Rejecting wake-rotor overlapping load disturbances: An extension to active power control of wind farms

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Abstract. This paper studies an extension to the active power control of wind farms for further structural load alleviation of waked wind turbines. We demonstrate that the structural fatigue loading of a downstream turbine, which its rotor overlaps with wakes of its upwind turbine, can be significantly alleviated, while the wind farm power production follows a power reference signal. A load variations model is proposed, based on the multi-rotor concept, to sense the variations of the wind velocity and the associated loading across the rotor area of a single wind turbine. Then, an individual rotor control is proposed to reject the rotor-wake overlapping load disturbances about an operating condition, commanded with the closed-loop APC at the wind farm level. The applicability and key features of the controller are discussed with a wind farm example consisting of 2×2 turbines. A large-eddy simulation model is employed for resolving the turbulent flow, the wake structures and its interaction with an atmospheric boundary layer. The effectiveness of the proposed load disturbance rejection is evaluated using the damage equivalent load of the tower base fore-aft bending and torsional moments 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. The increased turbulence intensity inside the wakes, wake meandering, and partial wake overlapping with the rotors of downwind turbines cause waked turbines to be prone to higher structural fatigue loading [1]. As a consequence, the lifetime of the individual turbines might be shortened.

Several studies have utilized optimization techniques to find optimal set-points to simultaneously maximize the total power production and prolong the lifespan of the wind farm by minimizing the structural fatigue loading [2, 3]. Nonetheless, from a control engineering perspective, these have been either open-loop or quasi steady-state optimization approaches, based on analytical static wake models and data-driven load models, which do not fully hold for dynamical wake interactions.

It is expected that future wind farms operate for a significant fraction of their lifetime in the derated mode while following a dynamically changing power reference (also known as active power control, APC) in order to contribute to stabilization of the grid frequency. Fleming et al. [4] have demonstrated difficulties in following the power reference with an open-loop APC due to highly turbulent flows in wakes. van Wingerden et al. [5] have introduced a feedback APC for a high-quality wind farm power reference tracking performance. Vali et al. [6] have proposed a new control approach, the so-called APC with a coordinated load distribution.
(CLD), which exploits the flexibility of the APC problem versus the individual turbines’ power set-points for alleviating the structural loading of waked turbines. Although that study has demonstrated a significant amount of wake-induced load reduction, it neglects variations of the wind profile across the rotors, caused mainly by partial rotor-wake overlaps, wake meandering, wind shear, and turbulence. These velocity variations result in inhomogeneous load and periodic load disturbances, which can lead to fatigue damage and thus shorten the turbine lifespan.

In this paper, we propose first an efficient method for sensing velocity and the associated load variations across the actuator disc rotors to further extend the wake-induced wind turbine load indicators [6] operating within a wind farm. Second, an extension is proposed to the closed-loop APC with CLD law [6] for further wake-induced load alleviation through rejecting asymmetric load disturbances, which originated mainly from wake meandering and partial wake-rotor overlapping. Large-eddy simulations (LES) are employed to examine the performance of the proposed load controller under turbulent wakes and detailed interactions with the neutral atmospheric boundary layer.

The remainder of this paper is organized as follows. In section 2, we briefly present the large-eddy simulation model, the employed wind turbine model, the wind farm layout example, and the implemented load variations model across every single rotor. The main focus of section 3 is on the APC architectures at both the wind turbine and the wind farm levels with extensions for wake-induced structural load alleviations. A test simulation scenario is introduced in section 4 for verification. Then, the performance of the proposed load disturbance rejection is discussed through comparative LES studies. Finally, section 5 outlines the conclusions and the outlook of the current study.

2. Wind farm simulation model
The wind power plant simulation model consists of an LES model coupled with the wind turbine models. The LES approach has shown the 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 [7] coupled with the Actuator Disc Model (ADM) of a wind turbine [8]. The ADM is computationally efficient and provides a good approximation of the far wake structure, which makes it suitable for the present study.

The exerted aerodynamic thrust force and the extracted power for a single wind turbine are respectively expressed as follows [9]:

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

\[
P = \frac{1}{2} \rho A_d U_{rel}^3 C_P(a), \quad C_P(a) = 4a (1 - a)^2,
\]

where \(U_{rel}\) is the relative wind speed [6] at a far distance upwind from the rotor disc, \(\rho\) is the air density, \(A_d\) is the swept area of the rotor plane, and \(C_T\) and \(C_P\) are the thrust and power coefficients of a wind turbine, respectively, which are functions of the axial induction factor \(a\). The axial induction factor is the ratio of the induced wind speed at the rotor to the relative wind speed and can be translated to the practical torque and pitch control inputs. Considering the induction effect of a rotor disc, the relative wind speed \(U_{rel}\) can be approximated from the measurable axial disc-averaged wind velocity \(U_d\) from the PALM code as [6]:

\[
U_{rel} = \frac{U_d}{1 - a},
\]

which enables us to model the applied aerodynamic thrust force (1) acting in the negative direction on the flow [8] and extract the aerodynamic power (2).
2.1. Case study:
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 [10]. The left plot of Fig. 1 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 wind turbines are spaced $5D$ in the stream-wise direction. The rotor centers of the downstream turbines are offset half a rotor diameter from the centers of the upwind ones to create partial wake overlaps with rotors of the downwind turbines (see the right plot of Fig. 1). Table 1 summarizes the key parameters of the LES simulations. Note that the geostrophic wind velocities $u_g = 9$ m/s and $v_g = -2$ m/s were defined empirically and iteratively to result in an ambient longitudinal wind velocity $U_\infty = 8$ m/s at hub height.

![Figure 1](image-url)

**Figure 1.** The instantaneous field of the $u$ component of the wind profile at the hub height of the turbines (left) and at the plane of the 4th turbine (right), which is partially overlapped with the wakes of the 2nd upwind turbine. To measure load variations across a single ADM, each turbine is implemented as a vertical multi-rotor with 4 sub-rotors and equal frontal area.

| Simulation parameter | Value |
|----------------------|-------|
| Grid mesh size $N_x \times N_y \times N_z$ | $1024 \times 256 \times 128$ |
| Cell mesh resolution $\Delta_x \times \Delta_y \times \Delta_z$ | $10 \times 10 \times 10$ m$^3$ |
| Ambient longitudinal wind speed $U_\infty$ at hub height | 8 m/s |
| Geostrophic wind velocity | $u_g = 9$ m/s and $v_g = -2$ m/s |
| Monin-Obukhov length scale | 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 |

2.2. Load variations model:
The ADM is extended to an equivalent multi-rotor [11] to approximately capture dominant load variations across the actuator disc rotors. The fact that the wakes of a multi-rotor turbine interact downstream and eventually form the wake of the original single turbine [12] motivates us to use it as a sensor for measuring wind velocity variations across the rotor discs. Compared with a single rotor, the wake of a multi-rotor recovers faster. However, the discrepancy is not significant at downstream distances larger than 5D, and it was thus neglected here. In this paper, a conventional turbine is implemented in the LES code with a vertical multi-rotor with 4 sub-rotors. The diameter of each sub-rotor is specified as $D/4$ to have an equal frontal area with a single rotor diameter $D$ [11]. The right plot of Fig. 1 schematically shows how the multi-rotor concept has been used here to capture the dominant wind velocity variations across the
$4^{th}$ turbine’s rotor due to its partial overlap with the wake of the $2^{nd}$ upwind turbine. While the employed sub-rotor $R_{42}$ fully operates inside the wake, covering only the left side of the single rotor, the sub-rotor $R_{43}$ presents the non-waked condition of the right side. Note that the sub-rotors $R_{41}$ and $R_{44}$ dominantly measure wind shear effects.

The structural load indicators, i.e., the tower base fore-aft bending and the torsional moments of the $i^{th}$ wind turbine are introduced respectively

$$L_i = \sum_{j=1}^{4} h_j F_{i,j},$$

$$T_i = \frac{D}{2} (F_{i,3} - F_{i,2}),$$

to reflect the contributions of the wind speed variations. $F_{i,j}$ represents the thrust force of the $j^{th}$ sub-rotor with the center height $h_j$. In the present study, we consider only primary impacts, i.e., impacts caused by load variations across a rotor in the non-rotating coordinate system, causing tower base fore-aft and torsional moments. Future works include more realistic load measurements and sampling by e.g., employing the coupling of the LES code with an aeroelastic wind turbine model. Other load quantities, e.g., variations of the flap-wise blade loading, short-term damage equivalent loads of the blade, main shaft response, rotational sampling, 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 sophisticated descriptors if their measurements (or estimates) would be available online.

3. Closed-loop APC for wake-induced load alleviation
A hierarchical active power control architecture, the so-called APC with a coordinated load distribution (CLD) law, has been proposed in [6] for wake-induced load alleviation of wind farms. It determines how the power productions of the individual wind turbines should be regulated to simultaneously ensure a satisfactory wind farm power reference tracking and a structural load equalization. At the lower level, the gain-scheduled wind turbine control systems locally realize the regulated power demands from the wind farm controller. Although the APC with CLD has demonstrated a significant reduction of wake-induced loads, it is only capable of rejecting rotor-averaged loadings and neglects impacts of load variations across a rotor, which are among the main drivers of dynamic loadings of large wind turbines [13, 14]. Hence, this study extends the wind turbine control systems for rejecting unbalanced load disturbances across rotor discs, while their power productions simultaneously contribute to wind farm power reference tracking and structural load equalization of the turbines.

3.1. APC with a coordinated load distribution (CLD)
The wind farm power reference $P_{\text{ref}}$, demanded by the transmission system operator (TSO), is adjusted first with the closed-loop APC and then distributed among the individual wind turbines using a coordinated load distribution (CLD) law [6]. Figure 2 depicts the main components of the synthesized wind farm controller. At each time instant $k$, the control signal $\Delta P_{\text{ref}} \in \mathbb{R}$ actively adjusts the wind farm power reference $P_{\text{ref}}$ for compensating the accumulated wake-induced local tracking errors [5]. The adjusted power reference is distributed among the individual wind turbines according to their power set-points $\alpha_i$. Using the CLD loop, the power demand of the $i^{th}$ turbine at the time instance $k$ can be represented as [6]:

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

Figure 2. Schematic illustration of the closed-loop APC of wind farms [6]. The gray block depicts the main components of the wind farm controller. One feedback loop focuses on APC, while a second feedback loop provides coordinated load distribution (CLD).

where the distributing power set-points $\alpha_{i,k}$ are adjusted, freely within the constraint $\sum_{i=1}^{N_t} \alpha_{i,k} = 1$, using feedbacks from structural load measurements of the individual wind turbines.

The CLD law adjusts the distributing power set-points $\alpha_{i,k}$ based on a local tracking problem for the individual wind turbines. Then, a load-based tracking error is defined as:

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

(7)

describing instantaneous deviations of structural loadings of the $N_t$ operating wind turbines from their mean value at each time instant $k$. The designed proportional-integral (PI)-based distribution law yields an structural load equalisation of the individual wind turbines. In the present study, we consider only the feedbacks from load measurements of the tower base fore-aft bending moment (4) as a descriptor for the structural loadings of the $i^{th}$ wind turbine operating in a waked wind farm. The reader is referred to [6] for more details on design procedure and performance of the APC with CLD.

3.2. Wake-rotor overlapping load disturbance rejection

Each wind turbine has its own feedback controller with a certain frequency and a damping ratio to realize the power demand $P_{i,\text{dem}}$ from the wind farm controller (see Fig. 3). The wind turbine controller (WTC) is designed as a proportional-integral (PI) control law [6] to collectively regulate the power production of the $i^{th}$ multi-rotor turbine with the local tracking error $e_{i,k} = P_{i,k}^\text{dem} - P_{i,k}$ at time instance $k$, wherein $P_i = \sum_{j=1}^{4} P_{i,j}$.

An individual rotor control (IRC) is proposed to individually adjust the induction factors of the sub-rotors $a_{ij}$ about their collective induction $a_{i0}$ for power regulation. The dark grey block of Fig. 3 illustrates the main components of the implemented IRC for unbalanced load disturbance rejection. Load variations are measured using the load variation model presented in section 2.2. The corresponding bending moment of the $j^{th}$ sub-rotor is simply calculated about the center point of the $i^{th}$ multi-rotor as $M_{ij} = \frac{1}{2} DF_{1ij}$. One important note is that the proposed
IRC approach would be accomplished through the individual pitch control (IPC) [13, 14] on real wind turbines, which is beyond the scope of the current study.

The main objective of the proposed IRC is to react against the asymmetric loadings across a multi-rotor frontal area. Therefore, the horizontal and vertical wind frame of the reference \{H–V\}, well-known as the tilt-yaw coordinate system, is employed to isolate the symmetric and asymmetric rotor loads. The following transformations are introduced to decouple the symmetric (denoted with the subscript 0) and asymmetric (denoted with the subscript H and V) modes. The forward and inverse transformations are respectively expressed as:

\[
\begin{bmatrix}
a_{i1}(t) \\
a_{i2}(t) \\
a_{i3}(t) \\
a_{i4}(t)
\end{bmatrix}
= \begin{bmatrix}
1 & -1 & 0 \\
1 & 0 & -1 \\
1 & 0 & 1 \\
1 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
a_{i0}(t) \\
a_{iH}(t) \\
a_{iV}(t)
\end{bmatrix},
\tag{8}
\]

\[
\begin{bmatrix}
M_{i0}(t) \\
M_{iH}(t) \\
M_{iV}(t)
\end{bmatrix}
= \frac{1}{2}
\begin{bmatrix}
1/2 & 1/2 & 1/2 \\
-1 & 0 & 0 \\
0 & -1 & 1
\end{bmatrix}
\begin{bmatrix}
M_{i1}(t) \\
M_{i2}(t) \\
M_{i3}(t) \\
M_{i4}(t)
\end{bmatrix}.
\tag{9}
\]

Two identical feedback loops are designed for rejecting the unbalanced yaw and tilt moments \(M_{iV}\) and \(M_{iH}\), after applying the inverse transformation (9) on the rotor load measurements \(M_{ij}\). Then, the control commands \(a_{iV}\) and \(a_{iH}\) are transferred back and superimposed to the collective induction \(a_{i0}\), using the forward transformation (8), to actively adjust the induction factors of the individual sub-rotors for simultaneous power regulation and load disturbance rejection of the \(i^{th}\) multi-rotor.

4. Results and discussion
This section focuses on a simulation scenario in which rotors of downwind turbines partially overlap with wakes of their upwind turbines (see the left plot of Fig. 1). The following three APC approaches are evaluated for wake-induced load alleviations in this study:

- A closed-loop APC at the wind farm level as a reference (Ref. APC) [5],

![Figure 3](image-url)
A closed-loop APC with a coordinated load distribution (CLD) law at the wind farm level (APC/CLD) [6],

The closed-loop APC with CLD at the wind farm level with the proposed individual rotor control (IRC) at the wind turbine level (APC/CLD + IRC).

Figure 4. Wind farm power reference tracking performance with closed-loop APC approaches. While Ref. APC relies on constant power set-points $\alpha_i = \frac{1}{4}$, APC/CLD actively adjusts the power set-points using feedbacks from the structural load measurements of the individual wind turbines (see Fig. 5).

Following [6], a wind farm power reference tracking scenario is conducted to evaluate the APC performance of the simulated wind farm with PALM. The TSO demands a time-varying power reference about 90% of the available power, i.e., $P_{\text{base}}^{\text{e}}$, perturbed with the normalized RegD type of an automatic generation control (AGC) signal [15] where its maximum amplitude is considered 10% of $P_{\text{base}}^{\text{e}}$. Figure 4 plots the wind farm power reference tracking performance with the studied APC approaches. The analyses are focused on the wind farm response after 300 s to allow time for wake developments and propagations. The accuracy of the APC approaches is compared using the root mean square (RMS) of the tracking errors.

Figure 5 depicts the trajectories of the regulated power setpoints $\alpha_i$ and induction factors $a_i$. The APC with CLD exploits the flexibility of the problem with respect to power distributions to find the APC solution yielding a more equalized loading of the individual wind turbines. Vali et al. [6] have thoroughly discussed how upwind turbines (#1 and #2) contribute more toward structural load reduction of the waked wind turbines. APC with CLD demands less power from downwind turbines (#3 and #4), compared with the Ref. APC with an equal power set-points $\alpha_i = \frac{1}{4}$, and thus avoid saturating their induction factors. IRC rejects load variations across the rotors, which causes fewer deviations in power set-point adjustments (see green versus dashed-dotted red lines). Note that the collective induction factors $a_{i0}$ plotted for the APC/CLD + IRC in green, contribute to APC at the wind farm level (see Fig. 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 [16]. Figure 6 shows the corresponding damage equivalent loads (DEL) of the tower base fore-aft bending (the left plot) and torsional (the right plot) moment of the individual turbines with different APC approaches. The Ref. APC experiences highest loading on the tower base fore-aft mode (see blue bars). On one hand, the waked turbines (#3 and #4) are mostly saturated due to lack of available power (see dashed blue lines of $a_3$ and $a_4$ in Fig. 5); On the other hand, the closed-loop APC transfers significant loads to the upwind turbines (#1 and #2) for compensating the accumulated wake-induced wind farm errors. The intensified tower base torsional moments of the waked turbines correspond to partial rotor-wake overlapping and wake meandering. A significant wake-induced load alleviation is achieved by APC with CLD (see red bars), which properly de-rates the power productions of the downwind turbines using local power/load feedbacks and avoids saturating the control inputs.
Figure 5. The trajectories of the power set-points $\alpha_i$ and induction factors $a_i$ for all four turbines with different APC approaches. The Ref. APC relies on equal power set-points, i.e., $\alpha_i = \frac{1}{4}$. The collective induction $a_{col}$ is shown for the APC/CLD + IRC.

Figure 6. Corresponding DELs of the tower base fore-aft bending (left) and torsional (right) moments of the individual wind turbines with the studied APC approaches.

Further structural load alleviation has been achieved using the proposed extension to IRC for rejecting the unbalanced load disturbances across the multi-rotors frontal areas (see green bars of Fig. 6). The tower base fore-aft moments are further reduced due to the reaction of the sub-rotors against vertical and horizontal wind velocity variations, originated by wake-rotor overlaps, wake meandering, wind shear, and turbulence. Note that the upwind turbines are mainly affected by the vertical load variation sources, e.g., wind shear. The tower base torsional moments of downwind turbines (#3 and #4) are significantly reduced, using the IRC mainly applied to sub-rotors $R_{i2}$ and $R_{i3}$, which reject the induced yaw moments due to wake meandering and the
partial wake-rotor overlaps.

Figure 7. The tower base fore-aft bending (left) and torsional (right) moments of the partially waked turbines #3 and #4 with different APC approaches from 600 s to 1200 s.

Figure 8. The trajectories of the individual induction factors of the 4th multi-rotor about their collective values from 600 s to 1200 s. The collective value $a_{40}$ is associated with the APC/CLD for wind farm power reference tracking and structural load coordination.

Figure 7 provides a closer view of the impact of the proposed load disturbance rejection on the tower base loading of the waked turbines (#3 and #4) when the total power production of the wind farm follows the TSO power reference. The tower base fore-aft bending moments (the left plots) are significantly reduced by coordinating the power productions using APC/CLD (dotted dashed red lines) and further alleviated by the extension to the IRC (green lines). As expected, the tower base torsional moments of the downwind turbines (the right plots of Fig 7) are in opposite directions due to the mirrored layout and partial rotor-wake overlaps in each row of wind turbines, as shown in Fig. 1. The torsional moments have been effectively reduced using the IRC (green lines) through balancing the loadings of the sub-rotors $R_{i2}$ and $R_{i3}$.

Figure 8 finally depicts the trajectories of the individual induction factors of the 4th multi-rotor about their collective values (green line). While the collective induction $a_{40}$ is commanded by the APC/CLD for 4th multi-rotor contributions in wind farm power reference tracking and structural load coordination, the IRC adjusts the inductions of the four sub-rotors to reject the asymmetric load disturbances. Thus, the induction of the sub-rotors $R_{41}$ and $R_{42}$ operating in lower wind velocities because of a lower height and wake, respectively, are increased to balance...
the loadings across the rotor area. In the same manner, the inductions of the sub-rotors $R_{43}$ and $R_{44}$ are reduced because of experiencing higher wind velocities.

5. Conclusion and future work
Active power control of wind farms has been extended to reject the unbalanced rotor load disturbances for further wake-induced load alleviation within waked wind farms. 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. A sensing approach is introduced to capture wind velocity variations across the actuator disc model. It allows us to analyze the asymmetric load disturbances due to partially rotor-wake overlapping in wind farms. The closed-loop APC is extended with an individual rotor control design to reject unbalanced load disturbances, while the power production contributes to wind farm power reference tracking. This study highlights a noticeable amount of structural load reduction without deteriorating total power production. In the future, the control design will be examined from more reliable and practical perspectives using large-eddy simulations coupled with aeroelastic wind turbine models, which was beyond the scope of the present study. The IRC would be implemented using the IPC for rejecting asymmetric rotor load disturbances.

Acknowledgments
This work has been funded by the Federal Ministry for Economic Affairs and Energy according to a resolution by the German Federal Parliament (“WIMS-Cluster” 0324005).

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