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Wind Turbine Power References in Coordinated Control of Wind Farms

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The new grid regulations require that a grid-connected wind farm acts as a single controllable power producer. To meet this requirement a traditional wind farm control structure, which allowed individual wind turbines to internally define their power production, has to be modified. This paper investigates the opportunity for wind turbine load reduction that arises from dynamic power control of wind turbines. The wind farm controller design is proposed that utilizes coordinated power control of all wind turbines to achieve the wind farm regulation requirements and to minimize the wind turbine loads.

Key words: Wind turbine control, Wind farm control, Model predictive control, Structural loads

Reference snage vjetroagregata u koordiniranom upravljanju vjetroelektranama. Nova mrežna pravila zahtijevaju da vjetroelektrane spojene na električnu mrežu djeluju kao jedinstveni upravljivi proizvođač električne energije. Da bi se zadovoljio takav zahtjev, tradicionalni način upravljanja vjetroelektranama, koji dozvoljava da vjetroagregati interno definiraju svoju referencu snage, treba biti modificiran. U ovom radu proučavaju se mogućnosti smanjenja opterećenja vjetroagregata korištenjem dinamičkog upravljanja snage vjetroagregata. Predložen je koncept regulatora vjetroelektrane koji koristi koordinirano upravljanje snagom vjetroagregata u svrhu zadovoljenja mrežnih pravila i smanjenja opterećenja vjetroagregata.

Ključne riječi: upravljanje vjetroagregatom, upravljanje vjetroelektranom, modelsko prediktivno upravljanje, strukturna opterećenja

1 INTRODUCTION

Traditionally, a wind farm (WF) is operated as a collection of individually controlled wind turbines (WTs), which attempt to maximize their power production. Consequently, the wind farm produces fluctuating power, which is dependant on the momentary wind conditions, and thus causes disturbances in grid operation. With an increasing wind energy exploitation, the wind farms are growing both in number and in size, i.e., they are quickly becoming significant contributors to electrical energy production as well as a significant generator of grid disturbances. Therefore, the traditional operation of wind farms is becoming unacceptable and the new control requirements for wind farm controllability are imposed, see e.g. [1]. The wind farms are required to operate as a single controllable entity on the power grid, much like conventional power plants. Typical requirements include limiting the power production to a certain constant level, maintaining a constant power reserve (i.e. producing less than the available power by the given amount), or increasing / decreasing the power production in response to changes in grid frequency. All these tasks can be readily accomplished once the wind farm is able to track specified (time-varying) power reference, see [2] for details.

In order to track the wind farm power reference the production of individual wind turbines needs to be coordinated. This task is handled by the wind farm controller. The wind farm controller receives the wind farm power reference (or the wind farm regulation requirement, which can be readily expressed as the wind farm power reference, see e.g. [3]) from the TSO and distributes the individual wind turbine power references, see Fig. 1. The wind farm controller can use the measurements from the wind farm as feedback. The sampling time for the wind farm controller has the order of 1 second.

The wind farm control setup form Fig. 1 implies that the wind turbine control system can handle external power references. This requirement is typically met in megawatt class state-of-the-art wind turbines. In this paper we study the behavior of the wind turbine with respect to the provided wind farm power reference. The aim is to assess the potential for improving wind turbine operation by the appropriate wind farm controller design. The interest for this issue is spurred by the fact that the controlled wind farm

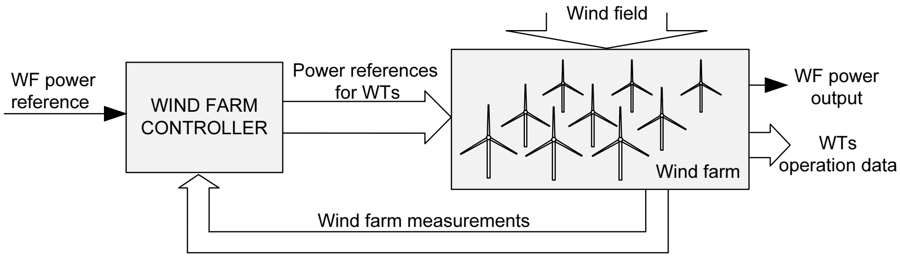

Fig. 1. Wind farm control system setup

is typically operating below its production limit. Namely, if the wind farm is to track a specified wind farm power reference then that power reference must be lower than the power available from the wind (the estimation of available wind farm power is used to determine the wind farm power reference, see [4]). In this paper we study the utilization of that power surplus in improvement of wind turbine dynamic operation. To the best of the authors knowledge this problem has not been tackled in wind energy literature.

The wind turbine considered in this paper is a conventional horizontal-axis three-bladed upwind variable-speed wind turbine with a blade-pitch-to-feather control system, which is the current state-of-the-art in wind turbine technology, see [5] . For simulations we use the MATLAB implementation [6] of a 5-MW reference wind turbine model for offshore system development (developed at National Renewable Energy Laboratory [7]).

The paper is structured as follows:
Section 2 describes the basics of wind turbine operation and the wind turbine controller. Section 3 tackles the problem of defining a practical (but also justified) cost function for validation of wind turbine operation. In Section 4 the wind turbine model aimed for the wind farm controller design is developed. Section 5 demonstrates and discusses the possibility for improvement of wind turbine dynamic behavior by adapting the power reference. Section 6 demonstrates the proposed wind farm controller design that tracks the wind farm power reference on the case study consisting of two wind turbines. In Section 7 we give some concluding remarks.

2 WIND TURBINE MODELING

The wind turbine is a complex system consisting of mechanical, aerodynamical and electrical subsystems. The overview of the wind turbine subsystems is given in Fig. 2. The individual subsystems will be briefly described in the following.

2.1 Wind turbine operation

The cardinal part of the wind turbine operation is the *aerodynamic conversion* that occurs at the rotor. The wind produces the force that acts upon the blades. This force can be decomposed into two components - the first that acts in the direction of rotation and causes the rotor torque, T_{r}, and the second in the direction perpendicular to the rotor that causes the rotor thrust, F_{T}. The input variables to this conversion are the wind speed, v, the rotor speed, ω_{r}, and the (controllable) blade pitch angle, β. The equations describing this conversion are:

$$P_{\mathrm{a}}(t) = \frac{\pi}{2}\rho R^2 v(t)^3 C_{\mathrm{P}}\left(\lambda(t), \beta(t)\right), \tag{1}$$

$$T_{\mathrm{r}}(t) = \frac{\pi}{2}\rho R^3 v(t)^2 C_{\mathrm{Q}}\left(\lambda(t), \beta(t)\right), \tag{2}$$

$$F_{\mathrm{T}}(t) = \frac{\pi}{2}\rho R^2 v(t)^2 C_{\mathrm{T}}\left(\lambda(t), \beta(t)\right), \tag{3}$$

where P_{a} is the aerodynamic power (the power input to the wind turbine), ρ is the air density, R is the radius of wind turbine rotor, and λ is the tip-speed ratio:

$$\lambda := \frac{\omega_{\mathrm{r}} R}{v}. \tag{4}$$

The functions $C_{\mathrm{P}}(\lambda, \beta)$, $C_{\mathrm{Q}}(\lambda, \beta)$ and $C_{\mathrm{T}}(\lambda, \beta)$ are the power, torque and thrust coefficient, respectively. The torque coefficient and the power coefficient are related according to (see [5]):

$$C_{\mathrm{Q}}(\lambda, \beta) = \frac{1}{\lambda} C_{\mathrm{P}}(\lambda, \beta). \tag{5}$$

Coefficients C_{P}, C_{Q} and C_{T} are turbine-specific nonlinear functions. They are obtained from experiments, or from software for aerodynamic simulation, and they are typically provided in the form of look-up tables.

Due to elasticity of the wind turbine structure, the thrust force causes the *tower nodding*, i.e. the oscillations of the tower in the fore-aft direction. Reduction of these oscillations is very important task for wind turbine controller. Namely, due to feedback that the tower motion provides to the wind at the rotor (see e.g. [5]), a poor design of the wind turbine controller could cause amplification of tower oscillations and eventually lead to the wind turbine break down, see e.g. [8]. A successfully designed wind turbine

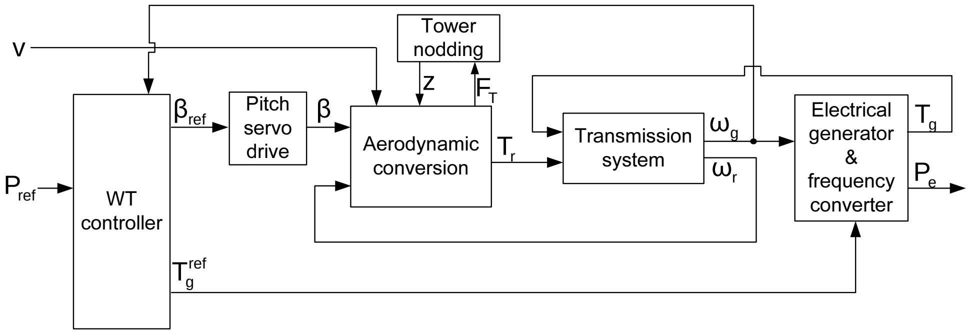

Fig. 2. Wind turbine model

controller can damp these oscillations significantly. The oscillations of the tower of the analyzed wind turbine occur at the frequency of 0.32 Hz, see [7].

The rotor shaft is connected to the electrical generator by a *transmission system* that usually consist of a low-speed shaft connected to the rotor (that presents a very large inertia), the gearbox and the high-speed shaft connected to the generator (with significant inertia). To achieve variable speed control a typical wind turbine today contains a doubly-fed induction generator (DFIG) with a power converter that enables active control of the generator torque, T_{g}, see e.g. [9]. Typically, the low-speed shaft is relatively long and therefore has significant torsional elasticity. The eigenfrequency of torsional oscillations for the turbine at hand is 2.23 Hz.

The subsystems that govern the transformation of the mechanical energy to electrical are the *electrical generator* and the *frequency converter*. The dynamics of these subsystems are in the range of milliseconds.

The *pitch servo drive* consists of a controller and a hydraulic or electric pitch actuator. It is provided with a pitch angle reference by the local controller. The blade pitching is a relatively slow process with the maximal pitching speed in the range of $5 - 10$ °/s, depending on the size of the blades. The limits on the pitching speed are taken into account when the local controller is designed, so a well designed local controller provides the pitch angle references that are in the operating range of the drive. The reaction speed is in the range of tens of milliseconds.

2.2 Wind turbine controller

The task of a wind turbine controller is to compute a pitch reference, β_{ref}, and generator torque reference, $T_{\mathrm{g}}^{\mathrm{ref}}$, and pass them along to the actuating subsystems, see Fig. 2. The baseline wind turbine controller typically uses only the generator speed, ω_{g}, as a feedback measurement. The system at hand uses a digital controller with the sampling time 0.0125 s.

The wind turbine controller is designed to accomplish two objectives, cf. e.g. [5]:

- If the available wind power is larger than the power reference, track the power reference. This is achieved by adjusting the generator and rotor torque to appropriate values. The generator torque is controlled directly, while the changes in the rotor torque are accomplished by modification of the blade pitch angle. The generator and rotor speed in this operating mode should remain at the nominal value.
- If the available wind power is smaller than the power reference, maximize the power production. This is achieved by ensuring that the wind turbine is operating close to the maximum of the power coefficient.

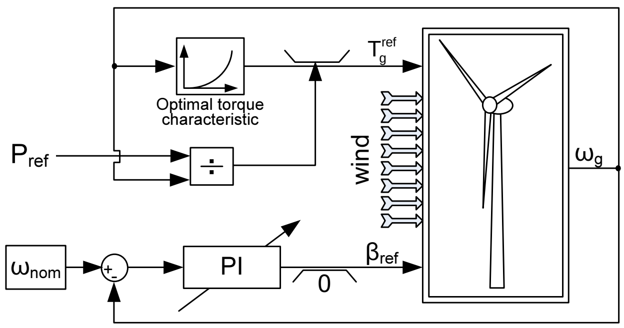

Fig. 3. Wind turbine controller operation principle

The operation principle of the wind turbine control system is depicted in Fig. 3. There are two control loops, the first one sets the generator torque reference and the second one sets the pitch angle reference. The generator torque reference is limited from above by the quotient of the power reference and the generator speed (i.e. the generator torque that produces the required power at given generator speed). The first control loop is active when the available power is lower than the power reference. This control loop maximizes the power capture of the wind turbine, which is accomplished by keeping the prescribed ratio between generator speed and torque. For the details on this control loop the reader is referred to [5]. While the first control loop is active the generator speed is lower than the nominal and therefore the pitch control loop is saturated. It is important to notice that in this mode of operation the power reference does not influence the wind turbine operation in any way.

Once the available power exceeds the power reference, the torque control loop saturates and the value $P_{\mathrm{ref}}/\omega_{\mathrm{g}}$ becomes the generator torque reference. Since the available power exceeds the power reference the rotor torque also exceeds the generator torque reference. This results in rotor and generator speed-up. Eventually, the generator speed surpasses the nominal value and the second control loop is activated. The second control loop typically uses a gain-scheduled proportional-integral controller.

For design of the wind farm power tracking controller it is necessary to ensure that the wind turbines are responding to the provided power references. This is possible if the wind turbine power references are larger than the available wind turbine power at all time. This requirement will be an integral part of the wind farm control design proposed here.

For the control scheme described here, the estimation of the available power is based on the expression 1 and the estimation of the (rotor) effective wind speed. The estimator design is outside of the scope of this paper. For details on effective wind speed estimation the reader is referred to [10].

3 WIND FARM CONTROL OBJECTIVES

The primary wind farm control objective is that the wind farm electrical power output tracks the provided wind farm power reference. However, we explore feasibility of (additional) objective: alleviation of the wind turbine loads. Note that in this paper the term loads refers to the forces and moments experienced by the wind turbine structure, specifically shaft and thrust-induced loads. The shaft loads are represented by the torsional torque of the low-speed shaft. This load measure is specially important for the wind turbine because this torque is transferred through the gearbox, which is a very vulnerable part of the wind turbine. The thrust force causes the tower and the blades of the wind turbine to bend and thus creates material stress.

It is important to emphasize that the static loads are not a large issue for controller design. The allowed levels of static loads are large since the construction is built to be robust. The much larger issue is dynamic stress that causes the structural damage of the wind turbine construction. The fluctuating loads tend to create micro cracks in the material that propagate and lead to component failure. This is describes and quantified by the term fatigue damage, see e.g. [11].

Many wind turbine controller improvements can be found in the literature (and practice) that aim at reducing the oscillatory loads. The most established are, [12]:

- Adjustment of the generator torque based on the generator rotational speed for enhanced damping of the first drive-train mode;
- Adjustment of the generator torque based on tower motion for enhanced damping of the first sideward bending mode;
- Collective pitch control based on tower motion for enhanced damping of the first fore-aft bending mode in full load conditions; and
- Individual pitch control based on blade loads for reduced flapwise blade loading and tilt- and yawwise nacelle loading.

These controller improvements aim at damping the fast periodic events. Unlike the wind turbine controller, wind farm controller has too large sampling time to be able to tackle the loads in such manner. In wind farm controller we aim at alleviating load oscillations due to deviations of the effective wind speed, which dominantly occur at a lower frequency. The idea of the wind farm controller we propose is to, instead of keeping the power output constant and allow loads to deviate with the wind, allow the power to deviate with wind speed (within allowed boundaries) while reducing load oscillations. This needs to be done in a manner that will ensure the tracking of the wind farm reference.

The remaining question is how to formulate a cost function that will penalize the fatigue. To achieve this it is necessary to know how to compare fatigue caused by different load histories.

3.1 Comparing the load histories

To estimate the fatigue damage from the load history one needs to:

1. extract the cycles from the signal history and determine their amplitude, and
2. compute how much damage those cycles cause to a particular material.

The algorithm used for extracting cycles from the signal history is called rainflow counting algorithm. It is based on extraction of local extrema that define the signal cycles. The rainflow counting algorithm is not analytic (details on the algorithm can be found in [11]). The output of the algorithm is a discrete set of pairs (σ_j, N_j), where σ_j denotes the centers of cycle amplitude bins and N_j denotes the number of cycles of amplitudes contained in the j-th bin. The number of bins (which is a tunable parameter of the algorithm) is denoted by M.

Every material can withstand a certain number of stress cycles of a given amplitude. This material property is described by the S-N curves, which can be well approximated by the expression:

$$\sigma = C \cdot N^{-\frac{1}{m}}, \tag{6}$$

where σ is the stress amplitude, N is the number of cycles of amplitude σ that the material can withstand, m is an empirically determined material-specific parameter denoted as Wöhler coefficient, and C is the maximal static stress that the material can withstand that is also material-specific parameter.

The total damage of the wind turbine can be determined by the Palmgren-Miner rule, see [11]. This rule defines the total damage of the wind turbine component as:

$$D_{\mathrm{t}} = \sum_{j=1}^{M} \frac{n_j}{N_j}, \tag{7}$$

where n_j is the number of cycles that the structure undergoes at stress level σ_j, and the N_j is the number of cycles at the stress level σ_j that leads to component failure (computed from the S-N curve). The Palmgren-Miner rule states that the component breaks when the total damage equals one.

The total damage is typically used for lifetime calculations, i.e. to determine when will the total damage reach one. To be viable, the lifetime calculation requires extensive simulations of different operating scenarios. For estimation of control benefits, however, it is more common to use the so-called damage equivalent loads. The damage equivalent load (DEL) is the amplitude of a sinusoidal stress of constant frequency f that produces the same damage as the original signal in the time T. By using the Palmgren-Miner rule (7) and the S-N curve (6), the DEL can be determined by, [13]:

$$DEL = \left(\sum_{j=1}^{M} \frac{\sigma_j^m n_j}{Tf} \right)^{\frac{1}{m}}. \tag{8}$$

If DEL is computed for different stress histories using the same frequency f and duration T, it is a good measure for comparison of damage produced by different stress histories.

The wind turbine simulation model at hand, [6], can provide the tower bending moment and the torsional torque of the shaft, but it is not able to compute stresses at different turbine parts (which requires a very complex computation). Therefore, we use the torque histories instead of stress histories to compute damage equivalent loads. This is a typical procedure for comparison between control strategies, see e.g. [14] and [15], and justified, see e.g. [16]. The DEL computation is performed by the MCrunch code (see [17]) with $C = 1$, $Tf = 1$, $m = 4$ for the tower bending moment and $m = 8$ for the shaft moment.

3.2 Control design cost function

Even though DEL is a convenient measure for qualitative comparison between load histories, it is not suitable for use in the (control design) cost function. The rainflow counting algorithm is not analytic and the function (8) is nonlinear. Therefore, the aim is to find the simpler objective formulation, which approximates DEL. DELs will be computed a-posteriori to evaluate the control effects.

According to (7), the stress amplitudes enter the Palmgren-Miner sum linearly, while the number of stress cycles enters with the exponent $\frac{1}{m}$. This means that the contribution of the large cycles to DEL is exponentially larger than that of the small cycles (e.g. one cycle of the shaft moment with the amplitude A contributes equally to DEL as 10^8 cycles of the amplitude $A/10$). Also, it should be noticed that the period of the cycles does not directly influence the damage equivalent loads, only the cumulative number of cycles.

Typically the oscillations of the wind turbine structures comprise of high frequency components (contributed to structure natural oscillations) and low frequency components (contributed to external excitation of the wind turbine subsystems). The low frequency components introduce larger cycles, while natural oscillations are smaller (especially if the wind turbine controller is well-designed). The aim of the wind farm controller design is to reduce the low frequency components in load histories. Thus the largest cycles of the load histories can be reduced, which would in turn reduce DEL, and also reduce the excitation of the structure natural oscillations.

The wind farm controller design presented in this paper assumes that the 10-minute mean wind speed at each of the turbines is known (estimated) and that an initial distribution of wind turbine power references is known, i.e., a mean wind speed V^0 and the constant power reference P_{ref}^0 is attributed to every wind turbine. The distribution of constant power references can be obtained by some simple distribution (e.g. $P_{\text{ref}}^0 = \frac{P_{\text{ref}}^{\text{WF}}}{N_{\text{WT}}}$, where $P_{\text{ref}}^{\text{WF}}$ is the wind farm power reference and N_{WT} is the number of wind turbines in the wind farm) or this distribution can also be optimised by taking into account the quasi-stationary aerodynamics of the wind farm (interaction of wind farms through wakes), see e.g. [18]. The mean wind speed and the constant power reference determine the wind turbine operating point, i.e. the values of the wind turbine steady state outputs and states can be uniquely determined. The cost function penalizes the deviations from this operating point.

The chosen control design cost function is:

$$\begin{aligned} &J(P_{\text{ref}}(t), F_{\text{T}}(t), T_{\text{shaft}}(t)) := \\ := \quad & r\left(P_{\text{e}}(t) - P^0_{\text{ref}}\right)^2 + q(T_{\text{shaft}}(t) - T^0_{\text{shaft}})^2 + \\ & +q_d\left(\tfrac{dF_{\text{T}}(t)}{dt}\right)^2, \end{aligned} \tag{9}$$

where r, q and q_d are the weighing coefficients, P_{e} denotes the produced power, T_{shaft} denotes the low-frequency shaft torque, T^0_{shaft} is the steady state shaft torque, and F_{T} denotes the thrust force. The last term in (9) penalizes derivation of the thrust force to prevent the drifting of the power reference due to changes of the wind speed. Namely, the steady-state thrust force is dependant on the wind speed (disturbance). On the other hand, the steady state shaft torque depends only on the power reference.

The expression (9) is essentially quadratic cost used for the formulation of the optimal tracking control problem. This is in line with the idea for the wind farm controller design - to move from constant power tracking to constant load tracking. The cost function (9) enables (through the choice of q, q_d and r) balancing between the two objectives.

4 WIND TURBINE MODEL FOR WIND FARM CONTROL DESIGN

For wind farm control design purpose it is important to obtain a simple wind turbine model that captures the relevant wind turbine dynamics with respect to (relatively slow) fluctuations in wind speed and describes the load measures to be used in (9). The interface of the model is depicted in Fig. 4. The inputs of the wind turbine model are the effective wind speed v (a disturbance) and the wind turbine power reference P_{ref} (control input). The outputs of the wind turbine model are the produced electrical power P_{e} and the load measures: the low-frequency low-speed shaft torsional torque T_{shaft} and the thrust force F_{T}.

The dynamic wind turbine model is obtained by linearization of the nonlinear equations describing the aerodynamics of the wind turbine (1)–(3). The fast dynamics of the wind turbine structure are disregarded. Therefore, the wind turbine transmission system can be described as

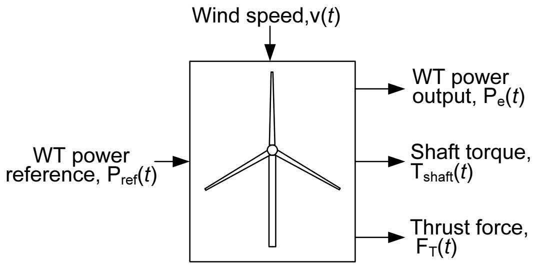

Fig. 4. Wind turbine as a wind farm actuator

a system with lumped inertia:

$$\frac{d\omega_{\text{r}}}{dt} = \frac{1}{J_{\text{r}} + i^2 J_{\text{g}}}(T_{\text{r}}(t) - iT_{\text{g}}(t)), \tag{10}$$

$$\omega_{\text{g}}(t) = i \cdot \omega_{\text{r}}(t), \tag{11}$$

where i is the gear ratio and ω_{g} is the generator speed. The torque that twists the low-speed shaft is then given by:

$$T_{\text{shaft}}(t) = i^2 \cdot \frac{J_{\text{g}}}{J_{\text{r}} + i^2 J_{\text{g}}} T_{\text{r}}(t) + i\frac{J_{\text{r}}}{J_{\text{r}} + i^2 \cdot J_{\text{g}}} T_{\text{g}}(t), \tag{12}$$

where J_{r} is the rotor inertia and J_{g} is the generator inertia. The dynamics of the electrical subsystems will be disregarded. The generator model comes down to:

$$P_{\text{e}}(t) = \mu T_{\text{g}}(t)\omega_{\text{g}}(t). \tag{13}$$

The torque control system are assumed to be perfect, i.e., $T_{\text{g}}(t) = T^{\text{ref}}_{\text{g}}(t)$. Under these assumptions, and assuming that the generator efficiency μ is well compensated in the controller (see Fig. 3), the power control of the wind turbine has dynamics of the 0-th order:

$$P_{\text{e}}(t) = P_{\text{ref}}(t). \tag{14}$$

The dynamics and the nonlinearities of the pitch servo system are also disregarded. The pitch system has significant inertia, however, this inertia is considered in the wind turbine controller design. In normal operation the dynamics is governed by the speed controller (see Fig. 3), which provides the pitch servo system with the pitch reference that can be tracked very well. The entire dynamics of the speed controller is included in the control design model. The nonlinearities such as signal saturations and rate limits are ignored during the modeling.

The overall wind turbine model dynamics around an operating point is described in the state-space form:

$$\begin{aligned} \dot{x} &= Ax + Bu + B_{\text{d}}d, \\ y &= Cx + Du + D_{\text{d}}d, \end{aligned} \tag{15}$$

where x, u, d and y are state, input, disturbance and output vectors, respectively. They are defined as:

$$x = \begin{bmatrix} \beta \\ \omega_\mathrm{r} \\ \omega_\mathrm{g}^\mathrm{filt} \end{bmatrix}, \quad u = \begin{bmatrix} P_\mathrm{ref} \end{bmatrix}, \quad d = \begin{bmatrix} v \end{bmatrix}, \quad y = \begin{bmatrix} F_\mathrm{T} \\ T_\mathrm{shaft} \end{bmatrix},$$

and the state space matrices are:

$$A = \begin{bmatrix} 0 & -\frac{K_\mathrm{P}^0 i}{T_\omega} & \frac{K_\mathrm{P}^0 - K_\mathrm{I}^0 T_\omega}{T_\omega} \\ \frac{K_{\beta T_\mathrm{r}}}{J} & \frac{1}{J}\left(K_{\omega \mathrm{T_r}} + \frac{P_\mathrm{ref}^0 i}{\mu {\Omega_\mathrm{g}^0}^2}\right) & 0 \\ 0 & \frac{i}{T_\omega} & -\frac{1}{T_\omega} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ -\frac{1}{J}\frac{1}{\mu \Omega_\mathrm{g}^0} \\ 0 \end{bmatrix}, \quad B_\mathrm{d} = \begin{bmatrix} 0 \\ \frac{1}{J} K_{\mathrm{vT_r}} \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} K_{\beta F_\mathrm{T}} & K_{\omega F_\mathrm{T}} & 0 \\ \frac{i^2 J_\mathrm{g} K_{\beta \mathrm{T_r}}}{J} & \frac{i}{J} \cdot \left(i J_\mathrm{g} K_{\omega \mathrm{T_r}} - \frac{i J_\mathrm{r} P_\mathrm{ref}^0}{\mu {\Omega_\mathrm{g}^0}^2}\right) & 0 \end{bmatrix},$$

$$D = \begin{bmatrix} 0 \\ \frac{1}{\mu \Omega_\mathrm{g}^0} \end{bmatrix}, \quad D_\mathrm{d} = \begin{bmatrix} K_{vF_\mathrm{T}} \\ i^2 \frac{J_\mathrm{g}}{J} K_{vT_\mathrm{r}} \end{bmatrix},$$

where P_ref^0, β^0, Ω_g^0 are the power reference, pitch angle and generator speed at the operating point, K_P^0 and K_I^0 are the proportional and integral gains of the speed tracking PI controller at a given operating point (the controller is gain scheduled), J is the equivalent inertia for the simplified shaft model, $J = J_\mathrm{r} + i^2 J_\mathrm{g}$; T_ω is the time constant of the generator speed filter used in the speed controller, and $K_{\beta \mathrm{T_r}}$, $K_{\omega \mathrm{T_r}}$, $K_{\mathrm{vT_r}}$, $K_{\beta \mathrm{F_T}}$, $K_{\omega \mathrm{F_T}}$, $K_{\mathrm{vF_T}}$ are the coefficients obtained from the first-order Taylor approximation of aerodynamic conversion expressions (1) and (3) at a given operating point.

Since wind farm controller needs to be a discrete controller with one second sampling time, the developed state space model is discretized. The outputs of the full-scale model against the outputs of the developed control design model are given in the Fig. 5. It can be seen that the control design model models the low frequency behavior well. The discrepancies between these two models are not the consequence of the simplifications in obtaining the continuous-time model (15). Actually, the outputs of this model match the full-scale model extremely well. The discretization is the larger source of modeling error, since the disturbance (the effective wind) comprises significant amount of energy content at higher frequencies, to which the model is "blind". However, the model performance is reasonable, it models well the frequency bend of the interest, and will be proved efficient in simulation.

5 CASE STUDIES

In this section the benefits of controlling the wind turbine via power reference are assessed. The following question is considered: can the wind turbine loads be reduced

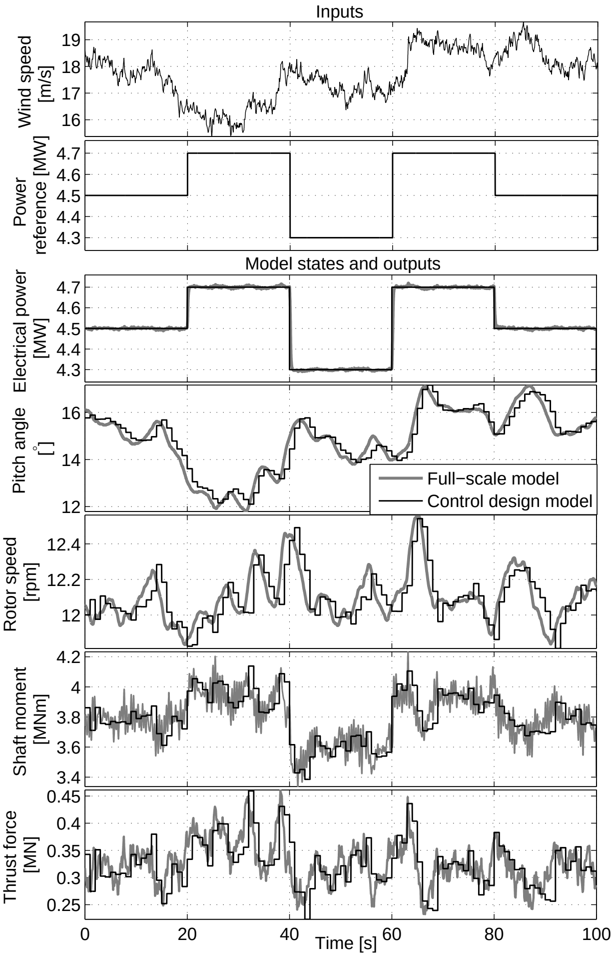

Fig. 5. Comparison between responses of the full-scale model and the control design model

by introducing the power reference deviations, P_ref, via a closed loop optimal controller? To answer this question first a wind turbine is exposed to an artificial deterministic disturbance and then to a disturbance characteristic for wind turbine operation. The system response in simulation to the case when the constant reference is provided to the system (i.e., the power reference deviations are zero).

Based on the discretized cost function (9) and wind turbine model (15), the wind turbine control problem is defined as a Constrained Finite-Time Optimal Control (CFTOC) problem ([19]):

$$\begin{array}{rl} \min\limits_{U} & U'\mathcal{R}U + Y'\mathcal{Q}Y + Y_d'\mathcal{Q}_d Y_d \\ \text{subject to} & \begin{cases} \mathcal{Y} = \mathcal{C}x_0 + \mathcal{D}_u U + \mathcal{D}_d D, \\ \mathcal{E}_U U \le \mathcal{F}_U, \end{cases} \end{array} \qquad (16)$$

where x_0 is the initial state of the system; N is the prediction horizon; U is the optimization variable, $U :=$

$[u'_1, \ldots, u'_{N-1}]'$; D is the vector of predicted disturbances, $D := [d'_0, d'_1, \ldots, d'_{N-1}]'$; Y is the vector of predicted outputs, $Y := [y'_0, \ldots, y'_{N-1}]'$; Y_d is the vector of predicted output differences, $Y_d := [y'_0 - y'_{-1}, \ldots, y'_{N-1} - y'_{N-2}]'$. The matrices $\mathcal{E}_U, \mathcal{F}_U, E$ define system constraints and $\mathcal{A}$, $\mathcal{B}, \mathcal{B}_d, \mathcal{C}, \mathcal{D}_u, \mathcal{D}_d$ describe the system evolution that can be obtained from the (previously discretized) system model (15), see e.g., [20].

In this paper only the constraints on the control variable are defined which are the most important for the control design:

$$P_{\text{min}} \leq P_{\text{ref}} \leq P_{\text{max}}, \tag{17}$$

where P_{min} denotes the minimal power reference, which is defined by generator properties, while P_{max} denotes the maximal power reference, which is defined by the nominal generator power or, at lower wind speeds, by the available power. Note however that the control formulation allows the introduction of arbitrary (linear) state and output constraints.

The control weighing matrices are, according to (9), defined as:

$\mathcal{R} := \text{diag}\,(R, \ldots, R)$, $\mathcal{R} = \mathcal{R}' \succ 0$ is the control weight matrix;

$\mathcal{Q} := \text{diag}\left(\begin{bmatrix} 0 & 0 \\ 0 & Q \end{bmatrix}, \ldots, \begin{bmatrix} 0 & 0 \\ 0 & Q \end{bmatrix}\right)$, $\mathcal{Q} = \mathcal{Q}' \succeq 0$ is the output weight matrix; and

$\mathcal{Q}_d := \text{diag}\left(\begin{bmatrix} Q_d & 0 \\ 0 & 0 \end{bmatrix}, \ldots, \begin{bmatrix} Q_d & 0 \\ 0 & 0 \end{bmatrix}\right)$, $\mathcal{Q}_d = \mathcal{Q}'_d \succeq 0$ is the output difference weight matrix.

The wind turbine states are not weighted in this control problem because, as will be shown in the simulations, the action of the controller designed according to (18) stabilizes and improves the behavior of the overall system. Further penalization of states therefore only complicates the weight tuning.

The controller is designed as an on-line Model Predictive Controller (MPC) that uses a sampling time of 1 second. Every time instant the controller is fed with the current state vector, x_0, and, due to delta formulation, the output (thrust force) from a previous time instant, y_{-1}. All states used in the model (15), as well as the thrust force, are measurable or easily estimated.

In the following the case studies will be presented that demonstrate the potentials of wind turbine control via a wind farm controller. This case studies are for demonstration purpose, while the design of the wind farm controller based on this will be demonstrated in the next section.

All case studies are performed on the full-scale nonlinear wind turbine model from [6].

5.1 Deterministic input

The first case study tests the controller performance in the case of a positive and negative step change of 2 m/s in wind speed. The aim of this case study is to determine the full potential of this type of the controller. Therefore, the prediction horizon $N = 10$ is used, to make sure that the entire transient is predicted, and the perfect disturbance prediction is used, meaning that the controller has the exact information about the wind speed in the next 10 seconds.

In the following experiments different weight settings are used to demonstrate the trade-offs between the competing objectives.

5.1.1 Reducing tower loads

In this experiment $\mathcal{Q}$ is set to zero in order to estimate the potential for minimizing tower loads. The results of the experiments are depicted in Fig. 6.

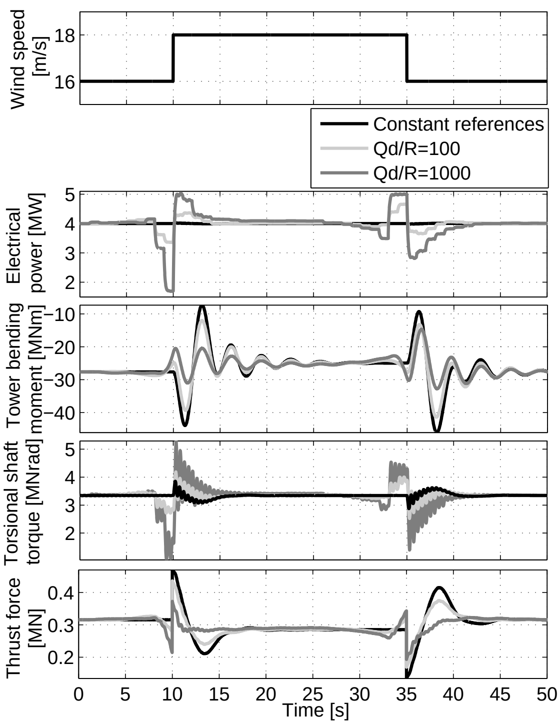

Fig. 6. Deterministic disturbance - Reducing tower loads

The first glimpse reveals that the controller has a substantial ability to reduce the tower bending, however at an extremely high control cost.

For weight ratio $Q_d/R = 1000$ during the positive wind step the tower deflection amplitude is reduced by more than 50%. This is achieved by the change in power of more than 2 MW. This large change in power is naturally followed by a large increase in shaft torque. During the positive wind step the controller ran into the constraint. This kind of system behavior is not acceptable. When the weight ratio is reduced to $Q_d/R = 100$ the system behavior improved, the reduction in tower bending is around $10\ \%$, which is achieved by power deviation maximum of around 750 kW. This power deviation is still large and the shaft oscillations are still much increased.

The Fig. 7 demonstrates the improved behavior of wind turbine states. There is less pitch action (with weighting $Q_d/R = 1000$ the pitch response is aperiodic, while weighting $Q_d/R = 100$ significantly reduces the response overshoot). The overshoot of the rotor speed is also reduced, the transient is less oscillatory and the nominal speed is restored faster.

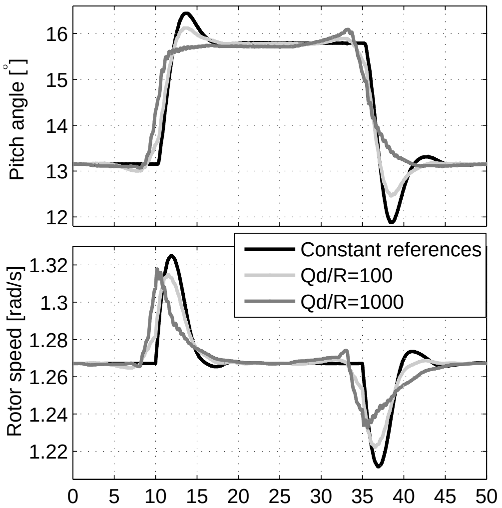

Fig. 7. Deterministic disturbance - Reducing tower loads (states)

One should notice that this controller relies very much on the feed-forward control action (the large drop in control variable before the positive step and the large increase before the negative step). This is problematic because it indicates that the inaccuracy in disturbance prediction might lead to poor performance. The assumptions on the perfect prediction will be weakened in the Section 5.2 where the realistic wind disturbance will be considered.

To conclude, this experiment reveals the potential for alleviating the thrust-induced loads, however, the weight that penalizes the thrust needs to be kept small to prevent violent control and increase in shaft loads. It has to be kept in mind that this type of disturbance is artificial and the typical wind disturbance is less violent, so the behavior of the controller can be expected to improve for different scenarios.

5.1.2 Reducing shaft loads

In this experiment $\mathcal{Q}_d$ is set to zero in order to estimate the potential for minimizing shaft loads. The results of the experiments are depicted in Fig. 8.

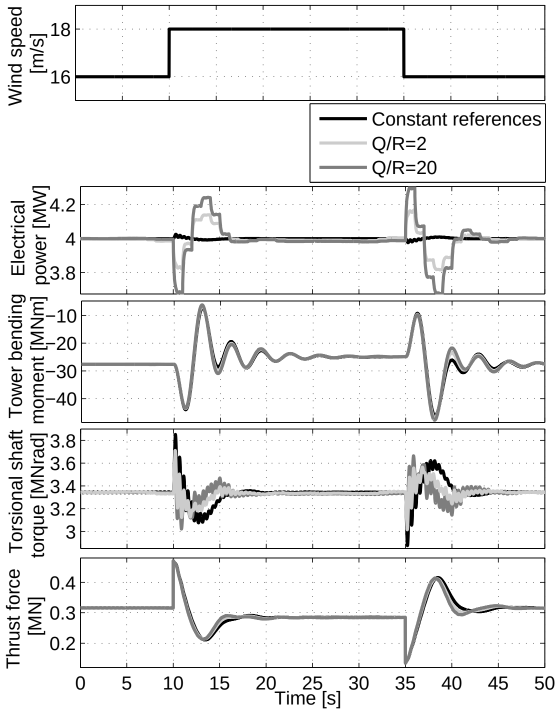

Fig. 8. Deterministic disturbance - Reducing shaft loads

The simulation outputs demonstrate the potential for shaft load reduction at a much smaller control cost. The system response for weight ratio $Q/R = 2$ is very satisfactory, the maximal power deviation is 200 kW, while the amplitude of the slow frequency load cycles has reduced significantly. The high frequency oscillations are not additionally excited. The tower loads remain much the same as in the case of constant reference. For the higher weight ratio $Q/R = 20$ the response of the shaft torque deteriorates because, due to more violent control actions, the high frequency oscillations increase in amplitude. In this case the low-frequency component of the shaft torque (the only one modeled in the control design model (15)) is still reduced, however the overall response deteriorated due to increased high-frequency oscillations.

Also in this case the response of the wind turbine states shown in Fig. 9 is improved, the speed tracking is improved and the pitch action is reduced. In this case there is no extra feed-forward control action.

To conclude, this experiment demonstrates that there exist an opportunity to improve the shaft loading at a relatively small control effort. However, to asses the benefits

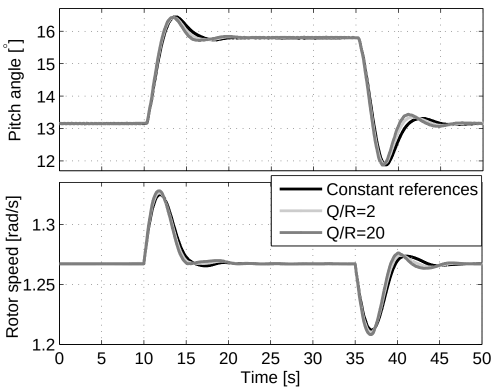

Fig. 9. Deterministic disturbance - Reducing shaft loads (states)

correctly it is necessary to apply the realistic disturbance and compute the damage equivalent loads.

5.2 Turbulent wind

In reality the wind turbine is exposed to turbulent wind. Turbulence can be described as a stochastic signal, by its turbulence intensity and its spectrum. To properly simulate the turbulence one needs to take into account the frequency characteristics of the point-wise wind speed, the spatial correlation of the wind, and the wind field propagation that renders the time-wise correlation.

In order to obtain a realistic excitation of the wind turbine, the turbulent wind speed for this case study is simulated according to the turbulence model implemented in [6]. The turbulence intensity used in simulations is 6%.

From the experiments with the deterministic disturbance the weights $Q/R = 2$ and $Q_d/R = 30$ are found satisfactory and will be used in further simulations. In the first simulation the assumption of perfect prediction of disturbances is kept and the prediction horizon is $N = 10$.

The results of this simulation are given in Fig. 10. The simulation outputs suggest that the variance of the shaft torque has been reduced, while the high frequency shaft oscillation have not been enhanced. The control action is in the acceptable range (± 150 kW) and there are no large jumps in the control variable. The effects on the tower bending can not be clearly assessed from the graphical depiction of the responses.

To asses the benefits of this control design one needs to perform the damage equivalent load analysis, which is reasonable since the applied disturbance (unlike the deterministic one) actuates the representative system modes. The statistics (tower and shaft DELs and standard deviations (STDs) of the pitch rate, rotor speed and electrical power)

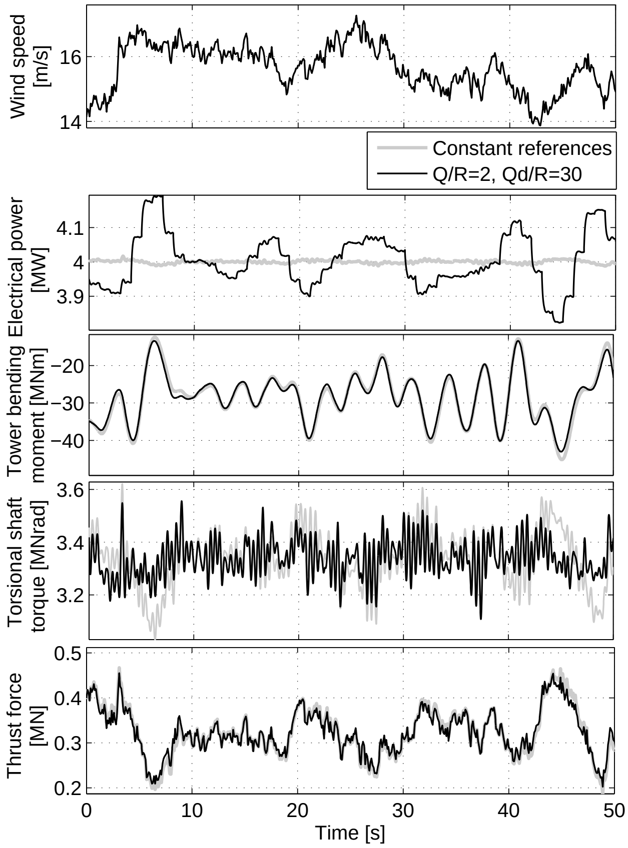

Fig. 10. Turbulent wind scenario

of the simulation responses are given in the second column (denoted Perfect prediction) of the Table 2. The statistics are performed on the 500 second simulation run.

Table 1. Turbulent wind scenario statistics

	Constant reference	Perfect prediction	Persistence assumption
T_{shaft} DEL [kNm]	762	625	676
M_{tow} DEL [MNm]	65.8	63.2	64.2
$d\beta/dt$ STD [°/s]	0.81	0.80	0.79
ω_{r} STD [rpm]	0.155	0.151	0.149
P_{e} STD [kW]	4.28	67.11	45.38

The statistics show that the shaft DEL has reduced by 18%, while the tower DEL reduced by 4%. The standard deviation of electrical power increased to 67 kW, which is a reasonable value. This results demonstrate a good trade-off between the increase in control effort and decrease in the turbine loads. It is also important to notice that the pitch angle activity is reduced and speed tracking is improved.

This shows that the added controller does not compete with the wind turbine controller, but improves the overall wind turbine behavior.

However, the assumption of the perfect wind prediction in the horizon of 10 seconds is unrealistic. For the next experiment this assumption is dropped and replaced by the assumption that the wind speed estimated wind speed at given time (d_0) will be constant during the prediction horizon. When this assumption is introduced it is not sensible to keep such long prediction horizon. Namely, due to relatively low frequency content of the turbulent wind such assumption (commonly referred to as *persistent* wind assumption) is valid for short horizons, however the validity severely deteriorates with increase of the prediction horizon. By performing several simulations the prediction horizon $N = 3$ was shown to provide the best results. The statistics of the results are given in the third column of the Table 1, denoted Persistence assumption.

The statistics show the expected decrease in performance in comparison to the assumption of perfect prediction. However, in comparison to simulation in which the power reference is kept constant there is still significant improvement, 11% improvement in shaft DEL and 3% reduction in tower DEL. The reduction in tower damage is very small, which can be contributed to the lack of feedforward action since the disturbances are not predicted. However, in several simulation that were performed with different excitations a small improvement showed consistent. The improvements in the shaft load are significant and also consistent. The support to speed control is evident in reduction of pitch action and improvement of speed tracking.

6 WIND FARM CONTROL FOR LOAD MINIMIZATION

In the previous section the case studies were shown that demonstrate the potential for improvement in wind turbine operation by controlling the power reference. Such control of an individual turbine is doubtfully beneficial, since the power production of the wind turbine is significantly deteriorated. However, this type of control can be used to control the clusters of wind turbines (i.e., wind farms). The costs of the individual wind turbine control problems (18) are added together and the constraint is added that has to ensure that the wind farm will deliver the required power.

To formulate the control problem we assume that the stationary power references, P_{ref}^{j0} (where j is an index that denotes an individual wind turbine in the cluster), are attributed to the wind turbines and that they add-up to the exact amount of the wind farm power reference, $\sum_{j=1}^{N_{\text{WT}}} P_{\text{ref}}^{j0} = P_{\text{WF}}^{\text{ref}}$, where N_{WT} denotes the number of turbines in the wind farm and $P_{\text{WF}}^{\text{ref}}$ is the wind farm power reference.

Then, we can define the simple wind farm optimal control problem as:

$$\begin{array}{cl} \min\limits_{U^1,\ldots,U^{N_{WT}}} & \sum_{j=1}^{N_{\text{WT}}} U^{j\prime}\mathcal{R}U^j + Y^{j\prime}\mathcal{Q}Y^j + Y_d^{j\prime}\mathcal{Q}_d Y_d^j \\ \text{subject to} & \left\{ \begin{array}{l} \mathcal{Y}^j = \mathcal{C}^j x_0^j + \mathcal{D}^j U^j + \mathcal{D}_d^j D^j, \\ \mathcal{E}_U^j U^j \leq \mathcal{F}_U^j, \\ \sum_{j=1}^{N_{\text{WT}}} \left[\begin{array}{cccc} 1 & 0 & \ldots & 0 \end{array}\right] U^j = 0 \end{array} \right. , \end{array} \tag{18}$$

where j denotes the variables and parameters attributed to the j-th wind turbine.

Essentially, this formulation allows only the control moves that add-up to zero. This seems rather conservative, however, one has to consider the fact that wind turbines in wind farms are relatively far apart and the turbulence that they experience at a certain moment are not significantly correlated. Therefore, the larger the controlled cluster gets the turbulence effects tend to level out (i.e., loosely put, there is a larger chance that there exists the turbine which requires the complementary control).

Here, we present the results of the simulation of a small wind farm consisting of only two wind turbines (statistically the worst case). The generated wind histories are not correlated. The wind histories, the constant power references and the power references obtained by the designed wind farm controller are depicted in Fig. 11. The statistics of the run are given in Table 2.

Table 2. Wind farm controller simulation statistics

	Wind turbine 1	
	Const. ref.	WF control
T_{shaft} DEL [Nrad]	$7.6108 \cdot 10^5$	$7.2495 \cdot 10^5$
M_{tow} DEL [Nm]	$6.5696 \cdot 10^7$	$6.5012 \cdot 10^7$
$d\beta/dt$ STD [°/s]	0.8095	0.8035
ω_{r} STD [rad/s]	0.0162	0.0158
P_{e} STD [kW]	4.2803	32.1285
	Wind turbine 2	
	Const. ref.	WF control
T_{shaft} DEL [Nrad]	$8.1920 \cdot 10^5$	$7.5618 \cdot 10^5$
M_{tow} DEL [Nm]	$7.5716 \cdot 10^7$	$7.4977 \cdot 10^7$
$d\beta/dt$ STD [°/s]	0.7394	0.7300
ω_{r} STD [rad/s]	0.0150	0.0148
P_{e} STD [kW]	4.6279	30.8181
	Wind farm	
	Const. ref.	WF control
P_{WF} STD [kW]	6.4017	6.4193

The shaft DELs were reduced by 5% on the first wind turbine and by 8% on the second wind turbine. The tower DELs were reduced by 1% on both wind turbines. The increase in standard deviation of the wind farm power is negligible. The improvement in speed control is still present.

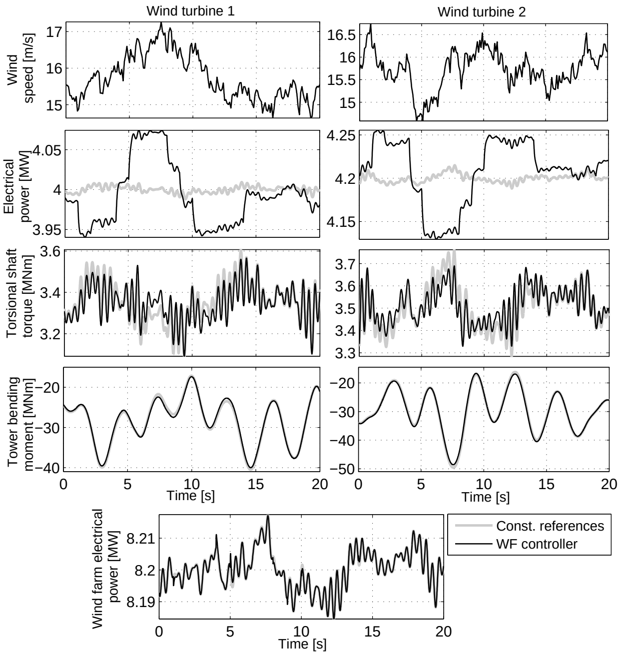

Fig. 11. Wind farm controller simulation detail

The overall (cumulative) percentage reduction of loads in the wind farm is around the same level as for the single controlled wind turbine.

7 CONCLUSION

The paper analyses the wind farm control problem and gives an assessment of the potential for reduction of wind turbine loads via power control of wind turbines. It is shown that the significant reduction of shaft loads can be obtained, while the potential for reduction of thrust induced loads is smaller.

Most importantly, it is demonstrated that it is possible to achieve reduction in loads without deteriorating any of the operating conditions – the wind farm power is maintained while all considered loads are reduced, the speed control is improved and the pitch action is reduced. Therefore, the wind farm can benefit from coordinated wind turbine control.

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