Numerical design of a wind observer and feedforward control of wind turbines

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Abstract. Wind speed is an unknown variable that is very difficult to measure relying on instruments that are commonly present on-board the wind turbine nacelle. The alternative to this approach is to extract a wind speed estimate from other measured quantities. The so-obtained wind speed could then be integrated in common power control algorithms as an additional scheduling variable or it can be exploited to realize feedforward actions to enhance the machine power capture and fatigue life. This work deals with the design of an observer to estimate the spatially-averaged wind speed on the rotor swept area. A linear model of the wind turbine drivetrain based on steady aerodynamics is introduced and used as the base for the wind speed observer. The observer is implemented on the DTU 10MW RWT and a feedforward action based on the estimated effective wind speed is added to the standard feedback controller. FAST co-simulations are performed to evaluate the performances of the implemented system in several wind turbine operating conditions. Its responsiveness is shown to be greater when operating in presence of above-rated winds due to the higher rotor aerodynamic sensitivity. The observer response is instead slower in below-rated winds, where its capability of predicting high-frequency wind gusts is limited by the combination of rotor inertia and generator torque control.

1. Introduction

Nowadays wind energy is one of the fastest growing renewable energy source. In order to decrease the levelized cost of energy (LCOE) modern wind turbines are multi-MW machines, their dimensions are year by year larger and larger, and their design and operation becomes more and more complex. A safe and robust operation requires an accurate design of control logics with the aim of producing high quality power for grid requirements and at the same time enhancing the fatigue life of crucial mechanical components to decrease maintenance cost. In this context, a possible way of improving the operation of the wind turbine is to relate the control action also to the wind speed crossing the rotor area, and not only to the measurement of rotor speed and power, as it is done in standard controllers. To this aim, it is particularly valuable the estimation of the Effective Wind Speed (EWS), the uniform equivalent wind speed yielding the same aerodynamic torque of the complex 3D and time-varying wind speed across the rotor area. Actually, the measurement of a significant value of wind speed in a wind turbine with conventional anemometry is highly inaccurate, while more sophisticated techniques like LIDAR are highly expensive. Several works exist on the topic of EWS estimation [1] [2] [3] relying on the power balance equation or the PI tracking of the aerodynamic torque. The present work proposes instead a Kalman filter for the estimation of the aerodynamic torque,
an Effective Wind Speed (EWS) estimator and the subsequent implementation of a feedforward pitch control action to be added to a standard variable speed variable pitch controller. Then, proposed techniques are implemented on the 10 MW DTU reference wind turbine [4], showing good performances both on the power production side and in the restraint of fatigue loads.

2. Wind observer design

The main task of the wind estimator is to estimate the EWS \( v_e \) yielding the same aerodynamic torque of the complex, 3-D wind field crossing the turbine rotor area. It is known that the rotor torque \( T_r \) can be expressed as a function of \( v_e \) as:

$$ T_r = \frac{1}{2} \rho \pi R^3 C_P (\lambda, \beta) v_e^2 \quad (1) $$

with the tip speed ratio \( \lambda \) as:

$$ \lambda = \frac{\Omega_r R}{v_e} \quad (2) $$

being \( \Omega_r \) the rotor angular speed, \( R \) the rotor radius and \( C_P \) the power coefficient. The rotor torque and angular speed can be estimated through a Kalman-Bucy filter relying on a 2-DOF dynamical model of the drivetrain [2] [1] [5], accounting for flexibility of the rotor shafts:

$$ J_r \dot{\Omega}_r = T_r - K_\theta \dot{\theta} - B_\theta \Omega_r - B_r \Omega_r + \frac{B_\theta}{N_g} \Omega_g $$

$$ J_g \dot{\Omega}_g = -T_g + \eta_R K_\theta \dot{\theta} + \eta_R \frac{B_\theta}{N_g} \Omega_r - B_g \Omega_g - \eta_R \frac{B_\theta}{N_g^2} \Omega_g $$

$$ \dot{\theta} = \Omega_r - \frac{\Omega_g}{N_g} \quad (3) $$

Figure 1: Drivetrain Model

Among the variables in equation (3) not reported in figure 1 \( \eta_R \) is the transmission efficiency and \( \dot{\theta} \) is the relative velocity between rotor and generator shafts. \( B_\theta \) and \( K_\theta \) are the drivetrain stiffness and damping, while \( B_r \) and \( B_g \) are respectively the low-speed shaft and high speed shaft bearing damping.

Equation (3) can be cast into a state space model of the form:

$$ \dot{x} = [F]x + [G]u + [L]w $$

$$ z = [C]x + n \quad (4) $$
with:

\[ x = \begin{bmatrix} \Omega_r & \Omega_g & \theta & T_r \end{bmatrix}^T \]  \hspace{1cm} (5)

\[
[F] = \begin{bmatrix}
-\frac{B_a}{J_r} & \frac{B_g}{N_g J_r} & -\frac{K_a}{J_r} & \frac{1}{J_r} \\
\frac{1}{N_g} & \ni \frac{B_a N_g^2}{N_g J_g} & \frac{1}{J_g} (\frac{B_a}{N_g^2} + B_g) & \frac{1}{N_g} & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]  \hspace{1cm} (6)

\[
[G] = \begin{bmatrix} 0 & -\frac{1}{J_g} & 0 & 0 \end{bmatrix}^T
\]  \hspace{1cm} (7)

\[
[C] = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}
\]  \hspace{1cm} (8)

The state vector \( x \), besides collecting the rotor shaft speed, generator shaft speed and the angular displacement between the two is extended to include the rotor torque, which is estimated as a parameter of the model with simple dynamical equation \( T_r = 0 \). The input of the state space model is the generator torque \( T_g \) and the available measurement is the generator speed \( \Omega_g \).

The disturbance matrix \( [L] \) is defined later during the design of the observer. The Kalman-Bucy filter algorithm is displayed in equation (9)

\[
\dot{\hat{x}} = [F] \hat{x} + [G] u + [K] (z - [C] \hat{x})
\]

\[ \hat{z} = [C] \hat{x} \]  \hspace{1cm} (9)

the gain matrix \([K]\) is derived as:

\[
[K] = [P] [C]^T [R]^{-1}
\]  \hspace{1cm} (10)

the state residual covariance matrix \([P]\) is defined as:

\[
[P] = E \left[ (x - \hat{x}) (x - \hat{x})^T \right]
\]  \hspace{1cm} (11)

and is the solution of the Algebraic Riccati Equation (ARE)

\[
[Q] + [F][P] + [P][F]^T - [P][C]^T [R]^{-1} [C][P] = 0
\]  \hspace{1cm} (12)

with:

\[
E[ww^T] = [Q']
\]  \hspace{1cm} (13)

\[
E[nn^T] = [R]
\]  \hspace{1cm} (14)

\[
E[[L]ww^T[L]^T] = [L][Q'][L]^T = [Q]
\]  \hspace{1cm} (15)

It is possible to adopt here the algebraic solution of the Riccati equation instead of the differential one because the system is LTI and the noise covariances are assumed as constant.
After that the rotor torque and speed are estimated by the filter, the equivalent wind speed is estimated through the analytical expression of the rotor torque in a given equivalent wind speed found in equation (1). The equation is indeed implicit, because the power coefficient $C_P$ is in itself a function of $v_e$ through the TSR, then it must be rearranged to be solved with the Newton-Raphson method:

$$f(\hat{\lambda}) = \frac{C_P(\hat{\lambda}, \beta)}{\hat{\lambda}^3} - \frac{2\hat{T}_r}{\rho \pi R^5 \hat{\Omega}^2}$$

(16)

where the ($\hat{\cdot}$) denotes the estimated quantities. A block scheme of the whole observer is available in Figure 2.

![Figure 2: Kalman filter with Newton-Raphson block scheme](image)

3. Feedforward pitch control action

The estimated EWS $\hat{v}_e$ is now exploited to generate a feedforward control action to be added to an already existing feedback control loop generally implemented on wind turbines [6] [7]. This control technique is thought to be used in above rated conditions, to keep more accurately the extracted power equal to the rated power of the machine. The procedure is partly derived from [7], even if here the control loop is based on the pitch angle and not on the pitch angle rate of change.

Once the EWS $\hat{v}_e$ is obtained, the corresponding pitch angle $\beta_{ff}$ to reach rated power is derived from the $C_P$ curve through the expression of rotor power:

$$P_r = \frac{1}{2} \rho \pi R^2 C_P (\hat{\lambda}, \beta_{ff}) \hat{v}_e^3$$

(17)

If the rotor power is equal to the rated one, then the pitch angle is equal to $\beta_{ff}$, and can be computed by solving the implicit equation with the Newton-Raphson method. The TSR is obviously known through the estimated $\hat{v}_e$. To avoid excessive loads on the pitch actuators and remove useless high-frequency fluctuations the difference between the actual pitch angle $\beta$ and the one computed through $\hat{v}_e$ is filtered with a second-order low-pass filter as in equation (18):

$$\frac{\beta_{ff,\Delta}}{\beta_{ff} - \beta} = \frac{\omega_b^2}{s^2 + 2\xi_b\omega_b s + \omega_b^2}$$

(18)

Due to the delay introduced in the filtering operation, it is necessary to introduce a simple extrapolation for the estimated EWS [7], given an integration time step $\Delta t$ and a preview time $\Delta T$:
\[ \hat{v}_e (t_i + \Delta T) = \hat{v}_e (t_i) + \Delta T \frac{\hat{v}_e (t_i) - \hat{v}_e (t_{i-1})}{\Delta t} \] (19)

The extrapolation is needed, otherwise the feedforward contribution would be performed on delayed data, and would result in poor performances.

The expression of the feed-back pitch control loop added with the feedforward contribution then can be written as a function of the Laplace variable \( s \):

\[
\beta_{\text{ref}}(s) = \left( k^*_{\Omega P} + \frac{k^*_{\Omega I}}{s} \right) e_\Omega(s) + \left( k^*_{P P} + \frac{k^*_{P I}}{s} \right) e_P(s) + \frac{\omega_b^2}{s^2 + 2\xi_b\omega_b s + \omega_b^2} (\beta_{\text{ff}}(s) - \beta(s)) \] (20)

where \( \beta_{\text{ref}} \) is the reference pitch angle, \( k^*_{\Omega P} \) and \( k^*_{\Omega I} \) are the proportional and integral gains on the speed error \( e_\Omega = \Omega - \Omega_0 \), and \( k^*_{P P} \) and \( k^*_{P I} \) are the same gains on the power error \( e_P = P - P_0 \). The present control system does not include any gain scheduling technique. A scheme of the implemented control system is available in figure 3.

![Figure 3: The scheme of the feedback-feedforward control system](image)

4. Application to the 10 MW DTU reference wind turbine

The wind observer and the feedforward pitch control action displayed respectively in sections 2 and 3 are now tested numerically on the 10 MW DTU reference wind turbine [4], whose gross-properties are listed in table 1.

4.1. Observer set-up

All the relevant data necessary to build the model in equation (3) are found in [4]. The observability of the system is checked, and all the states result to be observable. The observer
Table 1: DTU 10 MW reference wind turbine gross properties

| Parameter               | Value                  |
|-------------------------|------------------------|
| Rotor orientation       | Clockwise rotation, Upwind |
| Number of blades        | 3                      |
| Rated Power             | 10 MW                  |
| Rated rotor speed       | 9.6 rpm                |
| Rotor diameter          | 178.3 m                |
| Hub height              | 119.0 m                |
| Control                 | Variable speed collective pitch |
| Cut-in wind speed       | 4 m/s                  |
| Cut-out wind speed      | 25 m/s                 |
| Rated wind speed        | 11.4 m/s               |

Table 2: Extrapolation parameters

| Parameter | Value |
|-----------|-------|
| $\omega_b$ | 2.1991 rad/s |
| $\xi_b$   | 2     |
| $\Delta T$ | 1 s   |
| $\Delta t$ | 0.01 s |

The process noise and measurement noise matrices $[Q]$ and $[R]$ are set with a trial and error procedure as:

$$[Q] = \begin{bmatrix} 4 & 0 & 0 & 0 \\ 0 & 80 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 10^{15} \end{bmatrix}$$

$$[R] = 5000$$

The initial conditions are $\hat{x} = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}^T$. The poles of the observer show to be all stable with values:

$$-3.0144 + 25.2679i$$

$$-3.0144 - 25.2679i$$

$$-0.1042$$

$$-0.4137$$

The extrapolation in (19) is set with values in table 2 after some trials of the algorithm.

4.2. Simulation data

The operation of the DTU RWT is simulated with the FAST routine [8], running into the Simulink® environment, where the turbine control is implemented. In all the simulations the turbine is considered as rigid and fixed to the ground, the only enabled DOF are the generator rotation and the drivetrain torsional flexibility. The turbine feedback control has three main operation modes:

- **Region 1**: until cut-in, no power is demanded to the rotor, and the aerodynamic torque is used to accelerate the rotor
- **Region 2**: from cut-in speed to rated speed variable speed fixed pitch controller on rotor torque
• Region 3: variable pitch fixed speed controller to keep the rated power and speed

The observer receives blade pitch, generator speed and torque from FAST and evaluate $\hat{v}_e$. The generator speed is added with white noise with values 0.5% within the measured values. After that, if the machine is operating in Region 3 the feedforward pitch action is added to the feedback one. If the algorithm fails in converging to a solution, a zero contribution is given. The turbine is tested in different wind conditions, here resumed:

• Uniform wind field with steps of speed from the cut-in to the cut-out: in this conditions the EWS should be equal to the simulated wind speed;
• turbulent wind field according to IEC-61400-1 [9] [10] simulated through NREL TurbSim [11]. A realistic atmospheric boundary layer is also generated with the power law ($\alpha = 0.2$, $z_0 = 0.03$ m for onshore areas, $\alpha = 0.1$, $z_0 = 0.003$ m for offshore or coastal areas).

Figures 4 reports the estimated rotor torque, rotor, speed, generator torque, EWS in a wind step simulation, while figures 5, 6, 7 are results from simulations in turbulent wind.

The observer shows good stability also in case of sudden fluctuations due to turbulence, and it is responsive especially for above rated wind speeds. The estimation of the aerodynamic torque is instead nervous, but still satisfactory.

4.3. Fatigue loads reduction

The final aim of feedforward action is to smooth the control action to reduce the loads on crucial turbine components like blades, tower and hub. Here the comparison is made between fatigue loads with the standard feedback controller and with the feedforward action. The intensity of fatigue wear is determined with the equivalent load range approach. As showed in [12] the random load experienced by a component is divided into single amplitude load ranges, each one associated to the number of cycles to failure reported in the Wölfer’s curves. Then, load ranges are linearly summed following the Palmgren-Miner’s summation rule. Instead of using the experimental S-N curve, the Damage Equivalent Loading (DEL) is used, following its definition:

$$S_{tot} = \sum S_i^n n_i = DEL^m n_{eq}$$

where $S_i$ is the real $i_{th}$ load range and $n_i$ is the number of cycles of its application, while $m$ is the Wölfer’s exponent and $n_{eq}$ is an equivalent number of cycles. The DTU report in [4] suggests to adopt $m = 10$ for the turbine blades, $m = 3$ for the other components and $n_{eq} = 10^7$, which implies an infinite fatigue life. By rearranging equation (23) the DEL can be evaluated as:

$$DEL = \left(\sum S_i^n n_i \right)^{1/m}$$

The Rainflow counting algorithm implemented in the MATLAB® function rainflow.m is used to divide the random load in individual load ranges. The DELs are computed both for the standard controller and for the feedback-feedforward version; analyzed loads are the tower base fore-aft bending moment, the yaw bearing along wind force and the blade root flapwise bending moment. Results are compared in table 3.

A reduction of DEL between 1% and 6% is obtained in all the three analyzed loads, showing the applicability of feedforward control for the reduction of loads even in absence of other wind estimation techniques (LIDAR or anemometer reading).
4.4. Power, torque or angular speed fluctuations

Another desirable effect of feedforward control implementation is the reduction of rotor angular speed, torque and power to ensure good quality power production and reduced vibrations on rotational components. The intensity of fluctuations is evaluated as the standard deviation of a given analyzed quantity on its average, then the power, torque and speed fluctuation intensity are respectively:

Figure 4: Uniform wind steps from 4 to 25 m/s on DTU 10 MW
Figure 5: Category A turbulence on DTU 10 MW with feedforward action, 14 m/s hub height characteristic speed

\begin{align}
I_{P_r} &= \frac{\sigma_{P_r}}{\overline{P_r}} \\
I_{T_r} &= \frac{\sigma_{T_r}}{\overline{T_r}} \\
I_{\Omega_r} &= \frac{\sigma_{\Omega_r}}{\overline{\Omega_r}}
\end{align}

Table 4 reports the reduction of fluctuations obtained in feedback-feedforward controller with
Figure 6: Category A turbulence on DTU 10 MW with feedforward action, 16 m/s hub height characteristic speed

respect to the standard controller. A significative reduction is appreciated in all the quantities, and for all the analyzed wind scenarios. Moreover, during trials it is observed that the average value of speed, power and torque is closer to the rated value with respect to the standard controller case, showing an improvement in the tracking capabilities of the feedforward control.

4.5. Final remarks
All along the performed trials it is generally observed an increased actuation of blades pitch due to the feedforward contribution. This effect is predictable, and it is the price to be paid for an
increased responsiveness of the controller; however, simulations showed that its increase is always less than 1% and tends to decrease at higher wind speeds. Nevertheless, considering results showed in sections 4.3 and 4.4, the trade off between increased pitch actuation and improved machine operation is deemed positive. Moreover, the feedforward pitch action it is not adding detrimental high frequency components in the pitch reference signal, so partly mitigating the greater usage of actuators.
Table 3: Percentage reduction of DELs with the feedback-feedforward controller

|        | 14 m/s | 16 m/s | 18 m/s |
|--------|--------|--------|--------|
| $M_{yt}$ | 6.08%  | 3.48%  | 2.09%  |
| $F_{xp}$ | 6.27%  | 2.45%  | 1.19%  |
| $M_{yb}$ | 1.99%  | 4.93%  | 1.34%  |

Table 4: Percentage reduction of fluctuations with the feedback-feedforward controller

|        | 14 m/s | 16 m/s | 18 m/s |
|--------|--------|--------|--------|
| $I_{Pr}$ | 24.23% | 26.59% | 22.85% |
| $I_{Tr}$ | 23.76% | 26.58% | 23.93% |
| $I_{Ωr}$ | 25.22% | 26.80% | 21.06% |

5. Conclusion
The present article shows the design of a wind observer for the estimation of the equivalent wind speed on a conventional wind turbine, and the implementation of a feedforward pitch control action to be added to the standard feedback one in the above rated operation of the machine. The reported techniques are applied to the 10 MW DTU reference wind turbine and a comparison is made with the standard controller. The proposed control technique is able to reduce the fatigue loads in particularly stressed portion of the wind turbine, and moreover it is decreasing the amplitude of oscillations in the rotor torque and power. These effects are achieved at the expenses of an increased pitch actuation, even if in a fully acceptable range. Future work surely includes the extension of the presented control strategy to the below rated operation and the investigation of its feasibility on floating wind turbines.

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