Lifetime extension of waked wind farms using active power control

M Vali\textsuperscript{1}, V Petrović\textsuperscript{1}, L Y Pao\textsuperscript{2}, and M Kühn\textsuperscript{1}

\textsuperscript{1} ForWind–University of Oldenburg, Institute of Physics, Küpkersweg 70, 26129 Oldenburg, Germany.
\textsuperscript{2} Department of Electrical, Computer & Energy Engineering, University of Colorado Boulder, USA.

E-mail: mehdi.vali@uni-oldenburg.de

Abstract. This paper studies a new active power control (APC) of waked wind farms in order to extend the lifetime of highly loaded wind turbines. We demonstrate that the structural fatigue loading of a single turbine can be significantly alleviated, while the wind farm power production follows a power reference signal. Then, an optimization problem, subjected to a data-driven fatigue load model, is formulated to balance the lifetime fatigue loading of the wind turbines operating within a waked wind farm. A Game-Theoretic (GT) approach is employed to find a lifetime fraction, wherein a wind turbine should actively reject its own dynamic loadings due to turbulence. A large-eddy simulation model is employed for resolving the turbulent flow, the wake structures and its interaction with the atmospheric boundary layer. The applicability and key features of the controller are discussed with a wind farm example consisting of 2×2 turbines. The overall increase of wind farm lifetime is evaluated using the damage equivalent load (DEL) of the tower base fore-aft bending moment of the individual wind turbines.

1. Introduction

Waked turbines within a wind farm produce less power and experience increased fatigue loading because they operate inside the wake of their upwind turbines. During ordinary wind farm operation, the loading pattern and associated fatigue lifetime of wind turbines are quite irregular and governed by the wind speed and wind directional dependent wake interactions. As a consequence, the lifetime of the individual turbines might deviate quite significantly which might result in higher operations and maintenance (O&M) costs at some turbines. Moreover, the extension of the operational lifetime might be economically meaningful only for a fraction of the loadings inside a certain wind farm.

It is expected that future wind farms operate for a significant fraction of their lifetime to contribute to stabilizing the grid frequency. This so-called active power control (APC) can be achieved through derating of power production while following a power dynamic reference signal. Fleming et al. [1] have studied APC for a wind farm plant and demonstrated the wake challenge. van Wingerden et al. [2] have introduced a feedback APC for a high-quality wind farm power tracking performance. Vali et al. [3] have proposed a new control approach, the so-called APC with a coordinated load distribution (CLD), which exploits the flexibility of the APC solution for alleviating the structural loading of waked turbines. However, it is challenging to achieve a levelized lifetime fatigue loading due to the strong impact of the wind direction
on wake interactions and wind farm available power in reserve. Several studies have utilized
optimization techniques to find optimal set-points in order to simultaneously maximize the total
power production and prolong the lifespan of the wind farm by minimizing the structural fatigue
loading [4, 5].

In this paper, the non-uniqueness of the APC solution with respect to the distribution of the
individual turbine load/power is exploited for finding a control solution, which yields a more
balanced lifetime fatigue loading of the wind turbines operating within a waked wind farm.
Large-eddy simulations (LES) are employed to examine the performance of the load controller
under turbulent wakes and different wind directions. The results are then extrapolated to the
long-term statistics at a fictitious site.

The remainder of this paper is organized as follows. In section 2, we briefly present the main
components of our developed closed-loop wind farm control framework consisting of a large-
eddy simulation model, the wind turbine and the wind farm control systems. The main focus
of section 3 is on the proposed ancillary service and optimization method for lifetime extension
of wind farms. A test simulation scenario is introduced in section 4 for verification. Then,
the performance of the studied APC approaches is discussed through a comparative large-eddy
simulation study. Finally, in section 5 conclusions and an outlook of the current study are given.

2. Closed-loop wind farm control framework

Figure 1 schematically shows the main components of our closed-loop APC framework [3]. A
hierarchical control architecture is introduced as follows

- Level 0 stands for the wind power plant simulation model and illustrates how the employed
  LES model is coupled with the \( i \)th wind turbine model to establish a wind farm case study.
- Level 1 contains the main components of the gain-scheduled wind turbine control (WTC)
  system of the \( i \)th wind turbine (WT) with the main objective of locally following the power
demand \( P_{\text{dem}}^i \).
- Level 2 represents the closed-loop APC at the wind farm (WF) level, deciding how the power
  productions of the individual wind turbines should be regulated in order to simultaneously
  ensure a satisfactory wind farm power reference tracking and ancillary services.

2.1. Wind farm simulation model

The LES approach has shown capability of resolving the unsteady nature of the wake and
turbulent flows within a wind farm. In this study, we employ the PArallelized Large-eddy
simulation Model (PALM) version 4.0 [6] coupled with the Actuator Disc Model (ADM) of a
wind turbine [7] (see Level 0 of Fig. 1). The ADM is computationally efficient and provides a
good approximation of the far wake structure, making it suitable for the present study. The
wind turbines are modeled in PALM with only two degrees of freedom (DoF) as follows [3]

\[
\tau \dot{P} + P = P_a(a, U_0, \dot{x}_T) \tag{1}
\]

\[
m_T \ddot{x}_T + c_T \dot{x}_T + k_T x_T = F_a(a, U_0, \dot{x}_T) \tag{2}
\]

Equation (1) represents the power response of a wind turbine \( P \) to the aerodynamic power \( P_a \)
with the aerodynamic time constant \( \tau \), which can be associated to the drive-train dynamics.
The axial induction factor \( a \) stands for the ratio of the induced wind speed at the rotor to the
effective wind speed \( U_0 \) at a far distance upwind from the rotor disc and can be translated to
the practical torque and pitch control inputs of a wind turbine. Equation (2) describes the
first tower fore-aft dynamic mode with the tower top fore-aft displacement \( x_T \), the aerodynamic
thrust force $F_a$, and the tower equivalent modal mass $m_{Te}$, structural damping $c_T$ and bending stiffness $k_T$ according to [8].

The aerodynamic thrust force for a single turbine is calculated using the employed ADM in the PALM simulation code as follows [9]:

$$F_a = \frac{1}{2} \rho A_d U_{rel}^2 C_T(a), \quad C_T(a) = 4a(1-a),$$

where the thrust coefficient $C_T$ is described as a function of the axial induction factor $a$ and $\rho$ is the air density and $A_d$ is the swept area of the rotor plane. The relative wind speed $U_{rel}$ is defined as a superposition of the effective wind speed and the structural tower top velocity in order to model the aerodynamic damping of the tower fore-aft mode. Considering the induction effect of a rotor disc, the effective wind speed $U_0$ can be approximated from the measurable axial disc-averaged wind velocity $U_d$ from the PALM code and enables us to model the applied aerodynamic thrust force (3) acting in the negative direction on the flow [7]. Then, the aerodynamic power of an individual wind turbine is calculated as

$$P_a = F_a \cdot U_d,$$

The tower base fore-aft bending moment of an individual wind turbine is approximated as [8]

$$M_T = h_H (c_T \dot{x}_T + k_T x_T),$$

where $h_H$ is the hub height.

2.2. Wind turbine control system

Each wind turbine has its own feedback controller such that it behaves as a dominant second-order system with a certain frequency $\omega$ and a damping ratio $\zeta$ to regulate the rate of power
production (see Level 1 of Fig. 1). The objective of the wind turbine control system is defined to locally track the power demand $P_{i}^{\text{dem}}$, which is commanded by the high-level wind farm controller.

The wind turbine controller is designed based on a linear representation of the aerodynamic power with respect to the control input. Hence, the following mapping is applied to the axial induction factor $[10, 11]$:

$$\beta_i = \frac{a_i}{1 - a_i}$$  \hspace{1cm} (6)

A proportional-integral (PI)-based control law is defined for APC of the $i$th wind turbine with the local tracking error $e_{i,k} = P_{i,k}^{\text{dem}} - P_{i,k}$ at time instance $k$ [3].

2.3. APC with a coordinated load distribution (CLD)

Following [2], a gain-scheduled APC is designed to improve the wind farm power tracking performance by resolving undesirable local effects due to turbulence and wakes. Therefore, the control signal $\Delta P_{k}^{\text{ref}} \in \mathbb{R}$ actively adjusts the wind turbine power demands $P_{i,k}^{\text{dem}} \in \mathbb{R}^{N_t}$ in order to compensate for the accumulated local tracking errors at each time instant $k$. A closed-loop power distribution law, the so-called coordinated load distribution (CLD) law, is proposed in [3] based on the structural load measurement of the individual wind turbines as follows:

$$P_{i,k}^{\text{dem}} = \alpha_{i,k} \left( P_{k}^{\text{ref}} + \Delta P_{k}^{\text{ref}} \right),$$  \hspace{1cm} (7)

where distributing power set-points $\alpha_{i,k}$ can be chosen freely within the constraint $\sum_{i=1}^{N_t} \alpha_i = 1$. The existing DoFs have been exploited to actively adjust the power demand distribution factor $\tilde{\alpha}_k \in \mathbb{R}^{N_t}$ in order to alleviate wake-induced structural loadings, while the total power production follows a wind farm power reference. Therefore, a load-based tracking error is defined for the $i$th turbine at time instant $k$ as

$$e_{L,i,k} = \frac{1}{N_t} \sum_{l=1}^{N_t} L_{l,k} - L_{i,k},$$  \hspace{1cm} (8)

describing the deviations of the instantaneous structural loadings of the $N_t$ operating wind turbines from their mean value. A proportional-integral (PI)-based power distribution law is designed in order to adjust the power setpoints $\alpha_{i,k}$ for leveling the structural loadings of the individual wind turbines [3].

In the present study, we consider only the load measurements of the first tower base fore-aft bending moment, i.e., $L_i = M_{T,i}$, as a descriptor for the structural loadings of the $i$th wind turbine operating in a waked wind farm. Other load quantities, e.g., variation of the flapwise blade loading, short-term damage equivalent loads of the blade, main shaft response, and actuator wearing and tearing should be also considered to be more representative for a real plant. The proposed load control approach could be applied in principle as well for such more sophisticated descriptors if their measurements (or estimates) would be available online.

3. Lifetime extension of waked wind farms

The irregular load pattern, dependency of wake interactions on the wind direction, and associated fatigue lifetime demand a load control approach to be capable of balancing the lifetime structural loading of individual wind turbines. Therefore, data-driven analysis is conducted to evaluate the practical requirements of such a load control system.
3.1. Active load control (ALC) of a single wind turbine
We exploit the flexibility of the APC solution of a wind farm to mitigate the structural loading of the individual wind turbines. The arbitrary \( j \)th wind turbine is commanded to reject the load fluctuations due to the turbulence, as the main source of the fatigue loading, while other wind turbines cooperatively guarantee a satisfactory wind farm power tracking performance. The redundancy of the APC problem of wind farms allows us to keep the quality of the total power reference tracking insensitive. Therefore, a reduced order version of the closed-loop APC solution (7) is introduced as follows

\[
P_{i,k}^{\text{dem}} = \bar{\alpha}_{i,k} \left( \bar{P}_{k}^{\text{ref}} + \Delta \bar{P}_{k}^{\text{ref}} \right) \quad \text{with} \quad i \neq j,
\]  

where the power reference of the reduced order APC problem is defined as

\[
\bar{P}_{k}^{\text{ref}} = P_{k}^{\text{ref}} - P_{j,k},
\]

A proportional-integral (PI)-based control law is defined for ALC of the \( j \)th wind turbine as

\[
\beta_{j,k} = K_{P,j} e_{L,j,k}^{L} + K_{I,j} \sum_{n=1}^{k} e_{j,n}^{L},
\]

with the local load tracking error \( e_{L,j,k}^{L} = L_{j}^{\text{ref}} - L_{j,k} \) at time instant \( k \). Standard pole-placement is utilized for computing the gain-scheduled proportional and integral gains \( K_{P,j} \) and \( K_{I,j} \). It is assumed that there exists a design load reference for lifetime structural loading of an individual wind turbine at a specific site. In this study, the reference load \( L_{j}^{\text{ref}} \) is computed using the 30-minute time average of the \( j \)th tower base bending moment with the normal operation of a wind farm, e.g., greedy control, over the considered wind rose and depending on the mean wind speed. More details and discussion can be found in section 4.1.

3.2. Lifetime extension
In order to reduce O&M costs at wind turbines subjected to higher dynamic loadings, the power/load contributions of the individual turbines are investigated over the lifetime. As discussed in section 3.1, the fatigue load of an arbitrary wind turbine can be alleviated, while the total power production of the wind farm follows a power reference signal. The introduced APC is employed here to balance the lifetime fatigue loading of the individual wind turbines by defining the fractions of the lifetime, wherein their local ALC should be active. Therefore, the lifetime damage equivalent loading (DEL) \( L_{\text{eq}} \in \mathbb{R}^{N_t} \) is defined for a wind farm consisting of \( N_t \) wind turbines as

\[
L_{\text{eq}} = T_{0} \tilde{L}_{0}^{\text{eq}} + \sum_{j=1}^{N_t} T_{j} \tilde{L}_{j}^{\text{eq}},
\]

where \( T_{0} \in [0, 1] \) and \( \tilde{L}_{0}^{\text{eq}} \in \mathbb{R}^{N_t} \) respectively represent the fraction of lifetime and DEL of wind turbines operating with greedy control setting or active wake control for maximizing energy extraction [11, 12]. \( T_{j} \in [0, 1] \) and \( \tilde{L}_{j}^{\text{eq}} \in \mathbb{R}^{N_t} \) stand for the same quantities while the fatigue loading of the \( j \)th wind turbine is actively controlled during the APC of the wind farm. The lifetime fractions can be chosen freely subjected to the problem constraints to influence the lifetime damage loading and to levelize the irregular fatigue loading of the individual wind
turbines during ordinary wind farm operation. The optimization criterion with respect to the decision variable $T_j$ is defined as

$$
\min_{T_j} \{ \mu_1 \text{std}(L_{eq}) + \mu_2 \text{mean}(L_{eq}) \},
$$

(13)

subject to

$$
T_0 + \sum_{j=1}^{N_t} T_j = 1, \quad \text{with} \quad T_0, T_j \in [0, 1].
$$

(14)

The performance index includes the standard deviation (std) and the mean value of the lifetime DEL of wind turbines (12), respectively weighted with factors $\mu_1$ and $\mu_2$. A Game Theoretic (GT) approach, adapted from [13], is employed to iteratively find the optimal lifetime fraction $T_j$. Note that the lifetime fraction $T_0$ has been treated as a pre-selected or empirical parameter, representing the normal operation of the wind farm with irregular fatigue loading distribution among the wind turbines.

4. Results and discussion

A layout of a $2 \times 2$ wind farm example is considered here. The wind turbines with rotor diameter $D = 126$ m, taken from the freely available model of the NREL 5MW reference wind turbine [14]. Figure 2 shows the instantaneous field of the $u$-component of the wind farm example with a neutral boundary layer and a mean wind speed of 8 m/s at hub-height. The dashed rays represent the considered wind directions, which are simulated by rotation of the wind farm layout relative to the incoming LES wind field. The wind turbines are spaced $5D$ in both the stream-wise and the cross-wise directions with the wind direction of $0^\circ$. Table 1 summarizes the key parameters of the LES simulations. A fictitious wind rose is considered here for investigating the requirements for lifetime extension of a wind farm using active power control. Higher probabilities of occurrence are given to the wind directions $0^\circ$ and $45^\circ$ in order to emphasize the challenge of wake conditions. Note that the geostrophic wind velocities $u = 9$ m/s and $v = -2$ m/s were defined empirically and iteratively to result in an ambient longitudinal wind velocity $U_\infty = 8$ m/s at hub-height.

![Figure 2](image1.png)

**Figure 2.** The layout of the $2 \times 2$ wind farm. The dashed rays indicate different wind directions. The most highly waked conditions occur with wind directions $0^\circ$ and $45^\circ$.

![Figure 3](image2.png)

**Figure 3.** The lifetime DELs of the tower base fore-aft bending moment with the greedy control setting, i.e., $a_i = \frac{1}{3}$.

The fatigue load analysis is conducted by comparing the load spectra with the S–N characteristic curve with an inverse slope of $m = 4$, commonly used for steel components like the tower [15]. Figure 3 shows the corresponding averaged lifetime DELs of the tower base fore-aft
Table 1. The key parameters of the LES simulation.

| Simulation parameter                               | value                                      |
|----------------------------------------------------|--------------------------------------------|
| Domain size $L_x \times L_y \times L_z$            | $15.3 \times 3.8 \times 1.3 \text{ km}^3$ |
| Grid mesh size $N_x \times N_y \times N_z$        | $1024 \times 256 \times 128$              |
| Cell mesh resolution $\Delta_x \times \Delta_y \times \Delta_z$ | $15 \times 15 \times 10 \text{ m}^3$     |
| Wind directions                                   | $\{0^\circ, 9^\circ, 18^\circ, 27^\circ, 36^\circ, 45^\circ\}$ |
| Wind direction probability of occurrence          | $\{\frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\}$ |
| Number of wind turbines $N_t$                     | 68                                         |
| Wind turbine model                                 | Actuator disc model (ADM)                 |
| Wind turbine control DoF                           | Induction factor                          |
| Number of grid cells per turbine                  | 68                                         |
| Atmospheric stability condition                    | Neutral boundary layer (NBL)              |
| Ambient longitudinal wind speed $U_\infty$ at hub height | 8 m/s                                     |
| Geostrophic wind velocity                         | $u = 9 \text{ m/s}$ and $v = -2 \text{ m/s}$ |
| Monin-Obukhov length scale $L$                    | 3.8 km                                     |
| Longitudinal turbulence intensity of ambient wind | $I_u \approx 5\%$                         |
| Longitudinal turbulence intensity of wakes        | $I_u \approx 15\%$                        |
| Simulation sample time                             | 1 s                                        |

bending moment of the individual wind turbines with the greedy control over the considered wind rose from $0^\circ$ to $45^\circ$. The irregular fatigue loading of the downwind turbines is attributed to wind directional dependencies of the wake interactions and the added fatigue loads due to the higher turbulence intensity inside the wake. The 3rd wind turbine experiences the highest amount of structural fatigue loads because it fully operates inside wakes with both the wind directions $0^\circ$ and $45^\circ$. Note that the DEL of an upwind turbine with the greedy control is computed using the 30-minute time series of the tower base moment with 18 different seeds.

4.1. Power and load reference selection
In order to level the lifetime fatigue loading of a waked wind farm using APC, appropriate wind turbine load references are needed. Therefore, the performance of the studied wind farm with greedy control setting, i.e. $a_i = \frac{1}{3}$, is averaged over the considered wind rose $0^\circ$ to $45^\circ$ at the wind speed of 8 m/s.

Table 2. The 30-minute time average wind farm power and the tower base fore-aft bending moment $M_T$ of the wind turbines with greedy control setting over the considered fictitious wind rose $0^\circ$ to $45^\circ$ at the wind speed of 8 m/s.

| Wind direction | WF $P$ [MW] | WT1 $M_{T,1}$ [MNm] | WT2 $M_{T,2}$ [MNm] | WT3 $M_{T,3}$ [MNm] | WT4 $M_{T,4}$ [MNm] |
|----------------|-------------|---------------------|---------------------|---------------------|---------------------|
| $0^\circ$      | 4.59        | 44.2                | 43.9                | 18.2                | 18.4                |
| $9^\circ$      | 6.68        | 44.8                | 44.6                | 40.1                | 37.3                |
| $18^\circ$     | 7.53        | 45.0                | 45.8                | 45.4                | 45.1                |
| $27^\circ$     | 7.51        | 44.9                | 45.1                | 46.3                | 44.7                |
| $36^\circ$     | 7.47        | 45.3                | 46.1                | 44.3                | 44.5                |
| $45^\circ$     | 6.50        | 45.1                | 46.3                | 26.4                | 44.8                |
| Lifetime       | 6.42        | 44.8                | 45.3                | 33.2                | 37.3                |
The 30-minute time average wind farm power and tower base bending moment of the individual wind turbines are given in Table 2. The lifetime average wind farm power 6.42 MW is employed as the wind farm power reference. The load references are also defined as 90% of the time average tower base fore-aft bending moment of the individual wind turbines, given in the last row of Table 2. The lifetime average wind farm power 6.42 MW cannot be reached with wind direction $0^\circ$ due to strong wake interactions and the associated power losses, yielding a wind farm normal operation with the greedy control setting [3]. Moreover, with wind directions $9^\circ$ and $45^\circ$, the APC solution domain is so limited to be exploited for simultaneous structural load control of the wind turbines due to the high ratio of the lifetime power reference 6.42 MW to the available powers. These situations represent medium-waking conditions of the wind farm example. However, the non-wake conditions, i.e., with wind directions $18^\circ$, $27^\circ$, and $36^\circ$, result in larger APC solution domains, which are exploited for leveling the lifetime fatigue loading of the individual wind turbines.

Figure 4. The tower base fore-aft bending moment of the individual wind turbines with different APC approaches and wind direction $27^\circ$. For all cases, the total wind farm power follows the lifetime power reference with satisfactory accuracies due to the usage of feedbacks of the wind farm power tracking errors. Figure 4 plots the trajectories of the tower base fore-aft bending moment of the individual wind turbines, while the wind farm power tracks the lifetime power reference with wind direction $27^\circ$. Three different APC approaches are compared. The standard deviation (std) of the tower base fore-aft bending moments on all wind turbines is also denoted in the legend for each approach. Ref. APC (see red curves) improves only the accuracy of the wind farm power tracking against the undesired local wake and turbulent effects [2]. However, the standard deviation of the tower base loadings is reduced using the APC/CLD (see green curves) with a control solution, yielding more even dynamic loading of the individual wind turbines [3]. The blue curves reveal the performance of the proposed active load control in section 3.1, which acts on the 3rd wind turbine. The tower base bending moment is controlled to remain about the pre-defined load reference, while the other three turbines adjust their power demands to cooperatively track the wind farm power reference using the reduced order APC problem (9).
The next section studies the needed lifetime fraction, wherein each turbine should actively control its own dynamic loading during APC.

4.2. APC scenarios for lifetime extension

The lifetime of a highly loaded wind turbine is extended by looking for the lifetime fraction, wherein it should actively reject the dynamic loadings during the APC of the wind farm. A test case scenario is defined, in which the wind farm operates with the greedy control setting for half a lifetime ($T_0 = 0.5$) and the proposed APC is employed to balance the irregular lifetime DELs of the individual wind turbines. Each wind direction consists of four LES simulations, wherein one pre-selected turbine out of four actively rejects its own dynamic loading, while the remaining ones contribute to wind farm power tracking performance. In total, 48 LES simulations are conducted for the considered wind rose, wherein half the simulations use the ALC with the reduced order APC (9) and the other half of the simulations use the reduced order APC with CLD, as explained in section 3.1.

Table 3 outlines the optimal solution, obtained using a GT approach, with both the APC with and without CLD. The employed GT approach benefits from a model-free optimizing algorithm which iteratively converges to a globally optimal solution independent of the convexity of the problem. The weighting factors $\mu_1$ and $\mu_2$ are computed using the lifetime DEL of the greedy control $\tilde{L}^0_{eq}$ to create normalized quantities with respect to the standard deviation (std) and the mean value of DELs, i.e., $\frac{1}{\mu_1} = \text{std}(\tilde{L}^0_{eq})$ and $\frac{1}{\mu_2} = \text{mean}(\tilde{L}^0_{eq})$. As expected, the 3rd wind turbine, which operates in full wake conditions with both the wind direction $0^\circ$ and $45^\circ$, demands the highest lifetime fraction for locally active load control for both the lifetime extension cases. Note that $T_j = 0$ means that there is no need for ALC of the $j$th wind turbine because it is subjected to lower fatigue loading compared to other ones.

Table 3. Recommended lifetime fraction for ALC performance of the $j$th wind turbine in order to balance the lifetime fatigue loading of the wind turbines. The wind farm operates for half of its design lifetime with the greedy control setting, i.e., $T_0 = 0.5$.

|               | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---------------|-------|-------|-------|-------|
| Lifetime Extension with Ref. APC | 0.01  | 0.08  | 0.32  | 0.09  |
| Lifetime Extension with APC/CLD  | 0.05  | 0.02  | 0.31  | 0.12  |

The remainder of this section provides more insight into the performance of the proposed ancillary service for a waked wind farm. The following four APC approaches are compared in this study:

- A closed-loop APC at the wind farm level (Ref. APC) [2]
- A closed-loop APC with a coordinated load distribution (APC/CLD) [3]
- Lifetime extension with a reduced order Ref. APC and optimized lifetime fractions of ALC, given in the first row of Table 3 (Ext. APC).
- Lifetime extension with a reduced order APC/CLD and optimized lifetime fractions of ALC, given in the second row of Table 3 (Ext. APC/CLD).

Figure 5 compares the defined performance index (13), the mean value and the standard deviation of the lifetime DELs of the wind turbines, normalized with respect to those of the Ref. APC. All studied APC methods have satisfactory wind farm power tracking performance at each specific wind direction due to the usage of feedback at the wind farm level. However, it should be noted that the power reference, defined in section 4.1, is not realizable with wind direction $0^\circ$ due to having the highest wake-induced power losses. Therefore, the lifetime averaged power
Figure 5. The normalized cost function, mean value, and standard deviation of the lifetime DELs of the tower base fore-aft bending moment. The Ext. APC and Ext. APC/CLD benefit from the locally active load control to balance the lifetime fatigue loading.

Figure 6. The lifetime DELs of the tower base fore-aft bending moment with different wind farm control approaches. The Ext. APC/CLD benefits from the locally active load control to balance the lifetime fatigue loading.

production with the studied APC methods is limited to 96% of the lifetime production during the normal wind farm operation, i.e., with greedy control. Although the mean value of the lifetime DELs is slightly reduced, their standard deviation among the four wind turbines is significantly reduced using the proposed APC approach for lifetime extension. Indeed, the introduced decision variable, i.e., the lifetime fraction $T_j$, allows transferring the fatigue loading of the $j$th turbine to other ones during the wind farm power reference tracking in order to prolong the lifespan of a highly loaded wind turbine.

Figure 6 plots the lifetime DELs of the tower base fore-aft bending moment of all four turbines. Compared to the reference APC approach, the closed-loop APC with CLD influences the fatigue loading of the individual wind turbines when there exists enough available power in reserve, e.g., with wind directions $18^\circ$, $27^\circ$, and $36^\circ$, as discussed in [3]. The dependency of the wind farm available power and wake interactions on the wind direction makes the lifetime fatigue loading irregular (see red and green bars). However, the proposed APC approach based on the optimal lifetime fractions of locally ALC is capable of balancing the lifetime DELs of the waked wind farm (see blue bars). It can be seen that the DEL of the highly loaded wind turbines is reduced in return for load transfer to the wind turbines with lower fatigue loading.

5. Conclusion and future work
Active power control of wind farms has been employed in order to extend the lifetime of highly loaded wind turbines. Since there exist multiple solutions for the APC problem, it is possible to actively reject the dynamic loading of an individual wind turbine without deteriorating the wind farm power reference tracking performance. This study highlights the lifetime fraction for the active load control of a single turbine in such a manner that the irregular fatigue loading during ordinary wind farm operation is partly balanced. In the future, the analysis will be extended to the entire wind rose and will be extrapolated to the long-term statistics at a real site. Different time fraction of APC operation in the overall lifetime will be investigated as well. Moreover, an aeroelastic wind turbine model will be employed for a more reliable and practical fatigue load and lifetime analysis.
Acknowledgments

Thanks are given to Gerald Steinfeld for his kind support on PALM simulation code and LES analyses.

This work has been partly funded by the Ministry for Science and Culture of Lower Saxony through the funding initiative “Niedersächsisches Vorab” (project “ventus efficiens”) and by the Federal Ministry for Economic Affairs and Energy according to a resolution by the German Federal Parliament (“WIMS-Cluster” 0324005). Support from the Hanse-Wissenschaftskolleg in Delmenhorst, Germany and from a Palmer Endowed chair at the University of Colorado Boulder is also gratefully acknowledged.

References

[1] Fleming P A, Aho J, Gebraad P, Pao L Y and Zhang Y 2016 Computational fluid dynamics simulation study of active power control in wind plants American Control Conference pp 1413–1420, DOI: 10.1109/ACC.2016.7525115
[2] van Wingerden J W, Pao L, Aho J and Fleming P 2017 Active power control of waked wind farms IFAC-PapersOnLine 50 4484 – 4491 ISSN 2405-8963, DOI: 10.1016/j.ifacol.2017.08.378
[3] Vali M, Petrović V, Steinfeld G, Y Pao L and Kühn M 2019 An active power control approach for wake-induced load alleviation in a fully developed wind farm boundary layer Wind Energy Science 4 139–161
[4] van Dijk M T, van Wingerden J W, Ashuri T and Li Y 2017 Wind farm multi-objective wake redirection for optimizing power production and loads Energy 121 561 – 569 ISSN 0360-5442
[5] Kanev S K, Savenije F J and Engels W P 2018 Active wake control: An approach to optimize the lifetime operation of wind farms Wind Energy 21 488–501
[6] Maronga B, Gryschka M, Heinze R, Hoffmann F, Kanani-Sühring F, Keck M, Ketelsen K, Letzel M O, Sühring M and Raasch S 2015 The Parallelized Large-Eddy Simulation Model (PALM) version 4 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives Geoscientific Model Development 8 2515–2551, DOI: 10.5194/gmd–8–2515–2015
[7] Witha B, Steinfeld G, Dörenkämper M and Heinemann D 2014 Large-eddy simulation of multiple wakes in offshore wind farms Journal of Physics: Conference Series 555 012108
[8] Schlipf D, Schlipf D J and Kühn M 2013 Nonlinear model predictive control of wind turbines using LIDAR Wind Energy 16 1107–1129 ISSN 1099-1824
[9] Gasch R and Twele J 2011 Wind power plants: fundamentals, design, construction and operation, Second edition (Springer Science & Business Media)
[10] Boersma S, Vali M, Kühn M and van Wingerden J W 2016 Quasi Linear Parameter Varying modeling for wind farm control using the 2D Navier-Stokes equations American Control Conference pp 4409–4414
[11] Vali M, Petrović V, Boersma S, van Wingerden J W, Pao L Y and Kühn M 2019 Adjoint-based model predictive control for optimal energy extraction in waked wind farms Control Engineering Practice 84 48 – 62 ISSN 0967-0661
[12] Rott A, Doekemeijer B, Seifert J K, van Wingerden J W and Kühn M 2018 Robust active wake control in consideration of wind direction variability and uncertainty Wind Energy Science 3 869–882
[13] Marden J R, Ruben S D and Pao L Y 2013 A model-free approach to wind farm control using game theoretic methods IEEE Transactions on Control Systems Technology 21 1207–1214 ISSN 1063-6536
[14] Jonkman J M and Buhl M L 2005 FAST manual user’s guide NREL report No. NREL/EL-500-38230
[15] 2005 International Electrotechnical Commission, Wind turbines—Part 1: Design requirements IEC 61400-1:2005(E), Third edition