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Wind turbine optimal control during storms

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Abstract. This paper proposes a control algorithm that enables wind turbine operation in high winds. With this objective, an online optimization procedure is formulated that, based on the wind turbine state, estimates those extremal wind speed variations that would produce maximal allowable wind turbine loads. Optimization results are compared to the actual wind speed and, if there is a danger of excessive loading, the wind turbine power reference is adjusted to ensure that loads stay within allowed limits. This way, the machine can operate safely even above the cut-out wind speed, thereby realizing a soft envelope-protecting cut-out. The proposed control strategy is tested and verified using a high-fidelity aeroservoelastic simulation model.

1. Introduction

Wind speeds during storms can be very high, and this can lead to high wind turbine operational loads. These high wind speeds do not occur very often, and therefore it is not economical to design wind turbines capable of withstanding such high loads. In fact, the energy produced in storm wind conditions should be traded against the cost of material, manufacturing and installation for a wind turbine designed to withstand the associated high loads, as shown by models of the cost of energy [1]. The standard strategy for avoiding excessive loading, also known as sharp cut-out, is to shut down the wind turbine whenever high wind speeds are detected. Besides not using the available wind power, such an approach can lead to sudden shutdowns of the entire wind farm, causing instability of the power grid [2]. Furthermore, since it is not possible to reliably predict wind speed, it is also not possible to accurately predict the moment when wind turbines will shut down or the duration of their downtime. Therefore, the prediction error of produced power can be significant, which makes it difficult for transmission system operators to rely on wind power when storms are probable.

Modified control strategies, often called soft cut-out, have been proposed in the literature [3,4]. Soft cut-out approaches reduce the wind turbine power reference in strong winds, based on offline-shaped strategies. If the shaping is adequate, loads are reduced and the wind turbine can produce power even during storms, without negative impacts on the power grid. Such strategies are typically shaped based on mean wind speed value and do not take into account the current wind turbine state or the actual level of loading, resulting in lower power production than is strictly necessary to avoid excessive loading.

An improvement of the soft cut-out strategy was suggested in [5, 6]. There, wind and wind turbine states were actively monitored and the power reference was reduced only when there was a risk of excessive loading. With this objective, a linear optimization procedure was used

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to predict wind speed variations producing the highest possible loads. The optimization result was then used to find the highest possible power reference that would keep loads within allowed limits, even in the occurrence of the predicted extreme wind variations. Such an approach has all the positive aspects of using a soft cut-out strategy, but, additionally, it results in higher power production since it can increase the power reference whenever there is no danger of excessive loading. However, certain assumptions on wind characteristics had to be made for the prediction of worst-case wind speeds, and incorrect assumptions could lead to either excessively low power references or high loads. Therefore, for the control algorithm to work properly, wind characteristics should be monitored and adjusted online.

In this paper, a different approach is taken for using dynamic optimization in a soft cut-out strategy, derived from the idea of rotorcraft envelope protection presented in [7]. Instead of assuming certain wind characteristics, here an optimization procedure is used to find those wind speed variations that would keep the wind turbine as close as possible to the border of the safe operating region, without crossing it, a concept that could be termed *envelope-riding*. The optimization result is then compared to the actual wind speed (either measured or estimated) to detect if there is a danger of excessive loading, in which case the power reference is adjusted accordingly. The proposed strategy is tested and verified using the high-fidelity aeroservoelastic simulation software `Cp-Lambda` [8].

2. Wind turbine model

For the purpose of control synthesis, a simplified wind turbine mathematical model is developed. The rotor dynamic torque balance is described as

$$J_\mathrm{t}\dot{\omega} = Q_\mathrm{a} - Q_\mathrm{g}, \tag{1}$$

where J_t is combined rotor, drive train and generator inertia, ω the rotor speed, Q_g the generator electromagnetic torque, and Q_a the aerodynamic torque. The tower fore-aft dynamics is described with a second order system:

$$M\ddot{x}_\mathrm{t} + D\dot{x}_\mathrm{t} + Cx_\mathrm{t} = F_\mathrm{t}, \tag{2}$$

where M, D and C are modal mass, damping and stiffness of the tower, x_t the tower top displacement and F_t the aerodynamic thrust.

The aerodynamic torque Q_a and thrust force F_t are described with quasi-static equations based on torque $C_\mathrm{Q}(\lambda,\beta)$ and thrust $C_\mathrm{F}(\lambda,\beta)$ coefficients:

$$Q_\mathrm{a} = \frac{\pi}{2}\rho_\mathrm{a}R_\mathrm{r}^3 C_\mathrm{Q}(\lambda,\beta)\tilde{v}_\mathrm{w}^2, \tag{3a}$$

$$F_\mathrm{t} = \frac{\pi}{2}\rho_\mathrm{a}R_\mathrm{r}^2 C_\mathrm{F}(\lambda,\beta)\tilde{v}_\mathrm{w}^2, \tag{3b}$$

where ρ_a is air density, R_r the rotor radius, $\tilde{v}_\mathrm{w}$ the rotor effective wind speed, β the blade pitch angle and λ the tip speed ratio $\lambda = \omega R_\mathrm{r}/\tilde{v}_\mathrm{w}$. Due to the tower motion, the whole rotor moves fore and aft, thus creating oscillations in the effective wind speed:

$$\tilde{v}_\mathrm{w} = v_\mathrm{w} - \dot{x}_\mathrm{t}, \tag{4}$$

where v_w is the rotor effective wind speed without tower motion.

The blade pitch servo is modelled as a second order system:

$$\ddot{\beta} + 2\zeta\omega_n\dot{\beta} + \omega_n^2\beta = \omega_n^2\beta_\mathrm{r}, \tag{5}$$

where β_r is the pitch angle reference, $\omega_n = 10\,\mathrm{rad/s}$ the undamped natural frequency and $\zeta = 1$ the damping ratio. The generator dynamics are significantly faster and therefore, for the purpose of controller design presented in this paper, the actual torque is assumed to be equal to the torque reference, i.e. $Q_\mathrm{g} = Q_\mathrm{g,r}$.

The reduced wind turbine model is linearised around the operating points of interest (at cut-out wind speed, in the present case) and discretized to obtain a state space representation

$$x_{k+1} = A_\mathrm{d} x_k + B_\mathrm{d} u_k, \tag{6}$$

where A_d and B_d are model matrices, $x = \begin{bmatrix}\Delta\omega & \Delta x_\mathrm{t} & \dot{x}_\mathrm{t} & \Delta\beta & \dot{\beta}\end{bmatrix}^T$ is the state vector, $u = [\Delta v_\mathrm{w} \;\; \Delta\beta_\mathrm{r} \;\; \Delta Q_\mathrm{g,r}]^T$ the input vector and Δ indicates an increment with respect to a reference value at the linearization point. Index k denotes a value at the discrete time step k $(t = kT_\mathrm{s})$.

3. Standard wind turbine control system

The control goal of variable speed wind turbines in low winds is to maximize energy production. This is typically achieved with the blades pitched to an optimal angle and by controlling the rotor speed with generator torque. On the other hand, during strong winds, it is necessary to limit the power output to the nominal value. This is typically achieved by using the nominal generator torque, while the rotor speed is controlled by pitching the rotor blades (thereby changing the aerodynamic efficiency of the rotor). For a more detailed description of a standard wind turbine controller, see [9] and references therein.

However, as the wind speed increases, the loads that the wind turbine has to withstand increase as well. At a certain wind speed, loads get too high, as the cost of material needed to withstand such loads would be greater than the income from energy produced in such conditions [10]. Therefore, it is standard practice to shut down the wind turbine when such high wind speeds are detected, as shown in Fig. 1. Such an approach can lead to sudden shutdowns of the entire wind farm, thus generating considerable disturbances for the power grid [2]. Furthermore, since it is not possible to reliably predict when the wind turbine will be shut down due to high wind speeds when there is a risk of storms, one cannot make reliable predictions about the power output of wind farms in such situations. With the constant increase of wind power penetration in the power grid and of rated power of modern wind turbines, such a control strategy might have to be abandoned.

A modified control strategy, known as soft cut-out, has been proposed in the literature (see e.g. [3, 4]). Instead of abruptly shutting the wind turbine down in very high wind speeds, load reduction is achieved by reducing the power reference, as shown in Fig. 2. Although the wind turbine will produce less than the nominal power, P_n, there are numerous benefits for both the wind turbine and the power grid. In fact, by reducing the number of startups and shutdowns,

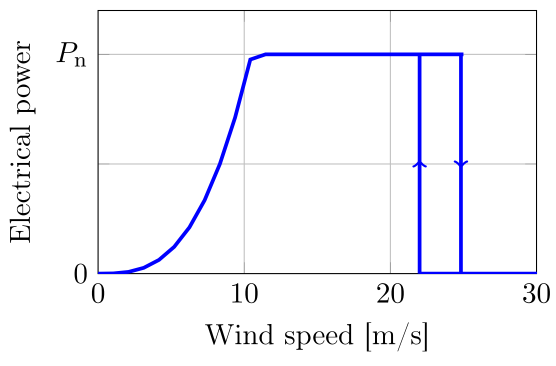

Figure 1. Sharp cut-out strategy.

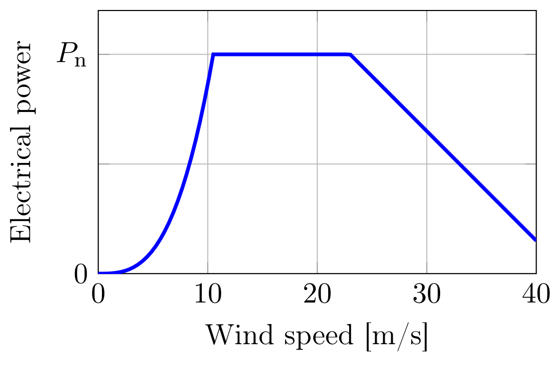

Figure 2. Soft cut-out strategy.

fatigue is lowered, annual power production is increased, disturbances to the power grid are minimized and the prediction of wind farm power output becomes more reliable.

However, standard soft cut-out strategies are shaped offline and based only on averaged wind speed. In order to ensure that loads remain within the allowed limits, machines often produce a lower power than really necessary to contain extreme loading. It is quite evident that an approach that could monitor both wind and wind turbine state could result in a higher energy production.

4. Cut-out strategy based on online optimization

In this section, a novel approach for soft cut-out is proposed. Instead of using predefined strategies, the wind turbine state is constantly monitored in order to verify how close the wind turbine is to reaching its maximal allowable loads. When the wind turbine gets close to the limits of its allowable loads, then the power reference is reduced. On the other hand, when loads are not close to the limit, the power reference is increased.

First, the wind turbine mathematical model used in the optimization procedures is described in §4.1. The problem of finding wind speeds that lead the wind turbine to the limit of safe operation is formulated in §4.2, while §4.3 describes the optimization procedure for selecting the power reference.

4.1. Closed-loop wind turbine mathematical model

The mathematical model expressed by (6) is augmented with an algorithm for power (i.e. rotor speed) control. Note that the proposed cut-out strategy can be used with any type of control algorithm for power control. In this paper, a gain scheduled PI controller is used:

$$\beta_{\mathrm{r},k} = K_{\mathrm{P}} \left(\omega_{\mathrm{r},k} - \omega_k + \frac{1}{T_{\mathrm{I}}} e_{\mathrm{I},k} \right), \tag{7a}$$

$$e_{\mathrm{I},k+1} = e_{\mathrm{I},k} + \frac{1}{T_{\mathrm{s}}} \left(\omega_{\mathrm{r},k} - \omega_k \right), \tag{7b}$$

where $\omega_{\mathrm{r},k}$ is the rotor speed reference, and K_{P}, T_{I} are the controller gain and integral time constant, respectively. To allow for the integration of the control law (7) into the state space model, a matrix $C_{\mathrm{d},\omega}$ is defined, such that $\Delta\omega = C_{\mathrm{d},\omega} x$, and a new symbol is assigned to each column of the input matrix $B_{\mathrm{d}} = [B_{\mathrm{d},v} \;\; B_{\mathrm{d},\beta} \;\; B_{\mathrm{d},Q}]$.

Typically, a wind turbine is not actively controlled with the generator in high wind speeds and, therefore, the generator torque is omitted from the mathematical model. With the modified state vector $x_{\mathrm{cl}} = \left[x^T \;\; \Delta e_{\mathrm{I}}\right]^T$ and input vector $u_{\mathrm{cl}} = [\Delta v_{\mathrm{w}} \;\; \Delta\omega_{\mathrm{r}}]^T$, the closed-loop state space model is written as:

$$x_{\mathrm{cl},k+1} = \underbrace{\begin{bmatrix} A_{\mathrm{d}} - K_{\mathrm{P}} B_{\mathrm{d},\beta} C_{\mathrm{d},\omega} & \frac{K_{\mathrm{P}}}{T_{\mathrm{I}}} B_{\mathrm{d},\beta} \\ -\frac{1}{T_{\mathrm{s}}} C_{\mathrm{d},\omega} & 1 \end{bmatrix}}_{A_{\mathrm{cl}}} x_{\mathrm{cl},k} + \underbrace{\begin{bmatrix} B_{\mathrm{d},v} & K_{\mathrm{P}} B_{\mathrm{d},\beta} \\ 0 & \frac{1}{T_{\mathrm{s}}} \end{bmatrix}}_{B_{\mathrm{cl}}} u_{\mathrm{cl},k}. \tag{8}$$

If a certain load is described with the output equation $y_k = C_{\mathrm{d}} x_k + [D_{\mathrm{d},v} \;\; D_{\mathrm{d},\beta} \;\; D_{\mathrm{d},M}]\, u_k$, then in closed-loop, this is given as:

$$y_k = \underbrace{\begin{bmatrix} C_{\mathrm{d}} - K_{\mathrm{P}} D_{\mathrm{d},\beta} C_{\mathrm{d},\omega} & \frac{K_{\mathrm{P}}}{T_{\mathrm{I}}} D_{\mathrm{d},\beta} \end{bmatrix}}_{C_{\mathrm{cl}}} x_{\mathrm{cl},k} + \underbrace{\begin{bmatrix} D_{\mathrm{d},v} & K_{\mathrm{P}} D_{\mathrm{d},\beta} \end{bmatrix}}_{D_{\mathrm{cl}}} u_{\mathrm{cl},k}. \tag{9}$$

Since the optimizations described later in the section are always performed over a horizon (i.e. time window), a corresponding mathematical model is derived from (8) and (9). First, the following vectors are defined:

$$\boldsymbol{X} = \left[x_1^T \ \ x_2^T \ \ \cdots \ \ x_{N_\mathrm{h}}^T\right]^T, \tag{10a}$$

$$\boldsymbol{Y} = \left[y_1^T \ \ y_2^T \ \ \cdots \ \ y_{N_\mathrm{h}}^T\right]^T, \tag{10b}$$

$$\boldsymbol{V} = \left[\Delta v_{\mathrm{w},0} \ \ \Delta v_{\mathrm{w},1} \ \ \cdots \ \ \Delta v_{\mathrm{w,N_h}-1}\right]^T, \tag{10c}$$

$$\boldsymbol{\Omega}_\mathrm{r} = \left[\Delta \omega_{\mathrm{r},0} \ \ \Delta \omega_{\mathrm{r},1} \ \ \cdots \ \ \Delta \omega_{\mathrm{r},N_\mathrm{h}-1}\right]^T, \tag{10d}$$

where N_h is the length of the prediction horizon. Next, the wind turbine mathematical model over the prediction horizon can be written as:

$$\boldsymbol{X} = \boldsymbol{A}x_0 + \boldsymbol{B}_V\boldsymbol{V} + \boldsymbol{B}_\Omega\boldsymbol{\Omega}_\mathrm{r}, \tag{11a}$$

$$\boldsymbol{Y} = \boldsymbol{C}x_0 + \boldsymbol{D}_V\boldsymbol{V} + \boldsymbol{D}_\Omega\boldsymbol{\Omega}_\mathrm{r}, \tag{11b}$$

where matrices $\boldsymbol{A}$, $\boldsymbol{B}_V$, $\boldsymbol{B}_\Omega$, $\boldsymbol{C}$, $\boldsymbol{D}_V$ and $\boldsymbol{D}_\Omega$ are constructed directly from state space model matrices (8) and (9).

4.2. Wind variations that produce maximal allowed loads

In this subsection, an optimization procedure is formulated for finding the worst wind variations that will not lead the wind turbine outside of its safe operating region. The goal is to find such wind speed variations on a given horizon, which will make the wind turbine ride its load envelope without exceeding it. The procedure has been derived by modifying the rotorcraft flight envelope protection concept presented in [7].

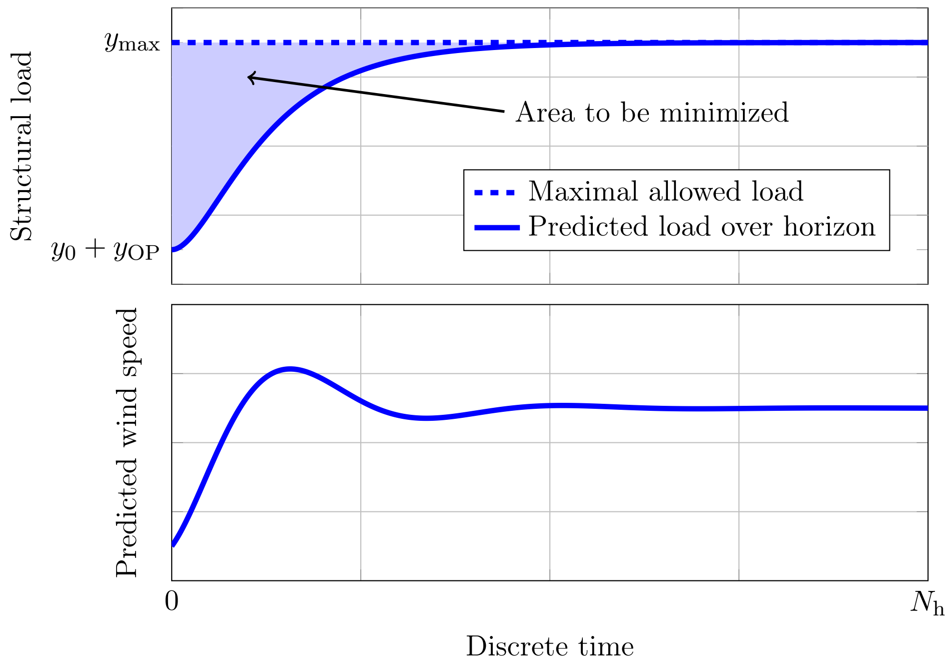

Figure 3. Illustrative example for the optimization procedure.

Figure 3 illustrates the problem considered here. Since the goal is to keep load y as close as possible to the maximal allowed load y_max, wind speed variations are computed that minimize the area between those two loads. In the discrete time domain, the area can be computed as:

$$J = \sum_{k=1}^{N_\mathrm{h}} \left(y_\mathrm{max} - y_k - y_\mathrm{OP}\right) T_\mathrm{s}, \tag{12}$$

assuming $y_k + y_{\mathrm{OP}} \leq y_{\max}$, for each k, where y_{OP} is the load at the observed operating point. Now, it is necessary to find the wind speed variations on a given horizon that minimize area J. For optimization, it is convenient to express this area as:

$$J = -\boldsymbol{e}^T \boldsymbol{Y} T_{\mathrm{s}} + \left(y_{\max} - y_{\mathrm{OP}}\right) N_{\mathrm{h}} T_{\mathrm{s}}, \tag{13}$$

where $\boldsymbol{e}$ is a vector comprised of ones, $\boldsymbol{e} = [1 \;\; 1 \;\; \cdots \;\; 1]^T$.

To reduce the number of optimization unknowns, cubic splines are used to express wind speed within the prediction horizon:

$$\Delta v_{\mathrm{w},k} = a_{\mathrm{s},i} + b_{\mathrm{s},i}\left(kT_{\mathrm{s}} - t_i\right) + c_{\mathrm{s},i}\left(kT_{\mathrm{s}} - t_i\right)^2 + d_{\mathrm{s},i}\left(kT_{\mathrm{s}} - t_i\right)^3, \quad t_i \leq kT_{\mathrm{s}} \leq t_{i+1}, \tag{14}$$

where $a_{\mathrm{s},i}$, $b_{\mathrm{s},i}$, $c_{\mathrm{s},i}$ and $d_{\mathrm{s},i}$ are the cubic spline parameters. Two new vectors are introduced: $\boldsymbol{V}_\xi$, comprised of wind speeds at time instances $t_i \geq 0$ that will be used as optimization variables, and $\boldsymbol{V}_{\mathrm{p}}$, comprised of past wind speed values, $t_i < 0$, that can be used to model the observed wind speed trend if such information is available. Time instances t_i are relative to the prediction horizon and they are defined in advance. Furthermore, spline parameters, $a_{\mathrm{s},i}$, $b_{\mathrm{s},i}$, $c_{\mathrm{s},i}$ and $d_{\mathrm{s},i}$, are linear functions of wind speed values $\boldsymbol{V}_\xi$ and $\boldsymbol{V}_{\mathrm{p}}$. Therefore, the wind speed vector $\boldsymbol{V}$ can be constructed as:

$$\boldsymbol{V} = \boldsymbol{W}_\xi \boldsymbol{V}_\xi + \boldsymbol{W}_{\mathrm{p}} \boldsymbol{V}_{\mathrm{p}}, \tag{15}$$

where $\boldsymbol{W}_\xi$ and $\boldsymbol{W}_{\mathrm{p}}$ are matrices used for calculation of the cubic spline interpolation over the prediction horizon.

The constrained optimization problem can be formulated as:

$$\underset{\boldsymbol{V}_\xi}{\text{minimize}} \qquad -\boldsymbol{e}^T \boldsymbol{D}_V \boldsymbol{W}_\xi \boldsymbol{V}_\xi, \tag{16a}$$

$$\text{subject to} \qquad \boldsymbol{C} x_0 + \boldsymbol{D}_V \left(\boldsymbol{W}_\xi \boldsymbol{V}_\xi + \boldsymbol{W}_{\mathrm{p}} \boldsymbol{V}_{\mathrm{p}}\right) + \boldsymbol{D}_\Omega \boldsymbol{\Omega}_{\mathrm{r}} \leq y_{\max} - y_{\mathrm{OP}}. \tag{16b}$$

Note that parts from the area (13) that do not depend on the optimization variable $\boldsymbol{V}_\xi$ are omitted, since they do not affect the result. The optimization is constrained to ensure that loads do not surpass the maximal allowed value $y_{\max}$. Since the solution of linear programs, such as (16), is always at the border of the feasible space [11], the optimization will result in wind speed variations that lead the wind turbine as close as possible to $y_{\max}$.

4.3. Reference selection

The previous section showed how to compute wind speed variations that will lead the wind turbine as close as possible to its maximal allowed loads. Here, it will be shown how this information can be used to avoid reaching (and surpassing) the allowed load limits.

The wind turbine control objective in strong winds is to generate as much power as possible without subjecting the wind turbine to excessive loading, which can be formulated as another linear optimization problem. Since the generator torque is assumed to be constant, a power reference can be translated directly into a rotor speed reference, and the goal is to maximize the integral of the rotor speed reference on a prediction horizon, $\boldsymbol{e}^T \boldsymbol{\Omega}_{\mathrm{r}} T_{\mathrm{s}}$. However, wind turbine power controllers are typically designed for disturbance rejection and not for reference tracking. Therefore, it is not advisable to freely change rotor speed (i.e. power) reference on the prediction horizon. Instead, a simplified curve can be used, as shown in Fig. 4, that avoids sudden and frequent changes in the rotor speed reference over the prediction horizon, and which can be written as:

$$\boldsymbol{\Omega}_{\mathrm{r}} = \boldsymbol{R}_{N_{\mathrm{h}}} \Delta\omega_{\mathrm{r},N_{\mathrm{h}}} + \boldsymbol{R}_{-1} \Delta\omega_{\mathrm{r},-1}, \tag{17}$$

where $\Delta\omega_{\mathrm{r},-1}$ is the current rotor speed reference (relative to the operating point), $\Delta\omega_{\mathrm{r},N_{\mathrm{h}}}$ the new rotor speed reference at the end of the prediction horizon, and $\boldsymbol{R}_{-1}$, $\boldsymbol{R}_{N_{\mathrm{h}}}$ are matrices used for generating appropriate reference curve. Besides changing the reference in a more suitable way, this approach also simplifies the optimization by reducing it to a one-dimensional problem. The solution can be found easily and stability issues associated with receding horizon control are avoided.

Let $\boldsymbol{V}_\xi^*$ be a minimizer of (16) for a given x_0, $\boldsymbol{\Omega}_\mathrm{r}$ and $\boldsymbol{V}_\mathrm{p}$. Then function $\mathbf{f}_V$ represents wind speed variations over the prediction horizon, obtained from the minimizer $\boldsymbol{V}_\xi^*$:

$$\mathbf{f}_V\left(x_0,\, \boldsymbol{\Omega}_\mathrm{r},\, \boldsymbol{V}_\mathrm{p}\right) = \boldsymbol{W}_\xi \boldsymbol{V}_\xi^*\left(x_0,\, \boldsymbol{\Omega}_\mathrm{r},\, \boldsymbol{V}_\mathrm{p}\right) + \boldsymbol{W}_\mathrm{p}\boldsymbol{V}_\mathrm{p} + v_{\mathrm{w,OP}}, \tag{18}$$

where $v_{\mathrm{w,OP}}$ is the wind speed at the observed operating point. In the optimization for reference selection, the result of (16), $\mathbf{f}_V$, is compared with the actual wind speed $\hat{v}_\mathrm{w}$ (either measured or estimated) in order to assess if the wind turbine is in danger of surpassing its maximal allowed loads $y_{\max}$. Furthermore, let function $\mathrm{f}_{V,k}$ represent wind speed at the k-th discrete time instance of the prediction horizon, i.e. $\mathbf{f}_V = \left[\mathrm{f}_{V,0} \quad \mathrm{f}_{V,1} \quad \cdots \quad \mathrm{f}_{V,N_\mathrm{h}-1}\right]^T$.

The optimization for reference selection is formulated as:

$$\underset{\Delta\omega_{\mathrm{r},N_\mathrm{h}}}{\text{maximize}} \quad \Delta\omega_{\mathrm{r},N_\mathrm{h}}, \tag{19a}$$

$$\text{subject to} \quad \omega_{\min} \le \Delta\omega_{\mathrm{r},N_\mathrm{h}} + \omega_{\mathrm{OP}} \le \omega_\mathrm{n}, \tag{19b}$$

$$\hat{v}_{\mathrm{w},k} + \alpha_v \le \mathrm{f}_{V,k}\left(x_0,\, \boldsymbol{\Omega}_\mathrm{r},\, \boldsymbol{V}_\mathrm{p}\right), \tag{19c}$$

$$\boldsymbol{\Omega}_\mathrm{r} = R_{N_\mathrm{h}}\Delta\omega_{\mathrm{r},N_\mathrm{h}} + R_{-1}\Delta\omega_{\mathrm{r},-1}, \tag{19d}$$

where $\omega_{\min}$ is the minimal allowed rotor speed, ω_{OP} the rotor speed at the operating point, ω_n the nominal rotor speed. Finally, α_v is a design parameter representing a margin between the actual wind speed and the wind speed that leads wind turbine loads to $y_{\max}$. Note that function $\mathrm{f}_{V,k}$ represents the solution of optimization problem (16), so the reference selection (19) is comprised of two optimizations: an optimization for finding the wind speed that produces loads as close as possible to $y_{\max}$ is used as a constraint of an optimization for reference selection. In other words, the optimization problem (16) has to be solved for each rotor speed reference signal that is being evaluated in the optimization for reference selection.

The optimization (19) may be infeasible when wind conditions require a rotor speed lower than $\omega_{\min}$. In such cases, the wind turbine could be shut down to avoid excessive loading, but the pursue of such a strategy is out of the scope of the present investigation.

An illustrative example of the procedure for reference selection is shown in Fig. 4. The goal is to find the rotor speed reference that is as close as possible to the nominal rotor speed ω_n. However, the search for an appropriate rotor speed reference is constrained, and it has to be ensured that the wind speed that takes loads to the limit $y_{\max}$ is greater than the currently observed wind speed $\hat{v}_{\mathrm{w},0}$.

5. Simulation results

As a proof of concept, the control algorithm described in the previous section is implemented and verified in `Cp-Lambda` [8], using a high-fidelity aeroservoelastic simulation model of the 10 MW variable speed wind turbine defined in the INNWIND project [12]. For this purpose, the rotor thrust force was used as the load that has to be limited. A controller sampling time $T_\mathrm{s} = 50\,\mathrm{ms}$ is used, and optimizations are performed over a horizon of $N_\mathrm{h}T_\mathrm{s} = 5\,\mathrm{s}$. On such a horizon, wind speed is defined at 20 points, while a cubic spline interpolation is used to obtain wind speed values at each time step of the horizon.

The proposed control algorithm is tested in simulations using turbulent wind speed conditions, limiting the thrust force not to exceed the predefined value $F_{\mathrm{a,max}} = 1\,\mathrm{MN}$. Wind series were generated using `TurbSim` [13] according to the IEC-61400-1 normal turbulence model for a class IA wind turbine [14].

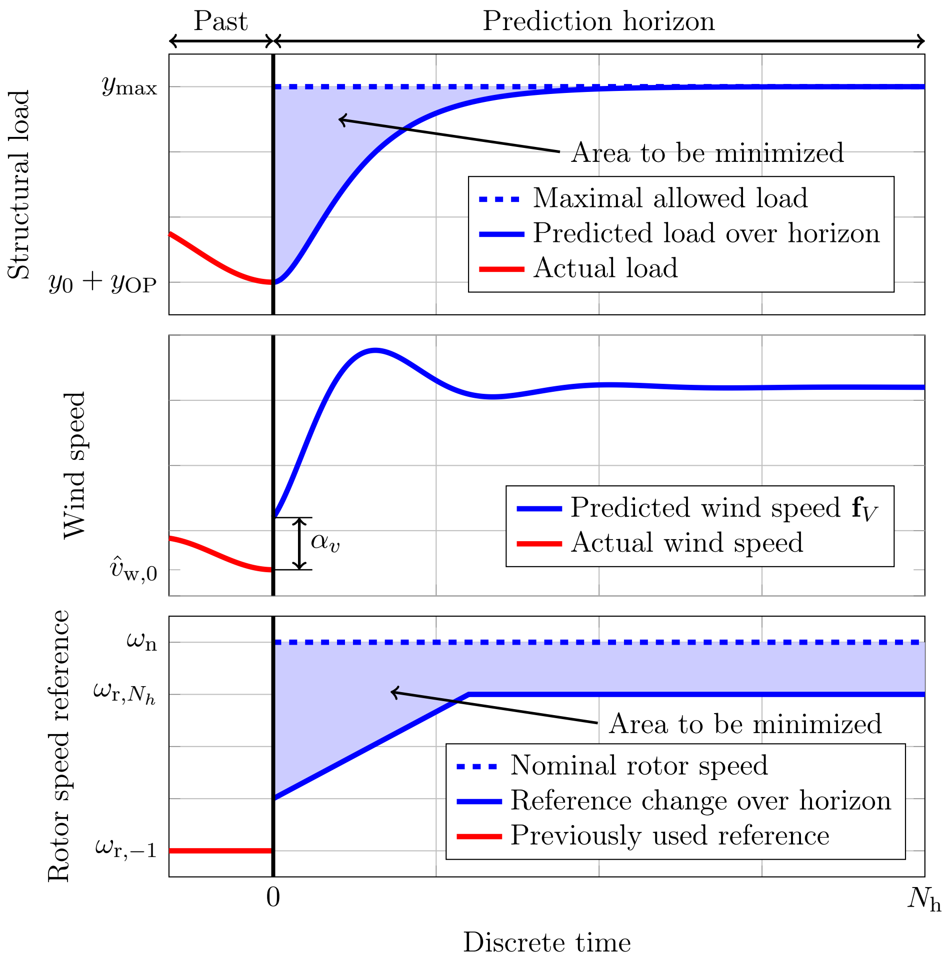

Figure 4. Illustrative example for reference selection.

An illustrative example of how the described control algorithm performs is shown in Fig. 5. The mean wind speed used in the simulation is 25 m/s, and therefore the solution can be compared directly to the one of the standard PI controller. The figure shows that the thrust force exceeds the maximal allowed value $F_{\mathrm{a,max}}$ when the standard controller is used. On the other hand, the online optimization manages to keep the thrust force within the defined limits. To achieve this, the mean rotor speed defined by the online optimization is lower than when the standard PI controller is used.

Note that the proposed control algorithm uses a simplified and linearised wind turbine model, and it is not expected that such a model can exactly capture all wind turbine dynamics. Furthermore, the present control algorithm does not use direct measurements of the thrust force, but it estimates its value based on the simplified model. Although the proposed control algorithm appeared to perform very well, it is unlikely that the control algorithm will be always able to keep the loads within predefined limits at all times. Therefore, a series of different 10 min simulations are performed in `Cp-Lambda`, with mean wind speeds equal to 23, 24 and 25 m/s, using both the standard PI controller and the optimal soft cut-out strategy. For each wind speed, 90 different realizations were considered, resulting in a total of 270 simulations, whose results are summarized in Table 1.

The proposed control algorithm resulted in a 13 % decrease of rotor speed (and therefore of

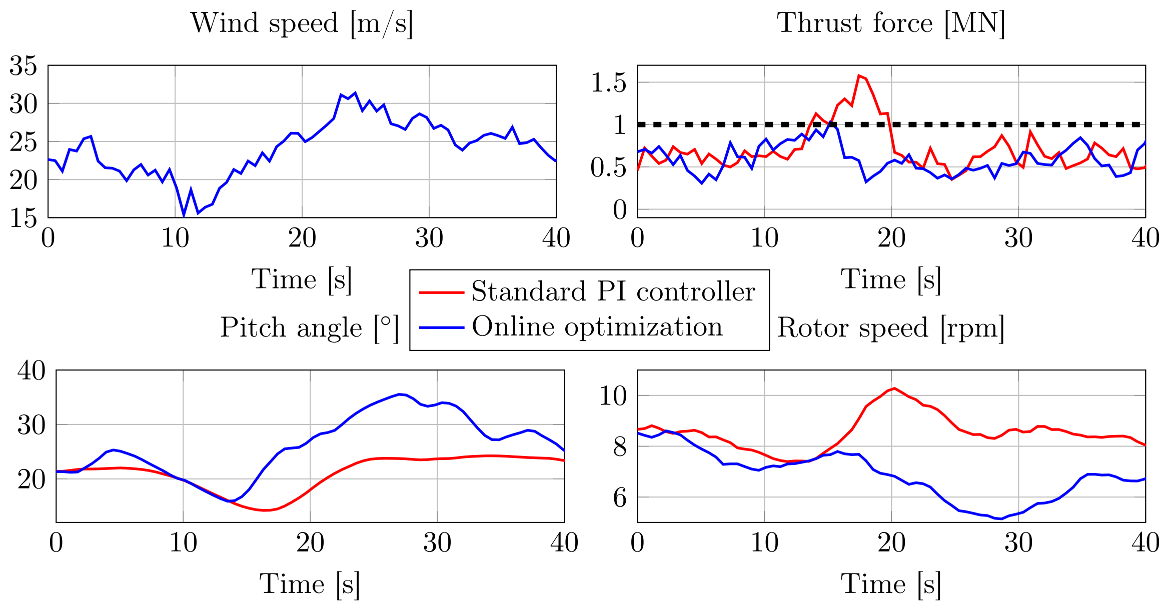

Figure 5. Prevention of excessive loading in turbulent wind by reducing the rotor speed.

Table 1. Comparison of standard PI controller and proposed online optimization.

	Control algorithm		
	Standard PI control	Online optimization	Ratio
Mean rotor speed	8.50 rpm	7.37 rpm	0.87
Maximal thrust value	1.89 MN	1.33 MN	0.70
Duration of thrust above $F_{\mathrm{a,max}}$	2.28 %	1.10 %	0.48
Integral (20)	1995.0 N	612.6 N	0.31

generated power). The table also shows that the proposed control algorithm did not manage to keep the thrust force in predefined limits at all times. This was expected, and it is due to the mismatch existing between the reduced model used for control synthesis and the high-fidelity plant model. However, both the maximal thrust force value and the duration of exceedance events are decreased, by 30 % and 52 %, respectively. Additionally, an integral is defined that computes the area between the thrust force and the limit $F_{\mathrm{a,max}}$ during exceedance events:

$$I = \frac{1}{T}\int_0^T \mathrm{pos}(F_{\mathrm{a}} - F_{\mathrm{a,max}})\,\mathrm{d}t, \tag{20}$$

where function pos(·) ensures that only values above limit $F_{\mathrm{a,max}}$ are considered, i.e.

$$\mathrm{pos}(x) = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{21}$$

Such an integral combines information about thrust values and duration above $F_{\mathrm{a,max}}$ into a single number. As shown by Table 1, the proposed control algorithm reduced this quantity by 69 %.

In order to avoid the thrust force from exceeding the limits, several approaches could be taken. First of all, the safety margin α_v could be increased, which would also reduce the wind turbine power output. However, storms and high wind speeds discussed in this paper occur rarely and therefore an increase of the safety margin should not affect the annual energy production considerably [5, 10]. To address plant-model mismatch directly, it would be useful to measure the load that has to be limited. Additionally, an adaptive procedure, as described in [7], could be implemented.

6. Conclusions

In this paper, a control algorithm for wind turbine protection during strong winds was presented. Control algorithms presented by other authors are typically based on predefined strategies based on average wind speed values. Since they do not account for the dynamic wind turbine response to changing wind conditions, they typically produce less electrical energy than strictly necessary to ensure a safe wind turbine operation.

The control algorithm presented in this paper monitors the wind turbine state and, when it determines that there is a danger of loads exceeding predefined values, it lowers the wind turbine rotor speed, thereby realizing a soft cut-out strategy. To this aim, two optimization procedures are formulated. The first optimization searches for wind speed variations that would lead the wind turbine as close as possible to the border of the safe operating region, without leaving it. The second optimization compares the actual wind speed to the results of the previous one, and it adjusts the rotor speed reference to keep the machine within its envelope.

The proposed strategy was verified using a high-fidelity aeroservoelastic simulation model of a wind turbine. The results showed that, although the algorithm cannot keep the loads within the predefined limits at all times, it has a very significantly improved performance with respect to a standard strategy. In future work, an adaptive load limit approach will be implemented to correct model mismatch, thereby ensuring the exact confinement of the response within the allowed envelope. Possibilities of reducing loads by changing both the rotor speed and the generator torque will also be analysed.

References

[1] Fingersh L, Hand M and Laxson A 2006 Wind turbine design cost and scaling model Tech. Rep. NREL/TP-500-40566 NREL, National Renewable Energy Laboratory
[2] Cutululis N A, Litong-Palima M and Sørensen P 2012 *European Wind Energy Conference and Exhibition EWEA 2012*
[3] Markou H and Larsen T J 2009 *European Wind Energy Conference and Exhibition EWEC 2009* vol 6
[4] Bossanyi E and King J 2012 *European Wind Energy Conference and Exhibition EWEA 2012*
[5] Jelavić M, Petrović V, Barišić M and Ivanović I 2013 *European Wind Energy Conference and Exhibition EWEA 2013* (Vienna, Austria)
[6] Petrović V 2013 *Wind turbine optimal control for reduction of structural loads in strong winds* Ph.D. thesis University of Zagreb
[7] Bottasso C L and Montinari P 2013 *AHS 69th Annual Forum*
[8] Bottasso C and Croce A 2009-2014 *Cp-Lambda User's Manual* Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano
[9] Bossanyi E 2000 *Wind Energy* **3** 149–163
[10] Burton T, Sharpe D, Jenkins N and Bossanyi E 2001 *Wind Energy Handbook* (Wiley) ISBN 9780471489979
[11] Boyd S and Vandenberghe L 2004 *Convex Optimization* (Cambridge University Press) ISBN 9780521833783
[12] 2014 Innovative wind conversion systems (10-20MW) for offshore applications URL `http://www.innwind.eu/`
[13] Kelley N and Jonkman B 2013 NWTC computer-aided engineering tools – TurbSim (accessed on 28 February 2014) URL `http://wind.nrel.gov/designcodes/preprocessors/turbsim/`
[14] 2005 *Wind Turbines – Part 1: Desing Requirements, Ed. 3.0* international Standard IEC 61400-1