Real-time available power estimation for offshore wind power plants

PO.ID 186

Tuhfe Göçmen Bozkurt[1]
mobile: +45 6139 6241

Gregor Giebel[1]

Poul Ejnar Sørensen[1] Pierre Elouan Réthoré[1] Mahmood Mirzaei[1]
Technical University of Denmark: Department of Wind Energy, Risø[1] (tuhf@dtu.dk)
Niels Kjølstad Poulsen[2]
Technical University of Denmark: Department of Applied Mathematics and Computer Science, Lyngby[2]
Mads Rajczyk Skjelmose[3] Jesper Runge Kristoffersen[3] Vattenfall[3]
Vattenfall Renewables Wind DK A/S , Fredericia, Denmark[3]

DTU Wind Energy
Department of Wind Energy

Introduction

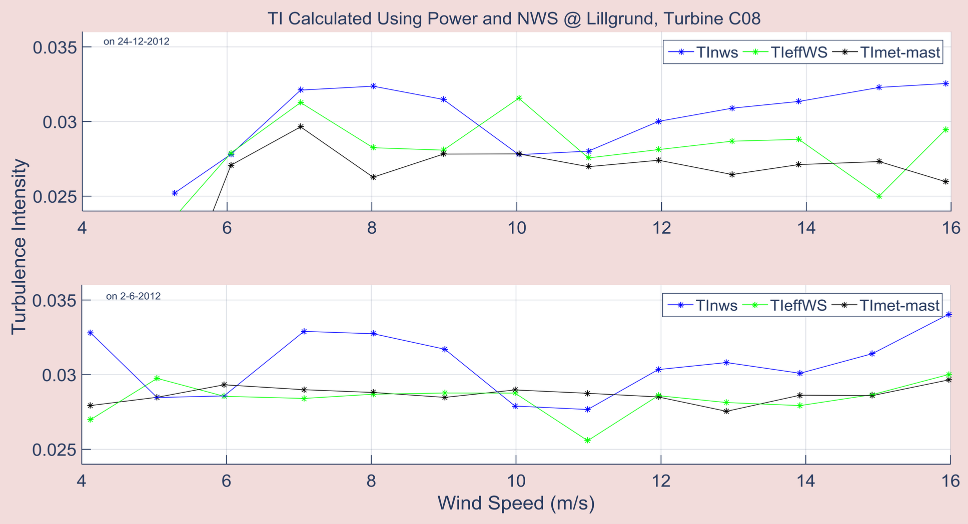
Currently, the possible (or available) power of a down-regulated wind farm is calculated as the summation of all individual possible power signals. However, this is a clear over-estimation considering the reduction in the wake deficit during downregulation. The main challenges of available power estimation are:

Determine the **wind speed** at the turbine level since the accuracy of nacelle anemometers are in question and power curve derivation is no longer applicable during downregulation

Apply **a real-time wake model** which can calculate the power production as if the wind farm was operating normally even in short downregulation periods. However, most existing wake models have only been used to acquire long term, statistical information and verified using 10-min averaged data- Therefore, one of the existing models has to be re-calibrated using the estimated effective wind speeds and the turbulence intensity

Estimation of the Atmospheric Turbulence Intensity

The turbulence is a very important concept in wake modelling as it contributes the wake recovery while increasing the fatigue loads on the downstream turbine(s). It is taken into consideration in the wake model re-calibration process in terms of atmospheric turbulence intensity, $TI = \sigma_U/_U$. It was computed using synchronous data extracted from the met-mast and the SCADA of the most upstream turbine in Lillgrund offshore wind farm during a winter and a summer day to see the seasonal effects.



Conventionally, the TI implemented in the analytical wake model applications is estimated using the met-mast data. However here, the TI is approximated using effective wind peed since

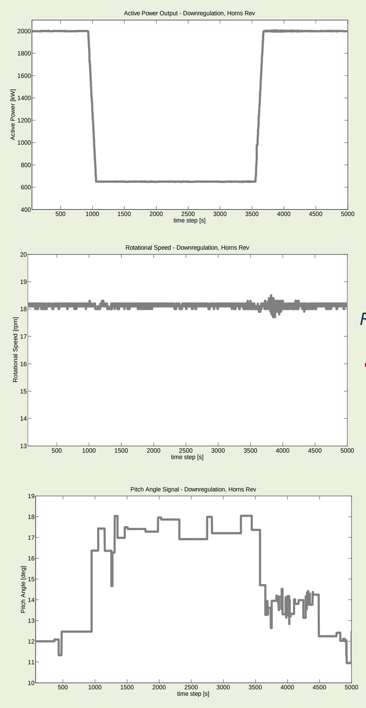
1. the wind speed is estimated purely from the SCADA measurements
2. concurrent met-mast data is generally not available.

Conclusion:

1. The effective wind speed (effWS) performs better than the nacelle wind speed (nws) when estimating the atmospheric turbulence intensity
2. effWS is in a good agreement with the met-mast data -> suitable to use in the wake model re-calibration

Effective Wind Speed Estimation Theory & Test Cases

Using the general power expression; $P = \frac{1}{2}\rho A_{rotor} c_P(\theta,\lambda) U_{eff}^3$



Estimation of $C_P(\lambda, \theta)$

analytical model by Heier (1998)

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

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

The coefficients in the expression, c_1 to c_9, strongly depend on the blade shape, in other words, the turbine type. They have been adjusted according to the turbines in the case studies, partially using the research of Raiambal et.al.[2] and partially the dataset itself.

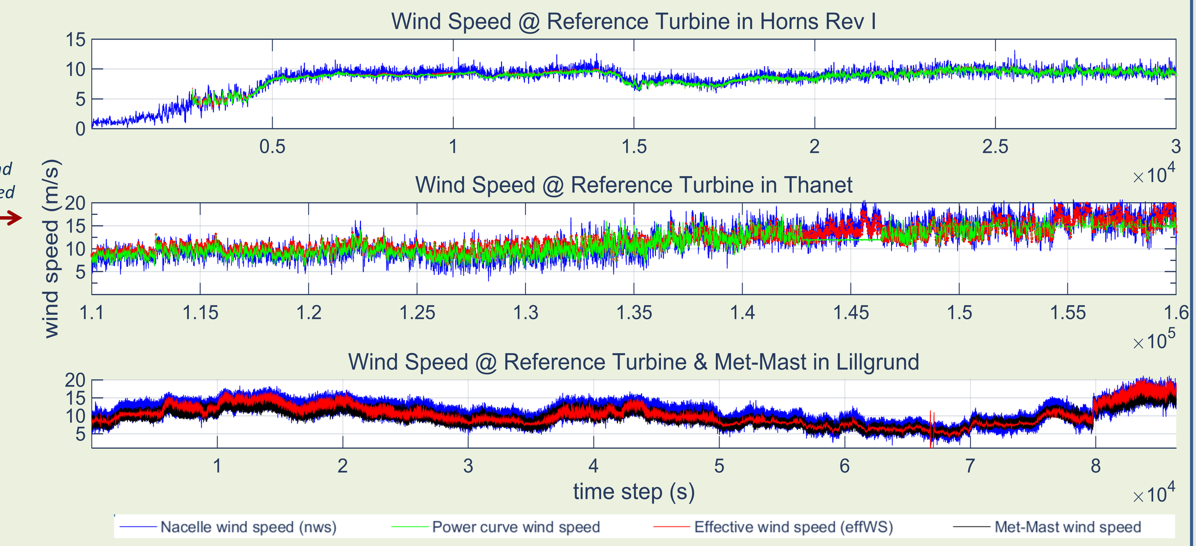
Temperature & Pressure

Wind Speed

The wind speed was calculated for each turbine iteratively using Horns Rev-I, Thanet and Lillgrund offshore wind farms and NREL 5 MW single turbine simulations [3]. Both cases have been investigated using second-wise datasets extracted during both normal operation and under curtailment.

Horns Rev & Thanet

The algorithm is tested using the dataset provided by Vattenfall which covers a 35-hours period for Horns Rev, 47 hours for Thanet and 24 hours for Lillgrund where the whole operational range is contained i.e. below cut-in to above rated region.

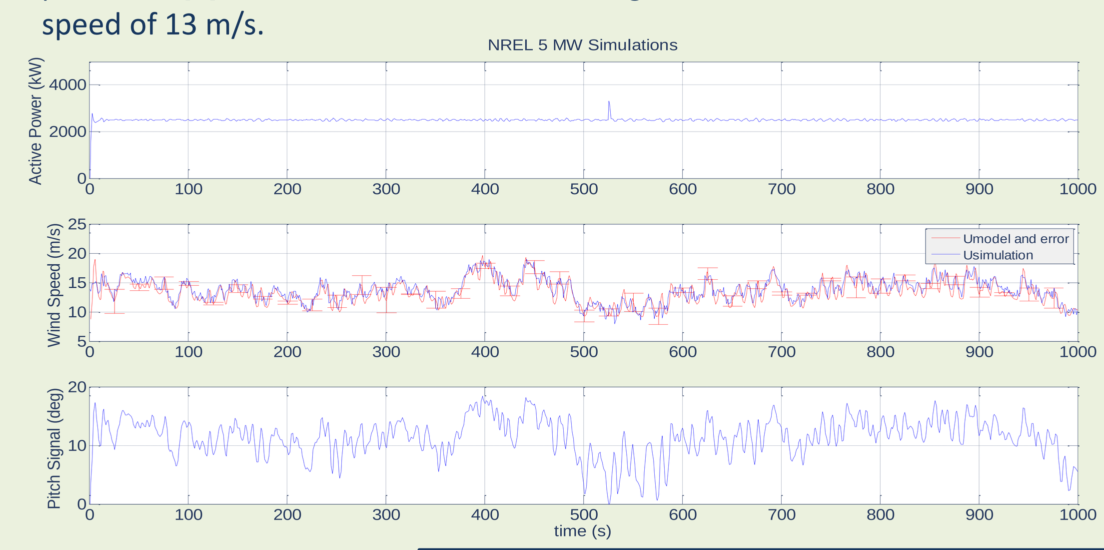


Thanet dataset also includes curtailment which can be seen between 1.4 and 1.5 $\cdot 10^5$. The power curve is not representative after that point but the agreement between the effective wind speed and the nacelle wind speed proceeds with the same trend.

For Lillgrund, estimated effective wind speed is in a very good agreement with the synchronous met-mast data where nacelle anemometer measurements seem to include high level of noise.

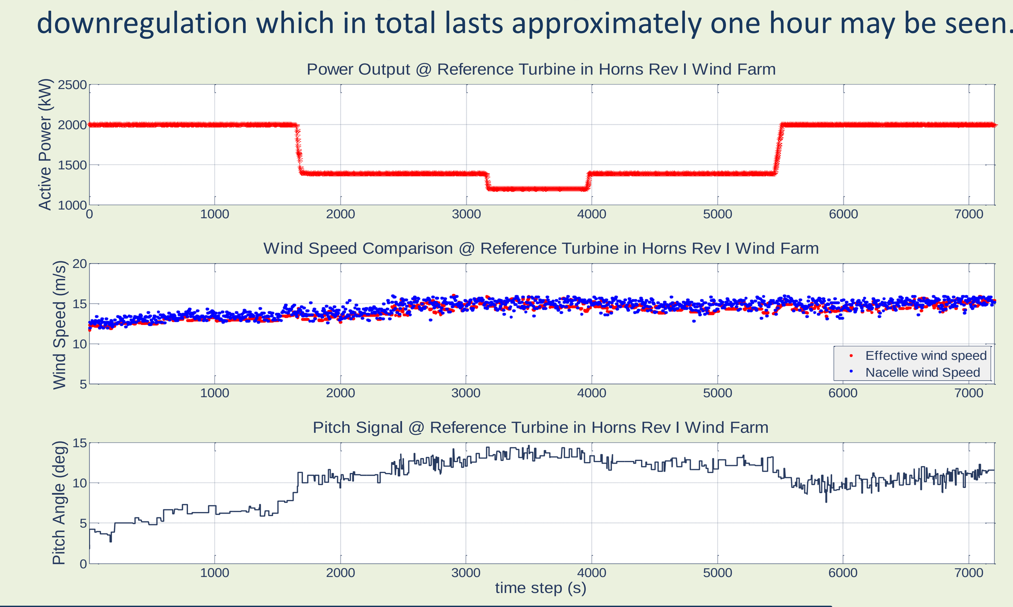
NREL 5 MW

NREL 5 MW is an artificial turbine widely used in simulations since -contrary to commercial turbines- all the aerodynamic and geometric properties are published [3]. The scenario is 50 % downregulation with a simulated mean wind speed of 13 m/s.



Horns Rev – *DownRegulation*

The second dataset from Horns Rev covers approximately 2 hours of data extracted during down-regulation. In Figure 2 (a), the characteristics of the downregulation which in total lasts approximately one hour may be seen.



Conclusion: the model is able to reproduce the wind speed averaged over the rotor for ;

1. Horns Rev - I (Vestas V80 - 2MW offshore), Thanet (Vestas V90 – 3MW offshore) and Lillgrund (Siemens SWT-2.3-93) offshore wind farms
2. NREL 5 MW simulations

Under both normally operated and downregulated cases.

Conclusion

- Real-time wind farm scale available power estimation
  - Also to be used for real-time wind farm power curve
- Second-wise effective wind speed estimation using Active Power, Pitch and Rotational Speed. Validated using:
  - Horns Rev-I (optimum operated + down-regulated)
  - Thanet (optimum operated + down-regulated)
  - Lillgrund (optimum operated)
  - NREL 5 MW (down-regulated)
- Effective wind speeds are used to estimate the atmospheric turbulence intensity and together they are used to calibrate GCLarsen single wake model for real-time
  - Significant improvement in wake recovery around ± 5° relative wind direction bin
- The calibrated model is then run on wind farm scale
  - Promising results were obtained applying time delay: maximum average error of 15.5%

Future Works

- Re-parameterization of the wake algorithm considering meandering
  - Pragmatic approach using wind direction fluctuations [6]
- Real-time wake model implementation on other offshore wind farms
  - Beginning with Horns Rev
- Uncertainty estimation of the available power estimation procedure in practice today and the developed algorithm
  - Summation of individual available powers vs. algorithm described
- Validation of the final algorithm via wind farm scale experiments on Horns Rev
  - **See Gregor Giebel's poster titled 'Experimental verification of a real-time power curve for down-regulated offshore wind power plants' PO.ID 087!**

Acknowledgements

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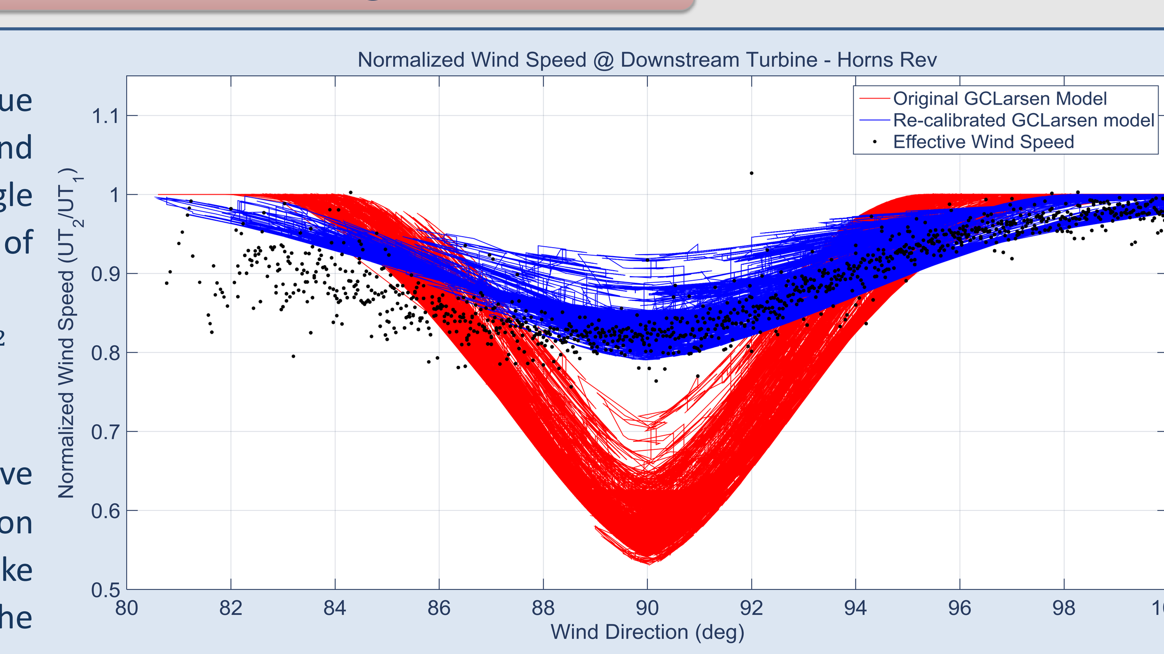
GCLarsen Wake Model Re-calibration for Real Time

Re-calibrated Model Results – Single Wake

The single wake model proposed by GCLarsen has been used for recalibration due to its robustness and simplicity. The model has been implemented in WindPro and shown to perform well also on offshore [4]. The GCLarsen velocity deficit for single wake is derived as below [5] with two variables that were modelled in terms of thrust coefficient, c_T and atmospheric turbulence intensity, TI.

$$u_x(x,r) = -\frac{U_\infty}{9}\left(c_T A (x_0+\Delta x)^{-2}\right)^{\frac{1}{3}}\left\{r^{\frac{3}{2}}\left(3c_1^2 c_T A(x_0+\Delta x)\right)^{-\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3c_1^2\right)^{-\frac{1}{5}}\right\}^2$$

With $x_0 = \boldsymbol{a}\cdot c_{\mathrm{T}}^{\mathbf{b}}$ and $c_1 = \boldsymbol{c}\cdot c_{\mathrm{T}}^{\mathbf{d}} + \boldsymbol{e}\cdot \boldsymbol{TI}$. The estimated second-wise effective wind speed values in Thanet during normal operation were used for calibration and the model is validated on Horns Rev data. For recalibration of the wake model, all data was filtered for north-west perpendicular winds i.e. 320±30°. The model was fit to the dataset using nonlinear least squares estimates.



The original GCLarsen model significantly under-predicts the downstream wind speed for the second-wise dataset. Better recovery achieved by the recalibration can be observed even for 90°±5° bin.

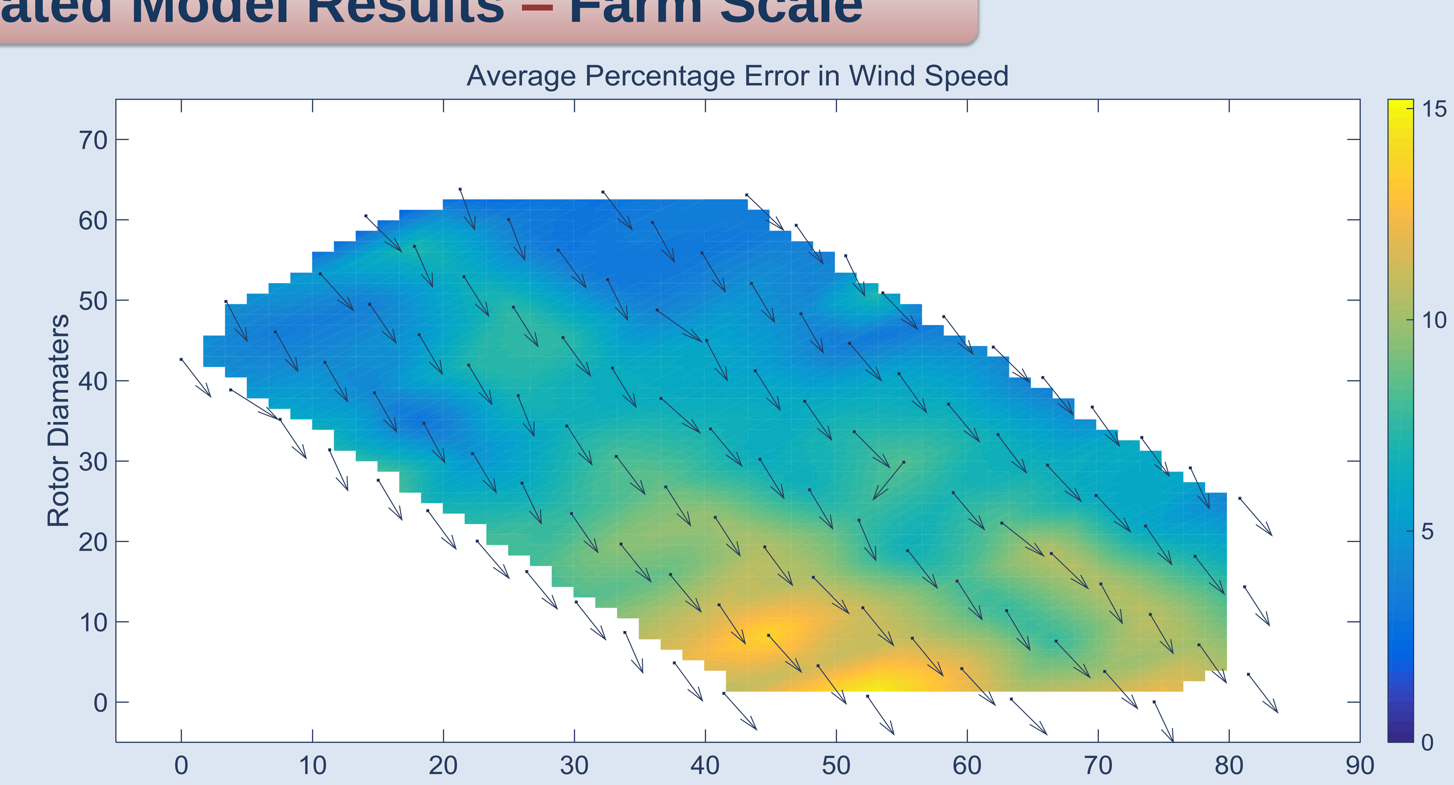
Re-calibrated Model Results – Farm Scale

Time it takes for a particle to move form the most upstream turbine(s) to the current turbine

$$\text{Time Delay} = \frac{\text{Upstream Distance}}{\text{Average Wind Speed}}$$

- Upstream Distance is calculated using the most upstream turbine location and the averaged wind direction
- The effective wind speed at the most upstream location is averaged to approximate the time delay over 90mins

Conclusion: the recalibrated GCLarsen wake model is able to reproduce the downstream effective wind speed for single wake case. On farm scale, time delay is critical for validation cases and the model can be further enhanced by a dynamic time delay algorithm as well as practically introduced meandering. The finalized algorithm can easily be used to achieve real-time wind farm power curve under various operational conditions.



The Percentage Error of the wind speed estimation using Re-calibrated GCLarsen model in Thanet- Averaging Period = 90mins