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Turbulence influence on optimum tip speed ratio for a 200 kW vertical axis wind turbine

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Abstract. The influence of turbulence intensity (TI) on the tip speed ratio for maximum power coefficient, here called $\lambda_{C_p\text{-max}}$, is studied for a 200 kW VAWT H-rotor using logged data from a 14 month period with the H-rotor operating in wind speeds up to 9 m/s. The TI-$\lambda_{C_p\text{-max}}$ relation is examined by dividing 10 min mean values in different turbulence intensity ranges and producing multiple $C_p(\lambda)$ curves. A clear positive relation between TI and $\lambda_{C_p\text{-max}}$ is shown and is further strengthened as possible secondary effects are examined and deemed non-essential. The established relation makes it possible to tune the control strategy to enhance the total efficiency of the turbine.

1. Introduction

Wind turbines can be categorized by the orientation of their axis of rotation, compared to the flow direction, into two groups: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Even though the HAWT has by far been the most successful concept, with the large and economically feasible turbines of today, the VAWT concept has several advantages. VAWTs typically have fewer moving parts and a generator located at ground level, which could ultimately lead to lower maintenance cost and higher availability [1]. Also, in [2] it has been shown that the concept is more suitable for up-scaling than the HAWT concept. Furthermore, the VAWT concept has potentially lower noise emission [3].

Turbulence is of great importance as it both affects the power output and causes random, fluctuating loads, which stress both the turbine and the tower structure. Turbulence needs to be addressed when designing the turbine, both regarding structural excitation, maximum load and fatigue predictions as well as power control routines [4]. Excessive turbulence has been found to be the most important factor in reducing the life time of the wind turbine structure [5]. The effect of turbulence on wind energy extraction is difficult to generalize since turbulent gusts affects wind alignment, airfoil performance and power control [6]. The effect of turbulence on HAWT power curves has been examined in [7-10]. In [11], the ability to cope with turbulence for small, urban-sited VAWTs are examined and deemed as good. Also by the authors of this work, [12] investigates the influence of turbulence on wind energy extraction. However, there is still a lack of experimental knowledge on the turbulence influence for larger VAWTs, for example how the turbine control strategy can account for turbulence to improve the energy extraction.
To quantify the wind turbulence, the measure turbulence intensity (TI) is commonly used. TI stems from the standard deviation of the measured wind speed values, thus it can be obtained using a cup anemometer normally used for measuring wind speed. Measuring turbulence intensity with a cup anemometer may be problematic, as noted in [13]. For example, mainly the horizontal turbulence is accounted for as the vertical turbulence will have small influence on the horizontal wind speed. It is also generally the case that large TI is accompanied by convective atmospheric conditions and low wind shear [14]. Wind shear affects power production since the mean wind speed varies within the rotor area, affecting the relation between the measured hub height wind speed and the effective mean wind speed for the rotor area. Using more advanced equipment such as a sonic detection and ranging (SODAR) apparatus, the wind speed can be tracked over the entire height of the rotor and all components of the turbulence can be measured, thus eliminating uncertainties from vertical turbulence and atmospheric conditions. However, cup anemometers are commonly used for measuring TI and while the TI values may be underestimated, the cup anemometer measurements do seem to correctly track changes in turbulence level [13, 14].

The tip speed ratio, i.e. the ratio between the speed of the blade tip and the undisturbed wind speed, has a large influence on the power coefficient for a wind turbine. To evaluate the performance for all possible tip speed ratios, a power coefficient curve, often stylized as $C_p(\lambda)$ curve, showing aerodynamic power coefficient as a function of tip speed ratio can be produced. The control strategy implemented for a variable speed wind turbine usually applies adapting the rotational speed to the tip speed ratio for maximum power coefficient, here called $\lambda_{C_P_{-\text{max}}}$.

In this paper, the impact of turbulence on optimum tip speed ratio for a 200 kW VAWT is investigated using turbulence intensity from cup anemometer measurements over a period of about 14 months. This is done by producing $C_p(\lambda)$ curves for different turbulence intensities and the results can be used when programming the control strategy to obtain maximum power coefficient regardless of turbulence intensity. All data used in this work is collected from periods of the turbine operating in normal mode, although somewhat affected by limitations regarding wind speed and rotational speed. Previously by the authors of this work, [12] has also been based on the same data.

2. Theory

2.1. Power absorption

The available power in the wind for a cross-section area $A$, can be described by

$$P_{\text{wind}} = \frac{1}{2} \rho A v^3$$  \hspace{1cm} (1)

where $\rho$ is the density of the air and $v$ the wind speed. For a vertical axis wind turbine, the cross-section area $A$ is a rectangle, calculated as the turbine diameter multiplied with the blade length. The aerodynamic power coefficient, i.e. the wind turbine’s ability to convert wind energy to mechanical energy, can be defined as

$$C_p = \frac{P_{\text{aero}}}{P_{\text{wind}}}$$  \hspace{1cm} (2)

where $P_{\text{aero}}$ is the aerodynamic power output, i.e. the amount of power extracted by the rotor and converted into mechanical power. $P_{\text{aero}}$ can be written as

$$P_{\text{aero}} = \frac{P_{\text{el}}}{\eta_d}$$  \hspace{1cm} (3)

where $P_{\text{el}}$ is the electric power output and $\eta_d$ is the driveline efficiency, i.e. the combined efficiency for generator and mechanical components, further described in “3.5.4. Normalization due to driveline
efficiency”. The aerodynamic power coefficient can be described as a function of the tip speed ratio, \( \lambda \), which is the ratio between the velocity of the blade and the wind speed, thus calculated as

\[
\lambda = \frac{\omega R}{v}
\]  

where \( \omega \) is the angular velocity of the turbine, \( R \) is the turbine radius and \( v \) is the wind speed.

2.2. Turbulence intensity

Turbulence intensity (TI) is a measure of the wind turbulence and thus also the wind's tendency to alter speed. It is defined as

\[
TI = \frac{\sigma_v}{\bar{v}}
\]  

where \( \sigma_v \) is the standard deviation of the wind speed for a time period and \( \bar{v} \) is the mean wind speed for the same period. The time period used must be longer than the turbulent fluctuations but shorter than periods associated with long-term wind speed variations such as diurnal effects [4].

3. Method

3.1. Wind turbine system

The VAWT we consider in this study is a so-called H-rotor, which is a Darrieus-type [15] turbine with straight fixed blades. A 200 kW VAWT (hereafter referred to as the T1-turbine) was designed and erected in 2010 by the company Vertical Wind AB in collaboration with Uppsala University. Only one 200 kW turbine was ever built by Vertical Wind AB, making the T1-turbine unique. The turbine, which is located at Thorsholm (56°56'29"N 12°30'38"E) just outside of Falkenberg at the west coast of Sweden, is today owned by Uppsala University and the subject of research in a variety of fields. This particular VAWT has a direct drive permanent magnet synchronous generator which is mounted at the bottom of the tower and connected to the rotor by a steel shaft. The rotor consists of three 24 m long straight blades that are connected to the shaft by two struts each. Both blades and struts are made out of fiberglass. The blades are fixed, but the variable speed of the turbine is used to control the stall effect so that the rated power can be obtained between the rated wind speed and the cut-out wind speed.

The T1-turbine has a tower made out of laminated wood, which from the start was free standing, but after two years was complemented with support from three guy-wires. The effect of the guy-wires on the tower dynamics has been examined in [16].

3.2. Wind turbine operation

As in [12], the measurements used in this work are from periods of automatic mode operation between June 2011 and August 2012. After adding the guy-wires, the tower was stiffened, raising the first mode eigenfrequency of the tower which is now excited at 23 rpm. Also, the eigenfrequency of the wire itself is excited at 17 rpm. This necessitates jump-routines which have been implemented for the 17 rpm case. Awaiting further dynamic tests, 22 rpm has been used as a new temporary upper limit for the rotational speed. Furthermore, as a precaution measure, the turbine has with few exceptions not been operating at wind speeds above 9 m/s.

Below the rated wind speed, the turbine is set to operate at a tip speed ratio of 3.8, which is slightly lower than optimal. This strategy enables more stable operation, as operating on the left side of the optimum operating point allows for more rapid stall control [12]. When the rated power is reached, the tip speed ratio control is abandoned for power control, with small variations in rotational speed to control the stall effect and thus keeping the power constant until the cut-out wind speed is reached. For more details about control of the T1-turbine, the control strategy is further described in [17] and the
stall control is demonstrated in [18]. Results in this paper are based on 1030 h of data, excluding data rejected according to “3.5.5. Data rejection”.

| Table 1. Properties of the T1-turbine. |
|--------------------------------------|
| Rated power                          | 200 kW            |
| Turbine diameter                     | 26 m              |
| Tower height                         | 38 m              |
| Hub height                           | 41 m              |
| Wing length                          | 24 m              |
| Swept area                           | 624 m²            |
| Cut-in wind speed                    | 4 m/s             |
| Rated wind speed                     | 12 m/s            |
| Cut-out wind speed                   | 25 m/s            |
| Survival wind speed                  | 60 m/s            |
| Rotational speed                     | 16-33 rpm         |
| Operational tip speed ratio          | 3.8               |
| Power regulation                     | Passive stall     |
| Wing/strut material                  | Fiberglass composite |
| Tower material                       | Laminated Wood    |

3.3. Experimental setup

The experimental setup consists of the complete grid-connected wind turbine, as described in Table 1, including the control system and the wind meteorological mast belonging to the turbine. The measurements were logged, at a sampling frequency of 1 Hz, on the same CompactRIO (NI cRIO9074) used for the control system of the turbine. The DC power was measured with a SSET CEIZ04-55E4-1.0/0-400A current transducer and a Tektronix P5200 voltage transducer. The rotational speed of the turbine was measured by a 10-bit rotational encoder placed on the lower end of the drive shaft.

3.4. Meteorological measurements

The wind speed was measured by a Thies Clima 4.3351.00.161 cup anemometer, placed at a height of 42 m on a wind measurement mast situated 100 m from the actual turbine. The signals from the anemometer are measured by a PLC and logged by one of the cRIOs of the wind turbine control system.

Air pressure and temperature were retrieved from the Swedish Meteorological and Hydrological Institute (SMHI). The temperature was retrieved as hour values from Hanarp (56°51'45.1"N 12°39'46.1"E) situated 12 km south-east of the T1-turbine. The air pressure was retrieved as hour values from Torup (56°56'58.6"N 13°3'45.0"E) situated 33 km to the east of the T1-turbine, and then recalculated to the elevation of the rotor centrum of the T1-turbine. For the measurements, the air temperature ranged between -10.9°C and 27.3°C and the air pressure ranged between 0.98 bar and 1.04 bar. Inserting the temperature and pressure values into equation (13), the air density will range between 1.16-1.38 kg/m³.

1 The hub height includes the tower, the small hill covering the generator and half the hub shaft that is carrying the struts.
3.5. **Data acquisition and treatment**
As mentioned, all data from the turbine and the adjacent wind measuring mast was logged at a rate of 1 Hz. Air pressure and temperature were retrieved as 1 hour values. Matlab was then used for further analysis of all values.

3.5.1. **Power coefficient curve**
Consistent with IEC61400-12-1 [19], a 10 min mean value for wind speed is used in equation (1). This wind speed mean value is simply calculated by

\[ \bar{v} = \frac{1}{N} \sum_{i=1}^{N} v_i \]  

(6)

where \( v_i \) is the 1Hz wind speed value and \( N \) is the number of values. Hence, the mean aerodynamic power coefficient is calculated by

\[ C_p = \frac{P_{aero}}{\frac{1}{2} \rho \bar{v}^3} \]  

(7)

with the mean extracted aerodynamic power \( P_{aero} \) calculated by equation (3) and averaged over the same relevant time period as the mean wind speed \( \bar{v} \). Since the turbulence influence on the energy content of a certain mean wind speed is not accounted for, this will, for the wind speeds of interest in this work, lead to an overestimation of both power coefficient and the power curve. If wanting to neutralize the influence of this so called cubic effect, the mean wind cube can be used instead of the mean wind speed when calculating the power coefficient. The influence of the cubic effect on power curves and power coefficient curves and how to neutralize this influence is more thoroughly explained in [12]. The mean wind cube \( \bar{v}^3 \) and the new power coefficient, called \( \bar{C}_p \), is obtained respectively according to

\[ \bar{v}^3 = \frac{1}{N} \sum_{i=1}^{N} v_i^3 \]  

(8)

\[ \bar{C}_p = \frac{P_{aero}}{\left(\frac{1}{2} \rho A \bar{v}^3\right)} \]  

(9)

The difference compared to the IEC61400-12-1 standard is, that regarding both power and power coefficient, here the aerodynamic power \( P_{aero} \) is considered rather than the electric power \( P_{el} \) as instructed in the standard.

The mean tip speed ratio used for \( C_p(\lambda) \) curve is calculated as

\[ \bar{\lambda} = \frac{\bar{\omega} R}{\bar{v}} \]  

(10)

where \( \bar{v} \) and \( \bar{\omega} \) are the mean wind speed and mean angular velocity over the relevant time period.

3.5.2 **Method of bins**
As recommended in IEC61400-12-1 [19], the method of bins has been used to analyze the measured data. The measured data, presented as 10 min mean values, are divided into bins, i.e. equally sized sections depending on the value of the x-axis. After that, the mean values of the x-axis variable and the y-axis variable are calculated by
\[ x_i = \frac{1}{N_i} \sum_{j=1}^{N_i} x_{i,j} \]  
(11)

\[ y_i = \frac{1}{N_i} \sum_{j=1}^{N_i} y_{i,j} \]  
(12)

where \( x_{i,j} \) and \( y_{i,j} \) are the variables of data set \( j \) in bin \( i \) and \( N_i \) is the number of data sets (usually 10 min) in bin \( i \). The averaged values of \( x_i \) and \( y_i \) can then be used to create a curve which presents the relation between the variables.

### 3.5.3 Normalization due to air density

The air density grows with raised air pressure and lowered temperature, typically peaking during the winter season. To compare the turbines true ability for extracting wind energy at different air pressures and temperatures, each 10 min measurement period is normalized by accounting for changes in the air density. In equation (1), the air density for the period can be calculated by

\[ \rho_{10\text{ min}} = \frac{B_{10\text{ min}}}{R_0T_{10\text{ min}}} \]  
(13)

where \( B_{10} \) and \( T_{10} \) are the measured air pressure and temperature for the specific 10 min period and \( R_0 \) is the gas constant (287.05 J/(Kg K) for air) [19]. When calculating \( C_P \) with equation (2), the normalization is incorporated in \( P_{\text{wind}} \). For power curves, the normalization is done by adjusting the power output according to

\[ P_n = P_{10\text{ min}} \cdot \frac{\rho_0}{\rho_{10\text{ min}}} \]  
(14)

where \( P_n \) is the normalized power output, \( P_{10\text{ min}} \) is the measured power averaged over 10 minutes and \( \rho_o \) is the reference air density, here set to the ISO standard atmosphere of 1.225 kg/m³ [19].

### 3.5.4 Normalization due to driveline efficiency

The driveline efficiency of a wind turbine can vary quite extensively depending on operating conditions and to compare the turbines aerodynamic performance, it needs to be accounted for. In this work, normalization for driveline efficiency is implemented for each 1Hz measurement value when calculating \( P_{\text{aero}} \) and \( C_P \). The driveline efficiency is retrieved from

\[ \eta_d = \eta_g \cdot \eta_m \]  
(15)

where \( \eta_g \) is the generator efficiency and \( \eta_m \) is the mechanical losses, for example in couplings and bearings. Here, the driveline efficiency \( \eta_d \) is the relation between the aerodynamic power converted by the rotor and the measured DC power, hence the efficiency of the DC/AC-converter does not need to be accounted for. The T1-turbines generator efficiency \( \eta_g \) used in equation (15) is found from simulations and presented in [20]. As an approximation, the mechanical losses of the T1-turbine is estimated to be equivalent to an efficiency of 0.99 at full power and maximum rpm and then set to vary linearly with the rotation speed. For the operational conditions of this work, \( \eta_d \) will mainly be found within 0.70-0.95 with a mean of 0.85.

### 3.5.5 Data rejection

Samples containing start or stop routines have been rejected. As low power data may magnify eventual measurement errors, samples with a mean power less than the approximate cut-in threshold of 5 kW have also been rejected. Sequences when the turbine was not operating in its normal routine, for example when testing or tuning the control system, were also rejected.
4. Results and discussion

In Figure 3a, the experimental $C_P(\lambda)$ curve of the T1-turbine is displayed in a similar way as in \[12\], indicating a maximum $C_P$ of 0.33 at a $\lambda_{C_P-\text{max}}$ of 4.3. Consistent with the IEC61400-12-1 standard, for Figure 3a (as well as Figure 2, 4 and 5), 10 min mean values are used and binned as described in “3.5.2 Method of bins”. The figures are all based on the same 1030 h of experimental measurements. In Figure 2, several curves are presented, each one representing a different TI span. Third grade curves are fitted so that the maximum $C_P$ value and thus $\lambda_{C_P-\text{max}}$ can be found, resulting in the plot of the relation between TI and $\lambda_{C_P-\text{max}}$, seen in Figure 3b. These figures display a clear positive dependence between TI and $\lambda_{C_P-\text{max}}$. Within TI of 6-16%; there is an approximate increase of 0.1 in $\lambda_{C_P-\text{max}}$ for every 5% raise of TI. For 16-20%; there is an even stronger relation; however, the results from this span are more uncertain as it has larger standard deviations and somewhat uneven distribution of mean $C_P$ values. With exception of the highest TI span of 16-20% in Figure 2, the fitted curves nearly intersect all mean $C_P$ values which adds reliability to the results. In Table 2, $\lambda_{C_P-\text{max}}$, mean TI, mean wind speed, mean $\lambda$ and number of 10 min samples can be seen for each TI interval.

The possible gain in $C_P$ from setting the control strategy so that $\lambda$ varies with TI according to Figure 3b can be estimated. By, for each TI interval in Figure 2, comparing the maximum $C_P$ values from the fitted curves with the $C_P$-values that are obtained using the fixed $\lambda_{C_P-\text{max}}$ (from Figure 3a). The average gain in $C_P$ for all TI intervals, weighted for the TI distribution, is found to be 0.6% (counted as relative percentage). The gain for each TI interval can be seen in Table 2, with the highest value (2.5%) found for the highest TI interval and the second highest value (0.7%) found for the lowest TI interval. For the mid-range TI intervals, the magnitude of the power coefficient gain is close to zero, this is natural as the $\lambda_{C_P-\text{max}}$ for these intervals are close to the fixed $\lambda_{C_P-\text{max}}$ used today.

![Figure 2. $C_P(\lambda)$ curves for different TI with standard deviation (blue), fitted curves (red) and maximum value (at $\lambda_{C_P-\text{max}}$) indicated with a black circle.](image-url)
Figure 3: Fig 2a (left): Experimental $C_p(\lambda)$ curve (black), with standard deviation for $C_P$ of each bin, made from binned 10 min mean values (green). Fig 2b (right): Relation between $\lambda_{CP_{-max}}$ and TI from $C_p(\lambda)$ curves (blue) and $\overline{C_p}(\lambda)$ curves (red). The upper right point is coupled to larger uncertainty due to anomalies in the high turbulence data (see Figure 2).

Table 2. $\lambda_{CP_{-max}}$ and various specifications for each TI span.

| TI (%) | Mean TI | $\lambda_{CP_{-max}}$ | Mean $\lambda$ | Mean wind speed (m/s) | No of 10 min Samples | Possible gain of $C_p$ (relative %) |
|--------|---------|----------------------|----------------|-----------------------|----------------------|------------------------------------|
| 6-10   | 8.40    | 4.08                 | 4.24           | 5.66                  | 913                  | 0.7                                |
| 10-12  | 11.08   | 4.15                 | 4.09           | 6.03                  | 1117                 | 0.2                                |
| 12-14  | 13.01   | 4.19                 | 4.18           | 6.12                  | 1508                 | 0.1                                |
| 14-16  | 14.90   | 4.23                 | 4.09           | 6.13                  | 1284                 | 0.0                                |
| 16-20  | 17.45   | 4.56                 | 4.16           | 5.91                  | 943                  | 2.5                                |

As discussed in section “3.5.1. Power coefficient curve”, the cubic effect leads to an overestimation of $C_p$ with higher TI. However, this does not seem to be linked to the rotational speed and thus does not affect the comparison of $\lambda_{CP_{-max}}$ for each different TI span. This can be seen in Figure 4 with two sets of $C_p(\lambda)$ curves for different TI, one set with $C_p$ from equation (7), and one set with $\overline{C_p}$ from (9). The $\overline{C_p}$ curves are, as could be expected, more pushed together than the $C_p$ curves. However, the relation between TI and $\lambda_{CP_{-max}}$ are the same for both cases which is displayed in Figure 3b where the $\lambda_{CP_{-max}}$-TI relation can be seen to be almost independent on which of the two methods that is used.

Also, it could be suspected that the shift in $\lambda_{CP_{-max}}$ upwards derives from a secondary effect linked to the turbulence rather than the turbulence itself. Most likely to interfere is the wind speed which is linked to the Reynolds number and thus could affect $\lambda_{CP_{-max}}$ [21]. For example, if the mean wind speed alters considerably between the different TI spans, the observed effect could have derived from the wind speed rather than the turbulence. However, as can be seen in Figure 5, there is no strong linkage between TI and the wind speed, so the main shift in $\lambda_{CP_{-max}}$ can be assumed to come from the turbulence.
Figure 4. $C_P(\lambda)$ curve for different TI with $C_P$ from mean wind (left) and $\overline{C_P}$ from mean wind cube (right).

Figure 5. The relation between TI and wind speed (black) with the standard deviation for TI of each bin, made from binned 10 min mean values (green).

The demonstrated increase of $\lambda_{C_{P\text{---}max}}$ with TI can partly be explained by the fact that a higher tip speed ratio raises the potential for extracting the energy-rich wind gusts. The cubic variation of power with wind speed makes it more beneficial with a higher $\lambda_{C_{P\text{---}max}}$ as the efficiency gain with the high-energy wind gusts is greater than the efficiency loss with the lower energy dips in wind speed. This is also illustrated by the indication that the largest potential for improvement is found at the highest TIs, where an increase of $\lambda$ leads to a higher $C_P$. Also interesting is that there is potential for improvement for the lowest TIs, where a decrease of $\lambda$ leads to a higher $C_P$. 
5. Conclusions
There is a clear influence from turbulence on $\lambda_{C_P{\text{max}}}$ for the 200 kW VAWT. Seemingly, $\lambda_{C_P{\text{max}}}$ increases with TI, giving an opportunity to tune the control strategy of the turbine to enhance the total efficiency of the turbine. The potential for improvement is largest for high TIs where an increase of $\lambda$ would allow the turbine to capture more of the high-energy wind gusts. However, perhaps more simple to implement will be to decrease $\lambda$ when TI is low, which will also lead to a higher $C_p$. The demonstrated relation is not due to linked secondary effects such as ones connected to either wind speed or the cubic variation of power with wind speed.

Being aware of and knowing how $\lambda_{C_P{\text{max}}}$ is affected by the amount of turbulence enables accounting for this when setting the control strategy and thus increasing the total $C_p$ of the turbine.

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