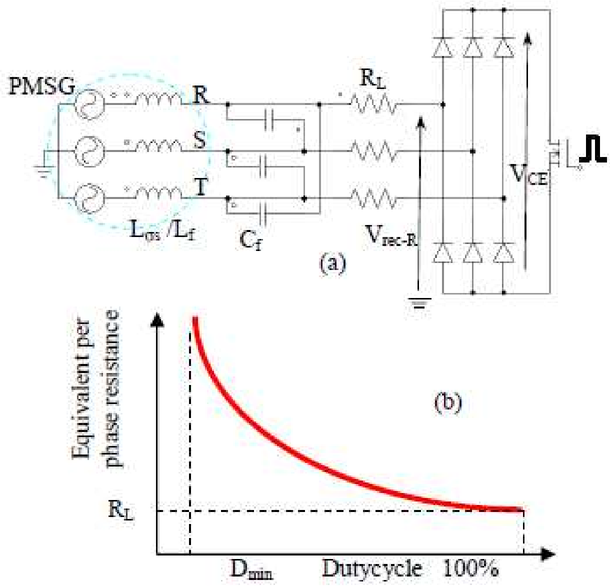

Figure 3: a) Schematic of the dump load with low harmonic impact; b) equivalent load resistance variation versus duty-cycle.

Figure 2 demonstrates that the spray technique for producing rain had an unintended effect in that it slowed the mean wind speed through the tunnel. This was found to be consistent over the range of velocities investigated here and the average loss is shown in the figure. This defect will not be significant in real atmospheric rain and this defect can be traced to the acceleration of the sprayed water drops as they enter the wind tunnel until they have reached the mean flow speed, which slows the mean velocity. This defect is less than 4% of the mean wind velocity in the worst case.

It should be noted that for the results shown in this paper, the velocity used has taken this defect into account. When this was not included, the drop of the optimal C_p was almost twice as large.

The load of the wind turbine was varied by the use of an innovative circuit that varied equally the load resistance for each of the three phases of the electrical generator $(R_{eq})$by using a single active switching device whilst causing insignificant level of current harmonics [7]. The output of the Permanent Magnet Synchronous Generator (PMSG) at the core of the wind turbine was controlled by a power electronic adjustable dump load topology as shown in figure 3a). The equivalence resistance (R_{eq})can be smoothly adjusted by changing the Duty cycle of transistor's gating signal and the fact that there are negligible harmonics mean that the control system can easily be upgraded to provide digital control system for a low power PMSG wind turbine in our wind tunnel (Figure 3 b) .

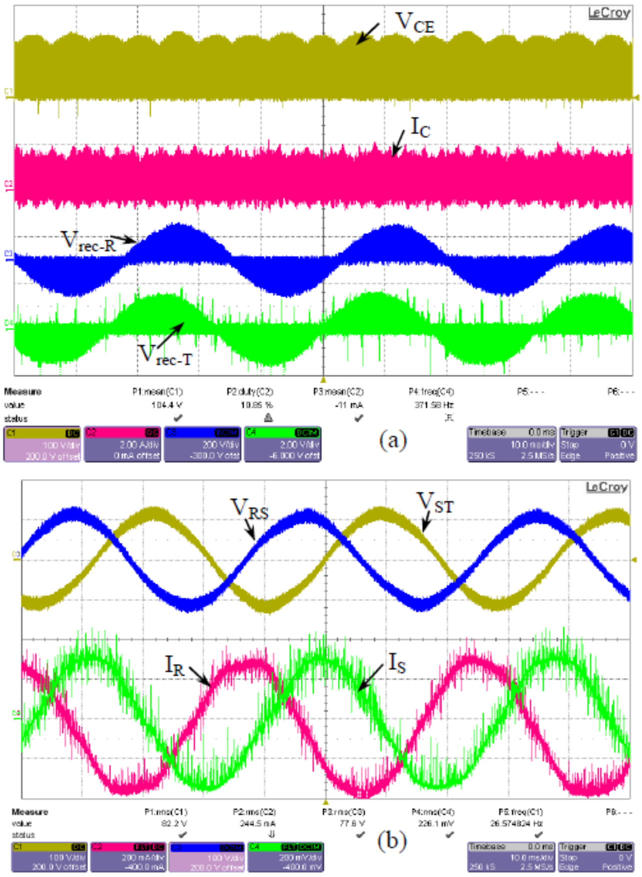

Figure 4: Experimental results: a) the voltage across (top) and the current though (second) the dump-load transistor and two of the resulting line-to-line voltages seen at the AC input of the diode rectifier (third, fourth) ; b) the generator line to line voltages (top) and two line current (lower).

The various voltage and current waveforms reflecting the operation of the electronic dump load and the fact that sinusoidal generator stator current obtained are shown in Figure 4. The result of decreasing the resistance was to increase the load current/braking torque that slowed the rotational speed of the turbine which changed the tip speed ratio $\lambda = \left(\frac{\omega r}{v}\right)$ of the turbine. This allowed the power performance coefficient C_p to be determined for a range of tip speed ratios to determine the most efficient tip speed ratio for this wind turbine.

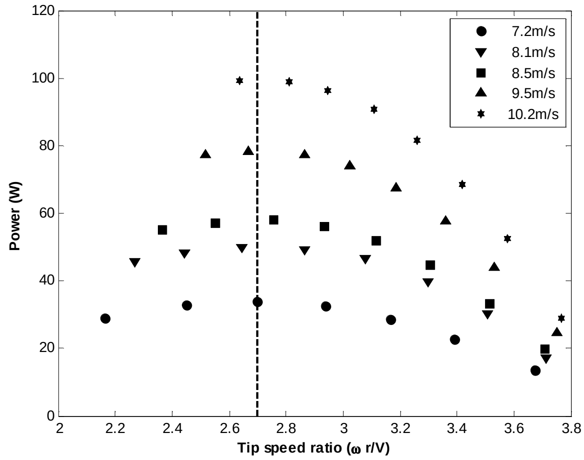

Figure 5: Variation of the Power output with Tip Speed Ratio and wind speed in dry conditions.

The Power conversion coefficient (C_p) was determined from the measured power (P) and wind speed (v) using:

$$C_p = \frac{P}{\frac{1}{2}\rho A\, v^3} \qquad (1)$$

where A is the cross-section area of the turbine and ρ is the density of the air. The torque coefficient (C_Q) is given by:

$$C_Q = \frac{C_p}{\lambda} \qquad (2)$$

Experimental Results

The usefulness of the power electronic adjustable dump load topology is shown in Figure 5. By changing the duty cycle of the square wave trigger, a spread of tip speed ratios could be achieved easily and quickly. The optimal tip speed ratio for this turbine is low, about 2.7, reflecting the high drag due to the width of the blades and the supports.

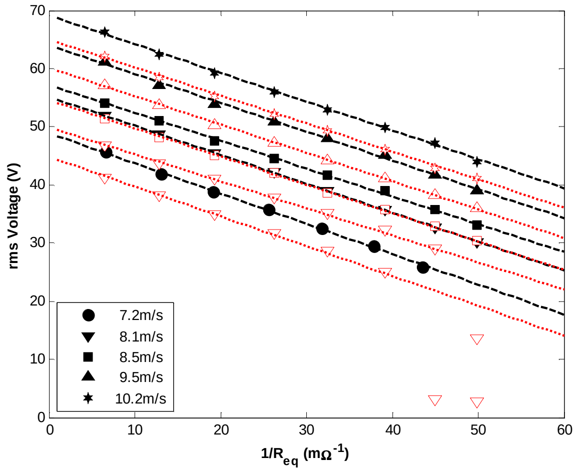

Figure 6: Variation of the averaged Voltage with resistance and wind speed for dry (solid symbols) and wet conditions (open symbols).

Figure 6 shows that the effect of rain is to decrease the available power, which for a given resistance results in slower speed and voltage at the generator terminals. The voltage and the rotational speed are linearly related and this indicates that the rotational speed of the generator decreases as the rainfall rate is increased for the same air flow and effective load of the turbine. The gradient of the voltage maintains the same proportional relationship to the inverse resistance, but the intercept of the line with the axis has decreased with decreasing wind velocity and when rain is introduced.

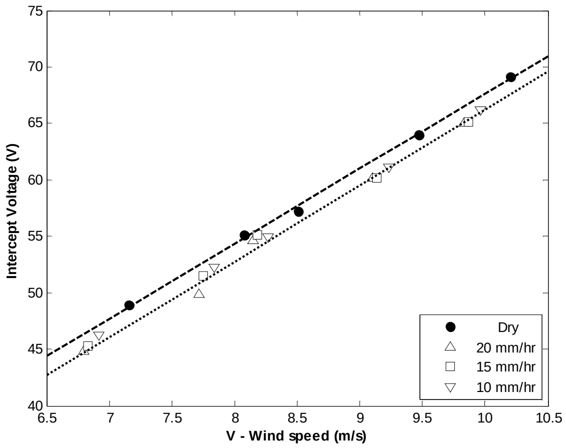

Figure 7: This graph demonstrates that the decrease in the voltage noted in Figure 5 is not related to the velocity decrease due to the rain.

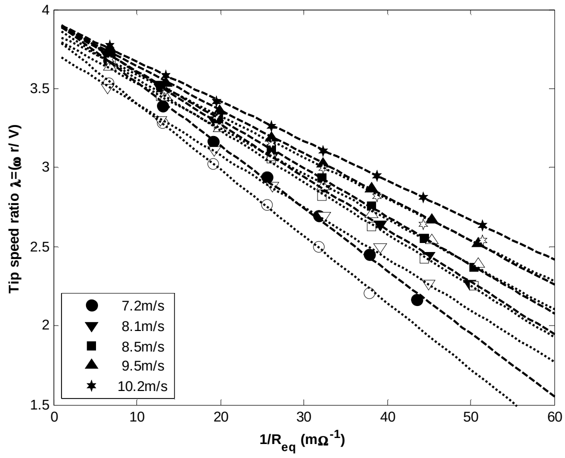

Figure 8: Variation of the Average Tip speed ratio with resistance load and wind speed showing the effect of rain (solid symbols are for dry conditions and open symbols are for wet conditions).

It might be argued that the decrease in the intercept of these voltage lines in Figure 6 is due to the decrease in the velocity of the wind when the rain is introduced. If this were true, then the intercept voltage would be proportional to the wind velocity. Figure 7 shows that the intercept voltage for the three cases of rain are all lower for the equivalent wind speed compared to the dry case. There is little scatter in the dry case, the results are very consistent. In the wet cases the results are much more scattered, since the distribution of the surface roughness induced by the droplets impacting on the surface will also be random.

The fact that the rotational speed has decreased is evident from the relationship of the tip speed ratio to the inverse load as shown in Figure 8. This decrease in rotational speed could have consequences in the choice of the control algorithm. It was also noted that the turbine was more liable to drop to the slower drag mode when λ dropped below 2 and so no longer be running in the more efficient lift mode.

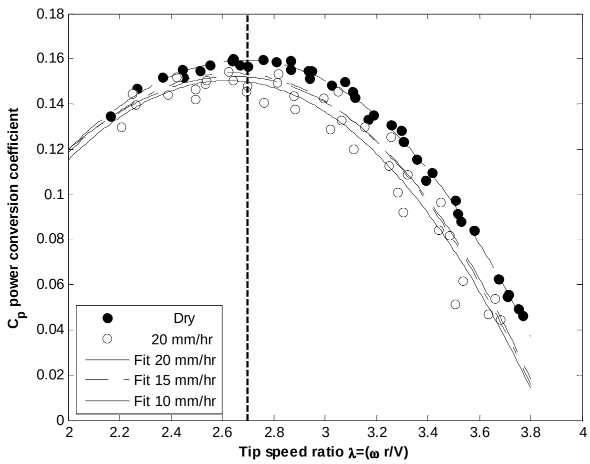

Figure 9: Graph showing that the optimal tip speed ratio of the wind turbine changes when rainfalls. Solid symbols are for dry conditions and open symbols are wet.

In Figure 9 it can be seen that variation of the wind speed and effective resistance produces a single curve relating the tip speed ratio to C_p for dry air. The effect of the three rainfall rates tested on the coefficient of performance of the turbine are also shown in Figure 9. It is clear that for these relatively light rains, the optimal tip speed ratio has decreased and the maximum value of C_p has decreased by about 10%. This is consistent with the increased drag losses that would be expected due to a roughening of the surface due to droplet adhesion, and the disruption of the leading edge boundary layer due to droplet impact.

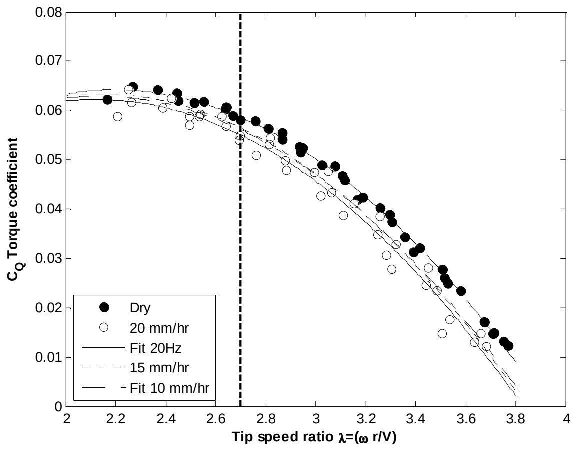

Figure 10: Graph showing the coefficient of Torque as it varies with tip speed ratio for wet and dry conditions. (solid symbols are for dry conditions and open symbols are wet).

Figure 10 shows that the coefficient of torque also decreases when the rain is introduced. Again there is little difference between the three rain conditions. It was also noted that the decrease in torque and power was maintained for some time after the rain was switched off, in some cases up to 10 minutes. This was similar to the time it took for the droplets on the wind turbine blades to disappear.

Discussion

The values of C_p and C_Q for the three wet cases are relatively close together and different than the dry case. For this rain type it was expected that there would be little splashing of the raindrop as it impacted, so no step change in behaviour was expected as the density of the rain was increased. This suggests that it is most likely that the roughening of the surface and the change in shape of the trailing edge due to the presence of water films is a stronger effect than the momentum defect due to droplet impact.

In wind turbine blade design it is possible to predict the optimal value of C_p by balancing the increase in the volume swept due to the increase in the tip speed ratio, to the increasing in the drag losses due to the increase in the tip speed ratio. An increase in the drag coefficient would have less effect at low TSR and an increased effect at higher TSR. It would also effectively shift the maximum to a lower TSR. All of these effects are visible in Figure 9.

The decrease in the optimal C_p is expected to increase with rainfall rate; although airfoil results in the rain suggest that different rain patterns and hence impact outcomes can have differing effects. For example Walker and Wade [5] suggested that a light misty rain could actually increase the optimal C_p. This was also noted as a possibility in other measurement not presented here for a Horizontal Axis Wind Turbine, where losses of up to 30% were noted in a situation with heavy rain.

Corrigan and Demiglio [3] predicted that that increasing the chord length of the blade would also increase the power loss, and, although care should be taken when comparing stationary airfoil results with those in a rotating and constantly accelerating frame of reference, this would suggest that the effect could be a bigger problem in larger wind turbines.

The rainfall type used here is that of a light shower. Other test performed in our climatic wind tunnel with this and other wind turbines suggest that a heavier rainfall rate will increase the power loss, but these preliminary results were not as rigorously verified as these results and are not presented here.

These results confirm the results by [3] and suggest that, in wet climates like the UK where rain can occur in some regions for 2/3rds of the days of a year; this power decrease should be included in predictor models. Perhaps the predicted rainfall should be used as well as the wind speed to predict if back-ups should be phased in when a weather front moves through an area. This will be especially true when wind supplies a significant portion of the power input into the national grids. Since offshore is likely to be wetter, then this argument is equally true here especially since turbines can generate their own moving fog bank in their wake in certain meteorological conditions. This could affect some of the turbines in the wind farm detrimentally.

Conclusions

This work presented confirmed the measurements noted in 1985 and suggests that further work is necessary to study the effect of the rain on the trailing edge and tip vortices to see if shape changes could decrease the loss of efficiency and to understand how this effect will affect chosen power optimisation strategies for domestic turbines. It has also been noted that the surface finish or coatings can affect the lift loss in airfoils and this might also be an area of study for the future.

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