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Published in:
Journal of Physics: Conference Series (Online)

Link to article, DOI:
10.1088/1742-6596/524/1/012156

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Göçmen Bozkurt, T., Giebel, G., Poulsen, N. K., & Mirzaei, M. (2014). Wind Speed Estimation and Parametrization of Wake Models for Downregulated Offshore Wind Farms within the scope of PossPOW Project. Journal of Physics: Conference Series (Online), 524(1), [012156]. https://doi.org/10.1088/1742-6596/524/1/012156

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Wind Speed Estimation and Parametrization of Wake Models for Downregulated Offshore Wind Farms within the scope of PossPOW Project

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Abstract. With increasing installed capacity, wind farms are requested to downregulate more frequently, especially in the offshore environment. Determination and verification of possible (or available) power of downregulated offshore wind farms are the aims of the PossPOW project (see PossPOW.dtu.dk). Two main challenges encountered in the project so far are the estimation of wind speed and the recreation of the flow inside the downregulated wind farm as if it is operating ideally. The rotor effective wind speed was estimated using power, pitch angle and rotational speed as inputs combined with a generic \(C_P\) model. The results have been compared with Horns Rev-I dataset and NREL 5MW simulations under both downregulation and normal operation states. For the real-time flow recreation, the GCLarsen single wake model was re-calibrated using a 1-s dataset from Horns Rev and tested for the downregulated period. The re-calibrated model has to be further parametrized to include dynamic effects such as wind direction variability and meandering also considering different averaging time scales before implemented in full scale wind farms.

1. Introduction

Wind power plants are important players in the energy market which have the capability to reduce their power supply to the grid, in other words to offer downregulation services to the balancing market. Downregulation of a wind turbine stands for an operational state in which the active power output is curtailed by pitching the blades. At this point, the concept of 'reserve power', i.e. how much the wind farm is downregulated, is substantial. Determination of possible (or available) active power is crucial firstly because the reserve power has considerable market value and also for wind farm developers to be compensated for the loss properly, during mandated downregulation. While the available power calculation is straight-forward and widely known for a single turbine [1], it gets rather complicated for the whole wind farm due to the change in the wake characteristics derived from the downregulated operational conditions. In fact, the wake losses generated by the upstream turbine(s) decrease during downregulation and the downstream turbines see more wind compared to the normal operation case. Currently, the Transmission System Operators (TSOs) have no real way to determine exactly the available power of a whole wind farm which is down-regulated. Therefore, PossPOW project aims to develop a verified and internationally accepted way to determine the possible power of a down-regulated offshore wind
The first phase of PossPOW project is to estimate the rotor effective wind speed since the nacelle anemometers are not available on every turbine and known to have high uncertainties. The proposed method is to use power, pitch angle and rotational speed as inputs and combine it with a generic $C_P$ model to estimate the wind speed. The performance of the model has been evaluated for both normal operation and downregulation periods using two different case studies: 1-s data from the Horns Rev-I wind farm and the NREL 5MW single turbine. Those estimated rotor effective wind speeds in the Horns Rev wind farm have been used to re-calibrate the GCLarsen single wake model to simulate the real time wind speed on the downstream turbine(s) which then has to be extended to the wind farm scale to consider dynamic effects inside the farm.

2. Rotor Effective Wind Speed Estimation

Since the nacelle region is exposed to highly distorted flow [2], the anemometers mounted on that region have always been approached with suspicion. Especially for real time calculations, using nacelle wind speed values measured during relatively shorter period, may induce higher uncertainties and can even lead to faults [3]. Therefore, the idea is to use the general power expression given in Eqn.1 with the turbine characteristics and second-wise SCADA signals namely the active power $P$, pitch angle $\theta$ and rotational speed $\omega$.

$$P = \frac{1}{2} \rho \, C_P (\lambda, \theta) \, \pi R^2 U^3$$

(1)

Since $C_P$ during downregulation does not follow the ideal curve and because generally very limited information is provided by the manufacturers, the generic $C_P$ expression proposed by Heier [4] was used to simulate the pitch angle, $\theta$, and tip speed ratio, $\lambda$, dependency of the power coefficient, $C_P$ (Eqn.2).

$$C_P (\lambda, \theta) = c_1 \left( \frac{c_2}{\lambda} - c_3 \theta - c_4 \theta^c c_5 - c_6 \right) \exp \left( \frac{-c_7}{\lambda} \right)$$

$$\lambda_i = \left[ \left( \frac{1}{\lambda + c_8 \theta} \right) - \left( \frac{c_9}{\theta^3 + 1} \right) \right]^{-1}$$

(2)

The coefficients in Eqn.2 are tabulated in Heier [4] but then modified by Ackermann [5] and Raiambal et al. [6] to fit for variable speed turbines and a specific turbine model, Vestas V-80, respectively. In this study, the latter version of coefficients with slight modifications (maximum change is less than 5 %) is applied where all the modifications are determined by the agreement between the modelled and the provided ideal $C_P$ curves.

2.1. Horns Rev-I Wind Farm Test Case

The Horns Rev-I offshore wind farm is located in western Denmark consists of 80 Vestas V-80, 2MW Offshore wind turbines. The wind speed was calculated for each turbine iteratively using two different dataset sampled at every second extracted from the wind farm. The first dataset presented is recorded under normal operational conditions and covers a 35-hour period where the other dataset is recorded when the wind farm is downregulated and includes 2 hours of information. The provided channels are the active power, blade pitch angle, rotor rpm, averaged temperature, the nacelle anemometer wind speed measurements, wind direction and individual possible power signal for both of the datasets.

In Figure 1, Rotor Effective Wind Speed refers to the wind speed calculated iteratively after writing $U^3 = \left( \frac{\Omega R}{\lambda} \right)^3$ and using the $C_P$ model in Eqn.2; the Nacelle Wind Speed is the wind speed
Figure 1. Wind Speed Comparison at the reference turbine located in Horns Rev Wind Farm, during normal (ideal) operation

Figure 2. (a) Power Output (b) - Wind Speed Comparison of the reference turbine located in Horns Rev wind farm during downregulation

measured using a nacelle anemometer and *Power Curve wind speed* is the wind speed calculated using the active power signal and the ideal power curve provided by the manufacturer.

It is seen in Figure 1 that the rotor effective wind speed is in a very good agreement with the wind speed calculated using the power curve and also consistent with the nacelle anemometer measurements. Even though the nacelle anemometers are not favoured due to the reasons mentioned earlier, during the periods when the power curve methodology can no longer be applied (i.e. before cut-in and along rated region) the only available information regarding the wind speed is the nacelle anemometer measurements. Figure 2(b) includes a similar comparison this time performed for downregulated conditions. Figure 2(a) schematically represents the active power signal, or in other words the downregulation strategy.

If a comparative analysis is performed between Figure 1 and 2(b), it might be said that the deficit between the wind speed values obtained using the nacelle anemometer measurements and
Figure 3. Wind Speed Comparison of a single NREL 5 MW turbine during (a) normal operation (b) 50% downregulation

the Rotor Effective Wind Speed remained approximately the same under standard operation and downregulated conditions. Therefore, assuming the power curve approach in 1 is representative enough for the wind speed, the estimation of the wind speed using the created algorithm for downregulation periods can be justified.

2.2. NREL 5MW Single Turbine Test Case
Since NREL 5MW is an artificial turbine with public features [7], the developed wind speed algorithm can easily be tested using different scenarios. The simulations performed for NREL 5 MW wind turbine are considered as dataset and they include two different scenarios: normal operation with a mean wind speed of 9 m/s and 50% downregulation with a mean wind speed of 13 m/s. For the first scenario, the simulated wind speed (dataset) was compared with the power curve and the modelled rotor effective wind speed - see Figure 3(a). The second simulation of wind speed was compared with the model estimation only since the power curve wind speed is not available for downregulation periods - see Figure 3(b).

In Figure 3(a), a very good agreement is observed between the simulated, power curve and effective wind speed values. It is also seen, especially between 2000-2750s time steps, that the power curve method is not applicable where the inflow velocity has exceeded the rated wind speed which is around 12 m/s for NREL 5 MW turbine. Figure 3(b) presents the agreement between the simulated (dataset) and modelled effective wind speed also during downregulation period.

3. Wake Model Recalibration for Real Time
To consider the changing wake effects for normal and downregulated operations, the rotor wind speed values of upstream turbines are to be taken as inputs to the wake model as they are not affected by the wake (downregulated or not). Then we apply the wake model directly to estimate the velocity deficit and calculate the possible power output of the wind farm. However, most of the computationally affordable wake models have only been used to acquire long term, statistical information and verified using 10-min averaged data. Therefore, re-calibration of the GCLarsen wake model [8], which has been implemented in WindPro and shown to perform also well on offshore in Wake Benchmark Work Package in EERA-DTOC [9], is performed and tested
3.1. GCLarsen Wake Model
Larsen has introduced a simple wake calculation procedure [8] and it has been implemented in many engineering applications due to its robustness and simplicity. In the model, the axisymmetric form of Reynolds Averaged Navier Stokes (RANS) equations with the thin shear layer approximation is used. In GCLarsen model, the upstream turbine is positioned at $x_0$ ($x_0 > 0$) and $r$ denotes the radius of the wake (See Figure 4). Where the free stream velocity is indicated by $U_\infty$, the mean velocities in the wake are $U_\infty + u_x$ and $u_r$ along axial and radial direction, respectively.

The final equation for wake deficit, Eqn.3, is obtained after a comprehensive order of magnitude analysis and a series of boundary conditions.

$$u_x(x, r) = \frac{-U_\infty}{9} \left( c_T \pi R^2 x^{-2} \right)^{1/3} \left\{ r^{3/2} \left( 3c_1^2 c_T \pi R^2 x \right)^{-1/2} - \frac{35}{2\pi} \left( 3c_1^2 \right)^{-1/5} \right\}^2$$

where $c_T$ is the thrust coefficient and $R$ is the rotor radius. The parameters to calibrate are $c_1$, which is explicitly seen in Eqn.3, and $x_0$, which is embedded in $x = x_0 + \Delta x$ with $\Delta x$ being the turbine spacing.

The second-wise dataset used in re-calibration process has been extracted during the normal operational case in Horns Rev-I, when the wind is easterly (i.e. wind direction = $90^\circ \pm 10^\circ$). Since the model (Eqn3) is nonlinear in $x_0$, non-linear least squares fitting has been performed to estimate the parameters ($c_1$ and $x_0$) - with a convergence criterion of $10^{-6}$. Each inside row in Horns Rev wind farm has been used for fitting individually and note that, in each calculation, thrust coefficient, $c_T$, was taken into account in such a way that the curve, $c_T(U_\infty)$ provided by the manufacturer. This curve was interpolated for each wind speed.

3.2. Time Delay Concept
Before using the dataset to determine the parameters $c_1$ and $x_0$, the time step at the downstream velocity has to be adjusted, considering the delay that occurs due to the distance between the turbines. The proposed methodology is to apply $t_{\text{down}} = t_{\text{up}} + t_d$ where $t_{\text{down}}$ and $t_{\text{up}}$ are the instants when the considered volume of air passes through the downstream and upstream locations, respectively and $t_d$ is the time delay estimated as; $t_d = \Delta x / \text{mean}(U_\infty)_{\text{down}}$ with $U_\infty_{\text{down}}$ being the rotor effective wind speed at the downstream turbine.

3.3. Re-calibration Results
In that process, the rotor effective wind speeds calculated for each turbine was used in pairs, i.e. turbine $\#94$ and $\#84$ in Figure 5, both to calibrate and validate the model. Note that for both processes, the dataset term in the legend indicates the rotor effective wind speed values modelled as described in the previous section.
As can be seen in Figure 5, the parameters found in the fitting are $c_1 = 2.5447$ and $x_0 = 40.1366$ while the goodness of fit can be expressed in terms of $R^2 = 0.92746$ and $RMSE = 0.69889$.

Unfortunately, the validation is performed using the downregulated dataset due to lack of data available during easterly winds (wind direction = $90\degree \pm 10\degree$). The downside of using the downregulated dataset is that the downstream wind speed estimated by the calibrated GCLarsen is expected to be lower than the effective wind speed. The reason is the fact that during downregulation, the wake effects are not as dominant thus leading the wind speed at downstream position to be higher than the standard operation. Because the $c_T$ characteristics of the turbines with respect to the changing pitch angles during downregulation are not publicly available, the re-calibrated GCLarsen model takes into account only the normal operational $c_T$ curve. As a result, the modeled wake effects are stronger therefore the wind speed downstream is lower. Having said that, the modelled, the effective and the measured wind speeds are compared in Figure 6.

First of all, from Figure 6, it can be observed that the variations in the measurements using nacelle anemometer are much higher than the ones in the rotor effective wind speed time series. This is in part due to the smoothing effect of the averaging over the entire rotor. Additionally, as expected, the GCLarsen model results in lower wind speeds at downstream. However, the difference is far from being significant and one of the reasons, maybe the most dominant one, can be the high wind speeds in the dataset, even along the wake since the thrust coefficient, $c_T$, behaves rather independent of the pitch angle variations (therefore the downregulation) for high wind speeds.

4. Conclusion & Future Work
The PossPOW project aims to develop an internationally accepted way to determine the available power in downregulated offshore wind farms. To be able to do that, the rotor effective wind speeds had to be estimated and the developed methodology has been verified and validated using Horns Rev-I wind farm and NREL 5MW single wake test cases, both during normal operation and downregulation. Using the effective wind speed values calculated second-wise, the
The Science of Making Torque from Wind 2014 (TORQUE 2014) IOP Publishing
Journal of Physics: Conference Series 524 (2014) 012156 doi:10.1088/1742-6596/524/1/012156

Figure 6. Comparison of Wind Speed values for filtered wind direction in $90^\circ \pm 10^\circ$ bin @ 7 diameters downstream of a turbine in Horns Rev, downregulation dataset

GCLarsen single wake model has been re-calibrated to simulate the real time wake properties. However, the re-defined parameters have been tested using the downregulated dataset which was not fully representative in terms of wake validation cases. Therefore, the first step ahead is to run the re-calibrated GCLarsen model for normal operation and compare the results. When the parameters for the single wake is validated, the model will be extended to the wind farm scale in which the dynamic effects inside the wind farm has to be included; such as the meandering concept, wind direction variability and partial wakes (or wake expansion).

Acknowledgement
The project partners of PossPOW are Vattenfall, Siemens, Vestas, and DONG. PossPOW is financed by Energinet.dk under the Public Service Obligation, ForskEL contract 2012-1-10763. The author would like to thank Mads Rajczyk Skjelmose and Jesper Runge Kristoffersen from Vattenfall for their cooperation and supply of the datasets.

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