Large-eddy simulation study of wind farm active power control with a coordinated load distribution

M Vali\textsuperscript{1}, V Petrovi\textacute{c}\textsuperscript{1}, G Steinfeld\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. In this paper, an active power control (APC) approach for wind farms is studied, for a case in which the wind turbines interact with each other aerodynamically through their wakes. We demonstrate that the structural loadings on the individual wind turbines can be coordinated to expand their lifetimes, while the wind farm production tracks a power reference signal. We propose an additional feedback control loop in order to adjust the distribution of the regulated power demands among the wind turbines, exploiting the non-unique solutions of APC for wind farms. The axial induction factor of each wind turbine is considered as a control input to influence the overall wind farm performance. The applicability of the controller is tested with a wind farm example consisting of $2 \times 3$ turbines with partial wake overlaps and detailed interactions with the atmospheric boundary layer, simulated with the PArallelized Large-eddy simulation Model (PALM). The results demonstrate the effectiveness of the proposed approach and point to some future studies that may improve and extend the performance.

1. Introduction

Future wind farms should be able to respond to grid requirements through control of their power production in order to balance power supply with demand, the so-called active power control (APC). Control of turbines in a wind farm is challenging because of the aerodynamic interactions among wind turbines through their wakes, which lead to a reduction of the total power and a higher dynamic loading on the downstream turbines. Wakes overlap fully or partly with rotors of downwind turbines and higher turbulence inside the wakes cause the wind turbines to experience different levels of dynamic loading, which lead to additional fatigue damage. Since during APC the total wind farm power is below the maximum available power, the coordination of the power and load distribution can be employed to optimize the structural loading of the individual turbines.

Aho et al. \cite{1, 2} investigate thoroughly providing APC services at the wind turbine level. Fleming et al. \cite{3} demonstrate the challenge of APC for a wind power plant in wake conditions. In their study, a time-varying wind farm power reference is distributed evenly among the individual wind turbines, neglecting the local turbulence and wake impacts on the power production of the downstream turbines. This open-loop method provides satisfying power tracking performance only in non-waked conditions of a wind farm. van Wingerden et al. \cite{4} have extended this approach to incorporate a classical feedback control to improve the power tracking performance.
of a waked wind farm. The total power production is fed back in order to adjust the pre-selected power set-points, by distributing wake-induced total power tracking errors among the wind turbines evenly. In their study, it is shown that there exist significant disparate loading patterns on wind turbine components, where the power set-points are determined differently.

Recently, several studies have developed model predictive active power control of wind farms for optimal distribution of the power reference among the individual wind turbines, taking their wake interactions into account [5, 6]. The systematic formulation of the MPC optimization problem allows exploiting non-unique solutions of APC for optimal structural loading distribution among wind turbines. MPC schemes typically rely on simplified wind farm models for capturing the dominant dynamic wake interactions in a computationally efficient manner [7, 8]. It has been shown that adequate MPC formulations can significantly reduce the computational complexity [9, 10, 11], however, the overall complexity of such a control system, including suitable mathematical model and measurement system, is still an open research topic, particularly for large wind farms. Distributed MPC has recently received attention in order to reduce the computational burden of model predictive APC [12].

On the other hand, model-free and classical control approaches have also received attention due to their simple control architecture and ease of implementation for real-time control of large wind farms. Both features allow the performance of the designed controllers to be evaluated with more realistic wind farm flow conditions, e.g., free field testing [13], wind tunnel testing [14, 15], and high-fidelity LES models [4, 16, 17].

In this paper, we propose an extension to the APC approaches in [3, 4] to coordinate actively the controlled power demands, tending to level dynamic loadings on the individual wind turbines more evenly. An additional feedback loop is introduced that takes advantage of the existing multiple solutions for APC of wind farms. Moreover, we utilize large eddy simulations in order to examine the performance of the controller under detailed dynamic wake and turbulence conditions in a simulated wind farm.

The remainder of this paper is organized as follows. In section 2, we briefly present the high-fidelity wind farm simulation model and the wind farm example layout used in our study. The main focus of section 3 is on the structure of the proposed closed-loop active power control. The baseline APC approaches are introduced in section 4. Then, the performance of the proposed controller is discussed through simulation studies. Finally, the effectivenesses and weaknesses of the proposed approach are collected in section 5 as conclusions. The potential methods for improving the performance are outlined as well.

2. Wind farm simulation model

In this study, an LES wind farm model is utilized, which is suitable for studying the evolution of turbulence and wind turbine wakes. It employs the PArallelized Large-eddy simulation Model (PALM) [18] coupled with the Actuator Disc Model (ADM) of a wind turbine [19]. Much more detailed wind turbine models with more realistic near wake structure, e.g., actuator disc model with rotation (ADM-R) and actuator line model (ALM) are also implemented in PALM. However, ADM is computationally efficient and provides a good approximation of the far wake structure, making it useful for the present study.

2.1. The PArallelized LES Model (PALM) of wind farms

 PALM is an open source LES code, which is developed for atmospheric and oceanic flows and optimized for massively parallel computer architectures. It uses central differences to discretize the non-hydrostatic, filtered, and incompressible Boussinesq approximation of the three-dimensional Navier-Stokes equations on a uniformly spaced Cartesian grid [18].

 The wind turbines are parameterized with an actuator disc model (ADM) [20] to exert a thrust force into the incoming flow and extract a certain amount of energy from the wind. The
The thrust force for a single turbine is expressed as follows:

\[ F_T = \frac{1}{2} \rho A_d U_\infty^2 C_T(a), \quad C_T(a) = 4a(1 - a), \]  

(1)

where \( \rho \) is the air density, \( A_d \) is the swept area of the rotor plane, \( U_\infty \) is the effective wind speed at a far distance upwind from the rotor disc, and \( C_T \) is the thrust coefficient of a wind turbine, which is a function of the axial induction factor \( a \). The latter is considered as the wind turbine control input, which is the ratio of the reduced wind velocity to the effective wind speed and can be translated to the practical torque and pitch control inputs of a wind turbine. The induction factor is limited to the Betz limit, i.e., \( a \leq \frac{1}{3} \) in order to avoid violating the results accuracy at higher induction factors according to BEM theory. Considering the induction effect of a rotor disc as

\[ U_d = (1 - a) U_\infty, \]  

(2)

enables us to estimate the exerted thrust force using the measurable axial disc-averaged wind velocity \( U_d \) from PALM and the axial induction factor \( a \). Therefore, the \( i^{th} \) turbine model is incorporated inside PALM as a thrust force acting against the mean flow [19]:

\[ T_i = -\frac{1}{2} \rho A_d \left( \frac{U_{d_i}}{1 - a_i} \right)^2 C_T(a_i) \]  

(3)

and the time-varying extracted power from the incoming turbulent flow is approximated as

\[ P_i = F_{T_i} U_{d_i} \]  

(4)

### 2.2. Case study

A layout of a 2×3 wind farm example with partial wake overlaps is considered here. The wind turbines with rotor diameter \( D = 126 \text{ m} \), taken from the freely available model of the NREL 5MW reference wind turbine [21], are spaced 5\( D \) in the stream-wise direction. The rotor centers of the middle turbines are offset half a rotor diameter from the centers of the upwind and downwind turbines. Figure 1 shows the instantaneous field of the \( u \)-component of the wind at hub-height of the wind turbines. Table 1 summarizes the key parameters of the simulation set-up.

![Figure 1: The layout of the 2×3 wind farm model simulated with PALM.](image-url)

A neutral boundary layer (NBL), with a mean wind speed of 8 m/s at hub-height is simulated [22]. Under such conditions, large wake losses can be expected during standard operation of the wind farm, i.e., without active power control. A precursor simulation of the atmospheric boundary layer is conducted without any turbines in order to allow for the generation of a fully developed undisturbed turbulent flow field which can then be used for the initialization of the main simulation runs in which a turbulence recycling method is used. For this study, PALM was run on the EDDY HPC (High-Performance Computing) cluster devoted to wind energy research at ForWind–University of Oldenburg [23].
**Table 1.** The key parameters of the PALM simulation set-up.

| 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 turbine model                         | ADM$^1$                        |
| Turbine rotor diameter $D$                 | $126\,\text{m}$                |
| Number of grid cells per turbine           | $68$                           |
| Hub-height                                 | $90\,\text{m}$                 |
| Atmospheric stability condition            | NBL$^2$                        |
| Effective wind speed at hub-height         | $8\,\text{m/s}$                |
| Geostrophic wind velocity $u$              | $9\,\text{m/s}$ and $v = -2\,\text{m/s}$ |
| Sample time $\Delta t$                    | $1\,\text{s}$                  |

$^1$ Actuator disc model  
$^2$ Neutral boundary layer

3. **Active power control with a coordinated load distribution**

When changing the wind farm power reference, it has to be decided how each of the turbines contribute to the power production. This degree of freedom, inherent to APC, is exploited here for coordination of the power distribution in order to reduce structural loadings of the wind turbines. In the current study, we propose an extension to the APC approaches in [3, 4] to actively regulate the distributing set-points, yielding more even structural loadings of the individual wind turbines when their total power production tracks a time-varying power reference, provided by the transmission system operator (TSO). The proposed control architecture for APC with a coordinated load distribution (CLD) is depicted in Fig. 2.

![Figure 2. Schematic illustration of the proposed closed-loop APC of wind farms. The grey block contains the main components of the APC with a coordinated load distribution (CLD).](image)

The wind farm power reference $P_{\text{ref}}$ is distributed among the individual wind turbines on the basis of a power distribution control law, e.g., an open-loop pre-selection of set-points [3, 4]. Note that each wind turbine has its own feedback controller with a certain frequency and damping ratio (not shown in Fig. 2) to follow locally the power demand $P_{\text{dem}}$, commanded by the high-level APC. Following [4], a gain-scheduled active power controller is designed to improve the wind farm power tracking performance by resolving undesirable local effects due to turbulence.
and wakes. Therefore, the control signal $\Delta P_{\text{ref}} \in \mathbb{R}$ actively adjusts the wind turbine power demands $P_{\text{dem}} \in \mathbb{R}^{N_t}$ in order to compensate the accumulated local tracking errors at each time instant. Although exploiting feedback improves the quality of the APC and grid stability, independent from the selection of the power set-points, different fatigue loadings have induced on the individual wind turbine components. The reader is referred to [4] for more details.

A closed-loop power distribution law is proposed based on the thrust measurement of the individual turbines $T_i$, considered as one source of wind loading. The main idea is to adjust the power demand distribution factor $\alpha_k \in \mathbb{R}^{N_t}$ to level dynamic loadings on the individual turbines more evenly during active power control. Therefore, a thrust-based tracking error is defined for the $i^{th}$ turbine at time instant $k$ as

$$e_{i,k}^T = \left( \frac{1}{N_t} \sum_{i=1}^{N_t} T_{i,k} \right) - T_{i,k},$$

(5)

describing the deviations of the applied thrust forces on the $N_t$ number of operating wind turbines from their mean value. A proportional-integral (PI)-based power distribution law is used in the current study as

$$\alpha_{i,k} = K_P e_{i,k}^T + K_I \sum_k e_{i,k}^T,$$

(6)

The pole-placement method is employed about one chosen operational point to design the proportional and integral gains $K_P$ and $K_I$ to guaranty closed-loop stability. Then, the local power demand of the individual wind turbines is defined as

$$P_{\text{dem}}^{i,k} = \alpha_{i,k} \left( P_{k}^{\text{pref}} + \Delta P_{k}^{\text{pref}} \right),$$

(7)

leading to smaller deviations of the thrust forces from their averaged value and active power control simultaneously. Indeed, the APC solution yielding a more even load distribution as intended using the introduced feedback loop.

In the present study we consider the thrust load variations of the individual turbine as a descriptor for the dynamic turbine loading inside the wind farm. It is straight forward to calculate the thrust from the employed ADM in the PALM simulation code and the large eddy simulation indeed reproduce higher thrust variations due to averaging the local turbulence over the rotor swept area and especially due to wake meandering. Nonetheless, other load quantities, e.g. variation of the flapwise blade loading or short-term damage equivalent loads of the blade or main shaft response, might be more representative for a real plant. The proposed CLD approach could be applied in principle as well for such more sophisticated descriptors if they are online available.

4. Simulation results

This study focuses on a simulation scenario, in which the wake interactions are problematic for a good wind farm power tracking performance, similar to [3, 4, 6]. Note that the APC of wind farms in a non-waked condition simplifies the control problem to a standard tracking one, which is not addressed here. The following three APC approaches are evaluated in this study:

- An open-loop power distribution approach as a baseline (Baseline) [3],
- A closed-loop APC at the wind farm level (Reference APC) [4],
- The proposed APC with a coordinated load distribution (APC/CLD).
The following wind farm power reference tracking scenario is conducted to evaluate the APC performance of the simulated wind farm with PALM. After inflow propagation and wake interactions, a time-varying power reference is demanded from the TSO beginning at time instant 400 s. The wind farm power reference is defined as 90% of the 20-minute averaged available power of the wind farm when operating with the locally greedy control settings \( a_i = 0.33 \), i.e., 7.49 MW, plus 10% of the normalized RegD type of an automatic generation control (AGC) signal, taken from [3], the most rapidly actuating test signal which is used for APC qualification by PJM, a regional transmission organization in the eastern United States [24].

4.1. Power set-points and thrust distribution patterns
A central open-loop control system, which is studied in [3], is considered here as a baseline to share an AGC power signal among the wind turbines. Similar to [6], two different power set-point cases are chosen here for evaluation. The corresponding fractions of the required AGC response for all six turbines are listed in Table 2. The first is based on the traditional APC idea that all wind turbines are de-rated equally. The second uneven distribution is introduced here to illustrate the dependency of the thrust distribution on the chosen set-points. Note that the sum of the power references for both cases is the same as the demanded power from the TSO.

|       | WT1 | WT3 | WT5 | WT2 | WT4 | WT6 |
|-------|-----|-----|-----|-----|-----|-----|
| 1st set-points | \( \frac{1}{6} \) | \( \frac{1}{6} \) | \( \frac{1}{6} \) | \( \frac{1}{6} \) | \( \frac{1}{6} \) | \( \frac{1}{6} \) |
| 2nd set-points | \( \frac{1.4}{6} \) | \( \frac{0.8}{6} \) | \( \frac{0.8}{6} \) | \( \frac{1.4}{6} \) | \( \frac{0.8}{6} \) | \( \frac{0.8}{6} \) |

Figure 3 plots the applied thrust forces on the individual wind turbines with both the pre-selected baseline set-points. In the first baseline case, the applied thrust forces on the downwind turbines are increasing compared to their upwind turbines because of wake induced energy losses for providing the one-sixth of the required AGC response. It can be seen that the thrust forces are reacting differently by choosing the second power set-points. The AGC responses of the baseline with both the pre-selected power set-points are illustrated in Fig. 4 and Fig. 5 (see dashed curves). The chosen power set-points, wake interactions, local turbulence effects, and time-varying changes in atmospheric conditions influence the quality of the open-loop APC. It should be noted that a gain-scheduling approach at wind turbine level causes a faster response of the wind farm for the baseline case.

4.2. Active power control of the wind farm
A closed-loop APC system, proposed in [4] for waked wind farms, is designed here as a reference APC. The total wind farm tracking error is fed back in order to adjust the open-loop distributed power references against losses caused by the local wake and turbulent effects. Figures 4 and 5 illustrate the total power productions of the simulated wind farm with the first and the second set-points of Table 2, respectively. The accuracy of the APC approaches is assessed using the root mean square (RMS) of the tracking errors over the whole simulation run-time. As demonstrated also in [4], the feedback controller compensates the local power-losses by demanding more from other turbines. Although the wind farm power tracking is improved for both cases, the patterns of the applied thrust distributions (see dashed curves of Fig. 8) remain similar to the open-loop baseline (see Fig. 3) due to the usage of the same power set-points.
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Figure 3. Applied thrust forces on the individual wind turbines with the pre-selected power set-points of Table 2 in order to illustrate different thrust distribution patterns.

Figure 4. Total power production of the wind farm with closed-loop APC with 1st pre-selected set-points, compared with the baseline.

Figure 5. Total power production of the wind farm with closed-loop APC with 2nd pre-selected set-points, compared with the baseline.

4.3. Active power control with even thrust distribution law

The distributed power set-points are actively adjusted at each time instant for the desired AGC response with smaller deviations of the thrust forces from their mean value. Figure 6 depicts the AGC response and the RMS of the wind farm power tracking error of the proposed approach. The APC with CLD is capable of regulating the wind turbine power productions with the same quality of AGC response, compared with the reference APCs. The performance of the proposed closed-loop distribution law, which is activated at time instant 400s, is illustrated in Fig. 7. Note that the distributing signals $\alpha_{i,k}$ are initialized with the second power set-points of Table 2 (the same as the dashed green curve). Compared to the reference APCs, the RMS of the defined thrust-based tracking error (5) reduces over time, meaning that the AGC response of the APC with CLD levels the applied thrust forces on the individual wind turbines more evenly. Figure 8 illustrates the time-series of the individual thrust forces, indicating that they tend to remain close to each other.

Table 3 summarizes the performance results of the studied APC approaches. Similar to [4], the accuracy of the APC is evaluated first with the RMS of the wind farm power tracking
error. Then, the standard deviations (STD) of the applied thrust forces on all wind turbines are outlined. Contrary to the baselines, the wind farm power tracking error is improved using the feedback for compensating local power losses with other wind turbines, which results in immediately higher thrust force variations. On the other hand, the chosen power set-points plays a key role in leveling the wind turbine dynamic loadings. The proposed APC with CLD is capable of leveling the applied thrust forces, taking advantage of the feedback in power distribution law. Compared to the reference APCs, the quality of the AGC response remains unchanged.

**Table 3.** Performance assessment of the studied APC approaches with PALM.

|                      | RMS error [MW] | changes1 [%] | STD thrust forces [kN] | changes1 [%] |
|----------------------|----------------|--------------|------------------------|--------------|
| Baseline: 1st set    | 0.493          | NA           | 37.89                  | NA           |
| Baseline: 2nd set    | 0.377          | -23.5        | 43.66                  | +15.2        |
| Ref. APC: 1st set    | 0.019          | -96.1        | 39.16                  | +3.35        |
| Ref. APC: 2nd set    | 0.021          | -95.7        | 46.58                  | +22.9        |
| APC with CLD         | 0.019          | -96.0        | 32.410                 | -14.5        |

1 Changes with respect to the baseline with the first power set-points.

Finally, we analyze the impact of the closed-loop APC approaches, which have the same AGC response quality, on dynamic loadings at the wind turbine level. Table 4 summarizes the STD of the applied thrust forces during the last 10-minute of simulation. Higher deviations for downwind turbines corresponds to the operation inside the wake with higher turbulence intensity, which is the key driver for fatigue loading under both ambient and wake conditions [25]. Moreover, the upwind turbines might experience higher dynamic loadings due to the compensation of wake-induced power losses of downwind turbines through the feedback. The proposed APC with CLD also has potential to reduce the fluctuations of the thrust forces at the wind turbine level, compared with the reference APCs. However, further investigations are needed to clarify the source of the reduction and possible impacts on the structural loadings. More reliable and practical assessment can be done through fatigue load analyses of the aeroelastic wind turbine models, e.g., FAST, operating in a wind farm flow, which is out of the scope of the current study.
5. Conclusion and future work
This paper proposes a new APC approach for wind farms to coordinate the structural load distribution (CLD) on the individual wind turbines while the sum of their actual power productions tracks a time-varying wind farm power reference. The impact of different power distributions and induced loading patterns is demonstrated first. A feedback structural load coordination law is proposed, which takes advantage of the existing multiple solutions for APC of wind farms, to result in more even dynamic thrust loadings on the individual wind turbines. The performance and the proposed controller is examined using the PArallelized Large-eddy simulation Model (PALM) for an example wind farm. The simulation results show that a high-quality AGC response and a more even thrust distributions can be achieved simultaneously using the APC with CLD.

In the future, we will extend the closed-loop control framework in PALM for optimal control of energy extraction, where model predictive control will be used for optimal power distribution. Furthermore, the proposed wind farm control approach will be examined from some practical perspectives, e.g., fatigue load analysis, using PALM coupled with FAST.

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References
[1] Aho J, Buckspan A, Laks J, Fleming P A, Jeong Y, Dunne F, Churchfield M, Pao L Y and Johnson K 2012 A tutorial of wind turbine control for supporting grid frequency through active power control American Control Conference (ACC) pp 3120–3131 ISSN 0743-1619
[2] Aho J, Fleming P A and Pao L Y 2016 Active power control of wind turbines for ancillary services: A comparison of pitch and torque control methodologies American Control Conference (ACC) pp 1407–1412
[3] Fleming P A, Aho J, Gebrael P, Pao L Y and Zhang Y 2016 Computational fluid dynamics simulation study of active power control in wind plants American Control Conference (ACC) pp 1413–1420
[4] 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
[5] Shapiro C R, Bauweraerts P, Meyers J, Meneveau C and Gayme D F 2017 Model-based receding horizon control of wind farms for secondary frequency regulation Wind Energy 20 1261–1275 ISSN 1099-1824 we.2093
[6] Vali M, Petrović V, Boersma S, van Wingerden J W, Pao L Y and Kühn M 2018 Model predictive active power control of waked wind farms Accepted in the 2018 American Control Conference (ACC)
[7] Boersma S, Doekemeijer B, Vali M, Meyers J and van Wingerden J W 2018 A control-oriented dynamic wind farm model: WFSim Wind Energy Science 3 75–95
[8] Rott A, Boersma S, van Wingerden J W and Kühn M 2017 Dynamic flow model for real-time application in wind farm control Journal of Physics: Conference Series 854 012039
[9] Goit J P and Meyers J 2015 Optimal control of energy extraction in wind–farm boundary layers Journal of Fluid Mechanics 768 5–50
[10] Vali M, Petrović V, Boersma S, van Wingerden J W and Kühn M 2017 Adjoint-based model predictive control of wind farms: Beyond the quasi steady-state power maximization IFAC-PapersOnLine 50 4510 – 4515 ISSN 2405-8963
[11] Vali M, Petrović V, Boersma S, van Wingerden J W, Pao L Y and Kühn M 2018 Adjoint-based model predictive control for optimal energy extraction in waked wind farms Submitted for publication in Control Engineering Practice (under review)
[12] Bay C J, Annoni J, Taylor T, Pao L Y and Johnson K 2018 Active power control for wind farms using distributed model predictive control and nearest neighbor communication Accepted in the 2018 American Control Conference (ACC)
[13] Fleming P, Aho J, Shah J J, Wang L, Ananthan S, Zhang Z, Hutchings K, Wang P, Chen W and Chen L 2017 Field test of wake steering at an offshore wind farm Wind Energy Science 2 229–239
[14] Campagnolo F, Petrović V, Schreiber J, Nanos E M, Croce A and Bottasso C L 2016 Wind tunnel testing of a closed-loop wake deflection controller for wind farm power maximization Journal of Physics: Conference Series 753 032006
[15] Petrović V, Schottler J, Neunaber I, Hölling M and Kühn M 2018 Wind tunnel validation of a closed loop active power control for wind farmsAccepted in the Science of Making Torque from Wind
[16] Ciri U, Rotea M, Santoni C and Leonardi S 2017 Large-eddy simulations with extremum-seeking control for individual wind turbine power optimization Wind Energy 20 1617–1634 ISSN 1099-1824 we.2112
[17] Vali M, Vollmer L, Petrović V and Kühn M 2017 A closed-loop wind farm control framework for maximization of wind farm power production Wind Energy Science Conference (WESC)
[18] Maronga B, Gryschkö 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 40 for atmospheric and oceanic models: model formulation, recent developments, and future perspectives Geoscientific Model Development 8 2515–2551
[19] 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
[20] Calaf M, Meneveau C and Meyers J 2010 Large eddy simulation study of fully developed wind-turbine array boundary layers Physics of Fluids 22 015110
[21] Jonkman J M and Buhl M L 2005 NREL report No. NREL/EL-500-38230
[22] Vollmer L, Steinfeld G, Heinemann D and Kühn M 2016 Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: an LES study Wind Energy Science 1 129–141
[23] 2016 URL www.uni-oldenburg.de/fk5/wr/hochleistungsrechnen/hpc-facilities/eddy/
[24] Pilong C 2013 PJM Manual 12: Balancing Operations 30th ed., PJM
[25] Frandsen S 2007 Turbulence and turbulence-generated structural loading in wind turbine clusters Ph.D. thesis Risø-R-1188(EN), Technical University of Denmark