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Wind turbine rotor design under wind farm control laws

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Abstract. In this work, we investigate the impact of different wind farm control techniques on the structural design of a 10MW reference wind turbine. Active wake mixing and wake redirection have been recently proposed as a way to reduce wake-turbine interference in a wind farm and both show potential for improving the overall power production. However, such controllers modify the dynamic behaviour of the individual turbine, so that a thorough assessment of the resulting loads and displacements becomes necessary. In fact, as most wind turbines are designed according to international standards, one or more structural constraints are active on the final design, meaning that an increase of the sizing loads, or deflections, would make necessary to modify the structural layout. To investigate these aspects, we compare three redesigns of the same rotor: the first is equipped with a standard controller, while the second and the third integrate different wind farm controllers. All the solutions are optimized with our in-house design tool so that the three configurations emerge from the same design process. Results are then compared in terms of ultimate and fatigue loads, displacements and blade mass.

1. Introduction

A fundamental problem in wind farms (WFs) is the interaction between the individual wind turbine (WT) and one or more wakes coming from upwind turbines. This phenomenon can reduce significantly the total power output of the wind farm and increase the main fatigue loads [1, 2, 3]. To limit these adverse effects, the wind energy community is developing dedicated wind farm controllers (WFC) which, typically, aim at increasing the power production of the wind farm by reducing the wake interaction between the turbines. The general idea behind a WFC is to purposely limit the operating range of some of the turbines, typically the upwind ones, so that the others can produce more energy and thus achieve an overall improvement or the complete farm. At present, different control strategies have been presented and discussed in the literature, while in this work we focus on two specific strategies. In particular, controllers based on wake redirection (WR) modify the yaw angle of the turbines in front in order to re-direct their wakes and steer them away from downstream turbines. In this context, a recent work by Fleming et al. [4] highlights the potential of WR techniques by measuring a 4% net increase in the overall energy production of a real WF in which some of the turbines are equipped with such controllers. Another recent work by Raach et al. [5] presents a feedforward-feedback WR approach to compute optimal yaw angles and improve the performance of a test WF. Another promising family of controllers is based on the active wake mixing (AWM) introduced by Goit and Meyers [6] and later formalized by Munters and Meyers [7, 8]. Here, the control strategy relies on the idea that the rotor thrust of the various WTs can be dynamically modified so that the overall power production is optimized. In particular the Authors found that, when the control is optimized, a quasi-periodic vortex shedding is experienced at the front turbines, and that this behaviour can be approximated by a sinusoidal thrust variation at a certain Strouhal number. The impact of such controllers on the wind farm production has been studied extensively, however, little is known about how these controllers affect the performance of an individual turbine. To improve this knowledge, in this work we study how the two proposed WFC methodologies affect the operational spectra of a reference wind turbine, in order to understand if the driving loads and displacements are modified when a certain controller is adopted. Most operating wind turbines, in fact, are designed according to standards (e.g. [9]) in a way that guarantees the fulfilment of fundamental structural constraints. As the considered WFC techniques modify significantly the dynamic behaviour of the turbine, it is reasonable to expect that driving loads and displacements on the system could change accordingly. If the sizing loads increase, for example, an existing turbine could not be equipped with a WFC unless a dedicated redesign is done on its structure. Alternatively, it could be necessary to limit the operational spectra of the chosen WFC so that the envelope of the sizing loads and deflections of the turbine is unaffected. Both ways, the theoretical advantages coming from the use of the WFCs should be downgraded to account for the necessary redesign effort or the limited control authority. In this work, we use a state of art structural design module to conduct the design of three different versions of the same wind turbine rotor. The first solution is only equipped with a standard controller, while the others embed different WFCs based, respectively, on the WR and on the AWM. The goal is to investigate how the use of WFC impacts on the design of a certain turbine and to understand if it would be theoretically possible to retrofit an existing wind farm with such controllers without the need to redesign at least the front-row turbines.

2. Methodology

2.1. Design assumptions

In this paper, the design studies are conducted by our multi-disciplinary design tool `Cp-Max`. The algorithm manages the complete design of wind turbines through the multi-level architecture described by Sartori [10] and by Bortolotti et al. [11]. The tool can be used to minimize the cost of energy (COE) of the wind turbine through the interface of several individual design modules. In particular, the Aerodynamic Design Submodule (ADS) manages the design of the rotor blade planform while the Prebend Design Submodule (PDS) optimizes the amount of prebend along the blade and the Structural Design Submodule (SDS) conducts the optimization of the internal structure of the blades and the tower. It is important to observe that each design module can be used within the main loop of `Cp-Max` as part of the global optimization, but it can also be used as a standalone tool to manage the detailed design of the required components. In this work, we limit the scope to the evaluation of the impact of the chosen WFC on the structural design of the rotor. Then, we only use the SDS to perform all the required optimization activities. In fact, the organization of the SDS allows to perform a full structural optimization of the rotor and the tower by computing relevant loads and displacements out of an arbitrary set of Design Load Cases (DLCs), (see the workflow in Fig.1). Along various iterations, the module automatically ensures that a list of structural integrity constraints is satisfied, so that the optimal design is compliant with the certification standards. These include maximum deflections, frequency placement, ultimate stress and strain, fatigue and buckling. If needed, local manufacturing requirements can be added as part of the structural optimization problem. During the optimization, all the required simulations are automatically run by our multi-body aero-servo-hydro-elastic solver `Cp-Lambda` [12].

All the design activities are based on the PoliMI version of the INNWIND.EU 10 MW rotor

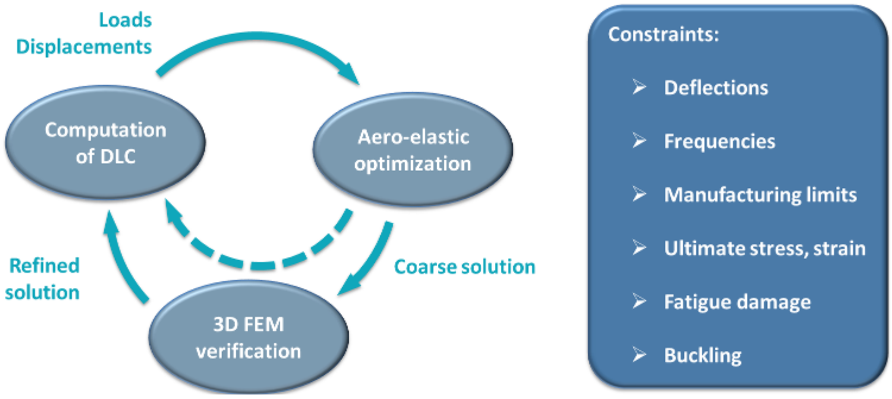

Figure 1. Architecture of the Structural Design Submodule (SDS).

(see [10] for details) which is equipped with a complete supervisor to control the system in all the different operating conditions. In this study, the turbine is controlled in the power production state by the CL-WINDCON standard controller [13], while the changes of the operating states, such as normal and emergency shutdowns and start-ups, are managed by the PoliMI supervisor [14]. The same supervisor is also used to model all the abnormal operations such as grid losses, short-circuits, pitch faults etc. as prescribed by the regulations. A dedicated automated procedure in the SDS ensures that the two controllers are suitably interfaced, so that abrupt peaks of torque or collective blade pitch are avoided during the switching from one controller to the other. The choice of the CL-WINDCON controller was based on the fact that this platform can easily integrate the two WFCs under investigation, so that a fair comparison could be achieved without the need to re-program the controller. Since the goal of this study is to evaluate the impact of selected wind farm control strategies on the design of a wind turbine, some limitations were taken on the design scope. In particular, we decided to focus on the sole structural design of the rotor, while the tower and the other components of the turbine will be optimized in a future development of this work. Similarly, we kept the aerodynamic shape of the blade as frozen during the design, and thus the spanwise distributions of chord, twist, prebend and thickness do not change. While we are aware that this choice somewhat reduces the optimization scope, in this way we can directly quantify the impact of each WFC on the structure, and in particular on the initial capital cost (ICC) of the rotor. On the contrary, a simultaneous redesign of the blade shape *and* the structure would make hard to separate the effects coming from the WFC from those ascribable to the different aerodynamic shape. Additionally, a different blade shape would require to manufacture new moulds for the turbine equipped with the WFC and this would amplify the associated costs. It must be noticed, however, that by following these simplifying assumptions it was possible to include a significant set of fully-resolved DLCs in the design. Table 1 gives a list of all the considered load cases.

This work follows three steps of design: initially, the PoliMI 10MW wind turbine was structurally redesigned for the standard CL-WINDCON controller without any WFCs, so that an optimized baseline could be achieved and used for later comparison. Then, a second solution is redesigned with an integrated AWM controller by taking into account an extended set of DLCs with and without the operating AWM. Eventually, a third redesign is made on the same rotor but equipped with a WR controller. In both cases, the WFC is operated in the wind speed range between 4 and 15 m/s, while the controller is disabled for higher wind speeds.

Table 1. Definition of the DLCs.

DLC	Wind Type	Wind speed	Horizontal Misalignment	Fault	Safety Factor	Performance indicator
1.1	NTM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	-	1.0	AEP, ADC, Fatigue
1.2	NTM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	-	1.35	Ultimate
1.3	ETM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	-	1.35	Ultimate
1.4	ECD	V_{r}, $V_{\mathrm{r}} \pm 2$, V_{out}	-		1.35	Ultimate
1.5	EWS	V_{r}, $V_{\mathrm{r}} \pm 2$, V_{out}	-		1.35	Ultimate
2.1	NTM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	Grid Loss	1.35	Ultimate
2.2(a)	NTM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	Pitch Freeze	1.35	Ultimate
2.2(f)	NTM	$V_{\mathrm{in}} : V_{\mathrm{out}}$	-	Pitch Runaway	1.35	Ultimate
2.3	EOG	V_{r}, V_{out}	-	Grid Loss	1.1	Ultimate
6.1	EWM	V_{ref}	$-8 : 8$ deg	-	1.35	Ultimate
6.2	EWM	V_{ref}	$-180 : 180$ deg	Grid Loss	1.1	Ultimate
6.3	EWM	V_{ref}	$-20 : 20$ deg	-	1.1	Ultimate

2.2. Definition of the AWM controller

The first WFC strategy we analyse is based on the active wake mixing. According to Munters and Meyers [7, 8], this technique requires to periodically modulate the rotor thrust, so that the wake mixing is enhanced by the resulting dynamic induction. As experimentally demonstrated by Frederik et al. [15], this allows to re-energize the wake and to recover the velocity faster, thus reducing the power loss of a downstream turbine. There are several ways to practically induce the active wake mixing, like for example controlling the reacting torque to achieve a periodic fluctuation of the rotor speed. In this work, however, we achieve the AWM control through a periodic collective motion (PCM) of the commanded pitch according to Eqs. 1a and 1b.

$$\beta_{\mathrm{C}}(t) = \beta_0(t) + \beta_{\mathrm{PCM}}(t) \tag{1a}$$

$$\beta_{\mathrm{PCM}}(t) = A_{\mathrm{PCM}} \sin\left(2\pi f_{\mathrm{PCM}} t + \varphi_{\mathrm{PCM}}\right) \tag{1b}$$

Equation 1a shows that, when the AWM controller is enabled, the time-varying collective blade pitch $\beta_{\mathrm{C}}(t)$ required by the controller is made up of two contributions: the standard trim value $\beta_0(t)$ as computed by the chosen pitch control strategy and a periodic term $\beta_{\mathrm{PCM}}(t)$. The latter depends on the amplitude A_{PCM}, the frequency f_{PCM} and (possibly) the phase φ_{PCM} as detailed by Eq. 1b. The choice of these parameters characterises the selected PCM strategy as both amplitude and frequency have a strong influence on the actual wake mixing. A possible way to relate the PCM frequency and the wind speed is through the Strouhal number defined in Eq. 2, where S_t is the Strouhal number, V the undisturbed wind speed impinging on the rotor and D the rotor diameter.

$$S_t = \frac{f_{\mathrm{PCM}} D}{V} \tag{2}$$

Given this relationship, setting up the AWM controller requires to determine the Strouhal number and then, for every required wind speed, to compute the relevant PCM frequency through the knowledge of the rotor diameter. Opinions about the optimal Strouhal differ significantly in the literature: Munters and Meyers [8] found an optimum value of 0.25 from CFD computations, while Frederik et al. proposed a value of 0.45 based on experiments [15]. Since there is no evidence of a unified way to determine an optimal Strouhal number, for the time being we assume that the ideal value is system-dependant. In this view, Croce et al. [16] have recently conducted a detailed parametric analysis in which several values of Strouhal, amplitude and phase were tested on the same wind turbine we investigate in this study. From their conclusions, we assume in the following a PCM controller characterized by $S_t = 0.5$ and $A_{PCM} = 2°$. To account for different combinations between the PCM motion and the wind conditions, four different phase angles from zero to 270 degrees were considered and four additional families of DLCs (corresponding to the different phase angles) were added to the structural redesign at this step. This approach therefore allows to consider different scenarios, assuming different phases between the, relative slow, AWM pitch actuation, and the faster gust peaks. This makes it possible to assess the most severe conditions and to track the associated loads and deflections. While all simulations enter the computation of ultimate loads and displacements, fatigue DEL were computed from each phase and applied to the design following a 'worst-case' criteria.

2.3. Definition of the WR controller

The wake redirection is a control technique that rotates the turbine(s) in the front row(s) so that the rotor plane is no longer perpendicular to the incoming reference wind. This way, the turbine works with a certain yaw angle with respect to the wind so that its wake is deflected away from the downstream turbines. Typically, this manoeuvre causes a loss in the power production of the front turbine while, due to the reduced interference with the impinging wake, back-row turbines increase their own power generation. In this work, we do not focus on how the wake redirection is managed within the controller. As we are concerned by the possible increase of ultimate and fatigue loads, we define a set of four different yaw angles corresponding to ± 15 and ± 30 deg. It must be noticed that, within our model, a certain yaw condition is simulated by rotating the nacelle of the turbine, while the wind is always assumed to blow in the same direction. In this convention, a positive yaw implies a counter-clockwise rotation of the rotor as shown (from above) in Fig. 2.

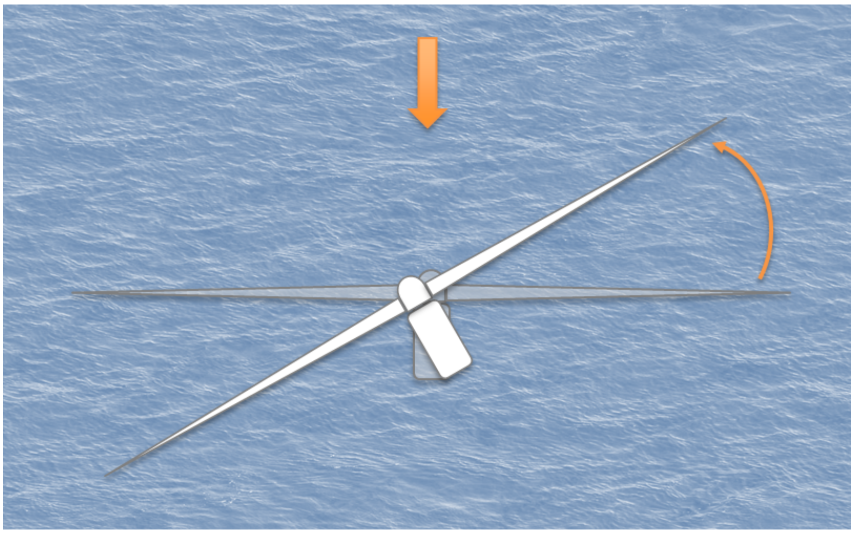

Figure 2. Definition of positive yaw angle in the multibody model (WT seen from above).

For each value of these yaw angles, an additional set of DLCs is added to the standard set of Table 1. In this way, as for the AWM case, we consider different scenarios, assuming that the wind turbine on which the wind farm control system is operating, is working at that yaw angle imposed by this WR control. This makes it possible again to assess the most severe conditions and to track the associated loads and deflections.

3. Impact of the AWM and WR controllers on the rotor design

As discussed, the first activity of this study was to perform a preliminary structural design of the PoliMI 10MW equipped with the standard CL-WINDCON controller. The details of this step are not presented here, while the interested reader can refer to the work of Croce et al. [16]. Then, we proceeded to evaluate the impact of the chosen WFC strategies by conducting the corresponding redesign. It's important to stress here that these analyses focuses on the upwind wind turbine, i.e. the one operating the WFC. The analysis on the downwind wind turbines is out of the scope of this work, and will be investigated in future activities. The redesign with AWM shows a 12% increase in the total blade mass, which largely depends on the maximum tip displacement experienced by the AWM solution. In fact, the additional excursion of the collective pitch due to the AWM/PCM drives the blades towards higher loads and larger deflections. This is clear by noting that both the Baseline and the redesigned rotor achieve the same tip displacement (16 meters) but the redesigned rotor needs a thicker spar cap to keep such deflections within the value prescribed by the constraint (see Fig. 3).

Table 2. Redesign with AWM:Impact of DLC families on maximum displacement

Relevance	DLC Family	WFC	δ/δ_{Max}
1	DLC 1.4 AWM	Yes	1.00
2	DLC 2.2(f) AWM	Yes	0.91
3	DLC 1.4	No	0.90
4	DLC 1.3 AWM	Yes	0.89
5	DLC 1.3	No	0.88

The impact of the AWM on the maximum displacement is interesting: Table 2 shows the maximum displacement registered during the most striking load cases. Here, the DLCs are divided in families and, for each family, the value of their maximum displacement (normalized with the global maximum one) is given. The tag 'AWM' means that the corresponding DLC includes the AWM controller. From the Table, we notice that the most demanding condition is DLC 1.4 with the AWM enabled, for which the normalized displacement is obviously 1. It's easy to notice how the same load case *without* the AWM barely achieves a normalized displacement of 0.9, which is the sizing case for the baseline rotor. Then, a first conclusion is that the AWM redesign is massively constrained by the tip deflection, to the point that it would be impossible to equip the baseline rotor with such controller without redesigning its structure. The fact that DLC 1.4 is so critical comes as little surprise if we consider that the corresponding simulations are very demanding. So, one could be tempted to see if the same conclusions hold true when DLC 1.4 is *not* considered. Looking again at Table 2 we can see that, apart from DLC 1.4, both DLC 2.2(f) and DLC 1.3 with AWM increase the maximum displacement, when compared with the solution without the wind farm controller (DLC 1.3, fifth row). That demonstrates that DLC 1.4 is very demanding, but it is not the only case which is negatively affected by the use of AWM and that, even if we take DLC 1.4 out of the picture, a certain level of redesign would be necessary. Obviously this is true only when the baseline rotor is constrained by the maximum displacement, as in this case.

Another interesting topics concerns the fatigue: while the direct impact of the AWM on the main fatigue loads is limited (see [16]), the increase in the total blade mass has definitely an impact. Figure 4 shows some Damage Equivalent Loads (DELs) normalized so that those of the baseline have unitary values. As shown, all the fatigue metrics increase, and this is mainly related to the higher blade mass associated to the higher displacement. The conclusion is quite interesting: while the adoption of this family of wind farm controllers does not carry an important impacts on fatigue, the fatigue is nonetheless increased as a consequence of the higher

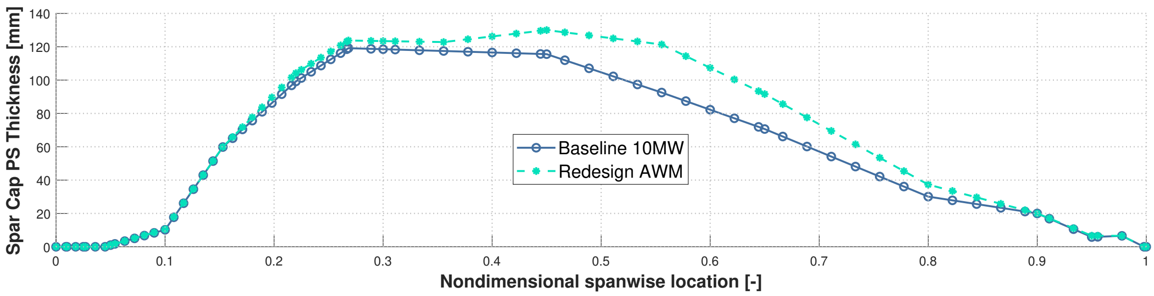

Figure 3. Redesign with AWM: thickness of the spar caps.

blade mass. The redesign activity shows that an increase of about 15% can be expected in the flapwise fatigue load, while about 10% can be expected at the tower base fore-aft component. A summary of ultimate loads is reported in Table 3, where the values of the baseline are compared against those of both redesigns. In the AWM case, the redesign equipped with the wind farm control leads to a 14.6% increase of the blade root load (due to DLC 1.4), while the hub load has increased of about 4% (due to DLC 2.2(f)) and the tower top is about 7% higher than the baseline (due to DLC 1.4). Ultimate loads at tower base are not reported as this component is sized in all cases by DLC 6.2, which is not affected by the WFC. The conclusion, for the redesign with AWM, is that the global impact on the ultimate loads is moderate and that the fixed infrastructure (hub, tower), would only require minor adjustments.

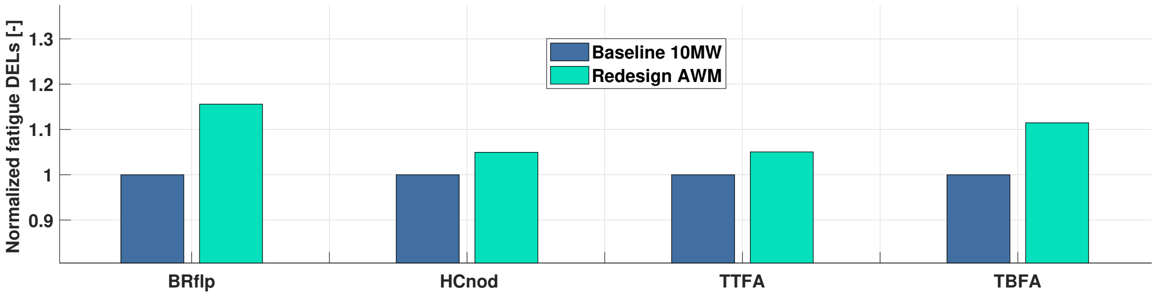

Figure 4. Redesign with AWM: normalized fatigue DEL. From left to right: blade root flapwise (BRflap), hub center nodding (HCnod), tower top fore-aft (TTFA) and tower base fore-aft (TBFA).

A similar trend can be observed when the turbine is equipped with the wake redirection controller, that is, when yawed DLCs enter the domain of the simulations. Once again, the main driver affecting the redesign is the maximum tip deflection which is increased in the misaligned conditions. Such increase ultimately leads the structural design to be 12.6% heavier than the baseline to fulfill the constraints. The resulting distribution of spar cap thickness is shown in Fig. 5. It must be noticed that, once again, DLC 1.4 is the most demanding condition, in particular when such load case is experienced at 30 degrees of negative misalignment. The analysis of the fatigue DEL shows that the loads are generally increased: the redesign with WR achieve about 7% increase in the flapwise DEL (better than the AWM) while a 9% increase is obtained at the hub center nodding and +11% at the tower top fore-aft. On the contrary, fatigue DEL at the tower base are basically unchanged when compared against those of the baseline. Looking at the comparison provided again in Table 3 it appears that, unlike the AWM case, the redesign with wake redirection produces a significant increase in the ultimate loads. In particular, the ultimate bending at tower top is more than 60% higher than the baseline, and that would probably imply a severe redesign of the tower if the controller is used on an existing turbine. It must be stressed however, that all these loads depends on the fact that DLC 1.4 is really demanding, in particular because the combination of extreme misalignment *plus* the sudden direction change prescribed by those DLCs pushes the turbine to the limits of its operating envelope and even to shutdown, causing high peaks of load in the various subcomponents. The partial conclusion is that a WFC based on wake redirection could be not used *as is* on an existing wind turbine without the need to redesign the structure of the rotor and the tower. Alternatively, the operator should conceive some way of mitigating the dramatic impact of DLC 1.4 in order to downgrade its importance. Such mitigation could be based, for example, on a LIDAR scanning of the incoming wind in order to avoid the extreme direction change. Another possibility, as hinted in the Introduction, could be a limitation of the WR controller so that it can not exceed a certain value of yaw misalignment. A future development of this work will investigate such possibility in order to quantify its feasibility.

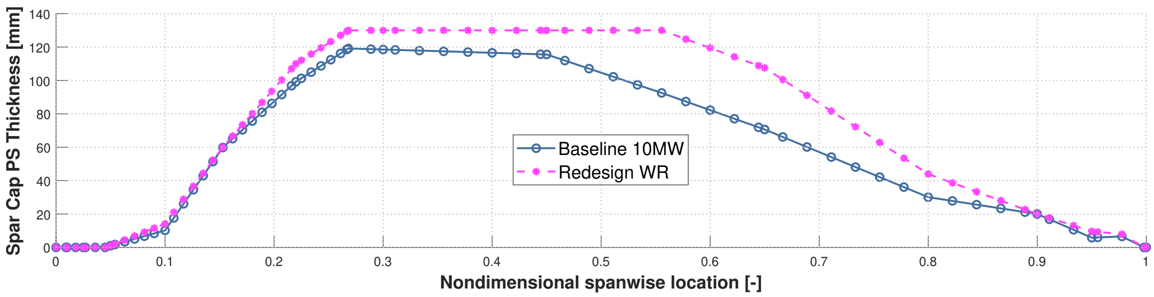

Figure 5. Redesign with WR: thickness of the spar caps.

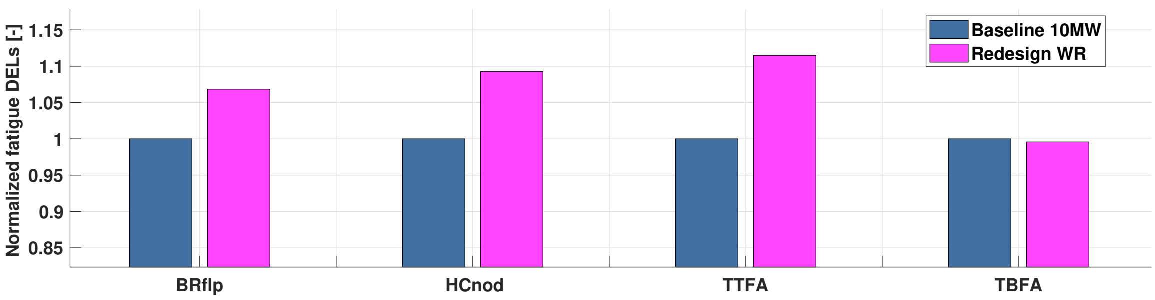

Figure 6. Redesign with WR: normalized fatigue DEL. From left to right: blade root flapwise (BRflap), hub center nodding (HCnod), tower top fore-aft (TTFA) and tower base fore-aft (TBFA).

4. Conclusions

In this study, we investigated how different wind farm controllers affect the loading, and thus the structural design, of a specific wind turbine. The idea is to understand if it would be possible to retrofit an existing wind turbine with a chosen WFC without the need to redesign some of its components. Among various wind farm controllers currently available, we decided to focus our investigation on two specific strategy: active wake mixing (AWM) and wake redirection (WR). Both techniques substantially modify the dynamic behaviour of the turbine and, according to our findings, this impacts both ultimate loads and blade deflections, whereas the direct contribution of the WFC on the fatigue loading is only limited. As the wind turbine

Table 3. Comparison between the KPIs of the Baseline and the redesigned rotors.

KPI	Baseline 10 MW	Redesign AWM	Redesign WR
Blade root ultimate load	72.0 MNm	+14.6%	+23.4%
Hub center ultimate load	81.5 MNm	+3.6%	+34.3%
Tower top ultimate load	69.8 MNm	+6.93%	+61.0%
Blade root flapwise DEL	34.3 MNm	+15.6%	+6.84%
Blade root edgewise DEL	27.1 MNm	+15.0%	+15.9%
Hub center thrust DEL	860 kN	+22.0%	+5.0%
Hub center nodding DEL	25.9 MNm	+4.95%	+9.25%
Tower top F/A DEL	25.6 MNm	+5.04%	+11.5%
Tower base F/A DEL	134.0 MNm	+11.5%	-0.43%
Blade mass:	40643 kg	+11.8%	+12.6%

under investigation is primarily designed by stiffness requirements, an increase of the maximum deflection certainly requires an increase of the structural thickness of some elements, in particular the spar caps, to cope with the maximum displacement constraint. Our analyses show that a similar mass increase (about 12%) is obtained as a result of the redesign in both cases. Ultimately, the increase in mass leads to higher ultimate and fatigue loads, with the actual proportion depending on which technique is considered. The main conclusion of this study is that, when the turbine topology is similar to the one we analyzed (10MW, class 1A, fiberglass design), it is not possible to adopt one of these WFC as is, as they would require a stiffer structure and a different structural layout. As discussed, it would be theoretically possible to reduce the impact of the redesign by assuming that some mitigating technique can be taken in order to avoid DLC 1.4 Such condition, in fact, resulted to be the most demanding for both controllers.

As we are fully aware that the findings of this paper strictly apply to this family of turbines, future developments of this work will try to generalize the conclusions. In this light, a primary goal is to repeat the analysis on different turbine classes and design (i.e. carbon) to see if similar results can be found. We also plan to extend the optimization scope by including additional variables like chord, airfoils, tower in the redesign effort to better quantify the impact of the chosen WFC on the COE. In this context, it would be also interesting to explore a solution in which WR and AWM controllers are used together. Finally, it would be interesting to study the problem in a wind farm perspective, in order to properly quantify the effects of WFC on the COE of the wind park.

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