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Preliminary design and optimization of a 20MW reference wind turbine

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Abstract. We use the capabilities of a multi-disciplinary design tool to provide a definition of a 20 MW wind turbine. Starting from an aero-elastic model obtained through a classic scaling procedure, we conduct an aero-structural optimization of the rotor through a staged redesign process, in which we optimize primary characteristics of the rotor including the blade shape, the solidity and a certain amount of native structural tailoring. The process is based on a series of parametric analysis, in order to assess the impact of a variation of macro design parameters on the fundamental performance of the turbine. The redesign activity shows remarkable advantages in terms of blade mass reduction and load alleviation, highlighting directions for the development and optimization of very large rotors.

1. Introduction

A growing interest about beyond state-of-art wind turbines leads the research to investigate the feasibility of 15-20 MW wind turbines, with the aim of providing guidelines for upscaling current industrial standards. Larger wind turbines, in fact, can provide higher energy capture, thus improving the ability of wind power to cope with the increasing demand for clean energy across the market. Although larger turbines will generally require higher CAPEX, it has been suggested that some cost reductions can be achieved at the O&M level. Additionally, given the higher capacity of the individual wind turbine, future wind farms could be equipped with a reduced number of turbines for a given nominal power or, alternatively, ensure a higher power for a given number of turbines.

However, the design of large wind turbines poses significant challenges, since it must account for complex phenomena and interactions which affect the operating conditions of the machine during its expected lifetime. In particular, designing larger rotors and taller towers requires to take into account the interaction of a complex unsteady aerodynamic field with flexible and slender components, so that the resulting couplings can dramatically affect the stability, the performance and the overall integrity of the wind turbine.

Several research activities have investigated the ability of classic numerical models to cope with increased level of aero-structural complexity for 10-20 MW wind turbines, and the relevant implications on the design of components. In this framework, the EU-funded project AVATAR [1] focused on the development of aerodynamic tools for the analysis of very large rotors, while the activities of the INNWIND.EU consortium covered a variety of studies concerning the development of conceptual 20MW wind turbines [2, 3, 4, 5]. Concerning the design process, reference 20 MW solutions have been tentatively proposed in the literature in the past years. In particular, Peeringa et al. [6] proposed a preliminary description of a 20 MW wind turbine, including the aerodynamic and structural characterization of the rotor and fundamental integrity verification. In a recent work, Ashuri et al. [7] employed multi-disciplinary optimization algorithms to achieve a common aeroelastic definition of a 20 MW reference wind turbine, in which several global and specific features of the rotor and the tower are designed in order to minimize the LCOE.

Recently, great efforts have been dedicated to the development and validation of automated design algorithms, which usually combine high-fidelity physical models with dedicated numerical optimization techniques in order to provide significant help during each phase of the design, from preliminary system characterization to the detailed sizing of specific components. These methods can also offer a valuable resource to conduct dedicate studies and trade-off analysis, which can help in the identification of promising trends and solutions to drive technological innovations and capital and operating costs reductions.

In this work, we use our multi-disciplinary design environment `Cp-Max` [10, 11] to conduct a preliminary definition of a conceptual 20 MW reference wind turbine. The work follows a step-wise approach, in which a tentative solution is recursively redesigned and improved by exploiting different `Cp-Max` submodules to optimize selected features of the rotor. The starting point of the activity is a reference configuration obtained from the INNWIND.EU 10 MW wind turbine through classical scaling laws [12]. From here, we initially conduct a structural optimization in order to identify a solution which minimizes the individual blade cost.

Subsequently, we exploit the features of our optimization suite to conduct parametric studies in which several features of the rotor are gradually changed and tested. Each solution is structurally optimized in order to ensure the fulfillment of the necessary integrity constraints. Variations of the rotor solidity and prebend, as well as the application of built-in structural couplings are investigated, showing a continuous improvement of the key performance of the turbine in terms of mass, ultimate and fatigue loads, energy production and LCOE.

2. Methodology

In this work, we focus on the definition and design of the rotor for a conceptual 20 MW wind turbine. The design process is formulated as a multi-step constrained optimization problem, which is solved by the holistic design tool `Cp-Max`. In its general formulation, the program can manage the complete design of rotor, blades and tower by targeting at the minimization of the LCOE as described by Bortolotti et al. [11].

The architecture of the program is shown in Figure 1 and it is based on a continuous interface among a primary (macro) design loop and several submodels. The former loop aims at the minimization of the cost of energy by automatically designing global characteristics of the wind turbine including radius, tower height, solidity, cone and tilt angles. At a lower layer, the submodules are responsible to perform the detailed design of specified subsystems in order to optimize certain performance of the wind turbine.

Both the macro design loop and the submodules rely on suitable simulations for the computation of time-histories of loads and deformations in the WT components. The analysis are automatically managed by the program and performed whenever required by the multi-body aero elastic solver `Cp-Lambda` [13].

Since the algorithm is based on different nested optimization cycles, a full design process can be managed according to three different strategies:

(i) **Individual component design:** In this scenery, each submodule is used as a standalone tool for the detailed optimization of system components, e.g. the structural design. The optimization is carried out according to the specific objective function and constraints of each module, as shown in Figure 1.

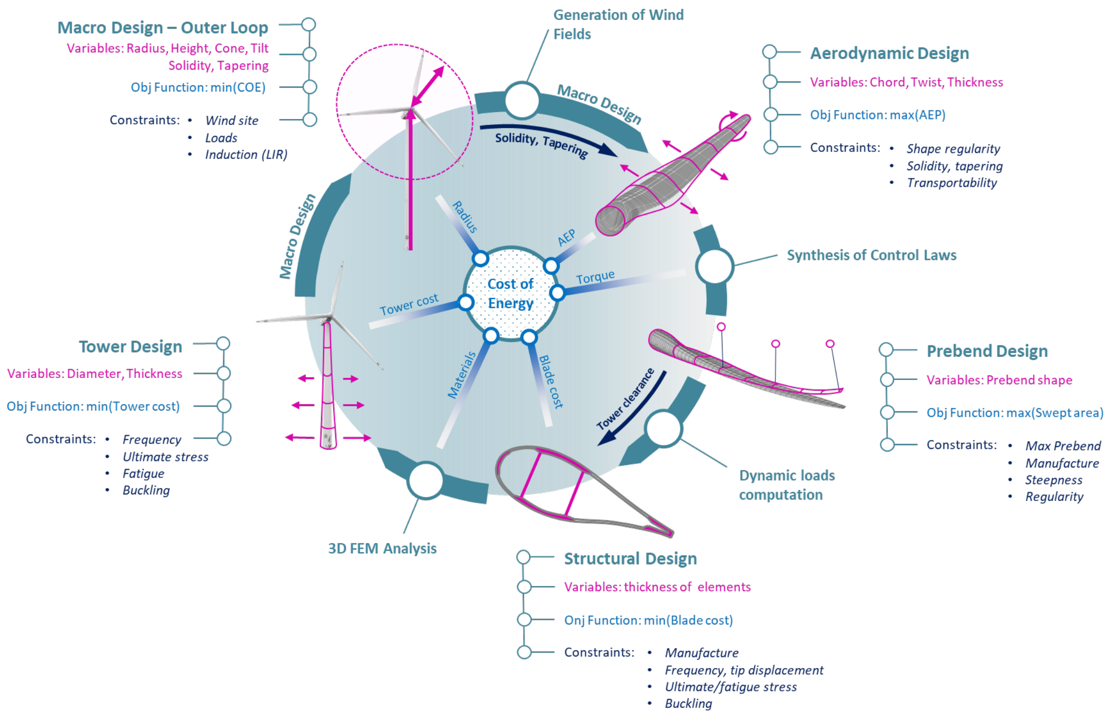

Figure 1: *Cp-Max* architecture.

(ii) **Automatic macro design:** The macro loop is operated automatically, so that the set of the macro design variables is optimized in order to minimize the LCOE of the wind turbine. The required submodules, or the whole sequence in a full analysis, are automatically run at each perturbation of the macro design variables.

(iii) **Parametric macro design:** The macro loop is operated manually instead of automatically: each of the macro design variables is parametrically changed and the required submodules are performed in sequence for each variation of the design variables. A set of required KPI can be compared at the end of the parametric analysis.

In this work we focus on a preliminary design and optimization, so that we decided to approach the investigation through the second strategy. In this view, we conducted a series of parametric design studies in order to investigate the impact of changing the value of several macro design features on a set of commonly used KPIs.

This choice has several advantages when compared against a fully automated one: *in primis*, a larger number of DLC can be used, because imposing discrete values of the macro design variables typically reduces the number of iterations required by the algorithm. This is particularly true when the initial configuration of the macro design loop is far from the optimum. Additionally, through a parametric approach it is possible to monitor a larger set of global KPIs rather than the sole LCOE and it is possible, at the end of each stage, to decide which way to go based on the analysis of the KPIs. Since we deal with a completely new class of wind turbine, in our opinion it is vital to monitor the evolution of several performance indicators before recurring to the automated macro design, which will be postponed to a future, dedicated investigation.

We started the design process from the aero-elastic model of a reference 20 MW wind turbine, which has been proposed within the INNWIND.EU [12]. This model, hereafter referred as Reference 20 MW, has been obtained after applying classic scaling laws to the INNWIND.EU 10

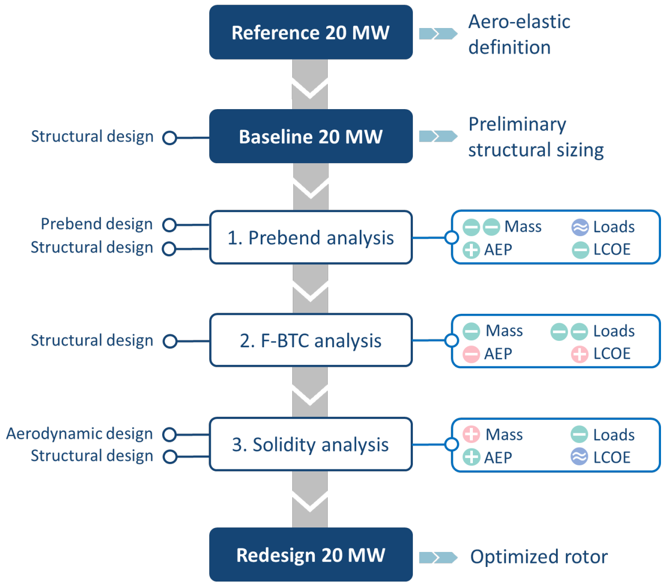

Figure 2: Staged design process and step-by-step qualitative results. Green is a beneficial effect, red is a detrimental effect. (+) is an increasing value, (-) is a decreasing value while (=) implies only minor variations.

MW base turbine. However, the resulting upscaled model is defined only through its properties of mass, stiffness and inertia, as no detailed structural design has been performed so far. So, as part of this work, we performed a complete structural optimization loop in order to define a feasible structural design which is consistent with the scaled model. The details of the procedure are reported by Croce et al. as part of the dissemination activities of INNWIND.EU [3]. The resulting configuration is referred as the Baseline 20 MW and is the starting point of this work. From this solution, in fact, we performed several design steps: at each level we performed a parametric analysis in which a macro feature of the rotor is changed and investigated. The following analysis have been included in the study:

1. Prebend analysis: starting from a straight-axis configuration, we followed the approach proposed by Sartori et al. [14] to optimize the spanwise prebend distribution along the blade. This concurs to relieve the constraint on the maximum tip displacement, resulting in a lighter structure.

2. F-BTC analysis: at this step, we were able to obtain a significant load reduction by exploiting the load-mitigating effect provided by the F-BTC induced by a rotation of the spar caps fibers [15]. A reduction of the total blade mass was also detected, together with a slight deterioration of the power production due to the larger torsional deformations.

3. Solidity analysis: given the massive chord of the initial solution, here we gradually reduced the target rotor solidity and redesigned the chord and twist distributions of the blade in order to achieve the maximum energy yielding. This way it was possible to reduce the maximum chord of the optimal rotor and to alleviate the transportation issues which would affect such large planform. Additionally, we achieved significant improvements in terms of loads alleviation at this step.

The three design steps are reported in the block diagram of Figure 1. Here, each parametric analysis is represented as a white block. To the left of each block are reported the submodules of `Cp-Max` that we used at that step whereas, to the right of each block, a qualitative assessment of the main KPI is reported, in order to identify the impact of particular design choices on the performance of the turbine.

At the end of each step, the best configuration was taken as the starting point of the following one, so that the advantages obtained at each level could be combined together in the final redesign. It must be noticed that we conducted a full structural redesign of each solution under investigation, so that all the configurations are obtained under the same criteria and constraints.

3. Optimization Set-Up

To further simplify the complexity of the problem, the design is limited to the rotor whereas tower, nacelle, hub and foundations are considered as frozen. Similarly, the airfoils and the corresponding aerodynamic data are not changing during the design, that is, the rotor was optimized for a given set of airfoils. A brief summary of the characteristics of the initial configuration is given in Table 1. A complete account is given in the mentioned references [3, 12].

Table 1: Main features of the reference Baseline 20 MW.

	Units	Baseline 20 MW
IEC Class	[-]	IC
Rotor radius	[m]	126
Hub height	[m]	168
Tower height	[m]	163
Total blade mass	[ton]	113.5
AEP	[GWh]	91.6
LCOE	[EUR/MWh]	84.9

During the design process, the performance of the wind turbine are computed from simulated time-histories according to international regulation standards [8]. These include the turbulent AEP and the relevant loads and deflections which are used to drive the design. A unique control system has been used for all the studies, which features a PID regulator on the collective blade pitch and a PI controller on the torque, as specified by Hansen and Henriksen [9]. The list of considered DLC includes normal and extreme turbulence models, gusty winds and extreme shears as well as fault conditions and different parking conditions. It must be underlined that, for sake of CPU time, only one seed of the turbulent simulations was considered. Throughout the design, we based our step-by-step decisions on the evolution of fundamental performance indicators and in particular the set of blade mass, AEP and LCOE, which according to our experience constitute a set of fundamental KPI for the design of wind turbine rotors. The cost was recursively computed according to the INNWIND cost model (see [2] and references therein). Since the reduction of the component mass, and possibly of the loads, is one of the main scopes of this work, we included the main fatigue and ultimate loads in the set of decisional parameters.

4. Results

4.1. Prebend analysis

The first parametric analysis investigates the impact of a varying distribution of prebend along the blade. The Baseline 20 MW rotor was compared against two solutions characterized by a tip prebend of 2 m and 4 m respectively. While the tip prebend was imposed as part of the parametric study, the optimal shape of the prebend was designed by the dedicated prebend design submodule of `Cp-Max`. The resulting distributions are illustrated for the three cases under consideration in Figure 3.

Figure 4 shows the variation of fundamental fatigue DEL experienced by the optimal solutions against those of the Baseline 20 MW. Similarly, Figure 5 shows the variation of the main KPI considered in this study. The results are normalized so that figures referring to the Baseline 20

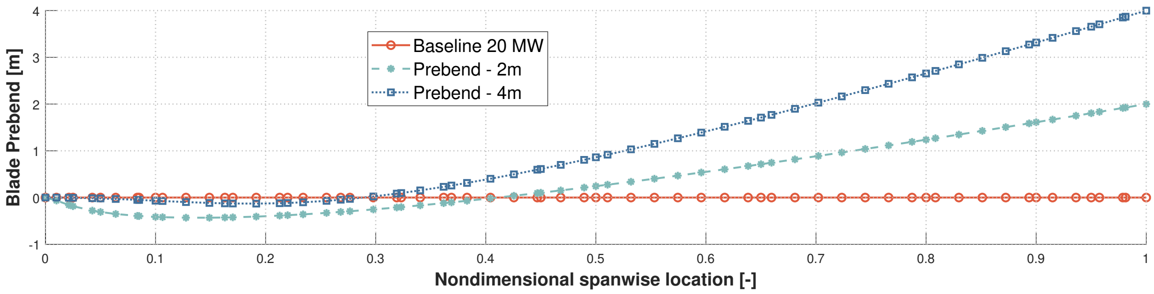

Figure 3: Prebend analysis: spanwise optimal prebend distribution.

MW are equal to one. The pictures shows that the main advantage associated to the introduction of prebend is a mass saving up to 5%: this is due to the larger clearance between blade and tower, which contributes to relax the constraint on the maximum tip displacement, which is an active constraint on the structural design of the Baseline 20 MW.

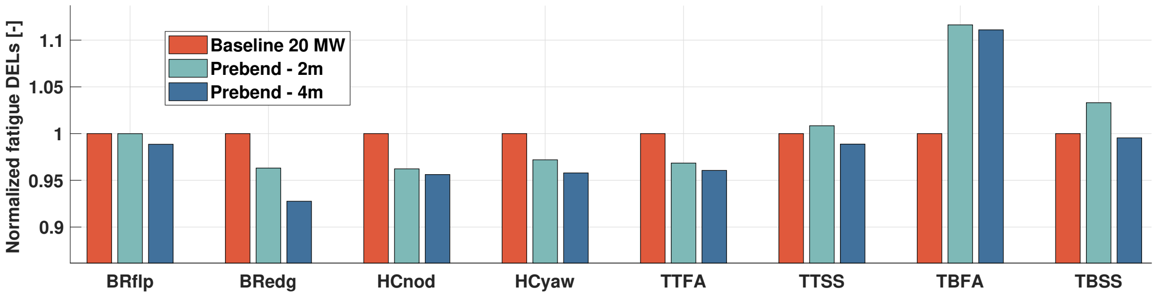

Figure 4: Prebend analysis: normalized variation of the fatigue DEL. BR is blade root, HC is hub center, TT is tower top and TR is tower root.

The effect on the fundamental fatigue DEL is generally beneficial, with reductions in the order of 3 to 5% at the blade root, hub center and tower top. In particular, the reduction of the blade edgewise DEL can be directly associated to the reduction in the total blade mass. However, the fore-aft DEL at the tower root is increased of about 10%. In our experience, however, the tower design is heavily constrained by buckling in the vicinity of the root, so that this increase is considered acceptable at this step. It is important to notice that the formulation of the prebend optimization seeks to maximize the rotor swept area under rated loads, and the typical main effect is a slight increase of the AEP which, together with the reduction of the blade mass, allows to achieve a LCOE reduction in both optimal solutions. However, since the Prebend - 4m configuration combines the higher cost reduction and the largest load alleviation, this solution is considered the best one and used to initiate the next design step.

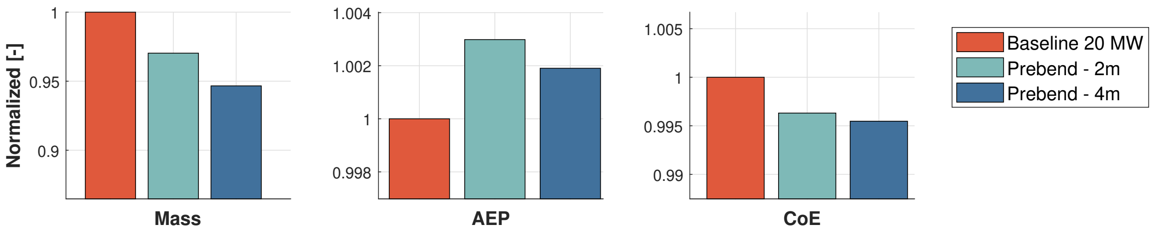

Figure 5: Prebend analysis: normalized variation of the KPIs.

4.2. F-BTC analysis

In the second parametric analysis of the design process, we focused at the reduction of the fatigue loads by introducing a varying amount of built-in structural tailoring to the layup of the blade. This was mainly achieved through a Fiber-induced Bend-Twist Coupling (F-BTC) according to the methodology illustrated by Bottasso et al. [15]. Three solutions have been tested, namely with 4, 6 and 8 degrees of fiber rotation. Again, for each solution we performed a complete structural optimization loop to ensure the minimization of the total blade mass. The comparison between the normalized fatigue DEL of the three solutions against the Prebend - 4m, which is the staring point of this second analysis, is given in Figure 6.

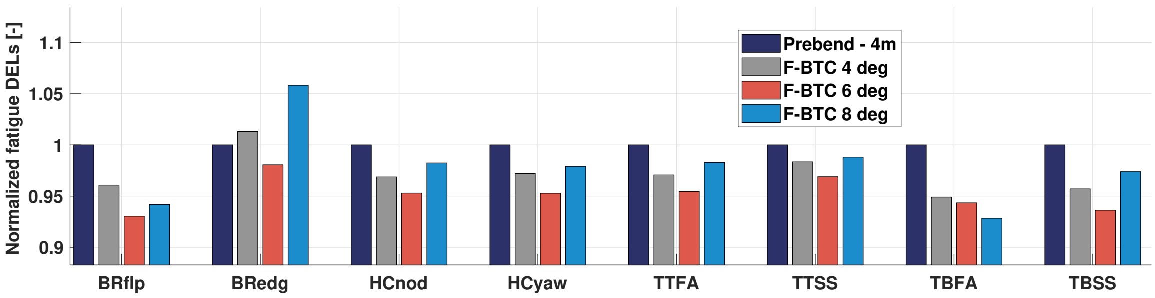

Figure 6: F-BTC Analysis: normalized variation of the fatigue DEL. BR is blade root, HC is hub center, TT is tower top and TR is tower root.

It is possible to observe how the F-BTC ensures a significant alleviation of the fatigue DEL. In particular, the flapwise DEL at blade root is reduced by 7% while the main DEL at the hub center are about 5% lower than the initial configuration. Finally, the fore-aft and side-side DEL at tower root are reduced by more than 5%, which in part contributes to compensate the increased loads experienced at the previous step. The normalized variation of the main KPI is given in Figure 7. As expected, the solutions with F-BTC lead to a small decrease in the AEP: this is a consequence of the additional torsion induced by the structural tailoring, which drives the individual airfoils along the blade away from their point of maximum efficiency. It is interesting to notice how the blade mass decreases for increasing fiber rotation. However, an excessive rotation of the fibers can significantly reduce the flapwise stiffness of the blade, leading to a higher thickness of the spar caps, which ultimately increases the mass. The overall impact on the LCOE is negligible for the three solutions, however, considering that the F-BTC 6 deg provides the best load alleviation effect, this is identified as the optimal solution at this step.

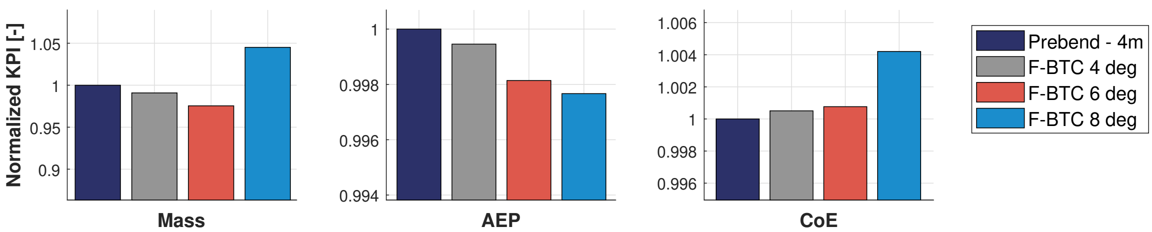

Figure 7: F-BTC Analysis: normalized variation of the KPIs.

4.3. Solidity analysis

In the last step of the design, we investigated the impact of a parametric variation of the rotor solidity. For each solution, we run the aerodynamic design submodule of `Cp-Max` to optimize the chord and twist distribution along the blade. The resulting shapes are compared in Figure 8. Subsequently, we run a full structural design to minimize the total blade mass.

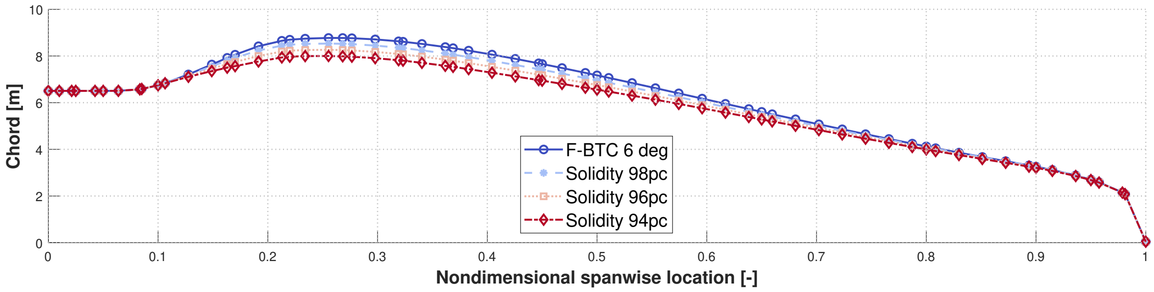

Figure 8: Solidity analysis: optimal chord distributions.

The main achievements in terms of fatigue loads are reported in Figure 9, while the variation of the main KPI is given in Figure 10. The main effect of the reduced solidity is a general alleviation of the fatigue loads, in particular at the tower base: this is mainly related to the lower planform of the blade. However, by reducing the solidity it is necessary to increase the thickness of the structural components, in particular of the spar caps, to compensate for the loss of sectional stiffness. The result is, unsurprisingly, an increasing blade mass for a decreasing solidity. This justifies the increase in the edgewsie DEL at root. At this step, the variations of the AEP and LCOE are indeed very small, however, we concluded that the Solidity 96pc gives the best advantages in terms of costs and load alleviation, so that we selected this configuration as the optimal point of the redesign process. This solution is hereafter referred as Redesign 20 MW.

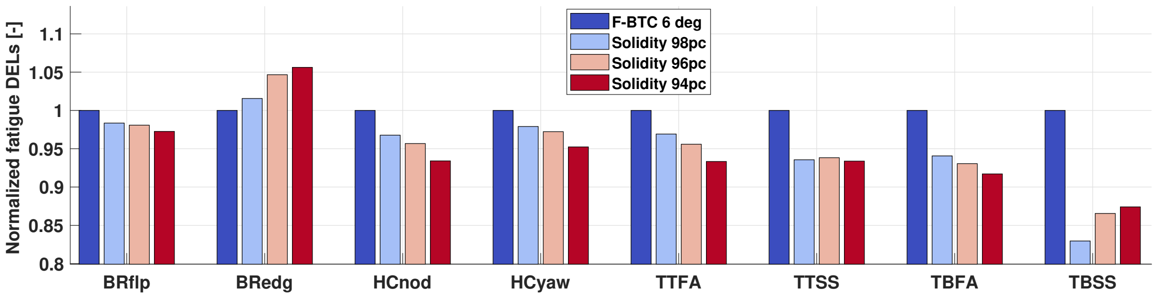

Figure 9: Solidity analysis: normalized variation of the fatigue DEL. BR is blade root, HC is hub center, TT is tower top and TR is tower root.

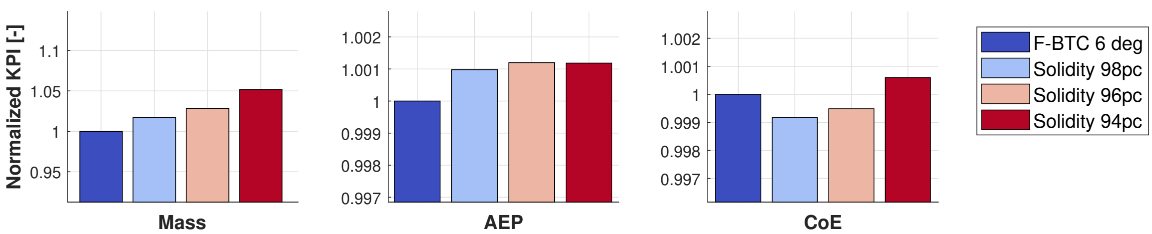

Figure 10: Solidity analysis: normalized variation of the KPIs.

Table 2: Performance comparison between the Baseline 20 MW and the Redesign 20 MW rotors.

	Units	Baseline 20 MW	Redesign 20 MW	Variation
Rotor speed	[RPM]	6.77	6.82	+0.74%
TSR	[-]	7.73	7.86	+1.68%
Rated wind speed	[m/s]	11.6	11.4	-0.95%
Max chord	[m]	8.77	8.27	-5.70%
Prebend at tip	[m]	0.0	4.0	
Spar caps fiber angle	[deg]	0.0	6.0	
Total blade mass	[ton]	113.5	107.8	-5.05%
AEP	[GWh]	91.6	91.7	+0.12%
LCOE	[EUR/MWh]	84.9	84.6	-0.42%
Blade root flap DEL	[MNm]	83.8	75.6	-9.79%
Hub nodding DEL	[MNm]	53.6	46.7	-12.83%
Tower base FA DEL	[MNm]	278.5	271.6	-2.48%
Tower base SS DEL	[MNm]	204.4	164.9	-19.2%

4.4. Summary of the redesign process

At the end of the process, we compared the Redesign 20 MW against the Baseline 20 MW. An overview of the results is given in Table 2 in terms of regulation parameters, geometry, KPI and fatigue DEL. The optimal rotor has a solidity 4% lower than the initial, while the chord is 6% shorter. An optimal prebend at tip of 4 meters was introduced in the final redesign. The redesigned rotor is also characterized by a rotation of 6 degrees applied to the plies of the spar caps. The comparison shows improvements in all the monitored indicators: in particular, a 5% reduction in the total blade mass was achieved through the design process. This saving is mostly related to the thickness of the spar caps and is a trade-off between the prebend, the F-BTC and the additional ply thickness needed by the lower optimal solidity. The turbulent AEP, which is computed by averaging the power production in DLC 1.2, is 0.12% higher than the Baseline, and the two advantages ultimately result in a 0.4% reduction of the LCOE.

All the fatigue load metrics are significantly reduced: this is in part due to the lower rotor mass, whereas the main load alleviation mechanism depends on the F-BTC effect introduced through the ply orientation. Similar results were obtained for the ultimate loads, although the values are not reported here. It is important to notice that, based on the lower loads in all the wind turbine components, a dedicated redesign of the hub and the tower could provide additional cost savings.

5. Conclusions

In this work, we performed a preliminary aero-structural optimization of a 20 MW wind turbine. The design focused mainly on the rotor, which was optimized through a combination of a staged design process and an automated design tool. At the end of redesign, we were able to achieve a global improvement of selected KPIs of the turbine. In particular, the total blade mass and the fatigue loads have been significantly decreased when compared against the initial configuration, making room for lighter and cheaper support structures. The main limitation of this work lies in the use of a parametric procedure instead of a fully automated one. However, this choice made possible to perform a great deal of analysis within a reasonable computational effort. On the other hand, in our opinion the satisfactory margins of improvement of the results fully justifies this course of action. These preliminary results will be compared against an automated macro design in a dedicated follow-up of this activity. Incoming activities will also focus on the detailed structural verification through 3D FEM, and on the application of additional load mitigating

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