Modelling, Parametrization and Observer Design of a 20 MW Reference Wind Turbine for Control Purposes

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Abstract. In the present contribution, the model development of a wind turbine with focus on an advanced control system design is reported. The aim is to produce a model that captures essential dynamics over the simplest cases but maintaining an acceptable level of complexity. The problem of parameter reduction from high-resolution models, as used in the simulation of reference turbines, to models with low number of parameters, as normally used for control purposes, is also studied. The obtained parametric model is validated by developing an observer, which can be used for state-space control as well as effective wind speed estimation. As numerical example, a 20 MW reference wind turbine is used. Very large wind turbines are very flexible and nonlinear, therefore very simple rigid models do not lead to satisfactory results. The proposed observer is adjusted during operation in order to overcome this problem.

1. Introduction

Modern multi-MW wind turbines, which are characterized by their large dimensions and flexible structures, require advanced control algorithms to reach a satisfactory performance. On the other hand, advanced control requires suitable dynamic models for control purposes, i.e. models that are able to capture the essential dynamic behaviour of the machine but keeping their simplicity such that a control system design of acceptable complexity can be achieved, in particular if controllers have to be implemented in real time.

The rotating subsystem of a wind turbine is a complex system if the rotor and flexible blades are taken into account. Standard approaches assume the drivetrain rigid as a two-mass-system, the rotor as a single mass and the generator as a second mass (see e.g. [1] and [2]). This model can be extended to three masses as in [3] and [4], if the mass of the gearbox is included. These approaches work fine for simple control objectives, e.g. the control of the rotational speed. However, they are not adequate if the aim is to implement model-based control including flexible blades, vibration control or blade tip deflection damping control (see [5, 6]).

Trying to maintain the mentioned compromise between necessary dynamics and simplicity, a model of seventh order is presented in this work for the rotating subsystem. It includes a collective edgewise blade tip deflection as well as torsion in the shafts. The model is parametrized by using a grey-box procedure and validated by developing an observer for the estimation of states variables as well as the effective wind speed. An important contribution of the work is the systematic parametrization of the proposed low-resolution model from a high-resolution model, which is used for simulation purposes. Hence, the estimated variables are compared with the simulation results provided by FAST [7]. Of particular interest are the edgewise blade oscillations and shaft torsional oscillations. In addition, partial derivatives of aerodynamic variables, which are necessary for adaptive controllers are summarized.
It is important to remark that fore-aft dynamics of the tower as well as flap-wise dynamics of the blades are not included in the present work. The paper is organized as follows: the dynamic model and the steady-state equations are derived in Section 2 and 3, respectively. The model parametrization is undertaken in Section 4. Section 5 is devoted to the observer design. In Sections 6, simulation results and model validation are presented. Finally, conclusions are drawn in Section 7.

2. Modelling the Rotating Subsystem of the Wind Turbine for Control Purposes

2.1 System Decomposition

The system decomposition is similar to one proposed in [8], which is presented in Figure 1.

![Figure 1. System decomposition of a wind turbine](image)

2.2. Simple aerodynamic model

The modelling of the aerodynamics is based on the assumption that the rotor is an actuator disk, through which the wind passes at the same speed. This leads to a model, which is very oft used in the control literature and it consists of mean equations describing total power, total torque applied to the rotor and thrust force acting on the rotor, i.e.

\[ P = 0.5 \pi \rho R^2 C_p(\beta, \lambda) \nu_{we}, \quad (1) \]
\[ T_s = 0.5 \pi \rho R^2 C_q(\beta, \lambda) \nu_{we}, \quad \text{and} \quad (2) \]
\[ F_t = 0.5 \pi \rho R^2 C_t(\beta, \lambda) \nu_{we}, \quad (3) \]

where \( \rho \), \( R \) and \( \nu_{we} \) are the air density, the rotor radius and the effective wind speed, respectively. \( C_p \), \( C_q \) and \( C_t \) are the power, rotor torque and thrust coefficients, which in turn depend on the pitch angle \( \beta \) and the tip-speed ratio \( \lambda = \frac{R \omega}{\nu_{we}} \). \( \omega \) is the rotor speed. Of particular interest are the partial derivatives \( \frac{\partial P}{\partial \beta}, \frac{\partial F_t}{\partial \beta}, \frac{\partial P}{\partial \nu_{we}} \), and \( \frac{\partial F_t}{\partial \nu_{we}} \), which are used in some adaptive control laws and observers.

2.3 Modelling the Rotational Subsystem

The rotating subsystem consists here of the wind turbine rotor, the drivetrain and the generator. The rotor includes three rotor blades and the hub. The drivetrain contains only the low-speed shaft, a gearbox and the high-speed shaft. On the other hand, the rotor can be represented as a multi-mass system of four masses, the gearbox contributes an additional mass and the generator mass completes a system of six masses. The simplified model for this system is developed under the following assumptions:

- postulates for the BEM method (Blade Element Momentum) are satisfied (see [9])
- distributed effects around the rotor can be considered concentrated on the rotation axis
- components have a linear behavior but inputs (\( T_s \) and \( T_g \)) can be nonlinear
- all three blades are identical and move synchronically at the same frequency

The first assumption is a necessary condition for the second assumption, which allows to consider a model of lumped parameters. The third assumption is necessary for obtaining a linear model, which is modelled with a time-frozen approach (e.g. [10]). The last assumption is required for the abstraction procedure of Figure 2 (proposed in [11]) and leads to a simplification from six to four mass system.
Figure 2. Abstraction process to represent the rotor as a two-mass rotating system [11, 12].

The advantage of this approach is to reduce the complexity but maintaining the first in-plane vibration frequency of the blades into the model. On the other hand, the limitation is to assume that all blades oscillate synchronically. However, this assumption is compatible with the postulation that the wind speed is the same over the whole rotor. The model formulation under this approach is given by the following set of differential equations

\[
J_{be} \ddot{\omega}_b + D_{be} \omega_b - D_b \omega_b + K_b (\theta_b - \theta_r) = T_a,
\]

\[
J_{he} \ddot{\omega}_r + (D_{he} + B + D_{inh}) \omega_r - D_{bhe} \omega_r \left(\frac{n}{n_e}\right) \omega_b - K_h (\theta_r - \theta_e) + (K_{inh} / n)(\eta \theta_e - \theta_e) = 0,
\]

\[
J_{ge} \ddot{\omega}_r + D_{ge} \omega_r - n_d D_{eh} \omega_r - n_r^2 D_{hss} \omega_g - K_{hss}(\eta \theta_r - \theta_e) + n_r^2 K_{hss}(\theta_e - \theta_g) = 0, \text{ and}
\]

\[
J_{ge} \ddot{\omega}_g + (D_{hss} + B_g) \omega_g - D_{hss} \omega_g - K_{hss}(\theta_e - \theta_g) = -T_g.
\]

Parameters \( J, B, D, K \) and \( n_e \) represent the mass second moments of inertia, viscous friction coefficients, damping coefficients, stiffness coefficients and the gearbox ratio, respectively. Variables \( \omega, \theta \) and \( T \) correspond to rotation speed, rotation angle and torque, respectively. Subscripts \( b, r, g, a, e, x, xl, xh, lss \) and \( hss \) denote blade, rotor, generator, aerodynamic, equivalent, gearbox, low-speed side of the gearbox, high-speed side of the gearbox, low-speed shaft and high-speed shaft, respectively. The moments of inertia are defined as \( J_{be} = 3J_{btip} \) and \( J_{he} = J_h + 3J_{broot} \), where \( J_h, J_{btip} \) and \( J_{broot} \) are the moments of inertia of the hub, blade tip and blade root, respectively. The equivalent parameters noted by the subscript \( e \) are defined by

\[
J_{ge} = J_{al} + n_r^2 J_{sh} \text{ and } B_e = B_{al} + D_{inh} + n_r^2 (B_{sh} + D_{hss}).
\]

State-space variables are defined as \( x_1 = \omega_b, x_2 = \omega_r, x_3 = \omega_{xh}, x_4 = \omega_g, x_5 = \theta_b - \theta_r, x_6 = n \theta_e - \theta_e, \) and \( x_7 = \theta_e - \theta_g \). \( x_3 \) is the angle of the in-plane collective blade tip deflection and, \((x_1 - x_2)\) is the speed. Moreover, \( x_5 \) and \( x_7 \) are the torsions in low-speed shaft and high-speed shaft, respectively. Hence, the state-space model is

\[
\dot{x}_1 = -\frac{D_{be}}{J_{be}} x_1 + \frac{D_{be}}{J_{be}} x_2 - \frac{K_b}{J_{be}} x_3 + \frac{1}{J_{be}} T_a,
\]

\[
\dot{x}_2 = \frac{D_{be}}{J_{be}} x_1 - \frac{(B_e + D_{inh} + D_{hss})}{J_{be}} x_2 + \frac{D_{inh}}{n_e J_{be}} x_3 + \frac{K_{hss}}{J_{be}} x_3 - \frac{K_{hss}}{n_r J_{be}} x_5,
\]

\[
\dot{x}_3 = \frac{n_r D_{hss}}{J_{ge}} x_2 - \frac{B_g}{J_{ge}} x_4 + \frac{n_r^2 D_{hss}}{J_{ge}} x_3 + \frac{K_{hss}}{J_{ge}} x_3 - \frac{n_r^2 K_{hss}}{J_{ge}} x_7,
\]

\[
\dot{x}_4 = \frac{D_{hss}}{J_g} x_3 - \frac{B_g + D_{hss}}{J_g} x_4 + \frac{K_{hss}}{J_g} x_3 - \frac{1}{J_g} T_g,
\]

\[
\dot{x}_5 = x_1 - x_2,
\]

\[
\dot{x}_6 = n_x x_2 - x_3, \text{ and}
\]

\[
\dot{x}_7 = x_3 - x_4.
\]
3. Steady-state Modelling

The steady-state model is obtained by setting the derivatives of the state variables in (6) equal to zero for the state variable $x_0 = [x_{10}, x_{20}, ..., x_{70}]^T$, i.e.,

$$-D_{x_0}x_{10} + D_{x_0}x_{20} - K_{x_0}x_{30} + T_{a0} = 0,$$

$$D_{x_0}x_{10} - (B_r + D_{x_0} + D_{x_0})x_{20} + (D_{x_0} / n_r)x_{30} + K_{x_0}x_{30} - (K_{x_0} / n_r)x_{60} = 0,$$

$$n_r D_{x_0}x_{30} - B_r x_{30} + n_r D_{x_0} x_{40} + K_{x_0} x_{30} - n_r K_{x_0} x_{30} = 0,$$

$$D_{x_0}x_{30} - (B_g + D_{x_0})x_{40} + K_{x_0} x_{30} - T_{g0} = 0,$$

$$x_{10} - x_{20} = 0, \; n_r x_{20} - x_{30} = 0 \; \text{and} \; x_{30} - x_{40} = 0,$$

where $T_{a0}$ and $T_{g0}$ are stationary values for inputs $T_a$ and $T_g$. From (7) as well as (10) and (11), it follows

$$K_{x_0} x_{30} = T_{a0} \; \text{and} \; K_{x_0} x_{70} - B_g x_{40} = T_{g0},$$

and solving for (8) and (9)

$$B_r x_{20} = T_{a0} - n_r T_{g0} \; \text{and} \; K_{x_0} x_{60} = n_r [(1 - B_r / B_g)T_{a0} - n_r T_{g0} / B_g]$$

is obtained, where $B_r = B_r + n_r^2 (B_g + B_{a0})$. In addition, one has from (11)

$$x_{30} = x_{20}, \; x_{30} = n_r x_{20} \; \text{and} \; x_{40} = x_{30}.$$

Hence, (12)-(14) determine univocally the steady-state $x_0$. On the other hand, given some known stationary inputs and state values, unknown parameters can be calculated. $T_{a0}$ is a nonlinear function of the wind whilst $x_{50}$ and $x_{20}$ are obtained from a linear model and therefore, (12) and (13) will not be always satisfied for different wind speed by the same constant parameters. This can be solved by considering variable parameters in both equations. Thus, $T_{a0}$ is computed for each wind speed and the parameters are also computed from (12) and (13) and will continuously be adjusted depending on the wind speed. Notice that the difference between the aerodynamic torque and the electromagnetic torque translated to the low speed shaft (eq. (13)) is equal to the total losses produced by the bearings.

4. Model Parametrization for a Numerical Example

For the implementation of the numerical example, the reference wind turbine of 20 MW, which is proposed in [13] and studied in [14], is used. Parameters, which are necessary to satisfy the aerodynamic properties as well as to parametrize the model of eq. (6), are obtained in the following subsections.

4.1 Aerodynamic Subsystem

The partial derivatives are calculated numerically as proposed in [7] as part of the linearization process of FAST [15], where the derivatives are elements of the Jacobian matrices. In addition, curve fitting is carried out in order to obtain polynomial functions for the derivatives. These are illustrated in Figure 3 and Figure 4.
In Region II, the derivatives are computed for $\beta=0$, and in Region III, the pitch angle is set to the value for the operating point, i.e. a value for which the rotational speed is rated at the given wind speed.

### 4.2 Parametrization of the Rotational Subsystem

The model formulation leads to the set of differential equations (6), where the parametrization is carried out by using a grey-box approach that combines known parameters, simulation data, steady-state conditions and optimization. Hence, the set of parameters consists of three subsets. The first subset contains the fixed known parameters of the wind turbine, which are summarized in Table 1. Rated values are given in Table 2.

**Table 1. Main design parameters of the 20 MW wind turbine.**

| Parameters                                | Values     | Units   |
|-------------------------------------------|------------|---------|
| Rotor mass moment of inertia             | $2919.66 \times 10^6$ | kg m$^2$ |
| Generator mass moment of inertia         | $7248.32$  | kg m$^2$ |
| Hub mass moment of inertia               | $2.1 \times 10^6$ | kg m$^2$ |
| Blade mass moment of inertia             | $972.52 \times 10^6$ | kg m$^2$ |
| Rotor radius                             | $138$      | m       |
| Blade cone angle                         | $4$        | deg     |
| Equivalent shaft spring constant         | $6.94 \times 10^7$ | Nm/rad |
| Equivalent shaft damping constant        | $4.97 \times 10^7$ | Nm/(rad/s) |
| Generator efficiency                     | $94.4$     | %       |
| Gearbox ratio                            | $164$      | ---     |
| First in-plane blade frequency           | $0.6277$   | Hz      |
| Structural damping ratio                 | $0.48$     | %       |

**Table 2. Rated values of the 20 MW wind turbine for the rated wind speed.**

| Variables                                | Rated values | Units |
|-------------------------------------------|--------------|-------|
| Wind speed                                | $10.715$     | m/s   |
| Wind speed, cut in / cut off values       | $4.38 / 25.00$ | m/s   |
| Mechanical / electrical power             | $21.191 / 20.0$ | MW    |
| Rotor speed                               | $7.1567$     | rpm   |
| Generator speed                           | $1173.7$     | rpm   |
| Rated generator torque                    | $0.17241$    | MNm   |

The second subset of parameters is obtained by using equations (12)-(14) and the steady-state values of the state variables, which are obtained by open-loop simulations. Simulations are carried out for constant wind speed values between 4.38 and 25 m/s. The steady-state values for the inputs and state variables are presented in Figure 5. Notice that steady-state variables are normalized such that the maximum values are equal to 1 ($T_{\alpha,\text{max}}=1.8336 \times 10^6$ Nm, $T_{\phi,\text{max}}=1.1172 \times 10^6$ Nm, $x_{2,\text{max}}=1.1228$ rad/s, $x_{6,\text{max}}=0.0301$ rad).
Frictions coefficients are unknown and therefore, they are chosen in such a way that they are compatible with real values from data sheets and in addition they meet steady state values. In general, friction coefficients depend on speed. Here, it is assumed that the friction coefficients are smaller at slow speed, i.e. $B_r = 2B_g$ and $B_x = 2B_{xh}$. A typical value for $B_g$ is e.g. 0.02 and from (13), the friction coefficient of the gearbox $B_{xh}$ is obtained for each value of $\omega_0$ as shown in Figure 6.

![Figure 5. Steady-state values used for parameter calculation](image1)

![Figure 6. Friction coefficients for the gearbox](image2)

The third subset of parameters are obtained indirectly combining steady-state values, design parameters and optimization. This is the case, for example, of some parameters related to blades and shafts. From (12), $K_b$ is calculated for different wind speeds such that the steady-states values are reached. The range for $K_b$ is then $3.5227 \times 10^6 \text{ Nm/rad} \leq K_b \leq 3.6599 \times 10^9 \text{ Nm/rad}$. Notice that the breaking point introduced in Section 2 changes the position with the wind speed. Since the first in-plane blade frequency is 0.6277 Hz, the moment of inertia of all three blade tips together is

$$J_{bc} = J_{3tip} = K_b / (4\pi f_{w}^2),$$

which leads to $7.1149 \times 10^5 \text{ kg m}^2 \leq J_{bc} \leq 1.2299 \times 10^8 \text{ kg m}^2$. The moment of inertia of the three blades together is $2.9176 \times 10^9$ and therefore, the moment of inertia of the three blade roots is

$$J_{3roots} = J_{blades} - J_{3tip},$$

i.e., $2.9168 \times 10^9 \text{ kg m}^2 \leq J_{brook} \leq 1.6877 \times 10^9 \text{ kg m}^2$. The damping coefficient is given in general by

$$D_b = 0.05 \times 2\sqrt{K_b J_{bc}},$$

where the 5% of the critical damping is used, such that for the values obtained for $K_b$ and $J_{bc}$, the range for $D_b$ is $1.5831 \times 10^4 \text{ Nm/(rad/s)} \leq D_b \leq 2.1216 \times 10^8 \text{ Nm/(rad/s)}$. The stiffness of the low speed shaft is estimated first as $5.57 \times 10^10 \text{ Nm}$ by using the formula $K_{ls} = G I / L_s$, where $G$ is the shear modulus of the material, $I$ the second moment of area and $L_s$ is the shaft length. Then, it is adjusted to obtain the range according to (13). The stiffness of the high-speed shaft is then calculated by using

$$1 / K_e = 1 / K_{ls} + 1 / (n_t^2 K_{hs}),$$

for $K_e = 6.94 \times 10^9 \text{ Nm/rad}$. The damping coefficients are obtained from $D_{ls} = 0.05 \times 2\sqrt{K_{ls} J_{ls}} = 1.99 \times 10^7$ and

$$1 / D_e = 1 / D_{ls} + 1 / (n_t^2 D_{hs}),$$

as $D_{ls} = 7.09 \times 10^8 \text{ Nm/(rad/s)}$ with $D_e = 4.97 \times 10^7 \text{ Nm/(rad/s)}$. 
5. Observer Design

The obtained model of the previous sections has been used for the design of an observer in order to estimate the unknown state variables as e.g. rotor speed, in-plane collective tip blade deflection and the effective wind speed.

The observer topology is inspired in the concept proposed in [16]. However, the design is different because the observer proposed here is adaptive and based on a time-frozen strategy, i.e. the observer is redesigned during operation by recalculating the parameters according to equations (14)-(16). From (6), it follows that the model for the observer is given by

\[
\dot{x}(t) = A(x,u_1,u_2) x(t) + b_1 u_1(t) + b_2 u_2(t)
\]

where \( u_1 = T_a \), \( u_2 = T_g \) and \( y = \omega_g \), respectively. Matrix \( A \) and vectors \( b_1, b_2 \) and \( c^T \) are given by

\[
A = \begin{bmatrix}
-\frac{D_b}{J_{ke}} & -\frac{D_g}{J_{he}} & 0 & 0 & \frac{K_b}{J_{ke}} & 0 & 0 \\
-\frac{D_b}{J_{ke}} & (B + D_2 + D_{ke}) & 0 & 0 & \frac{K_b}{J_{ke}} & -\frac{K_{ge}}{J_{he}} & 0 \\
0 & n_2 J_{ke} & n_2 J_{ke} & 0 & \frac{K_{ge}}{J_{he}} & -\frac{n_2^2 K_{ke}}{J_{he}} & 0 \\
0 & 0 & 0 & 0 & -\frac{B_g}{J_{ge}} & -\frac{B_g + D_{ke}}{J_{ge}} & 0 & 0 & K_{ke} \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & n_e & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
\end{bmatrix}, \quad \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 1/J_{ke} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad (21)
\]

Notice that parameters of \( A \) are computed in the previous section in dependence of design parameters and steady-state values, which also depend on the wind speed in a determined range. This justifies the notation \( A(x,u_1,u_2) \) in (20). Hence, the scheme for the observer is presented in Figure 7a. The aerodynamic torque is a non-measurable input. Therefore, it is estimated in [16] by using a PI controller, whose input is the difference between the measured and the estimated generator rotational speeds, as shown in Figure 7b.

\[
\dot{x}(t) = A(x,u_1,u_2) x(t) + b_1 u_1(t) + b_2 u_2(t)
\]

\( y(t) = c^T x(t) \)

Figure 7. (a) Scheme for the online adaptation of the observer. (b) Observer in details
The observer design is carried out by using the pole placement method according to the algorithm proposed in [17]. Thus, all poles of the observer assigned by mean of $P(s)$ and obtained from
\[ det(sI - A + k_o c^T) = P(s) = 0, \tag{22} \]
are always maintained in the same position by recalculating $k_0$ according to the changes produced on $A$. The observer design for linear, time-invariant (LTI) systems requires the observability of the pair ($A$, $c^T$). However, the matrix $A$ is not constant and therefore the observability condition is more complex. The variable parameters of $A$ are defined in (12)-(14), where $T_{ao}, T_{gb}, x_{20}, x_{50}, x_{60}$ and $x_{70}$ depend on the wind speed $v_w$. On the other hand, $v_w$ is bounded between the cut-in and cut-out values, i.e. $v_{cutin} \leq v_w \leq v_{cutout}$, such that $A$ is an interval matrix defined by $A \leq A \leq \bar{A}$. A set of matrices $A$ is obtained by performing simulations at constant wind speed between $v_{cutin} \leq v_w \leq v_{cutout}$. Thus, the observability check is carried out off-line by applying the test provided in [18]. Notice that adaptive approach with redesign during the operation reduces the effect of possible parametric uncertainty.

The PI controller can also be formulated in the state-space representation as
\[
\dot{x}_4(t) = -\frac{K_p}{K_p} \dot{x}_4(t) + \frac{K_i}{K_p} \hat{T}_o(t),
\]
\[
\hat{T}_o = \dot{x}_4 + K_p \dot{x}_4(t) - K_p \omega_g(t)
\]
where $y = x_4 = \omega_g$. Hence, the state-space equation in (20) can be augmented as
\[
\begin{bmatrix}
\dot{x}(t) \\
\dot{\hat{x}}(t)
\end{bmatrix} = 
\begin{bmatrix}
A(u_1, u_2, x_1 - k_o c^T) & 0 \\
-K_p / K_p & 0
\end{bmatrix}
\begin{bmatrix}
\dot{x}(t) \\
\dot{\hat{x}}(t)
\end{bmatrix} + 
\begin{bmatrix}
b_2 \\
K_p / K_p
\end{bmatrix} u_2(t) + 
\begin{bmatrix}
b_1 \\
K_p / K_p
\end{bmatrix} y(t) + 
\begin{bmatrix}
b_1 \\
K_p / K_p
\end{bmatrix} \hat{T}_o(t).
\]
\[
\begin{bmatrix}
\dot{\hat{y}}(t) \\
\hat{T}_o(t)
\end{bmatrix} = 
\begin{bmatrix}
c^T \\
0 0 0 K_p 0 0 0 1
\end{bmatrix}
\begin{bmatrix}
\dot{x}(t) \\
\dot{\hat{x}}(t)
\end{bmatrix} + 
\begin{bmatrix}
0 \\
-K_p
\end{bmatrix} y(t)
\]
such that the observer is implemented in a compact way.

6. Simulation and Results
The reference wind turbine is simulated in FAST 8.16 and the observer is implemented in Matlab/Simulink. In order to appreciate the tracking properties of the observer, the wind is assumed to be 15 m/s constant with a step change of 1 m/s after 100 s. For the effective wind speed estimation, two wind profile are use. The first one is a stochastic wind field with 20 % turbulence and the second one is an extreme operating gust (EOG) at 18 m/s according to IEC 61400-1 standard. Results are summarized in Figure 8.

![Figure 8. Validation results for effective wind speed.](image-url)
Tracking of other important variables are shown in Figure 9. Notice that figures are strong zoomed in order to appreciate the differences between simulated and estimated signals.

![Image](image.png)

**Figure 9.** Validation results for aerodynamic torque, blade tip deflection and rotor speed

In the figures, it can be appreciated that one characteristic of the adaptive observer is that signals are filtered attenuating the amplitudes of oscillations but maintaining the phase. The rapid response of the observer is due to the poles selected for the observer design, (w.r.t. eq. (22)).

The normalized root-mean-square error (NRMSE) for the wind gust reconstruction for stochastic wind profile with 20 percent turbulence intensity is computed to be 0.2869 and the NRMSE for the wind gust reconstruction is 0.4927.

It is important to remark that the bandwidth of the effective wind speed is much lower than the frequency of any blade or drivetrain mode. Hence, it is normal to filter out their contribution to the effective wind speed. However, filters are not included in the work in order to avoid hiding the real dynamic performance of the observer. In case of need, filters can be added at a later stage.

7. Conclusions

In the present work, a model for the rotating subsystem of a wind turbine as well as the aerodynamic subsystem are derived with the aim of control system design. Simulation results show that the obtained model is able to represent the essential dynamics of the wind turbine. For this model, an extended observer for states variables and wind speed is designed and validated. The observer is redesigned during the operation in order to maintain its performance for different wind speeds. Due to the fact that the model results to be of medium complexity, it can be used for model-based control system design. In particular, it can be used for blade tip deflection damping control, as well as damping control of drive-train vibrations, since the observer provided a fast estimation of the tip deflection. This will be the next steps in this research.

The proposed model does not include the side-to-side tower interaction. This is the next step in the work. Considerations of fore-aft tower dynamics, as well as flap-wise blade dynamics, leads to very complex models, which will be studied in the future, as well.

References

[1] Ashwini P and Archana T 2016 *International Journal of Emerging Trends in Electrical and Electronics* vol 12 p 18-23

[2] Boukhezzar B and Siguerdidjane H 2011 *IEEE Transactions on Energy Conversion* vol 26 p 149-162

[3] Gonzalez-Longatt F, Regulski P, Novanda H and Terzija V 2012 *Automation of Electric Power Systems* vol 36

[4] Xu H, Xu H, Chen L and Wenske J 2013 *International Conference on Electric Power and Energy Conversion Systems* (Istambul: IEEE)
[5] Gambier A 2019 IFAC-PaperOnLine vol 52 p 274-279
[6] Gambier A 2017 1st IEEE Conference on Control Technology and Applications (Kohala Cost: IEEE) p 1679-1684
[7] Jonkman J and Jonkman B 2016 Journal of Physics: Conference Series vol 753 p 082010
[8] Leithead W E, de la Salle S A, Reardon D and Grimble M J 1991 International Conference on Control ’91 (Edinburgh: IET)
[9] Hansen M O 2015 Aerodynamics of wind turbines, 3rd ed (London: Routledge)
[10] Tóth R 2010 Modeling and identification of linear parameter-varying systems, 1st ed (Berlin: Springer)
[11] Ramtharan G, Anaya-Lara O, Bossanyi E and Jenkins N 2007 Wind Energy vol 10 p 293-301
[12] Gambier A 2017 IFAC-PapersOnLine vol 50 p 9896-9901
[13] Ashuri T, Martins J R, Zaaijer M B, van Kuik G A and van Bussel G J 2016 Wind Energy vol 19 p 2071-2087
[14] Gambier A and Meng F 2019 12th Asian Control Conference (Hong Kong: ACCA) p 258-263
[15] Jonkman J M 2013 51st AIAA Aerospace Sciences Meeting (Grapevine: AIAA)
[16] Østergaard K Z, Brath P and Stoustrup J 2007 Journal of Physics: Conference Series vol 75 p 012082
[17] Kautsky J, Nichols N K and Van Dooren P 1985 International Journal of Control vol 41 p 1129-1155
[18] Wang K and Michel A N 1994 IEEE Transactions on Automatic Control vol 39 p 1443-1447

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