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Ultimate loads of upstream and downstream turbines in the presence of wake steering-based wind farm control: preliminary analysis and quantification

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1 Introduction

The synthesis of any wind farm control aimed at real applications is based on an important compromise: the increase in the overall farm power output that could be achieved should be balanced against the possible increase in the loading status of each wind turbine. As one of the most effective wind farm control techniques, wake steering is no exception.

In fact, according to this technique, the upstream turbine is intentionally misaligned to deflect its wake out of the downstream turbines, with a beneficial impact on downstream turbine power and farm energy production. However, the fact that the turbines may undergo large or very large yaw misalignment represents a cause of concern, when it comes to testing wake steering in the field and, especially, in wind farms comprising turbines that were not originally designed to operate in such large misaligned conditions. To cope with this, strong limitations on turbine misalignment or one-sided rotations are typically enforced during real testing [1, 2].

To have an overall overview of the impact of wind farm control on loading, it is important to stress that modern wind turbines are designed according to rigorous standards that prescribe a precise list of Design Load Cases (DLC) to evaluate the load envelope characterizing the turbine. Fatigue, ultimate loads and maximum displacements represent the set of constraints in the design of the turbine.

The quantification of fatigue loads in wind farms is a long-standing topic in wind energy literature, where Refs. [3, 4, 5] are only some of the most significant contributions. However, very little is written on the impact of wake steering on the ultimate loads, defined as in the existing Standards. Previous works, on a reference 10 MW turbine, suggest that operating in large misalignment conditions may lead to a significant increase in some ultimate loads, being the maximum tip deflection during extreme gusts with direction change (EDC) one of the most affected indicators [6]. In [7] it was additionally proposed the possible combination of wake steering and derating to increase the wind farm power output while maintaining the turbine loading within predefined limits. This work, however, was limited to considering only fatigue and ultimate loads of the upstream turbine, i.e. the one performing the wake steering. A clear prosecution of the work presented in [7] is that of considering also the ultimate loads of the inner turbines.

The work object of this abstract has the following goal: analyzing and preliminarily evaluating the impact of wake steering on the ultimate loads and maximum deflection of the downstream turbines, i.e. the inner ones in a wind farm, according to the present Standards.

2 Methodology

In the quantification of the impact of a control technique on the loading status of a single turbine, there are three critical aspects.

First, the problem appears to be highly farm-specific. Wake impingements depend on the farm spacing and the site-specific wind speed, rose and turbulence intensity. This fact could hamper the attempt to derive generic results.

Second, the single turbine, in a wind farm, can be exposed to a large variety of inflow conditions: any machine may see a clean or waked inflow, or be yawed to deflect its wake out of downstream turbines, or even it could be both yawed and waked. All these cases can be visualized in the example reported in the left plot of Fig. 1, representing the simulated wakes of three turbines in a row. In that case, the flow is coming from the northwest, while the misalignment of each turbine is computed to solely optimize the farm production. The first turbine is exposed to a clean inflow and is yawed to deflect the wake out of downstream turbines. On the other hand, the last turbine is partially impinged by the wake of the upstream turbine, but, being the last of the row, is not yawed. Finally, the inner turbine feels a partial impingement from the first turbine, and, at the same time, is yawed to deflect the wake out of the third turbine. From this brief discussion, it can be concluded that an analysis conducted on a simple farm with three turbines could provide a good representation of all possible interactions among the machines belonging to a generic farm.

Finally, it is important to stress that wind turbines are designed following the International Standards, which prescribe a specific list of DLCs to test in order to quantify the design loads and displacements. The load impact of the farm control, as suggested in [6] is to be evaluated within the regulation context. In order to give an insight into the impact that wind farm control may have on DLCs, let us focus on the right plot of Fig. 1, showing the contour plot of the optimal yaw angle of the first turbine of the same farm, depicted in the left plot, as functions of wind speed and TI. As expected, the yaw redirection is active only in a limited region of the operative condition with low speed and low turbulence intensity. The same plot reports also the conditions prescribed by the Standards through black lines and triangle markers. Immediately, one may recognize that wake redirection may not have an impact on the Extreme Turbulence Model (ETM) case, because in such conditions the very high turbulence intensity makes the farm control ineffective. A different discussion is to be done for Extreme Wind Shear (EWS), Extreme Change of Direction (ECD) and Extreme Operating Gust (EOG), which refer to conditions at low speed and TI. In those cases, one might expect the ultimate may be significantly impacted by the activation of the farm control.

With the goal of evaluating the ultimate loads of all turbines of a wind farm, we are replicating the DLC list in the FAST.Farm environment, [8]. Inspired by the previous discussion, in the redevelopment of this work we are focusing only on a simple three-turbine farm and the DLCs concerning extreme events, i.e. ECD, EWS and EOG.

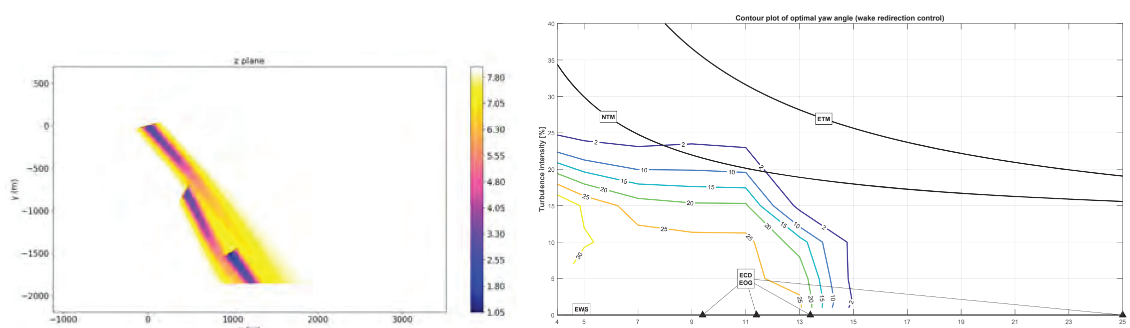

Figure 1: Investigation of wake redirection technique as function of wind speed and TI. Left plot, Floris simulation of three-turbine farm at 8 m/s and TI 2%. Right plot: contour of optimal yaw angles of the first turbine superimposed to the conditions prescribed by Standards for design load cases (DLC) calculation.

To demonstrate the complexity of the problem to be analyzed, this abstract also displays an example of the response of a simple two-turbine wind farm to a wind gust inspired by the Extreme Operating Gust (EOG) Class I-A of the present Standards. We modeled, two reference 5 MW wind turbines aligned and spaced by 5 diameters in FAST.Farm. The EOG was simulated at rated wind speed and no additional failures were included.

Figure 2(left) shows the inflow wind measured turbine vanes, featuring the classical mexican hat. 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 [6]. The gust is imposed at the inlet domain face at 200 seconds and reaches the first turbine 10 seconds later. The downstream turbine feels the gust at second 260, as visible in Fig 2. The gust entails a significant increase in the maximum tip displacement of the upstream machine quantified in about 1.5 meters, i.e. from an average value of 5.2 m before the gust to 6.7 m. On the other side, 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 rather than for the downstream one. Clearly, such a result represent only a puzzle piece, as one has to repeat the same analysis for different DLC and different spacing and include the presence of the wind farm control to have a thorough quantification of the ultimate loads of all turbines in a farm and of the impact that wind farm control may have on these indicators.

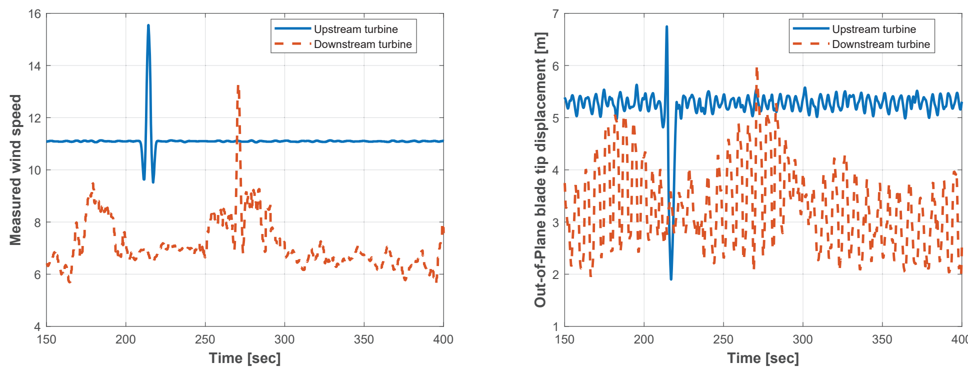

Figure 2: Wind measured by wind vanes (left) and blade tip displacement (right), during an EOG.

3 Expected outcomes

We have defined the procedure to quantify ultimate loads in downstream turbines and are currently pursuing these goals: 1) Perform a sensitivity analysis on the impact of wake redirection on the ultimate loads of all turbines in a controlled farm; 2) Identify the critical situations, if any, where ultimate loads affected by wake redirection strategies. 3) Analyse the possibility of using surrogate models for ultimate loads taylored for farm control synthesis.

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