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# Wind turbine power control for coordinated control of wind farms

**Vedrana Spudić** **Mate Jelavić** **Mato Baotić**

*Faculty of Electrical Engineering and Computing*
*University of Zagreb, Croatia*
*e-mail: vedrana.spudic@fer.hr, mate.jelavic@fer.hr, mato.baotic@fer.hr*

**Abstract:** 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, needs to be modified. In this paper the opportunity for wind turbine load reduction that arises from dynamic power control of wind turbines is studied. 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.

*Keywords:* Wind turbine control, Wind farm control, Model predictive control, Structural Loads

## 1. INTRODUCTION

With the increasing exploitation of wind energy, wind farms are growing both in number and in size and quickly becoming significant contributors in production of electrical energy. Consequently, the requirement emerges for large wind farms to function as a single controllable entity on the power grid, much like conventional power plants, see e.g. Elkraft System and Eltra (2004). For example, wind farm may be required to track the power reference provided by the Transmission System Operator (TSO) or to reduce the power production in order to contribute to the grid frequency regulation.

Traditionally, wind farm is operated as a collection of individually controlled wind turbines. Due to the new control requirements, however, the wind farm controller needs to take into account the interaction of wind turbines. 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. Hansen et al. (2006)) from the TSO and distributes the individual wind turbine power references, see Figure 1. The wind farm controller uses the measurements from the wind farm as feedback. The sampling time for the wind farm controller has the order of 1 second.

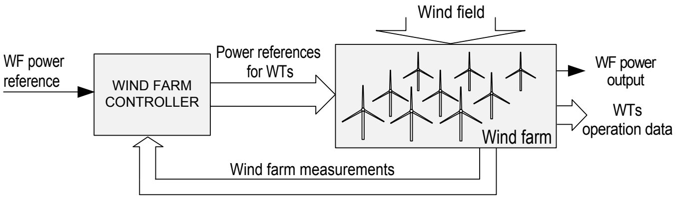

Fig. 1. Wind farm control system setup

A modern variable-speed wind turbine needs to be actively controlled to be operable. The state-of-the-art wind turbine control system has the ability to receive an external power reference. In this paper we study the behavior of the wind turbine with respect to the provided wind turbine 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 new wind farm control requirements. Namely, if the wind farm is to track a 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 Sørensen et al. (2005)). Therefore, the wind turbines are not necessarily producing all the available power (as it is typically the case in the wind farms). In this paper we study the idea of utilizing this power surplus to improve 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. This control system uses the increase in pitch angle to reduce the angle of attack of the blade and thus reduce lift force and the rotor torque. This is the current state-of-the-art in wind turbine technology. For simulations we use the MATLAB implementation (Soltani et al. (2010)) of a 5MW reference wind turbine model for offshore system development developed at National Renewable Energy Laboratory and described in Jonkman et al. (2009).

The paper is structured as follows:
Section 2 tackles the problem of defining a practical (but also justified) cost function for validation of wind turbine operation. Section 3 demonstrates and discusses the possibility for improvement of wind turbine dynamic behavior by adapting the power reference. In Section 4 the wind farm control system that utilizes the demonstrated benefits is proposed. Section 5 concludes the paper. For a brief overview of wind turbine operation and the description of

wind turbine control design model used in the paper the reader is referred to Spudić et al. (2010).

## 2. 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.

As discussed in Section 1, the reserve in the wind power that occurs while tracking the provided power reference can be utilized for improvement of wind turbine operation. Here, we are interested in reducing the loads experienced by the wind turbines. Note that in this paper the term loads refers to the forces and moments experienced by the wind turbine structure. To define the control objective one needs to resolve how to relatively compare two different load histories.

### *2.1 Comparing the load histories*

The main driver of the wind turbine damage is the dynamic stress experienced by the structure. The cyclic stress causes material fatigue, which reduces the wind turbine operational life. The standard fatigue analysis is based on the Palmgren-Miner rule, see e.g. Sutherland (1999). This rule defines the total damage of the wind turbine component as:

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

where $n_j$ is the number of cycles that the structure undergoes at stress level $\sigma_j$, and the $N_j$ is the number of cycles at the stress level $\sigma_j$ that leads to component failure. The different stress levels are denoted by indices $j = 1, \ldots, M$. The Palmgren-Miner rule states that the component breaks when the total damage equals one.

The relation between the stress levels $\sigma_j$ and the maximum number of cycles at that level $N_j$ is described by the S-N curve, which can be well approximated with:

$$\sigma = CN^{-\frac{1}{m}}, \tag{2}$$

where $m$ is denoted as Wöhler coefficient, the empirically determined parameter that characterizes the material, and $C$ is the maximal static stress that the material can withstand.

The notion of total damage is typically used for lifetime calculations that aim at determining when will the total damage reach one. The lifetime calculation requires extensive simulations of different operating scenarios to be viable. For estimation of control benefits it is more common to use the damage equivalent loads. The damage equivalent load (DEL) is the amplitude of a sinusoidal load of constant frequency $f$ which produces the same damage as the original signal. It is determined by (Bossanyi (2003a)):

$$DEL = \left( \sum_{j=1}^{M} \frac{\sigma_j^m n_j}{Tf} \right)^{\frac{1}{m}}, \tag{3}$$

where $T$ is the duration of the load history.

The question remains how to extract the individual cycles from the complex signal. The method that is commonly used in fatigue analysis is the rainflow counting procedure described in Sutherland (1999).

The wind turbine simulation model at hand, Soltani et al. (2010), can provide the tower bending moment and the torsional torque of the shaft. In this work we use the damage equivalent loads computed from those load histories. This is a typical procedure for comparison between control strategies, see e.g. Bossanyi (2003b) and Bossanyi (2005). The DEL computation is performed by the MCrunch code (see Buhl (2010)) with $C = 1$, $Tf = 1$, $m = 4$ for the tower bending moment and $m = 8$ for the shaft moment.

### *2.2 Control design cost function*

According to the previously described DEL is not a suitable load measure for use in the control design cost function. The rainflow counting algorithm is not analytic and the function (3) is nonlinear. Therefore, the aim is to find the cost function that is simpler, but which consequents in the reduction of DEL. The DELs will be computed a-posteriori to evaluate the control effects.

According to (3), 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 the 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 frequency of the cycles does not influence the damage equivalent loads.

Typically the oscillations of the wind turbine structures comprise of high frequency components (contributed to structure eigen-oscillations) and low frequency components (contributed to external excitation of the wind turbine subsystems). The low frequency components introduce larger cycles, while eigen-oscillations are smaller (especially if the wind turbine controller is well-designed, see Spudić et al. (2010)). The aim of the wind farm controller design is to reduce the excitation of these modes. Thus the largest cycles of the load histories can be reduced, which would in turn reduce DEL.

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 $P^0_\mathrm{ref}$ is attributed to every wind turbine. The distribution of constant power references can be obtained by some simple distribution (e.g. $P^0_\mathrm{ref} = \frac{P^\mathrm{WF}_\mathrm{ref}}{N_\mathrm{WT}}$, where $P^\mathrm{WF}_\mathrm{ref}$ is the wind farm power reference and $N_\mathrm{WT}$ 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. Spruce (1993). The mean wind speed and the constant power reference determine the wind turbine operating point. The cost function penalizes the deviations from this operating point.

The chosen control design cost function is:

$$\begin{aligned} &J(P_\mathrm{ref}(t),\ F_\mathrm{T}(t), T_\mathrm{shaft}(t)) := \\ &\quad := rP_\mathrm{e}(t)^2 + qT_\mathrm{shaft}(t)^2 + q_d \left( \frac{F_\mathrm{T}(t)}{dt} \right)^2, \end{aligned} \tag{4}$$

where $r$, $q$ and $q_d$ are the weighing coefficients, $P_\mathrm{e}$ denotes the deviations in produced power, $T_\mathrm{shaft}$ denotes the low-frequency shaft torque deviations, and $F_{\mathrm{T}}$ denotes the deviations of the thrust force (which is the excitation for the tower bending). The thrust force is penalized by its derivation 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. Therefore, the shaft torque deviation can be penalized by its absolute value.

## 3. 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 by introducing the power reference deviations, $P_{\mathrm{ref}}$, 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 is compared to the case when the constant reference is provided to the system (i.e., the power reference deviations are zero).

To state an optimization problem the wind turbine model is required. Here we use a discrete linear state-space model of the wind turbine developed in Spudić et al. (2010):

$$\begin{aligned} x[t+1] &= Ax[t] + Bu[t] + B_d d[t], \\ y[t] &= Cx[t] + Du[t] + D_d d[t], \end{aligned} \tag{5}$$

where $x := \left[\beta, \omega_{\mathrm{g}}, \omega_{\mathrm{g}}^{\mathrm{filt}}\right]'$ ($\beta$ is the pitch angle, $\omega_{\mathrm{g}}$ is the generator speed and $\omega_{\mathrm{g}}^{\mathrm{filt}}$ is the filtered generator speed), $u = [P_{\mathrm{ref}}]'$, $d = [v]$, $y = [F_{\mathrm{T}}, T_{\mathrm{shaft}}]'$ and $t$ denotes the discrete time instant.

Based on the discretized cost function (4) and wind turbine model, the wind turbine control problem is defined as a Constrained Finite-Time Optimal Control (CFTOC) problem (Borrelli et al. (2005)):

$$\begin{aligned} &\min_{U} \; U'\mathcal{R}U + Y'\mathcal{Q}Y + Y_d'\mathcal{Q}_d Y_d \\ &\text{subject to} \begin{cases} \mathcal{Y} = \mathcal{C}x_0 + \mathcal{D}U + \mathcal{D}_d D, \\ \mathcal{E}_U U \leq \mathcal{F}_U, \end{cases} \end{aligned} \tag{6}$$

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 $\mathcal{E}_U, \mathcal{F}_U$ define system constraints and $\mathcal{C}$, $\mathcal{D}$, $\mathcal{D}_d$ describe the system evolution that can be obtained from the wind turbine state-space model, see e.g., Maciejowski (2002). In this paper only the constraints on the control variable are defined. The minimal power reference is defined by generator properties, while the maximum is defined by the nominal generator power or, at lower wind speeds, by the available power.

The control weighing matrices are, according to (4), defined as: $\mathcal{R} := \mathrm{diag}\,(R, \ldots, R)$, $R \in \mathbb{R}$, $R > 0$ is the control weight matrix; $\mathcal{Q} := \mathrm{diag}\left(\begin{bmatrix} 0 & 0 \\ 0 & Q \end{bmatrix}, \ldots, \begin{bmatrix} 0 & 0 \\ 0 & Q \end{bmatrix}\right)$, $Q \in \mathbb{R}$, $Q \geq 0$, is the output weight matrix; and $\mathcal{Q}_d := \mathrm{diag}\left(\begin{bmatrix} Q_d & 0 \\ 0 & 0 \end{bmatrix}, \ldots, \begin{bmatrix} Q_d & 0 \\ 0 & 0 \end{bmatrix}\right)$, $Q_d \in \mathbb{R}$, $Q_d \geq 0$, 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 (7) 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, 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 Soltani et al. (2010).

### *3.1 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.

*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 Figure 2. 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 $Q_d/R = 1000$ the tower deflection amplitude during the positive wind step 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 control input ran into the constraint. This kind of system behavior is not acceptable.

When the weight ratio is reduced to $Q_d/R = 100$ the reduction in tower bending is around 10 %, which is achieved by the maximal power deviation of around 750 kW. This power deviation is still large and the shaft oscillations are still much increased.

Introducing the power controller also 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.

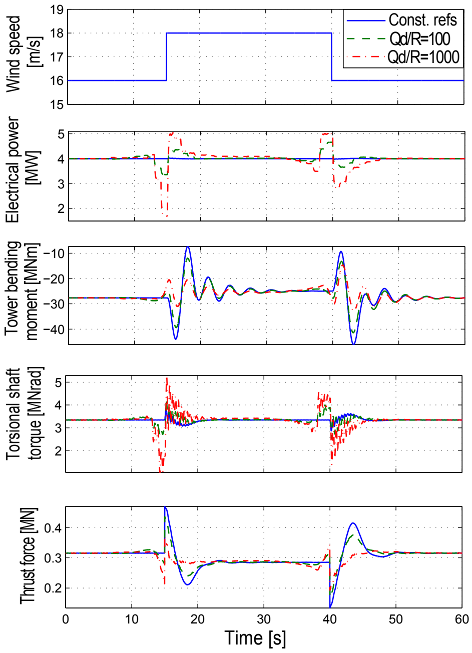

Fig. 2. Deterministic disturbance - Reducing tower loads

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 3.2 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.

*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 Figure 3. 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) 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 is improved, the speed tracking is improved and the pitch action is reduced. Also, there is no significant feed-forward control action.

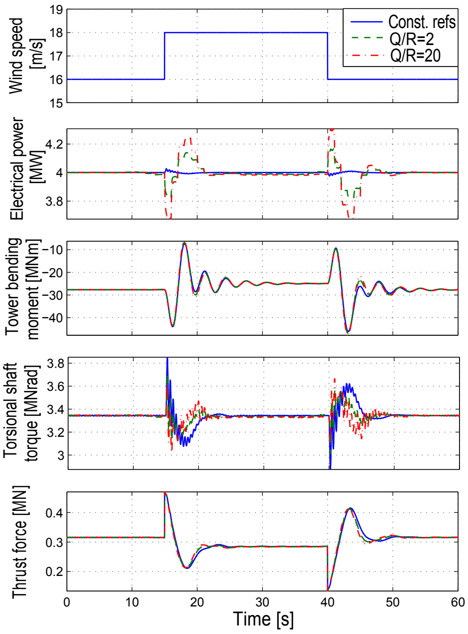

Fig. 3. Deterministic disturbance - Reducing shaft loads

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

### 3.2 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 Soltani et al. (2010). 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 Figure 4. The Figure 5 shows the magnification of the response in order to depict the fast scale dynamics. The simulation outputs suggest that the variance of the shaft torque has been reduced, while the high frequency shaft oscillation have not been enhanced (apparent from the response detail in Figure 5). 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.

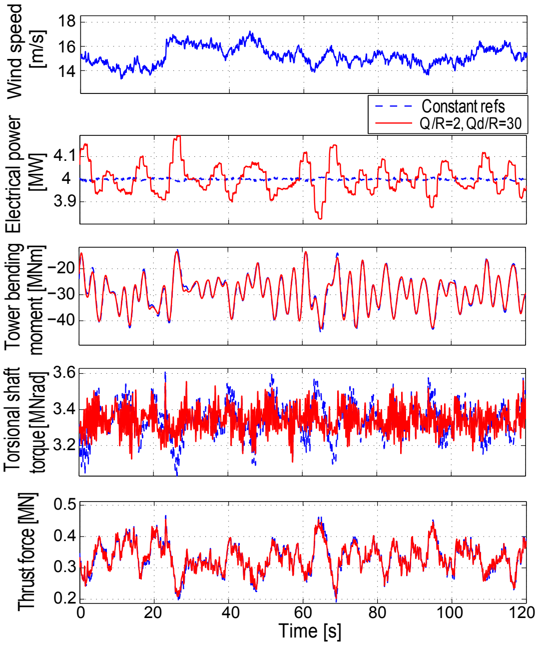

Fig. 4. Turbulent wind scenario

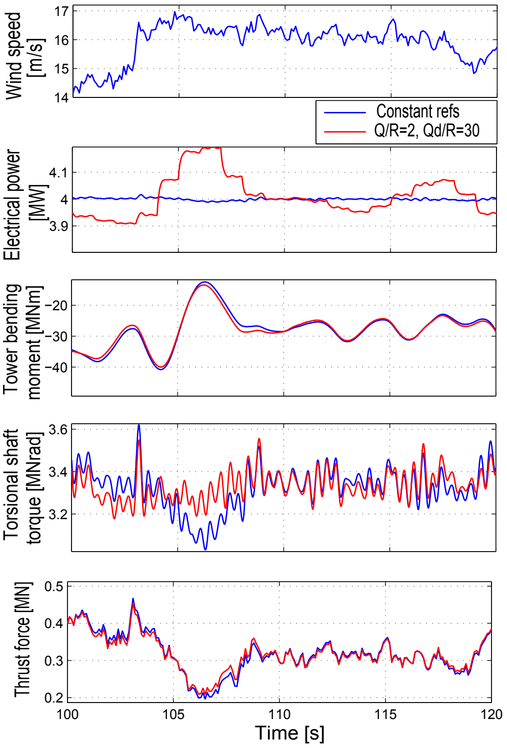

Fig. 5. Turbulent wind scenario (detail)

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 all the representative system modes. The statistics (tower and shaft DELs and standard deviations (STDs) of the pitch rate, rotor speed and electrical power) 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. 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.

Table 1. Turbulent wind scenario statistics

| | Constant reference | Perfect prediction | Persistence assumption |
|---|---|---|---|
| $T_{\mathrm{shaft}}$ DEL [Nrad] | $7.6203 \cdot 10^5$ | $6.2449 \cdot 10^5$ | $6.7610 \cdot 10^5$ |
| $M_{\mathrm{tow}}$ DEL [Nm] | $6.5793 \cdot 10^7$ | $6.3153 \cdot 10^7$ | $6.4097 \cdot 10^7$ |
| $d\beta/dt$ STD [°/s] | 0.8085 | 0.8027 | 0.7935 |
| $\omega_{\mathrm{r}}$ STD [rad/s] | 0.0162 | 0.0158 | 0.0156 |
| $P_{\mathrm{e}}$ STD [kW] | 4.2817 | 67.1112 | 45.3780 |

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 *persistence* 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 feed-forward action since the disturbances are not predicted. However, in several simulation that were performed with different excitations a small improvement in tower loads proved to be 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.

## 4. 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 (7) are summed 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, $P_{\mathrm{ref}}^{j0}$ (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, $\sum_{j=1}^{N_{\mathrm{WT}}} P_{\mathrm{ref}}^{j0} = P_{\mathrm{WF}}^{\mathrm{ref}}$, where $N_{\mathrm{WT}}$ denotes the number of turbines in the wind farm and $P_{\mathrm{WF}}^{\mathrm{ref}}$ is the wind farm power reference.

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

$$\min_{U^1,\ldots,U^{N_{WT}}} \sum_{j=1}^{N_{\mathrm{WT}}} U^{j'} \mathcal{R} U^j + Y^{j'} \mathcal{Q} Y^j + Y_d^{j'} \mathcal{Q}_d Y_d^j$$

$$\text{subject to} \begin{cases} \mathcal{Y}^j = \mathcal{C}^j x_0^j + \mathcal{D}^j U^j + \mathcal{D}_d^j D^j, \\ \mathcal{E}_U^j U^j \leq \mathcal{F}_U^j, \\ \sum_{j=1}^{N_{\mathrm{WT}}} [\,1\ 0\ \ldots\ 0\,]\, U^j = 0 \end{cases} \tag{7}$$

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 statistics of the run are given in Table 2.

Table 2. Wind farm controller statistics

| | Wind turbine 1 | |
|---|---|---|
| | Const. ref. | WF control |
| $T_{\mathrm{shaft}}$ DEL [Nrad] | $7.6108 \cdot 10^5$ | $7.2495 \cdot 10^5$ |
| $M_{\mathrm{tow}}$ DEL [Nm] | $6.5696 \cdot 10^7$ | $6.5012 \cdot 10^7$ |
| $d\beta/dt$ STD [°/s] | 0.8095 | 0.8035 |
| $\omega_{\mathrm{r}}$ STD [rad/s] | 0.0162 | 0.0158 |
| $P_{\mathrm{e}}$ STD [kW] | 4.2803 | 32.1285 |
| | Wind turbine 2 | |
| | Const. ref. | WF control |
| $T_{\mathrm{shaft}}$ DEL [Nrad] | $8.1920 \cdot 10^5$ | $7.5618 \cdot 10^5$ |
| $M_{\mathrm{tow}}$ DEL [Nm] | $7.5716 \cdot 10^7$ | $7.4977 \cdot 10^7$ |
| $d\beta/dt$ STD [°/s] | 0.7394 | 0.7300 |
| $\omega_{\mathrm{r}}$ STD [rad/s] | 0.0150 | 0.0148 |
| $P_{\mathrm{e}}$ STD [kW] | 4.6279 | 30.8181 |
| | Wind farm | |
| | Const. ref. | WF control |
| $P_{\mathrm{WF}}$ 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. The overall (cumulative) percentage reduction of loads in the wind farm is around the same level as for the single controlled wind turbine.

## 5. 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.

## ACKNOWLEDGMENTS

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