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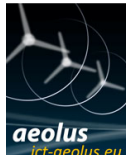
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Prediction Models for Wind Speed at Turbines in a Farm with Application to Control

Torben Knudsen, Mohsen Soltani and Thomas Bak

Aalborg University

October 22, 2009



The Aeolus project

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Overall
control
engineering
view

Wind speed
models for
farm level
control

Estimation
of effective
wind speed

Measurements

System
Identification

Conclusion

This work is part of the EU-FP7 project with the title:
Distributed Control of Large - Scale Offshore Wind Farms
(Aeolus).

The problem from a control point of view

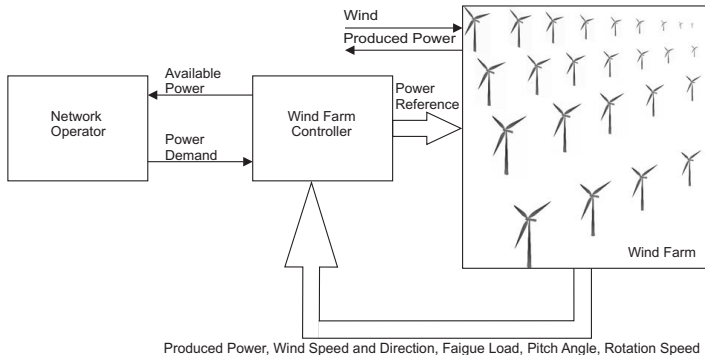


Figure: Block diagram illustrating the centralised control problem.

Wind speed models for farm level control

Motivation and objectives

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Motivation

- Modern control design methods is model based.
- Prediction models are used explicitly (MPC) or implicitly (LQG).
- A wind farm models includes the dynamics of the wind field.
- The important time scale is the average time for wind to travel between turbines which is typically 1 minute.

The objective is then:

*Develop a method for making models for wind speeds at turbine positions in a wind farm where the available measurements are standard signals from the turbines.
The models must be suitable for prediction.*

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Results from the literature

- In Sørensen (2005) it is concluded that the the prediction of wind speeds from upwind turbines is not useful.
- Nielsen (2004) reports useful models for *point* wind speed at separation 300 m but a very weak relation over 600 m.
- Point wind speed coherence functions in e.g. Panofsky (1984) also support the above statement.

New challenges

- Try to develop methods that improves prediction performance over distances typical for a wind farm.
- A hypothesis is that the effective wind over the rotor should be more predictable.

Estimation of effective wind speed

Estimation task

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Estimation task

Approaches from the literature

Estimation model
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Estimation of effective wind speed can be approached as a standard estimation problem.

$$\begin{aligned}\dot{x} &= f(x, u, w), \\ y &= h(x, u, v)\end{aligned}$$

Given the system model above in SS form and the input u output y estimate the state x .

- x is the state which would include the effective wind speed.
- u is the input i.e. blade pitch and generator torque or power reference
- w is process noise which maybe drives the wind model.
- y is measurements e.g. rotor speed, generator speed, produced power and maybe more.
- v is measurement noise.

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- Models used are either one or two inertia drive train models.
- The literature investigated uses a Kalman filter (KF) to estimate rotor torque.
- From this rotor torque plus rotor speed and pitch a direct calculation of wind speed is performed based on c_p tables.
- Consequently, no wind speed model is used.

One inertia drive train model plus wind speed model

State equations

$$I\dot{\omega}_r = T_r - T_g ,$$

$$\dot{v}_t = -a(t)v_t + n_1 ,$$

$$\dot{v}_m = n_2 ,$$

$$T_r = \frac{1}{2}\rho v_r^3 A c_p(\lambda, \beta) \frac{1}{\omega_r} , \quad \lambda = \frac{\omega_r R}{v_r} ,$$

$$T_g = \frac{p}{\mu \omega_r} ,$$

$$v_r = v_t + v_m$$

Tower was initially included both gave to poor observability.

Measurement equations

$$\omega_m = \omega_r + v_1 ,$$

$$v_n = v_r + v_2$$

Detailed wind speed model

- The wind turbulence model is time varying as it depends on average wind speed.
- This improves performance.

$$dv_t = -a(v_m)v_t dt + dw_1,$$

$$dv_m = dw_2,$$

$$w \in W(Q),$$

$$Q = \begin{pmatrix} Q_{11}(v_m) & 0 \\ 0 & Q_{22} \end{pmatrix}, \quad Q_{11}(v_m) = \frac{\pi v_m^3 t_i^2}{L}$$

$$a(v_m) = \frac{\pi v_m}{2L}$$

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- Based on the above models.
- A extended continuous-discrete Kalman filter has been developed.
- It has acceptable observability.
- An reasonably white prediction errors.

An example of the obtained estimates is seen below

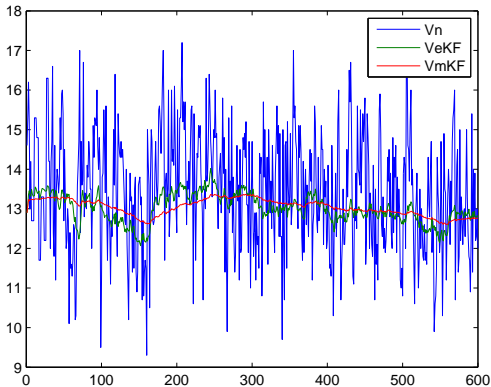


Figure: Comparison of nacelle wind speed and estimated effective wind speed.

Vestas kindly provided 1 second measurements from the OWEZ farm for the project.

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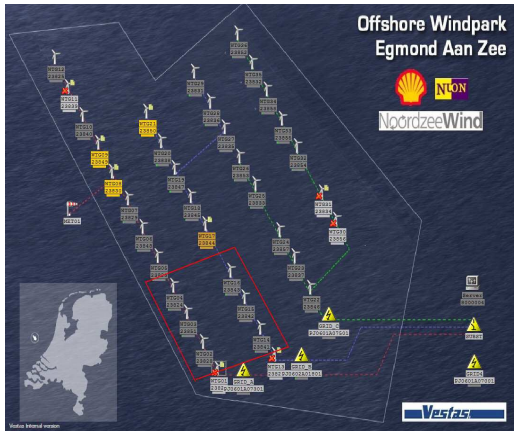


Figure: Layout of OWEZ. The six turbines in the red box is the ones there are measurements for.

Example of 1 days measurements

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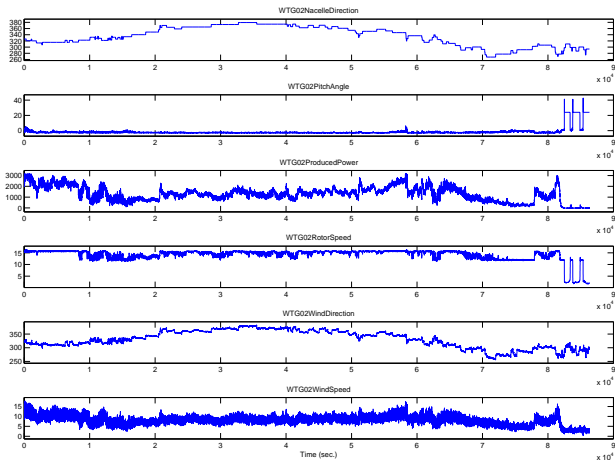


Figure: Time plot for signals from WT02 for one day 2009-02-11.

For single input single output (SISO) systems a linear time invariant (LTI) model can be defined as follows.

$$y(t) = G(q^{-1})u(t - n_k) + H(q^{-1})e(t), \quad e(t) \in \text{ID}(0, \sigma^2)$$

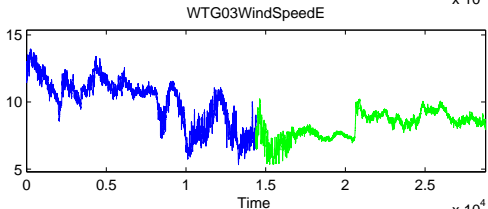
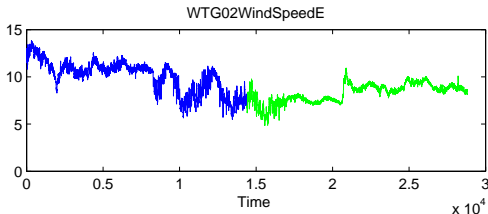
$$G(q^{-1}) = \frac{B(q^{-1})}{A(q^{-1})}, \quad H(q^{-1}) = \frac{C(q^{-1})}{D(q^{-1})}$$

ArxDel ARX model with delay. $n_a = n_b = 2, n_k = 60, C(q^{-1}) = 1, D(q^{-1}) = A(q^{-1})$.

BJDel Box-Jenkins model with delay.
 $n_a = n_b = n_c = n_d = 2, n_k = 60$.

Per Persistence model, no input from upwind i.e.
 $\hat{y}(t + k|t) = y(t) \forall k$.
 $A(q^{-1}) = 1 - q^{-1}, B(q^{-1}) = 0$.

- For estimation the first 4 hours is used.
- And for cross validation the next 4 hours is used as illustrated in the figure.



- The RMS error is the standard error estimate for the predictions.

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{t=1}^N (y(t) - \hat{y}(t|t-k))^2}$$

- The Fit is how much of the standard deviation in the output that is explained by the model.

$$\text{Fit} = 1 - \frac{\text{RMS}}{\hat{\sigma}_y}$$

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Effective wind speed

One minute

Fit (%)			
Pred. hor.	ArxDel	BJDel	Per
1 sec.	37.558	42.233	28.535
30 sec.	23.943	32.062	-9.159
60 sec.	23.937	31.548	-6.071
∞	23.937	32.153	
RMS (m/s)			
1 sec.	0.816	0.755	0.934
30 sec.	0.994	0.888	1.187
60 sec.	0.994	0.894	1.227
∞	0.994	0.886	

Table: Predictability for nacelle wind speed using one upwind turbines and LTI models.

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Effective wind speed

One minute

Fit (%)				
Pred. hor.	ArxDel	BJDel	Per	ArxDel4To2
1 sec.	94.466	94.520	94.380	94.454
30 sec.	68.346	67.928	59.516	64.846
60 sec.	66.862	66.056	52.501	61.178
∞	65.208	65.736		55.140
RMS (m/s)				
1 sec.	0.055	0.054	0.056	0.055
30 sec.	0.314	0.318	0.402	0.349
60 sec.	0.329	0.337	0.472	0.386
∞	0.345	0.340		0.445

Table: Predictability for effective wind speed using one upwind turbines and LTI models.

One minute prediction example

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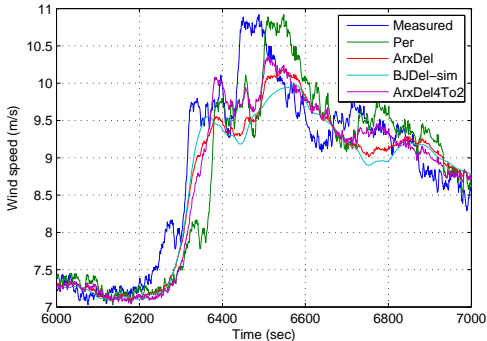
Nacelle wind speed Effective wind speed

One minute

The figure below zooms in on one of the largest gusts in the validation data.

It is clear that a simple prediction model based on the first or second upwind turbine outperforms the persistence method.

Prediction of EWS



Conclusion

Effective wind speed estimation

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- In this paper an estimator for effective wind speed is developed.
- This estimator includes the wind speed in a more “correct” way compared to the estimators found in the literature.
- Using the estimator the effective wind speed for six turbines in the OWEZ farm has been estimated.
- The effective wind speed is more suitable for predictions compared to the nacelle wind speed.

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- Based on simple classical models the prediction error for this effective wind speed can be reduced with 30% using a upwind turbine compared to the persistence method.
- This reduction is for a prediction horizon of 1 minute and a distance of 632 m.
- The smallest standard deviation for this prediction error is 0.33 m/s corresponding to a 95% confidence interval at ± 0.66 m/s which can be sufficiently small to be useful.
- When the distance is approximately doubled to 1277 m the reduction goes from 30% to approximately 15%.