DETERMINATION OF STATIONARY AND DYNAMICAL POWER CURVES USING A NACELLE-BASED LIDAR SYSTEM

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Summary

This paper investigates the determination of stationary and dynamical power curves using a nacelle-based lidar system. Wind speed measurements on one of the REpower 5MW turbines at the German offshore test site "alpha ventus" were carried out with a pulsed lidar system that is capable of measuring the wind field at different measurement planes over the rotor swept area. The results show that the stationary lidar-based power curve has a small scatter but is shifted towards lower wind speeds compared to a conventional power curve measured with a cup anemometer from a met mast. The new approach of calculating dynamical power curves shows short-time dynamics of the turbine and allows a quick detection of changes such as the icing of an anemometer or the reduction in the maximum power output of the wind turbine.

1. Introduction

To calculate the annual energy production of a wind turbine and to quantify its efficiency, it is crucial to determine accurately the power curve of the turbine which defines the electrical power output for a given mean wind speed. The conventional approach to determine the power curve is defined in the IEC 61400-12-1 and uses a cup anemometer mounted at hub height at a met mast to measure the wind speed at a single point in a given distance from the turbine. However, the erection of such a met mast is expensive and even more so considering the future demand on power curve verification of offshore wind turbines. In addition to that, the single point measurement of a cup anemometer does not take into account the wind field over the rotor swept area and therefore is not necessarily representative for the wind field in front of the rotor.
The solution is the new technique of a nacelle-based lidar system which is able to measure the inflowing wind field at a high spatial and temporal resolution. The determination of stationary and dynamical power curves using the wind speed measured with such a device is presented in the following.

2. Site description

The measurements are performed at alpha ventus, the first German offshore wind park, from March 2011 to January 2012. The wind park is situated in the North Sea and comprises 12 turbines on a 4x3 grid. The lidar measurements were carried out on the AV4, a 5 MW REpower turbine with a rotor diameter D of 126 m and a hub height of 92 m. The turbine is located on the western side of the park with five adjacent turbines with a minimum distance of 6 D. In a distance of 3.5 D to the west of the AV4, the research platform FINO 1 is located [1]. The valid measurement sectors according to IEC 61400-12-1 are therefore reduced to sectors between 206°-255° and between 285°-328°.

3. Measurement Setup

On the nacelle of the AV4 the SWE lidar system is installed to measure the incoming wind field. The system was developed at the SWE and consists of a commercial lidar device from Leosphere and a self-developed scanner system which enables the pulsed laser beam to be diverted in different directions, cf. [2]. Via a mirror, which can rotate vertically and horizontally, the beam can be directed to prescribed points and thus arbitrary trajectories are formed along which the wind speed is measured. Since it is a pulsed system, the measurements can be taken at five planes simultaneously.
In Figure 1 the trajectory used in this campaign is shown. A 3x3 grid trajectory with 10 measurement points is chosen where the center point of the trajectory is passed through twice during a single scan. The advantage of this trajectory is a high sampling rate of around 4.8 Hz and the possibility of reducing the measurement points to e.g. a vertical line during post processing which could be of interest for the analysis of wind shear. The measurement system is able to measure up to a distance of 2 D in front of the turbine. However, for the power curve analysis, data sets with measurement planes in a range from 0.5 D to 1.5 D with equidistant distances are considered, since the data availability for this configuration is higher. It has to be noted that the usual measurement area of 0.75 D x 0.75 D with a distance of 1 D in front of the turbine has to be reduced significantly due to the collision of the laser beam with the hub.
Simultaneously to the lidar measurements, a cup anemometer wind speed is recorded at hub height at FINO1 as a reference to the lidar measurements and temperature and pressure measurements are taken into account to normalize the wind speed.

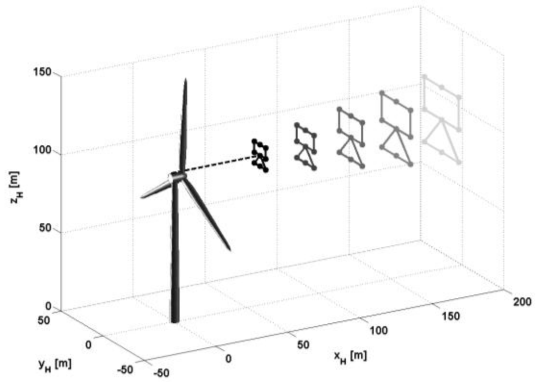

Figure 1. 3x3 grid trajectory used for the power curve measurements.

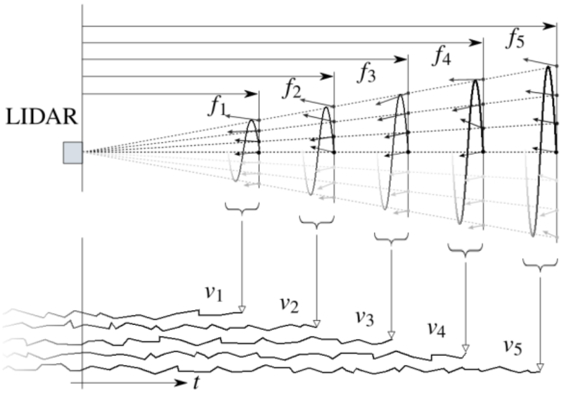

Figure 2. Schematic drawing of the incoming wind field measured by a lidar at different focus distances.

4. Stationary power curves

4.1 Rotor effective wind speed

The standard approach to determine a power curve is to set the power output of the turbine in relation to a single point wind speed measured at hub height at a met mast. The lidar system, however, measures the wind speed at a high spatial and temporal resolution simultaneously in five measurement planes at ten different measurement points over the rotor swept area. These wind speeds can be combined to one wind speed which will henceforth be called the rotor effective wind speed v_{0L}. In [3] is explained how to calculate v_{0L}, in the following a short explanation is given.

To obtain the rotor effective wind speed, in a first step the line-of-sight wind speeds measured at each discrete measurement point are filtered and then corrected using assumptions such as a non-existing yaw misalignment and homogeneous flow at one height. In a second step a moving average runs over the wind speed vector of each measurement plane, averaging over the number of points of the trajectory and thus calculating a wind speed v_i. In Figure 2 a schematic drawing of the lidar measurement is shown. In a final step, the wind speeds v_i of each plane are merged to one rotor effective wind speed v_{0L} taking into consideration Taylor's hypothesis which is valid for horizontal lidar measurements [4]. In simple words, Taylor claims that turbulent eddies are transported with the mean flow and do not change their properties [5]. Consequently, the wind speeds v_i of each plane can be time shifted and then merged at one distance in front of the turbine, thus capturing the information of each measurement plain, i.e. the wind field, in one single wind speed. The validity of the rotor effective wind speed for power curve measurements has been already shown in [6].

4.2 Results

To obtain a stationary power curve and following the IEC norm 61400-12-1, the density normalized lidar wind speed v_{0L} and the power P are averaged over ten minutes and filtered according to the valid sectors. After filtering 341 ten minute blocks remain.

The resulting scatter plot is given in Figure 3. The plot also includes the met mast power curve. What is most noticeable when comparing the two curves, is that both have a low scatter and that the lidar power curve lays above the met mast power curve. This is confirmed by comparing the scatter plots to the binned power curves in Figure 4. Here the wind speeds data is binned and averaged in 0.5 m/s bins and set in ratio to the respective power average. The scatter is represented in scatter bars for each bin.

The fact that the lidar power curve lays above the met mast power curve leads to the conclusion that the lidar measures a lower wind speed than the cup anemometer at the met mast. One reason could be that the assumptions used to calculate the rotor effective wind speed v_{0L} might not be true at all times. Assuming there is a yaw misalignment γ and the inflow is therefore not perpendicular to the rotor plane, the wind speed may be underestimated by a factor $cos(\gamma)$.

Another reason for measuring a lower wind speed with the lidar is the blockage effect of the turbine. With a maximum distance of 1.5 D in front of the turbine, the measurements might be affected by the deceleration of the wind speed due to the power extraction in the rotor plane. To investigate this effect, the binned power curve is also calculated with the wind speeds v_i from the respective measurement planes. The results are shown in Figure 5 where for clarity reasons only the power curves calculated with the wind speeds v_i from plane 1-3 are compared to the original lidar power curve. Following the blockage thesis, the power curves calculated with wind speeds measured farther away from the turbine plane should be shifted to higher wind speeds. However, this is not the case. Therefore it can be concluded that the turbine blockage most likely does not affect the power curve measurements when using a lidar system.

A third reason for the difference in wind speed between the lidar and the cup measurement could be that the cups are influenced by the mast itself. Shadowing and over speeding is not yet considered and the cup wind speed needs to be corrected to include the effect of the met mast.

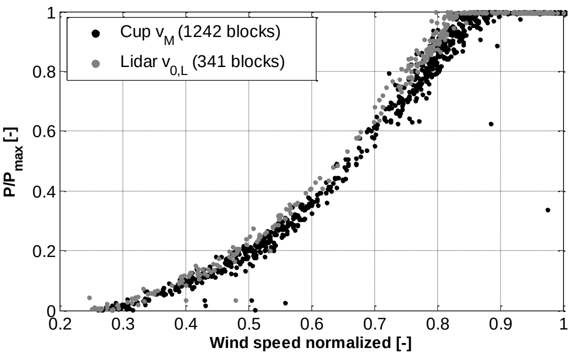

Figure 3. Scatter plot of lidar and met mast power curves.

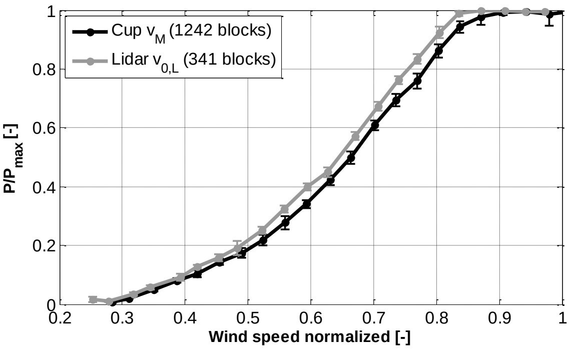

Figure 4. Lidar and met mast power curves.

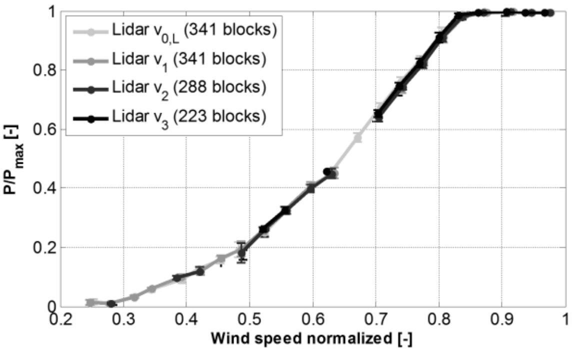

Figure 5. Comparison of lidar power curves calculated with rotor effective wind speed $\boldsymbol{v_{0L}}$ and wind speeds $\boldsymbol{v_i}$ from measurement plane 1-3.

5. Dynamical power curves

5.1 Method

The dynamical approach of the Langevin Power Curve models the short-time dynamics of the wind power conversion as a relaxation process, driven by the turbulent wind [8][9]. These short time dynamics are disregarded by the averaging defined in the IEC procedure.

For the (clearly hypothetical) case of a constant wind speed u, the electrical power output of a wind energy converter (WEC) would relax to a fixed value $P_L(u)$. Mathematically, these power values $P_L(u)$ are called stable fixed points of the power conversion process. It is possible to derive them even from strongly fluctuating data. To this end the wind speed measurements are divided into bins u_i of 0.5 m/s width, as it is done in [7]. We can derive for each wind speed bin u_i the so-called drift function[1] directly from measurement data as

$$D_i(P) = lim_{\tau \to 0} \frac{1}{\tau} \langle P(t+\tau) - P(t) \rangle |_{P(t)=P} \qquad (1)$$

where the condition means that only those power values $P(t)$ are considered for which $u(t)$ is within u_i and $P(t) = P$. The average is thus performed over t, but separately for each wind speed bin u_i and each power value P. If we consider the state of the system as defined by u and P, we could therefore speak of a state-based averaging in contrast to the temporal averaging in [7]. $D_i(P)$ has the meaning of an average slope of the power signal $P(t)$, depending on the power value P. Because for constant $u(t)$ the power would also be constant, the average slope of the power signal in that case would vanish, and the drift function would be zero, thus defining a stable fixed point. The task is therefore to find the zeros of the drift function $D_i(P)$ for every wind speed bin u_i and every power value P. We then consider the drift field including its stable fixed points for the different wind speeds as the Langevin Power Curve (LPC). An example of the LPC for a wind turbine in normal operation is presented in Figure 6.

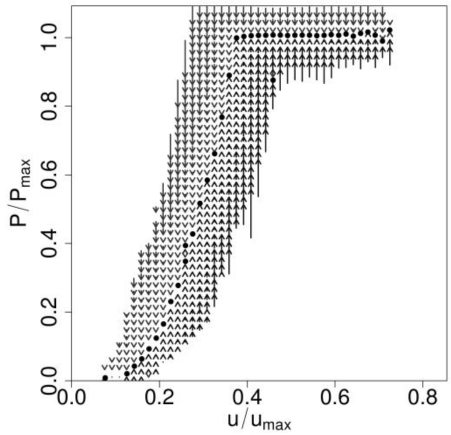

Figure 6. Complete Langevin Power Curve, i.e. drift field including stable fixed points, of the WEC under consideration in normal operation. Measurement period was January 2011.

The concept allows also for multiple fixed points if, for a given wind speed, the WEC control system aims for different power levels, depending on the specific situation, see [8].

5.2 Results

Langevin Power Curves of the REpower 5M turbine have been derived from the measurements as described above. The lidar wind measurements turned out not to allow for the derivation of the power conversion dynamics. One possible reason could be desynchronized clocks of the measurement systems, which could significantly affect the reproduction of short-time dynamics. This problem is currently under investigation. Hence, nacelle anemometer measurements are used here. The sampling frequencies of the anemometer and the power output

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[1] For clarity, $D_i(P)$ should be distinguished from the rotor diameter D as defined above.

were 1 Hz and 50 Hz, respectively. Before analysis the power data were down-sampled to 1 Hz. Because of the disturbed measurement by the nacelle anemometer, the following LPC examples are obtained from a rather long period of one month of measurement data, if not noted otherwise.

An example of the LPC including the drift field during normal operation is presented in Figure 6. Its shape is similar to the IEC power curve, where the most striking difference is the absence of smoothing in the transition to the rated power level around $u = 0.35u_{max}$.

During February 2011 several additional fixed points occurred for low wind speeds, combined with a high power level around rated power, see Figure 7. After consulting the manufacturer and the operator of the WEC, this effect could be addressed to icing of the anemometer, leading to a significant underestimation of the wind speed.

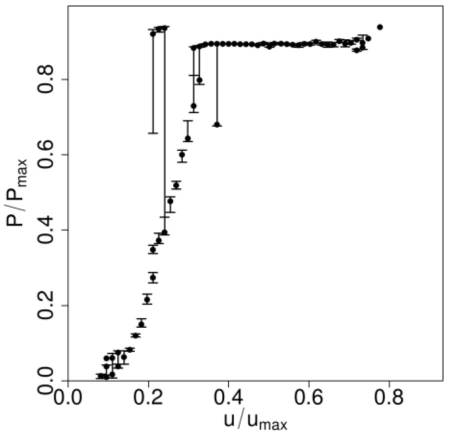

Figure 7. LPC of the WEC under consideration, detecting ice formation on the nacelle anemometer. Measurement period was February 2011.

Also in February 2011, an apparent change in the rated power level of the turbine was visible in the region of rated power, see Figure 8. According to the manufacturer, a previously active limitation of the maximum power level by the wind farm control system was deactivated in this period. This effect, which appears like a step function, is only visible when a shorter measurement period of only ten days is used, which enlarges the uncertainty of the LPC. The effect of anemometer icing is also present in this figure, as the measurement period contains both phenomena. For additional comparison, in Figure 8 a power curve derived from 10 minute mean values, similar to the IEC concept, is shown as a solid grey line. Here, only a slight deformation of the power curve is visible.

6. Outlook

Due to the collision of the lidar beam with the hub, the quality of the lidar measurements was diminished during this campaign. Therefore ongoing measurements are performed with the lidar system mounted on an elevated position above the nacelle. With this new data, higher data availability is achieved, the measurement distance is extended to over 2 D and dynamical power curves using lidar data will hopefully be possible. Furthermore, investigations concerning the influence of different boundary layer conditions on the determination of power curves will be carried out, the effect of a probable met mast shadowing will be analyzed and a comparison with CFD calculations concerning the turbine blockage effect will be conducted.

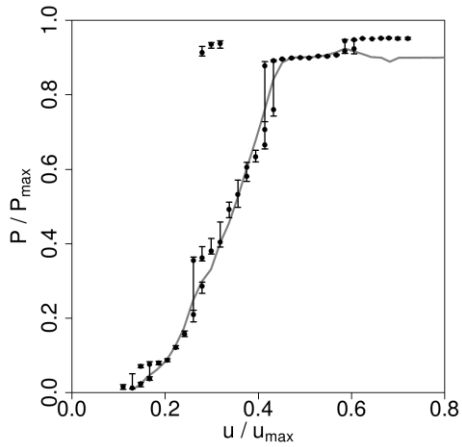

Figure 8. LPC of the WEC under consideration, showing the effect of the cancellation of a maximum power limitation by the wind farm control system (around $u=0.6u_{max}$). Measurement period was ten days in February 2011, in contrast to the other LPCs in this section. Grey line: power curve derived from IEC conform 10 minute mean values.

Acknowledgements

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