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Mechanical behaviour of wind turbines operating above design conditions

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Abstract

Improving production of electric power from renewable sources is fundamental in order to decrease the use of fossil fuels. A crucial aspect for future development of renewable sources is to guarantee competitive prices to end users and profitably economic returns to those who invest in these technologies. This can be reached by constantly surveying plants performances, optimizing the operative conditions and evaluating the possibility to implement upgrades. For what concerns wind turbines, there are many possibilities to increase power production. This study is focused on analyzing the HWRT (High Wind Ride Throughout) cut-out strategy: it is a method that allows extending the power curve of a wind turbine above the cut-out wind speed (25 m/s, typically) at which the wind turbine is abruptly shut down for structural integrity issues. The HWRT instead is a particular generator and pitch control strategy that maintains the turbine productive for higher wind speeds (up to at least 30 m/s) through a soft cut-out strategy. Starting with a reverse engineering approach, this study aims at creating a mathematical model of a real wind turbine operating with the HWRT control, and then evaluating the effects of this control strategy on stresses and structural vibrations. The point of view of this study fills a lack in the way this kind of issues is commonly approached in the wind energy practitioners community: actually, wind turbine power capture optimization strategies are typically assessed mainly by the point of view of the energy balance and insufficient attention is devoted to the mechanical aspects and the possible consequences on the wind turbine remaining useful lifetime. The research is structured in the following steps. At first, the wind turbine model is constructed and the characteristic dimensions, blade shapes and natural frequencies are found. Subsequently, with this information, aeroelastic simulations through the FAST (Fatigue, Aerodynamics, Structures and Turbulence) software are implemented and validated against operation data. Finally, conclusions are drawn about the impact of the soft cut-out strategy on structural health and fatigue.

Keywords: Wind energy; wind turbines; control and optimization; aeroelasticity

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1. Introduction

The optimization of horizontal-axis wind turbine power capture has recently been a major topic in the scientific literature. The practical implications are promising, because MW-scale wind turbines (especially onshore) are likely to be the most efficient renewable energy technology in the next decades.

In particular, wind turbine control optimization is a very fertile subject and it is remarkable that it can be conceived at the level of each single wind turbine or at the wind farm level. This work deals with the former type of approach; nevertheless it is important to recall that cooperative control Park and Law (2015, 2016); Wang and Garcia-Sanz (2018) and wind turbines wake steering Gebraad et al. (2017, 2016); Fleming et al. (2016); Campagnolo et al. (2016); Fleming et al. (2017) are two closely related aspects: the objective is adopting non-trivial yaw and-or pitch control strategies Ciri et al. (2018); Ciri et al., in order to optimize the power production and possibly mitigate mechanical loads at the level of wind farm.

As regards single wind turbine control optimization, two are the main fields of intervention: the yaw and the pitch and in both cases the potential energy improvement can be remarkable. In order to appreciate the importance of the yaw behavior on wind turbine power capture efficiency, consider that in Wan et al. (2015) it is estimated that a 10° yaw error can cause a power loss up to the 10%. For this reason, there several studies dealing with the design of innovative yaw control strategies at the aim of diminishing as much as possible the wind turbine operation time with non-vanishing yaw angle. It should be noticed that this objective is non-trivial because the yaw motor modulates the fast wind flow variations through the movement of the nacelle having a very high inertia. In Song et al. (2018b), a new yaw control structure is designed, basing on a wind direction predictive model; simulations are performed and the results are compared against operation data of wind turbines adopting the state of the art in industrial yaw controls and it is supported that the proposed novel yaw control can diminish the yaw error. In Song et al. (2018a), two yaw control systems are designed (a direct measurement-based conventional logic control and a soft measurement-based advanced model predictive control) and a multi-objective Particle Swarm Optimization-based method is employed to optimize control parameters. Operation data of a 1.5 MW wind turbine are employed in order to estimate the possible power capture improvement provided by each of the two proposals. In Saenz-Aguirre et al. (2019), a novel data driven yaw control algorithm synthesis method based on Reinforcement Learning is introduced and the potential power capture improvement is simulated under several wind speed scenarios using the TurbSim software. In Astolfi et al. (2019b), the objective is the assessment of the production improvement obtained through the yaw control optimization adopted in an industrial wind farm in Italy: a devoted statistical analysis is formulated and conducted and it results that the production gain is non-negligible (order of the 1% of the annual energy production).

As regards pitch control optimization, in Lee et al. (2015) the assessment of production improvement is conducted through a modification of the Kernel regression method. In Astolfi et al. (2018c), the impact on power production of pitch angle optimization near the cut-in wind speed is discussed through the analysis of operational data of an operating wind farm featuring multi-megawatt wind turbines. These studies indicate that there is an interesting line of research about the assessment of wind turbine control optimization. This objective is challenging because the order of magnitude of the production improvement is the percent of the annual energy production: due to the multivariate dependence of wind turbines power on ambient conditions and working parameters, detecting this kind of performance improvement is a complex task, calling for devoted techniques. Test case studies and methodologies have been collected in several studies, as for example Hwangbo et al. (2017); Astolfi et al. (2018a); Terzi et al. (2018); Astolfi et al. (2019a, 2018b, 2019b); Astolfi and Castellani (2019).

Another promising line of research as regards wind turbine control optimization is the so called soft cut-out strategy. The basic idea is the following: wind turbines typically stop abruptly when the gust wind intensity (measured with time scale of 1 second) exceeds a certain threshold or when the average wind intensity (measured with time scale of 10 minutes) exceeds another threshold, named cut-out wind speed. The order of magnitude of the cut-out wind speed is 25 m/s. The control system operates with the hysteresis logic: the wind turbine starts again when the wind speed lowers several m/s with respect to the cut-out, reaching a high wind speed cut-in value (typically, 20 m/s). In Horváth et al. (2007), for example, the influence of the hysteresis on the power output is studied.

This work deals with a soft cut-out strategy named HWRT (High Wind Ride Throughout). It is based on extending the operation of the wind turbine above design condition (i.e. above cut-out) according to these guidelines:

- extending the operation above the cut-out, by gradually de-rating the power output until a new, higher, cut-out at which the wind turbine definitely stops;
- raising up the high wind speed cut-in wind speed, so that the hysteresis logic is shifted at higher wind speed and therefore is less frequent;
- raising up the shut-down wind speed for gusts.

This subject has attracted a certain attention in the scientific literature: soft cut-out strategies have been addressed in Markou and Larsen (2009) and Bossanyi and King (2012) and further developed in Jelavić et al. (2013), where wind and wind turbine states were actively monitored and the power reference was reduced only when there was a risk of excessive loading. In Petrović and Bottasso (2014) and Petrovi and Bottasso (2017), a different approach has been taken for dynamic optimization in a soft cut-out strategy, derived from the idea of rotor craft envelope protection.

One important point as regards wind turbine power optimization in general is the fact that the assessment of this kind of technological developments in the wind energy practitioners community is commonly based mainly on considerations about the production improvement. Unfortunately, stresses, structural vibrations, fatigue and in general mechanical aspects are overlooked and this work aims at furnishing a contribution about this issue. A real test case is considered: a wind farm sited in Italy, featuring 17 wind turbines having 2.3 MW of rated power each. After some years of operation, the wind turbines have been optimized through the adoption of the HWRT cut-out strategy. Starting with a reverse engineering approach based on the operation curves before and after the HWRT adoption, this study aims at creating a mathematical model of a real wind turbine operating with the HWRT control, and then evaluating the effects of this control strategy on stresses and structural vibrations. At first, the wind turbine model is constructed and the characteristic dimensions, blade shapes and natural frequencies are found. Subsequently, with this information, aeroelastic simulations through the FAST (Fatigue, Aerodynamics, Structures and Turbulence) software are implemented and validated against operation data. Finally, conclusions are drawn about the impact of the soft cut-out strategy on structural health and fatigue.

The structure of the manuscript is therefore the following. The test case wind farm and the operation data at disposal are described in Section 2. The methods (data analysis and simulations) are described in Section **??**. Results are collected and discussed in Section 3; conclusions are drawn and some further direction of this work is outlined in Section 4.

2. The wind farm and the data set

This study is based on reproducing, through aeroelastic simulations, the operative conditions of a wind power plant, located in southern Italy, where 17 multi-megawatt wind turbines are installed. The scenario that characterizes this wind farm is challenging because of the presence of mountain ridges, with slopes up to 60% Francesco Castellani and Terzi (2016), that cause abrupt vertical components of wind speed. In addition even the climatic conditions are non trivial, as the wind farm altitude is between 700 m and 1100 meters above sea level: the presence of snow, ice and hailstorms in wintertime makes the turbine operative conditions very stressful for what concerns mechanic loads. Turbines on this site are build by one of the leader company. With a 80 meters hub height and a 93 meters of rotor diameter. This kind of machine produces a rated power of 2.3 MW with a wind speed of 12 m/s or higher. This model of wind turbine is specially used in heavy condition applications both onshore or offshore.

On these grounds, the wind farm of interest is an interesting case study as regards advanced soft cut-out strategies. The presence of rapidly changing gusts forces the wind turbine to frequently work around its cut-off speed. In these conditions, with the classic control strategies the wind turbine uses to have an hysteretic behaviour: in fact, as the cut-off wind speed (23-25 m/s) is reached, a sudden shutdown of the turbine occurs, pitching the blades, turning off the generator and activating safety brakes. When the wind slows down, below a threshold value (18-20 m/s), the turbine is then activated again. From this kind of control strategy, it follows that if the wind speed is frequently oscillating between cut-off and high wind speed cut-in threshold values, the wind turbine energy production is not optimized as it remains turned off for most of time: this phenomenon is called hysteresis.

On these grounds, the soft cut off strategy consists in extending the maximum admissible wind speed, up to 30-32 m/s without an abrupt shutdown, but controlling pitch and generator in order to slowly decrease the energy production. The benefit of this advanced control consist not only on extending the operative conditions of the wind turbine, increasing the maximum wind speed: the most effective result is actually diminishing the impact of the hysteresis, because this phenomenon is shifted for higher wind speeds, that occur more rarely. The effect of the control upgrade on the wind turbine operation can qualitatively be appreciated from the power curve plot: in Figure 1, a typical power curve without HWRT is reported and in Figure 2 the power curve with HWRT is reported.

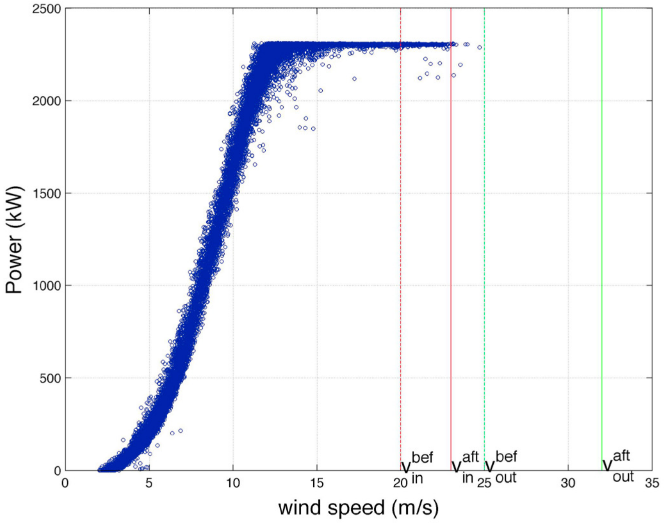

Fig. 1. An example of wind turbine power curve without HWRT control.

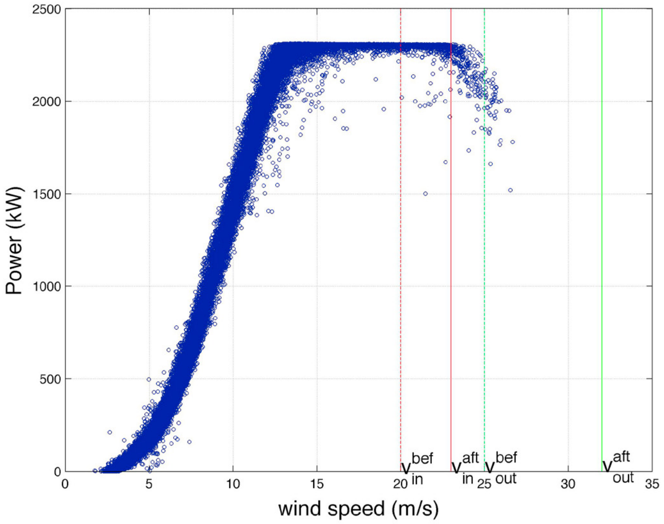

Fig. 2. An example of wind turbine power curve with HWRT control.

From the wind farm anemometers a time series of about 2 hours has been recorded (Fig 3), in this time lapse the mean speed has reached 21.4 m/s with a lowest value of 11 m/s and a maximum of 39.4 m/s. Under this condition it is possible to simulate, with an appropriate software, the turbine's behaviour with and without the HWRT control and assess a comparison of the mechanical loads.

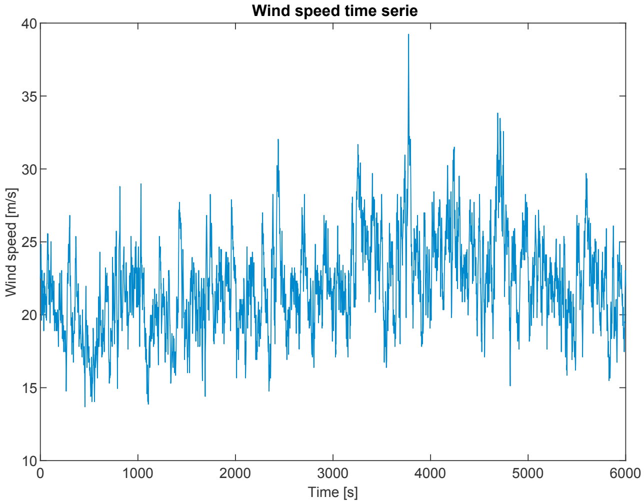

Fig. 3. Recorded wind speed time series

2.1. FAST Software

In this section, the FAST simulation software will be described and all the steps that bring to the implementation of wind turbine numerical model, following a reverse engineering method, will be explained. As this kind of wind turbine is frequently used in many multi-megawatt plants all over the world, the scientific literature is rich in useful technical information that have been used in this paper to prepare the model. In particular, for the purpose of this study, it is necessary to deeply understand not only the energetic characteristics of the wind turbine, such as power curve, generator behaviour and actuator logic of control, but also the mechanic qualities, the materials and the dimensions of the main component. This is essential in order to estimate loads, stresses and resonance frequency leading to aforementioned analysis.

FAST (Fatigue, Aerodynamics, Structures,and Turbulence) is a simulation code realized by the NREL (National Renewable Energy Laboratory) and it is widely used for scientific and designing purposes concerning wind turbines. The code is based on Blade Element Momentum (BEM) theory, a mathematical approach used to estimate aerodynamic loads on wind turbine blades Lanzafame and Messina (2007) and that, subsequently, allows to calculate energy production, forces and moments in different points of the machine (blades, shafts, tower).

FAST turns out to be extremely useful and flexible thanks to the possibility of creating an interface with external software, as LabView or Simulink, that can be used to set up customized logic of torque and pitch controllers. To create a model of wind turbine with FAST ,it is necessary to compile some textual files with all the necessary information regarding the wind turbine characteristics. The number of input file is variable according to simulation configurations. The most used files can be summarized as:

- Primary: is the main file where the simulation parameters can be set and includes the link to the other files.
- InflowWind: in this input, file wind characteristics are described: steady state or time varying wind can be implemented, such as uniform or rough wind profiles. In addition, data about computational spatial resolution grid have to be included.
- AeroDyn: it includes environment air condition, links to the table of blade airfoils polars and tower aerodynamic properties.
- ElastoDyn: in this file, the wind turbine mechanical design (pre-cone, tilt angle, masses and inertia) is described. Links to blades and tower shape modes are also included.
- ServoDyn: it manages the behavior of the controllers. Through this file it is possible to implement generator, pitch, yaw and braking models.

Compiling the input files with all the information required about wind turbine and wind profile it is possible to set-up the simulation in FAST. The first step of this study regarded the research, from bibliographic sources, of the wind turbine features, as blade airfoil, tower dimensions and generator performance curve. Some of these information, that in section 2.2 will be resumed, have been found in Churchfield M.J. (2012) and in Bas et al. (2012)

2.2. *Development of Wind Turbine Model In FAST*

The aerodynamic properties of wind turbine blades is one of the crucial points of the FAST model. The simulation software requires, in the AeroDyn file, that the blade is discretized in a finite number of sections and, for each, the lift and drag coefficient as well as the geometric and mechanic properties of the airfoil have to be provided. To do this, some information is gathered from Churchfield M.J. (2012). The main information concerning the blades are listed in the following:

- root airfoil profile: cylindrical;
- central airfoil profile: FFA-W3 serie;
- tip airfoil profile: NACA-63 serie;
- root chord: 2.036 m;
- tip chord: 0.735 m;
- maximum chord: 3.485m at 30% of the length, measured from root;
- blade length: 45.43 m;

In addition, using an airfoil analysis software, based on the Xfoil code, the polar curves of the different profiles that are present in the blade have been obtained. The polar curve represents how drag and lift coefficients of an airfoil vary with respect to the angle of attack: these coefficients are required by the FAST software in order to compute the aerodynamic forces acting on the blades for different yaw angle and wind velocity. In Figure 4, the composition of the blades sections is represented.

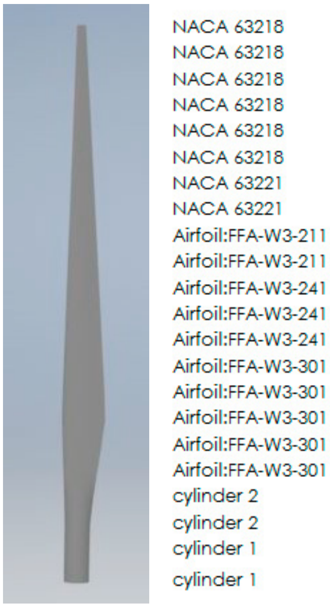

Fig. 4. Composition of blade profiles

Furthermore, some additional mechanical properties of blades have to be added in FAST input files. This software, under a mechanical point of view, consider the blades as cantilevered beams: for this reason both these components have to be discretized in a finite number of sections and, for each, some parameters have to be provided inside the input file. In particular, cross-section area, surface density and moment of inertia have been calculated at different points of the blade and then inserted in the appropriate input file in a tabular format.

Similarly to the blades, the wind turbine tower is modeled in FAST as a cantilevered beam: for this reason it has been necessary to compile an input file with the mechanical properties of a total of 80 discrete sections of the tower. Information about tower has been gathered in Bas et al. (2012), where base and top sections dimensions resulted to be:

- tower height: 78.54 m;
- material: steel plate;
- base diameter(maximum): 4.2 m;
- top diameter(minimum): 2.392 m;
- wall thickness: 13-41 mm;

Knowing the geometry of tower top and base sections, diameter and wall thickness have been linearly interpolated to find the dimensions of intermediate sections. To confirm the assumption of linearly variable diameter and thickness from base to top, the total weight of the tower has been calculated and compared with the technical data sheet of the turbine. As the error on the weight is limited (less than 5%), the estimation of middle sections geometry has been considered reliable.

As done for blades, for the tower, the areas and moments of inertia have been calculated areas for all the sections and then implemented in FAST through a tabular input file.

Once all the aerodynamic and mechanical properties have been defined, in the subsequent step, generator and pitch controllers are implemented. Since FAST offers many alternatives to simulate the controllers, for this study an interface between the software and an external environment has been realized. Whereas it would be possible to manage torque and pitch actuators inside FAST routines, in this peculiar case, where non-standard control strategies have to be tested, it has been preferred to use an additional software with whom FAST can be interfaced.

In a wind turbine the generator applies a resistant torque to the high speed shaft producing electric power as output. In order to ensure the optimal power production, the relation between shaft speed and torque has to be defined with accuracy. The wind turbine generator characteristic curve is usually divided in four sections, or area:s

- area 1: when the shaft speed is lower than a reference startup speed, the generator is turned off and the generator applies no torque;
- area 2: above the startup speed, in the second area, with an extension of about 1000 RPM, the dependency of torque with respect the shaft speed is parabolic. In this area, the shaft is accelerated and the electric power is produced:
- area 2+1/2: in this zone the torque is increased linearly respect shaft speed;
- area 3: when the shaft reaches the rated speed, the torque is kept constant at its maximum value.

Information about speed vs torque curve have been found in Churchfield M.J. (2012): the startup speed results to be 560 RPM and the rated one 1456 RPM; in addition mathematical formulas for area 2 and 2+1/2 are provided, and resumed in Eq.1 and Eq. 2

$$T_2 = 0.004 HSSV^2 \tag{1}$$

$$T_{21/2} = 424.3 HSSV - 602039, \tag{2}$$

where T_2 and $T_{21/2}$ are the torque values in areas 2 and 2 1/2 expressed in Nm, HSSV is the High Speed Shaft Velocity in RPM. Thanks to this relations, it is possible to obtain in each moment the torque that the generator has to apply to the shaft. The produced power is then calculated as product between torque and HSSV, converted in rad/s. Once the torque has been calculated according to the previous equations, the values are provided to a Proportional

Integrative (PI) controller with a retroactive loop with the purpose of keeping the turbine at the expected rotational regime.

Additionally to torque controller, the wind turbine manages the rotational speed acting on blade angle of attack and thus modifying the magnitude of aerodynamic forces generated by the airfoil. A method to regulate pitch is to set it at 0°, or slightly negative, until the rotor speed is slower than rated: in this case the rotational speed is regulated by the generator torque. When the rated speed is reached, the blade pitch is increased and the torque is maintained at a constant value.

In the FAST model, a pitch regulator is implemented through a PI controller. Preliminarily to the simulation of interest, some tests with steady wind have been executed in order to find the best relation between wind speed and blade pitch. Once for each wind speed the respective optimal pitch value has been found, a look up table is implemented inside the turbine model: its purpose is to provide a reference set point to PI controller.

In this study two models have been used: the first has standard logic of control with an hysteretic behaviour: the turbine works at its nominal regime until the ten minute mean wind speed is lower than 23 m/s and, when this value is exceeded, the turbine rapidly shuts down. The safety brakes are deployed, blade are feathered pitched at 90° and the generator is turned off. The machines keep this safety configuration for 600 s, after this waiting time if the ten minutes mean wind speed decreases below 20 m/s the turbine begins to startup and is fully available again and until another shut down condition is detected.

The second model has in common with the previous all the the mechanical and aerodynamic features, but the controllers are set up in order to simulate an HWRT logic. HWRT is implemented by modifying pitch and torque controllers. When the mean wind speed goes above 23 m/s, the wind turbine is not shut down but the blade pitch is increased in order to diminish the aerodynamic torque: as consequence even the generator controller slowly decreases its torque in order to maintain constant the rotational speed at the rated speed. This behaviour continues up to a wind speed of 32 m/s, where the generated power is zero: only in this moment the brakes are deployed and the turbine is arrested. Thanks to the HWRT logic, a wind turbine can be active in the range of 23-32 m/s of wind speed even with reduced produced power. The focal point of this study is to understand if this optimized power production can cause mechanical issues or a reduced expected life.

For both models, the FAST software gives many outputs, for the purpose of this study the most interesting are:

- high speed shaft velocity;
- generator torque;
- generator produced power;
- forces and moments at the root of the blades;
- forces and moments at tower base section.

Forces and moments are calculated with respect to two perpendicular axis (X and Y), respectively parallel and normal to wind direction.

3. Results

With the same input wind speed time series (Figure 3), two tests in standard and HWRT configuration are run with FAST.

The first comparison between the two models is addressed as regards the generator power. As can be seen in Figure 5 and Figure 6, the operation according to the standard model is abruptly shut down when the 5-minutes mean wind speed reaches the upper limit of 23 m/s: at this moment the turbine ceases to be productive. When the turbine is active (0-3000s), the mean power is practically rated; the average power on the whole time series is computed to be 1.14 MW. The average generator power for the HWRT model is almost the double on the whole time series: 2.16 MW. In the first 3000 seconds of the time series, the average power is slightly lower (2.24 MW) with respect to the standard model. This behaviour is justified considering that, if short gusts occurs without a significant increment of 5-minutes mean, the standard model keeps working at its rated power and instead the upgraded model reduces its produced power (compare Figure 1 to 2).

An additional useful consideration can be drawn calculating the standard deviation of the power on the first 3000 s. of the time series: for the baseline model, it results to be 26.4 kW, while for HWRT is 135 kW (order of 5 times). This is a first evidence that may lead to suppose that the HWRT has a more stressful behaviour on mechanical components of the wind turbine and for this reason a deeper study is necessary.

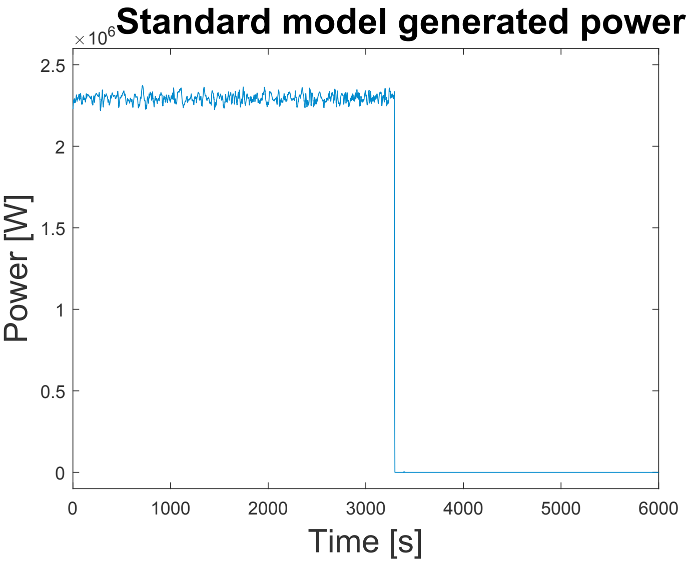

Fig. 5. Standard model produced power

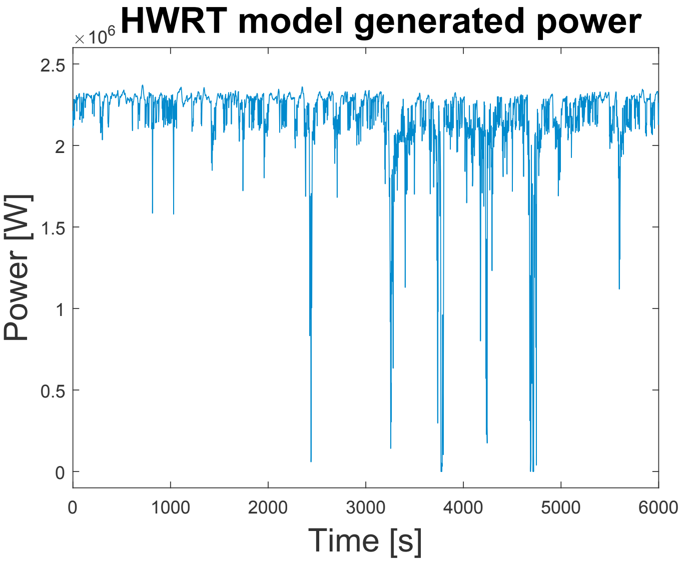

Fig. 6. HWRT model produced power

A second analysis is performed considering the *X* direction forces acting on the blade root and on the tower base.

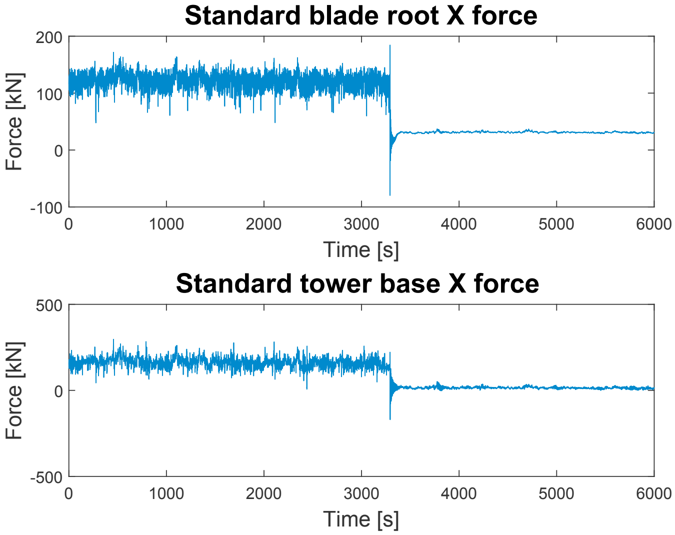

Fig. 7. Standard model forces in *X* direction.

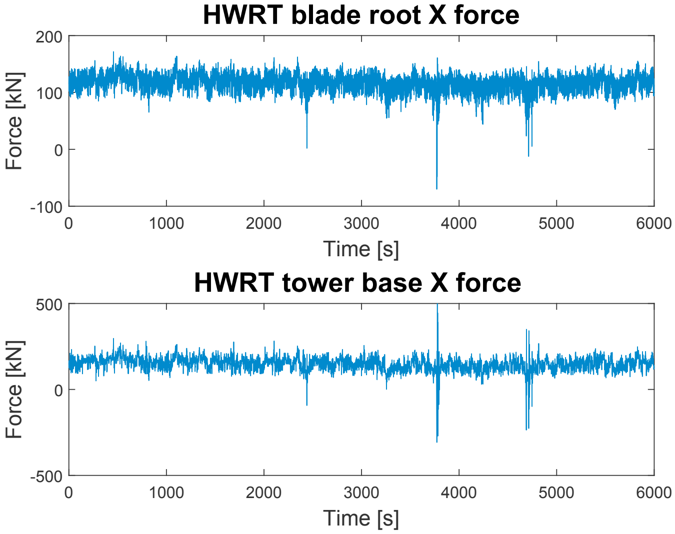

Fig. 8. HWRT model forces in *X* direction.

In Figure 9 and Figure 10, the out of plane and fore-aft moments, respectively calculated at blades roots and tower base, are shown for both cases of standard and upgraded models. As can be seen from the Figures, the most stressful instant for the standard model takes place during the shutdown event when the quick maneuvers on pitch angle and generator torque and the deployment of safety brakes tend to increase the forces acting on blades and, as consequence, on the tower. After the shutdown event, the turbine is kept in a safety state where moments are limited, with a mean values of 1800 kNm. For what concerns the HWRT model, it can be seen that moments mean values are 9162 kNm for the root of blade and 2146 kNm for tower base: these values are similar to the standard model ones calculated before the shutdown event (0-3000s): they result to be respectively 10530 kNm and 2344 kNm. While the mean values are of the same order of magnitude, remarkable differences occur when maximum values are taken in account: in the HWRT model, in fact, when the high speed gust occurs at 39 m/s the turbine is stressed with a force oscillation that is greater than the one that takes place during the shutdown event of the standard model.

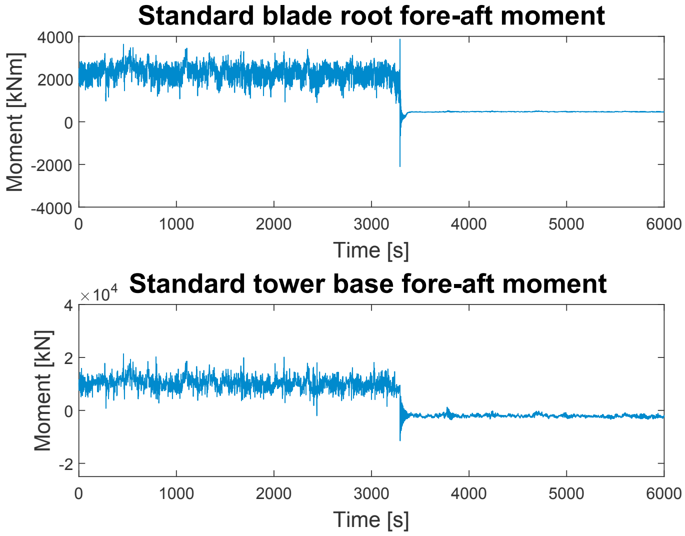

Fig. 9. Standard model out of plane moments and tower fore aft moment

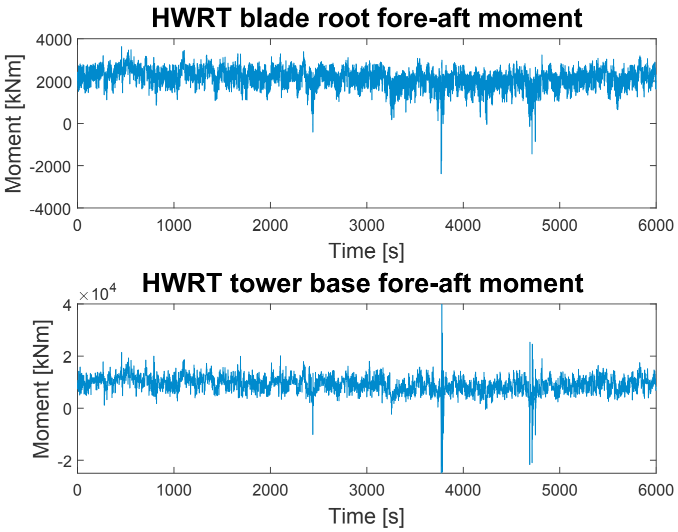

Fig. 10. HWRT model out of plane moments and tower fore aft moment

To have a deeper outlook on the effects of the stresses on the main components of the turbine, a rainflow counting algorithm is applied to base tower fore-aft moment induced stresses, obtained following ASTM E 1049 standard. This method is frequently used to analyze the cyclical loads of mechanical components and it can be profitably applied to wind turbine components, as shown for example in Rubert et al. (2019).

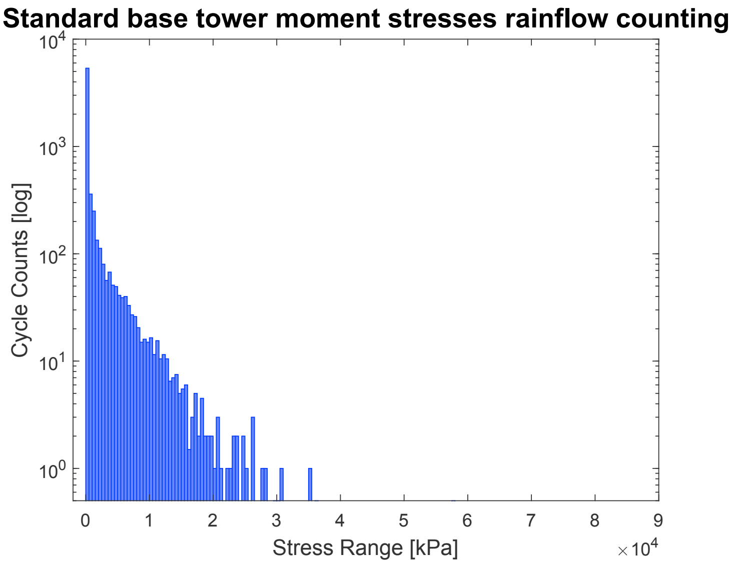

Fig. 11. Rainflow counting of tower base stresses induced by fore-aft moment, standard model

At first, moments obtained from the software have been used to calculate the stresses at the tower base section following the Navier formula:

$$\sigma_z = \frac{M_x}{I_{xx} r}, \tag{3}$$

where:

- σ_z: normal tension;
- M_y: moment load in $\mathrm{N/m^2}$;
- I_{xx}: inertia moment in m^4 about neutral axe;
- r: external radius.

Later on, the calculated stressed are used to assess a rainflow count in order to have a comparison between the standard model and the upgraded one. Rainflow algorithm allows counting how many times a cyclical stress with a defined amplitude takes place during the simulated interval. Thanks to this, it is possible to understand if the HWRT control can impact on the lifetime of the turbine. It has to be considered that only the stresses at tower base produced by fore-aft moment are taken in account in this analysis as they results to be of the highest magnitude. Side to side bending moments, in fact, are calculated too but their mean value is lower of a scaling factor of about 10 with respect the fore-aft moment.

Applying the rainflow counting algorithm, the histograms in Figure 11 and Figure 12 are obtained. It can be seen that the HWRT model is more subjected to high amplitude stress oscillations and even low amplitudes oscillations take place more frequently because of the more intense power fluctuations.

In the following, it has been supposed the turbine tower is realized in AISI A36 steel, a common steel frequently used for constructions purposes. The S-N curve of this material has been studied by Wang et al. (2010) and the fatigue limit has been estimated as 160 MPa within a range of ±1.25%. For each cycle, the rainflow counting algorithm gives as output the mean and the upper and lower values: in this way, it is possible to bring back the cycle with non zero mean in an equivalent one that has zero mean value and the same fatigue duration of the previous, as described by Goodman's theory. The formula used to calculate the purely alternate stress is the following:

$$\sigma_{ea} = \sigma_a - \frac{\sigma_a}{\sigma_m - \sigma_u}\sigma_m \tag{4}$$

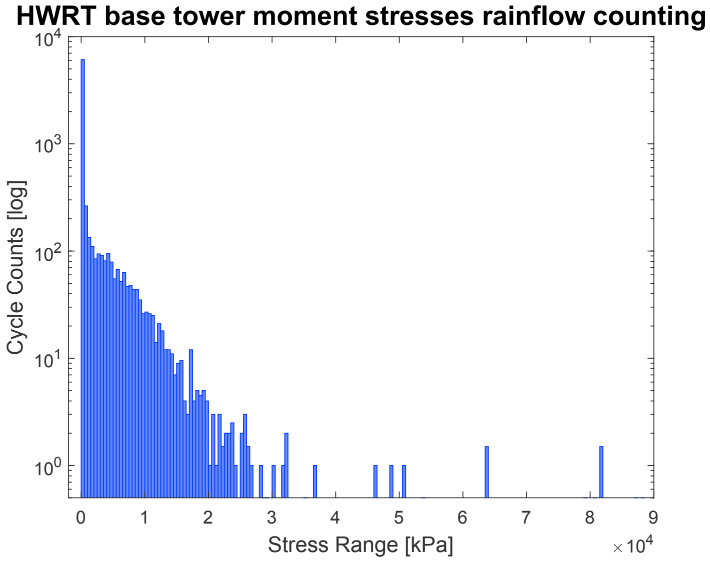

Fig. 12. Rainflow counting of tower base stresses induced by fore-aft moment, HWRT model

where:

- σ_{ea}: purely alternating stress;
- σ_a: amplitude of non-zero mean oscillation, calculated from rainflow counting;
- σ_m: mean value of stress oscillation;
- σ_u: ultimate yield 500 MPa.

From this, the maximum purely alternating stress for the y direction bending moment is 120 MPa, lower than than the fatigue limit of 160 MPa. Stresses related to shear forces or x direction moment results to be extremely lower than y direction moment generated stress: for this reason only this tension is considered to be the most relevant in this analysis. Knowing that the maximum stress calculated from rainflow counting does not decrease the fatigue life of the turbine tower, it can be stated that, whereas WHRT causes higher load level with respect the standard control, the safety margin are guaranteed even in consideration that the selected wind time series in real conditions has a very occasional occurrence.

4. Conclusions

In this work, a study has been set up in order to evaluate the effect of an innovative control for wind turbines, called HWRT, useful to increase the productivity of wind farms above design conditions (i.e. for extremely high wind speed). The employed methods involve a combination of operation data analysis (for a reverse engineering approach to the operation curves) and numerical simulations (through the aeroelastic software FAST, developed at the NREL). The motivations of this work lie in the fact that commonly the control optimization of operating wind turbines is assessed on the grounds of energetic considerations and little attention is devoted to the mechanical aspects and to the impact on the expected lifetime. In this sense, the selected test case is particularly meaningful because it deals with operation of the wind turbine at particularly extreme regimes.

Through the FAST simulation software, frequently used for scientific purposes in wind energy research, two models, with standard and HWRT control, have been implemented and then subjected to the same wind speed time series. As a preliminary investigation, the produced power according to both models is studied: the mean power of standard model results to be 1.14 MW while for HWRT model it is 2.16 MW. This happens because the HWRT model allows wind turbine operation for the whole time series, while according to the standard control the wind turbine stops at more or less half time series and does not restore operation until the end of the time series. The different dynamic behaviours can be highlighted by simply comparing the power standard deviation in the first half time series (when the wind turbine produces according to standard and upgraded control). For the standard model, the standard deviation is 26.4 kW and for the HWRT it is 135 kW: from this, it can be argued that the HWRT control may be more stressful on the machine.

To study in deep the implication of the HWRT control on mechanical stress, forces and moments at the base of the tower and the blade have been simulated. From this, it resulted that the HWRT model frequently shows wide peaks in correspondence of strong gusts. According to this, a rainflow counting algorithm has been used to make a comparison between standard and HWRT stresses at the base of the tower. It results that the operation according to the HWRT model undergoes high amplitude oscillation that are not present on the standard model; even low amplitude oscillations are more frequent in this model if compared to the standard one. To evaluate if the stress may have an impact on fatigue life of wind turbine, Wohler diagram has been used to find the limit fatigue stress. It resulted that all stresses are lower than limit one and therefore it can be stated that the HWRT control does not affect the expected lifetime of the turbine even if loads are higher than standard model.

The main future development of this study is to apply this method to other component of wind turbine that are more susceptible to loads oscillation. Under this point of view an advisable development of this study is to precisely characterize the material of the blade, in order to repeat the estimation of fatigue damage on this critical component. In general, developing reliable models for fatigue life of wind turbine components with innovative logic of control may be useful to optimize power production of wind farm without reducing the expected lifetime of turbines.

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