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A Numerical Study on the Impact of Wake Steering on Ultimate Loads of Downstream Wind Turbines

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Abstract. There is an inherent dilemma in the synthesis of any wind farm control: optimizing farm power output must not lead turbines to operate under conditions in which excessive loading is expected. Wake steering-based control techniques, recognized as a highly effective means of increasing farm output, are no exception. In fact, the potential increase in fatigue and ultimate loads associated with the large misalignment operations prescribed by wake steering represents a source of concern, especially for machines that were not originally certified to operate under such conditions. The purpose of this work is to analyze and evaluate the impact of wake steering on ultimate loads and maximum deflections of a pair of upstream and downstream turbines, with a specific focus on cases involving the Extreme Operating Gust and Extreme Coherent gust with Direction change. The study is based on a simulation campaign using a reference 5-MW turbine. Results show that the maximum loads experienced by a waked downstream turbine during these extreme events do not exceed the maximum loads on the upstream turbine, even when both turbines operate under yawed conditions.

1. Introduction

Wake steering-based wind farm control has definitely emerged as an effective strategy to optimize the overall energy output of a wind farm[1]. However, operations at large yaw misalignment angles, often required to redirect the wake effectively, represent off-design conditions that could be associated with an increase in the loading status of a machine. This is evidenced by the strict limitations on maximum yaw misalignment angles often imposed during field testing of wake steering, for example, allowing misalignment only on one side, to avoid potential increases in fatigue [1]. Furthermore, in Ref. [2] it was demonstrated, through simulations, that operating at large misalignment angles can also lead to increases in ultimate loads and displacements under extreme events.

In this context, it is essential to note that a potential increase in turbine loads should not be viewed as inherently negative. For example, a general load increment induced by farm control is not problematic if that load remains within its safety margins. In contrast, more serious implications are associated with increases in design loads, i.e. fatigue and ultimate loads and displacements evaluated through the set of Design Load Cases (DLCs) prescribed for turbine design and certification [3]. This fact is particularly true for existing turbines, constrained by their original design parameters, where any unexpected increase in fatigue or ultimate loads could lead to premature failure. Because of these concerns, real field tests of wake steering often required conservative constraints on yaw misalignment angles, such as the one-sided wake steering [1]. More generally, there exists a delicate balance between the desire to increase power production and the imperative to preserve turbine structural health.

In the study presented in Ref. [2], it was demonstrated that ultimate loads on individual wind turbines can increase significantly when large yaw misalignment angles are applied, especially when ultimate loads and displacements are considered.

In Ref. [4], it was demonstrated that derating a wind turbine, that is, intentionally operating it below its rated power, can effectively compensate for potential increases in design loads introduced by wake steering strategies. By reducing the aerodynamic thrust and overall mechanical stress on the turbine, derating helps maintain load levels within acceptable limits even when the turbine operates at non-zero yaw angles. Moreover, the authors introduced the concept of a “safe envelope”, which defines a region in the yaw-derating parameter space where combinations of misalignment and derating do not lead to an increase in fatigue and ultimate loads. The authors of Ref. [4] also proposed an integrated control strategy (combination of wake steering and derating) defined according to a simple heuristic rule, i.e., wake redirection supports the increase in overall power output while derating is possibly employed to reduce the turbine loading status, yielding a *design load*-constrained wake redirection strategy. However, all these analyses were carried out considering isolated wind turbines, without accounting for the influence of a possible impinging wake. Quantifying how these strategies affect the design loads of downstream turbines is crucial to understanding whether it is possible to employ the combined control developed in [4] on all turbines of the farm without modification.

The work presented in this abstract is a direct continuation of the work presented in [2], where the impact of wake steering on ultimate loads and displacementes was quantified for an isolated wind turbine. The scope is to conduct a similar analysis across all turbines in a wind farm. This includes quantifying the maximum loads experienced under various wake-steered scenarios by upstream and downstream machines and comparing them to baseline (non-steered) configurations. Note that, since typically farms consist of a single turbine type, computing the ultimates requires identifying the maximum loads and displacements across all turbines, no matter their position, a task that can be in principle time-consuming as it will be pointed out later on.

The objective is not only to evaluate whether wake steering introduces new critical load cases but also to provide an interpretation of the obtained results that can ease the understanding of how extreme events may affect the behavior of waked turbines. The study focuses on reference 5-MW wind turbine [5], modeled in the FAST.Farm simulation environment [6].

By developing a clearer understanding of the impact of wake steering on ultimate loads, operators and designers can make more informed decisions. This may include defining safe yaw limits, modifying control algorithms to avoid load issues, and adapting control co-design procedures.

The paper is organized as follows. Section 2 presents a preliminary discussion on the importance of evaluating ultimate loads while accounting for large yaw-misalignment angles in wake-steering-controlled wind farms. This section serves to clarify the connection between wake steering control and the conditions prescribed by the Standards for quantifying turbine design loads including ultimate loads and displacements. Subsequently, Sec. 3, which describes the analyses performed to quantify the impact of wake steering on the behavior of a pair of upstream and downstream turbines under extreme events. Section 4 reports the results of these analyses and provides a preliminary interpretation of the results. Finally, Sec. 5 summarizes the main outcomes of the study and outlines potential directions for future research.

2. Preparatory discussion

Extreme events, as defined by IEC standards, such as gusts or sudden wind direction changes, represent key conditions in wind turbine design, particularly for assessing ultimate loads. Simulating these events is relatively straightforward for upstream turbines, which operate in undisturbed wind. However, for downstream rotors impinged by the wake of an upstream machine, the procedure becomes more complex and critical due to the turbulent and unsteady flow they experience.

To provide insight into the possible impact of farm control on DLCs, multiple steady-state analyses were carried out in FLORIS [7] for a simple wind farm consisting of three aligned reference 10-MW turbines [8] spaced by 5 diameters. These analyses are presented to illustrate that the DLCs prescribed by the Standards for computing ultimate loads, besides fatigue loads, may be influenced by operations at large yaw-misalignment angles typically associated with wake-steering-based wind farm control. Given the general purpose of these analyses, the parameters governing wake shape and development in FLORIS were kept at their default values, without performing a detailed sensitivity study.

The main outcomes are reported in Fig. 1, which shows a contour plot of the optimal yaw angle of the upstream turbine, computed solely to maximize overall farm power, for all possible combinations of wind speed and turbulence intensity (TI) shown on the x- and y-axes, respectively. The outermost contour line corresponds to an optimal yaw angle of 2 deg and may be regarded as the boundary beyond which wake steering is no longer effective at increasing the overall farm output. As expected, at high wind speeds, due to reduced thrust coefficients, and at high TI levels, due to strong turbulence mixing, operating at misaligned conditions does not significantly affect the wake experienced by a downstream turbine.

The same plot also includes the conditions prescribed by the Standards, shown through black lines and triangular markers. Extreme events such as the Extreme Change of Direction (ECD) and the Extreme Operating Gust (EOG), occurring below or near rated speed, could reasonably be influenced by farm control. Conversely, Extreme Turbulence Model (ETM) conditions are not expected in scenarios where wake steering is effectively employed.

The discussion indicates that it is reasonable to expect a possible impact of wake steering on ultimate loads, particularly when these arise from events such as ECD and EOG.

Additionally, if a wind turbine is to be designed to operate in an arbitrary position within a wake-steering-controlled farm, then maximum loads and displacements, representing design constraints, should be first computed for all possible turbine locations and yaw-misalignment conditions. Eventually, the ultimate quantities must be determined by taking the maximum among all peak values experienced by all turbines, regardless of their position. Clearly, such a "brute-force" approach can be extremely time-consuming for large farms and, even worse, overly specific to the particular layout under analysis.

3. Methodology

As stated in the previous section, when it comes to designing a turbine operating in a controlled wind farm, the effects of extreme events on downstream machines are expected to be wind farm layout dependent, raising the question of whether general conclusions can be drawn or if one is irremediably tied to the specific case studies at hand.

To provide a general answer to the problem of evaluating the ultimate loads and displacements for upstream and downstream machines operating with large yaw misalignment angles, the simplest possible farm configuration, i.e. a pair of two turbines in a row, is examined in this work.

In particular, a sensitivity analysis of ultimate loads under various yaw angles for both turbines are then performed. While this is not an actual farm control study, it allows one to simulate the impact of extreme events on downstream machines and explore possible general

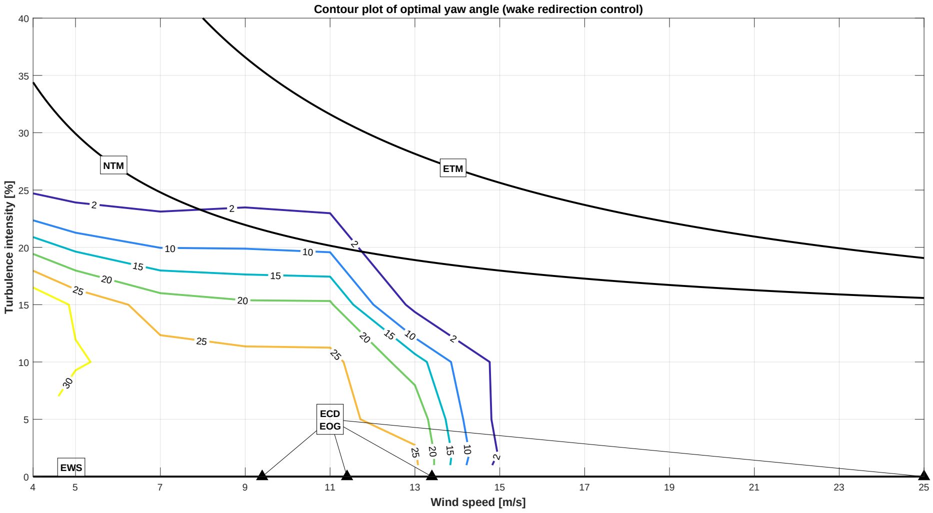


Figure 1: Contour of optimal yaw angles of the upstream turbine in a three-turbine farm, superimposed to the conditions associated with the Design Load Cases (DLC) prescribed by Standards [3], Extreme Wind Shear (EWS), Extreme Coherent gust with Direction change (ECD), Extreme Operting Gust (EOG), Nominal Turbulence Model (NTM) and Extreme Turbulence Model (ETM).

trends when wake steering is employed.

All simulations are conducted using FAST.Farm [6]. FAST.Farm is a state-of-the-art wind farm simulation tool developed by the National Laboratory of the Rockie (NLR). It integrates detailed aeroelastic modeling of individual turbines with advanced wake modeling to accurately capture turbine interactions within a wind farm. FAST.Farm enables realistic simulations of turbine loads and performance under complex, unsteady wind conditions, including wakes and turbulence. This makes it a valuable resource for analyzing both power production and structural loading of all turbines in a farm. The reference 5-MW baseline turbine [5] was used in all FAST.Farm simulations. The scenario involves two reference 5-MW turbines aligned with the wind direction and spaced 5 rotor diameters, ensuring full wake impingement on the downstream machine. The aerodynamics of the two turbines are modeled using the standard blade element momentum (BEM) theory, whereas their structural behavior is represented through a modal condensation of the Elastodyn module in OpenFAST [9]. The wake development is computed within a dedicated domain in which all cells have a height and width of 10 m and a streamwise length of 10.17 m.

The EOG is characterized by a sudden and sharp increase in wind speed followed by a return to the mean wind speed and is applied during normal operational conditions from cut-in to cut-out speeds. The ECD, on the other hand, is a sudden increase in the wind speed that occurs in conjunction with a significant change in the direction of the wind. In both conditions, the extreme events are experienced by the downstream turbine while it may operate in waked conditions, providing the opportunity to assess the possible mutual influence of wakes and gusts on turbine loads.

The present analysis focuses only on extreme events, e.g., ECD (extreme coherent gust with direction change) and EOG (extreme operating gust), without considering failures.

For all tests, the time histories of selected sensors on both turbines were recorded, and the corresponding maximum values were extracted. In general, the evaluation of ultimate loads and displacements requires identifying, for each structural component of the turbine, the maximum loads and displacements over the full set of DLCs. In this work, a DLC-specific investigation was carried out, to identify generic trends in the loads and displacements of upstream and downstream turbines associated with the particular DLC under consideration and to assess whether, and to what extent, operations at large yaw-misalignment angles may affect turbine maximum loads during specific gusts.

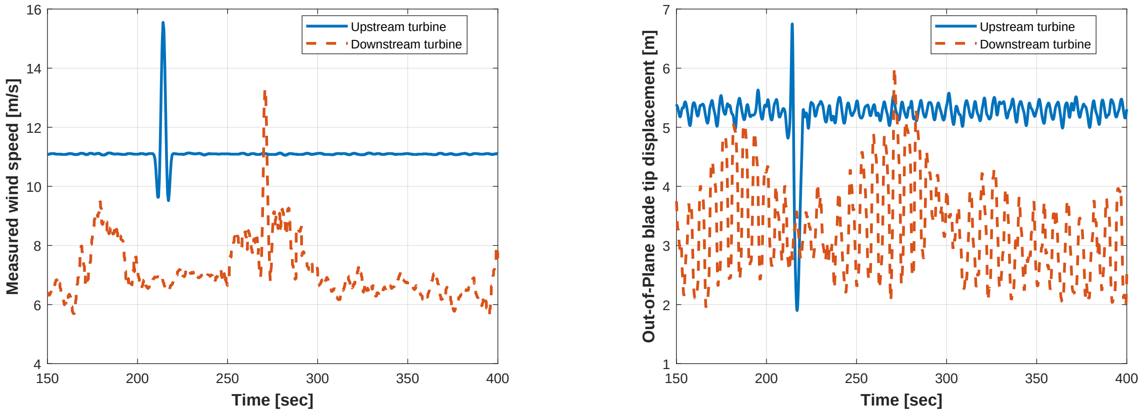
4. Results

In the following, the results of simulation examples aimed at assessing maximum loads and displacements under extreme conditions as defined by the Standards, IEC 61400-1, is presented. The EOG case will be considered first, followed by the analysis of ECD.

4.1. Analysis on EOG at rated wind speed

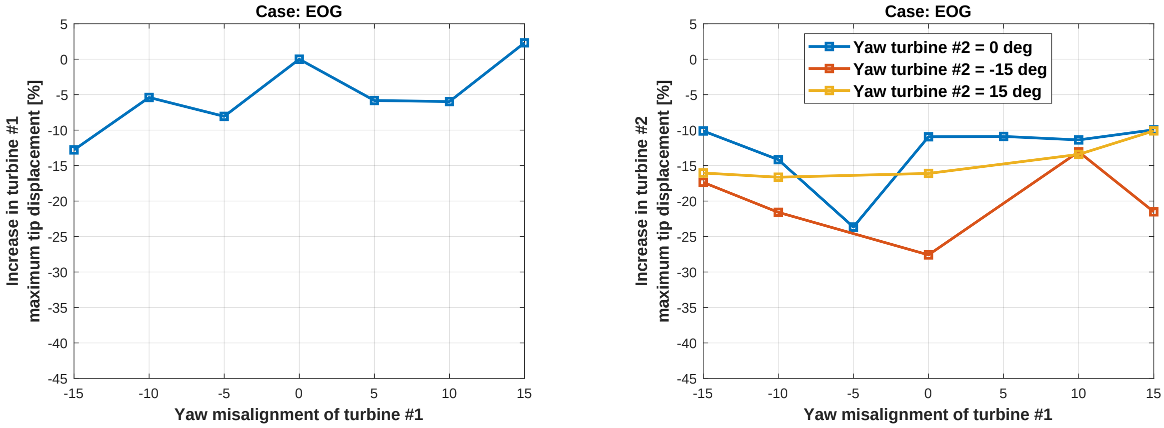
An example of the response of a simple tandem of two turbines to a wind gust inspired by the EOG Class I-A of the current Standards is displayed in the following. The two turbines of the farm are aligned and spaced by 5 rotor diameters, while EOG was simulated at rated wind speed, and no additional failures were included. In FAST.Farm the EOG was simulated by reproducing the gust velocity in a binary TurbSim-style flow field [10]. The wind flow is then used as inlet condition, allowing the gust to propagate throughout the farm.

Figure 2 (left) shows the inflow wind measured by the turbine anemometers, featuring the classical Mexican hat profile. Additionally, Fig. 2 (right) displays, for both turbines, the time histories of the out-of-plane blade tip displacements, which represent a typical driver in modern wind turbine design [2]. The gust is imposed at the inlet domain face at 200 seconds and reaches the first turbine 10 seconds later. The downstream turbine experiences the gust at second 260, as shown in Fig 2. The extreme event entails a significant increase in the maximum tip displacement of the upstream machine, quantified in about 1.5 m, i.e., from an average value of 5.2 m before the gust to 6.7 m. On the other hand, the downstream turbine experiences a maximum tip deflection of 6.0 m, which is lower than that of the upstream machine. At least in this specific scenario, the EOG is more critical for the upstream turbine than for the downstream one. Clearly, such a result represents only one piece of the puzzle, as the same analysis should be repeated for different DLCs and different spacing and include the presence of the wind farm control to obtain a thorough quantification of the impact that wind farm control may have on the ultimate loads of all turbines in a farm.



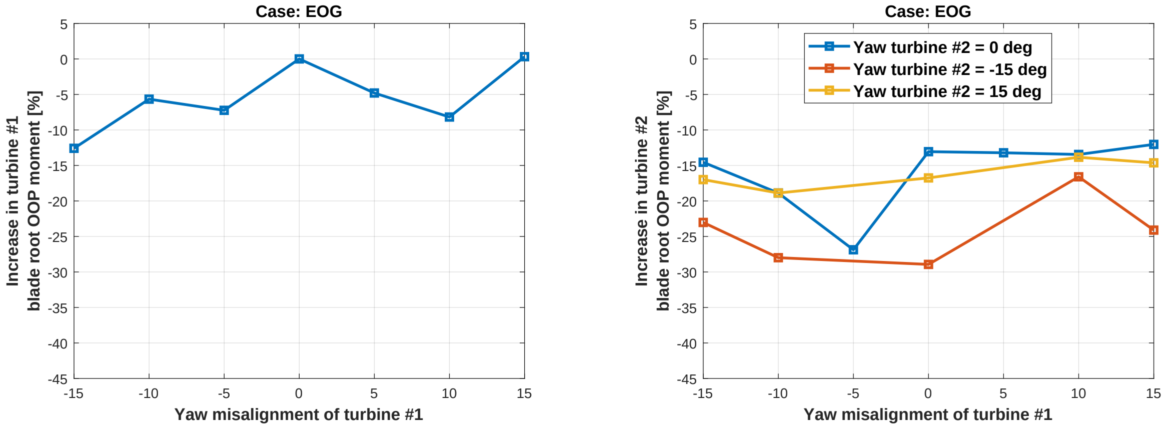
(a) Measured wind speed (b) Out-of-plane blade tip displacement.

Figure 2: Wind measured by wind vanes (a) and blade tip displacement (b), during an EOG.



(a) Upstream turbine (b) Downstream turbine

Figure 3: Maximum blade tip displacement during EOG for both turbines.



(a) Upstream turbine (b) Downstream turbine

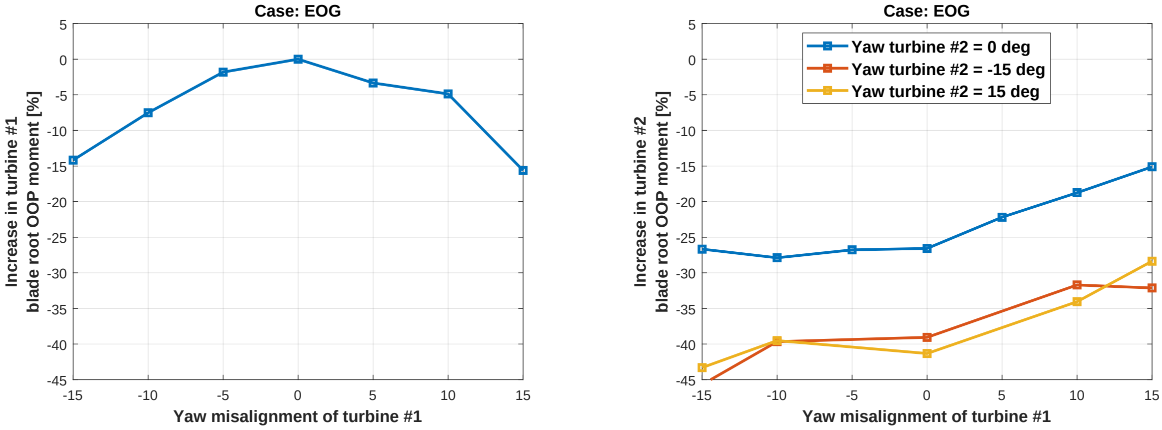
Figure 4: Blade root out-of-plane moment during EOG for both turbines.

To this end, the same analysis was repeated multiple times, modifying the yaw misalignment of both turbines to evaluate the impact of misaligned operations on the structural response of the pair of upstream and downstream turbines.

Figure 3, on the left, shows the maximum blade tip displacement of the upstream turbine as a function of its own yaw misalignment. The right subplot, in contrast, presents the maximum blade tip displacement of the downstream turbine as a function of both upstream and downstream yaw misalignments: each curve corresponds to a different yaw misalignment angle of the downstream turbine, while the x-axis indicates the yaw misalignment of the upstream turbine. The upstream turbine experiences its maximum load at a yaw misalignment of 15 deg, identifying a potential critical operating point. The downstream turbine consistently exhibits lower loads, attributed to the reduced wind speed in the wake.

Figure 4, organized as in Fig. 3, presents the blade root out-of-plane moment under EOG conditions. Results are consistent with the case of maximum tip displacement: the highest loads occur at a 15 deg misalignment on the upstream turbine, while the downstream machine remains less loaded because the in-wake flow speed is lower than the free-stream velocity.

Figure 5 displays the same analysis considering the tower-base combined load. The results



(a) Upstream turbine (b) Downstream turbine

Figure 5: Tower-base combined load during EOG for both turbines.

show that wake redirection does not affect the ultimate tower loads of either turbines, upstream and downstream, as the largest value is experienced by the upstream turbine for null yaw misalignment. Additionally, due to the lower speed experienced in the downstream (waked) turbine, its maximum load results significantly lower than that of the upstream one.

4.2. Analysis on ECD at rated wind speed

The same pair of upstream and downstream turbines was also analyzed under ECD conditions. In the simulation, the ECD is included using the “uniform wind” option in the OpenFAST “InflowWind” module. Accordingly, a simultaneous alteration of the wind field across the entire domain is generated. In this scenario, both turbines experience the change in the wind direction at the same time, as if they were hit by a lateral gust, and in particular, the downstream turbine is subject to the gust while it is operating in waked conditions. The present implementation is considered a good approximation of the ideal ECD wind prescribed by the Standards at least for the purpose of the present investigation.

Figure 6 shows a typical turbine response to an ECD. The left plot displays the wind component perpendicular to the rotor measured by the turbine anemometers, while the right plot shows the time histories of the out-of-plane blade tip displacements.

The gust reaches the two turbines at 200 seconds; however, while the first experiences the coherent gust operating in free-stream condtions at 11.4 m/s, the downstream one encounters it while operating within the wake of the upstream machine, as witnessed by its lower measured wind velocity (about 8 m/s).

The reduction of the measured wind speed, following an initial increment, is due to the direction change, occurring simultaneously with the velocity increase. After the second 210, as a result of the direction change, both turbines, initially aligned with the wind direction, are now facing the free stream and operating with a large misalignment angle.

As shown in the right plot of Fig. 6, the extreme event entails a significant increase in the maximum tip displacement, with the peak values experienced after the end of the transient, i.e. when the wind velocity and direction already reached their respective maximum values.

Both the upstream and downstream machines experience an increase in tip deflection, reaching a maximum value of about 10 m. Interestingly, in this case, both turbines exhibit the same maximum displacement, which occurs once the gust subsides. This observation suggests that, at least in the present case, operating in waked conditions has a minimal impact on the

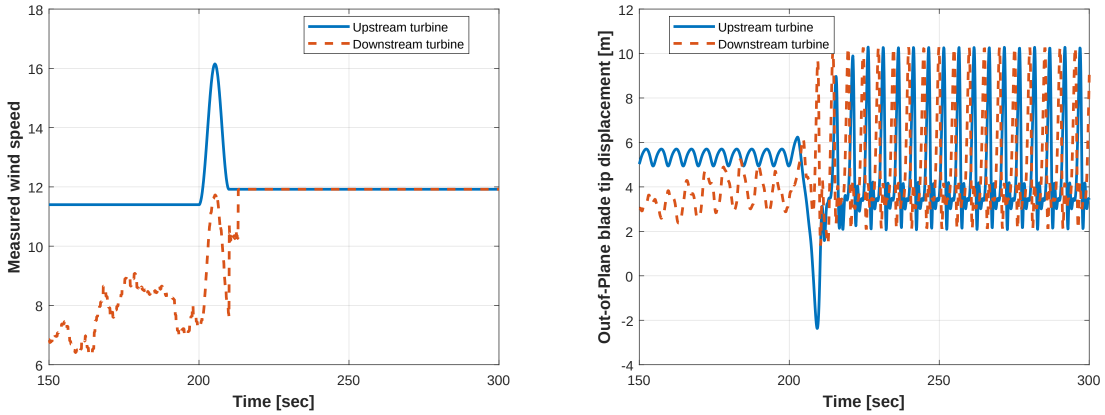
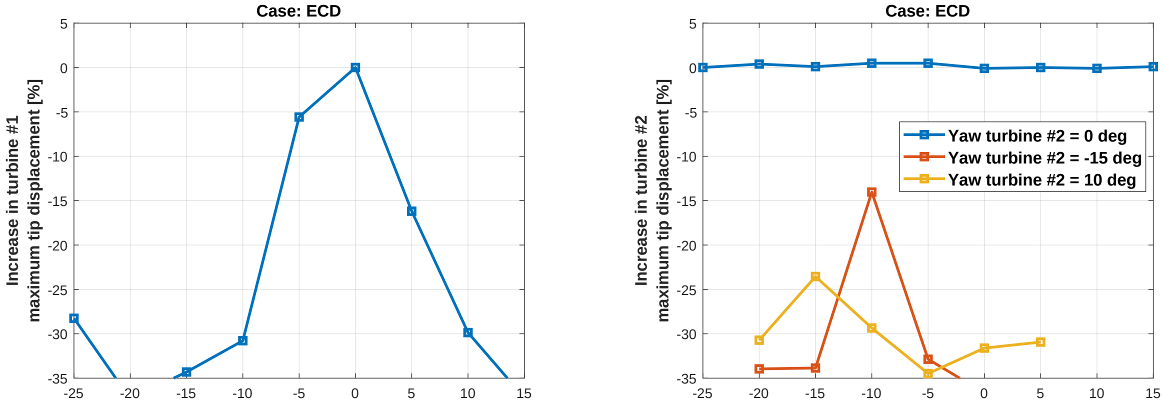


Figure 6: Wind measured by wind vanes (left) and blade tip displacement (right), during an ECD.



(a) Upstream turbine

(b) Downstream turbine

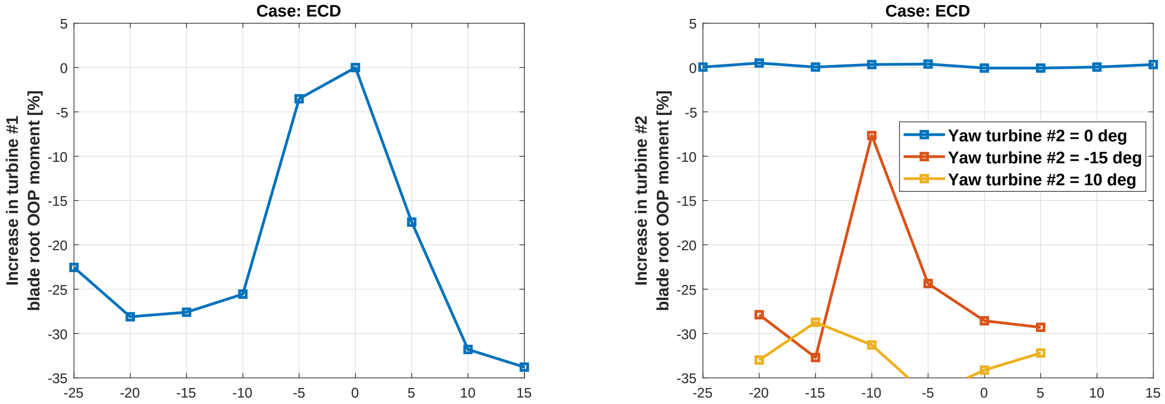
Figure 7: Maximum blade tip displacement during ECD.

ultimate loads and/or displacements, which do not significantly exceed those characterizing the upstream turbine. This result represents only a snapshot of a more complex picture, which can be clarified only by repeating the analysis for different turbine yaw misalignments to gain insight into the impact that wake redirection may have on ECD outputs.

Figure 7 and 8 illustrate the blade tip displacement and the blade root out-of-plane moment under ECD conditions. The plots are organized in the same way as those reported in Sec. 4.1.

For both outputs, the behavior of the turbines remains consistent with EOG scenarios. The maximum load experienced by the upstream turbine is associated with null yaw misalignment (see Fig. 7(a) and 8(a)), whereas the downstream turbine exhibits only a marginal increase in load (+0.5%) with respect to that value in a condition with null downstream turbine yaw and upstream turbine yaw angle equal to -20 deg (see Fig. 7(b) and 8(b)), indicating limited sensitivity to this type of gust.

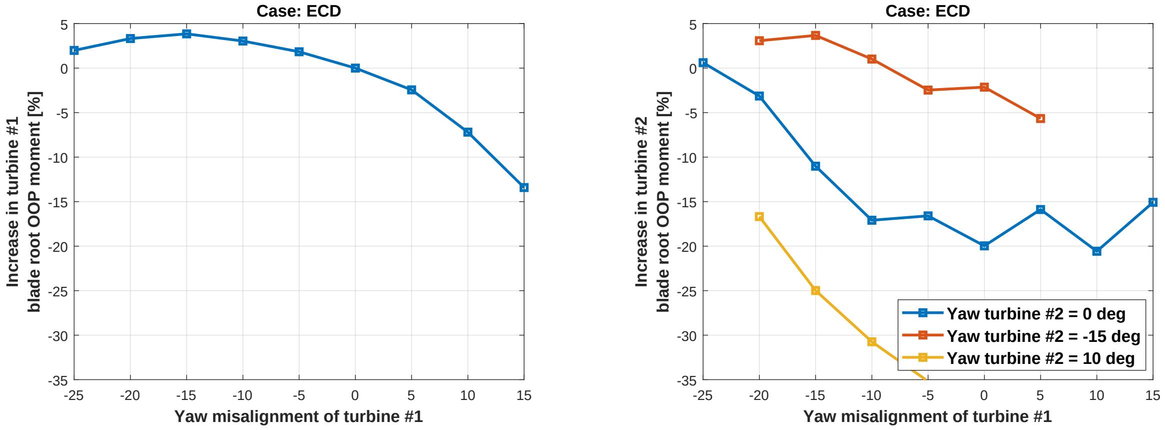
Blade out-of-plane moment measurements and maximum tip displacement are certainly highly correlated and one might expect that an increase in the blade root out-of-plane load is associated with an increase in the blade tip deflection. However, in the design phase, these two variables are treated independently and are possibly subject to different constraints, such



(a) Upstream turbine (b) Downstream turbine

Figure 8: Blade root out-of-plane moment during ECD.

that one of them (for example, the tip displacement) may be an active design constraint, while the other is not. Hence, it makes perfect sense to study these two quantities independently.



(a) Upstream turbine (b) Downstream turbine

Figure 9: Tower-base combined load during ECD.

Figure 9 presents the results of the same analysis in terms of combined tower-base loads. Both turbines experience an equal increase in ultimate tower-base load of approximately 4%. The upstream turbine reaches this value at a yaw misalignment of −15 deg, while the downstream one in the condition when both turbines are misaligned by −15 deg. From these results, it can be concluded that operating at large yaw misalignment angles may affect the maximum load exerted on the tower base moment during an ECD in both the upstream and downstream turbines. However, the increase observed in the downstream machine is comparable to that of the upstream turbine.

4.3. Preliminary interpretation of the results

Based on these simulation results for the EOG and ECD cases, the upstream turbines experience the most critical loading conditions. In contrast, the waked downstream turbine consistently exhibits a lower or equal maximum value for blade tip displacements, blade root, and tower base loads.

This trend likely arises from the dependence of ultimate loads on the pre-event loading status of the turbines: machines already operating under high loads tend to respond more severely to extreme events.

If this hypothesis holds, it implies that ultimate loads observed on upstream turbines, i.e., those not subjected to wake impingement, may serve as a reasonable approximation or upper bound for estimating the behavior of a downstream turbine. This observation could prove useful in future control-oriented design frameworks aimed at balancing energy maximization with structural safety. In particular, this supports the idea that the safe envelope, which is defined by combining wake redirection and derating, as it was already proposed in [4] for an isolated turbine, can be used for all turbines in the farm. This could lead to a very simple load-constrained wake steering control strategy that balances power maximization and its impact on design loads, where the latter can be evaluated through a faster process considering only one isolated turbine.

5. Conclusions and outlook

This paper presents a preliminary investigation of the impact that wake steering may have on the ultimate loads and displacements of a pair of upstream and downstream turbines.

This study is a direct extension of previous works evaluating the impact of wake steering on isolated wind turbines, which showed that operations at large and very large yaw misalignment may be associated with an increase in design loads. Understanding how extreme events affect turbines under yawed conditions is crucial to ensure that load increases do not compromise structural integrity in case an extreme event occurs.

Using FAST.Farm simulations, extreme events, specifically EOG and ECD, are replicated in a domain comprising a pair of upstream and downstream turbines for different yaw misalignment angles of the turbines.

The analysis does not refer to a wind farm control scenario but rather to a parametric study that can support the development of farm control strategies that explicitly consider design load constraints while utilizing wake redirection.

Although the investigation is preliminary and based on simplified scenarios, it provides important information on the behavior of structural loads and displacements, particularly for a downstream turbine operating in waked conditions. In particular, the simulations allowed a comparison between the maximum loads and displacements caused by EOG and ECD on both an upstream turbine operating with significant yaw misalignment angles and those experienced by a downstream turbine subjected to combined yawed and waked inflow conditions. The results showed that the maximum loads and displacements of the downstream turbine are affected by the yaw misalignment imposed on both turbines, indicating that wake-steering control can influence the ultimate loads of waked turbines. However, the same analyses also showed that, for the downstream turbine, the maximum loads and displacements do not significantly exceed those obtained for the upstream turbine. This suggests that the ultimate loads observed on the upstream turbine may also provide a reasonable approximation for the ultimate loads of the downstream turbine.

This work can be extended in several directions. Firstly, the analysis should include additional cases with different wind speeds and different farm layouts. Furthermore, power derating could be considered as an additional parameter that may impact the design loads of both upstream downstream turbines. Finally, once a complete picture is obtained, the values of the ultimate loads and displacements as functions of the yaw misalignment angles and derating levels could be used to design a load-constrained wake steering strategy that also accounts for the downstream machine loading status, improving control approaches already developed in literature.

Acknowledgments

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