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Comparison of Down-Regulation Strategies for Wind Farm Control and their Effects on Fatigue Loads*

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Abstract— **With the growth of wind energy worldwide, an increased interest in wind farm control has become visible, with Active Power Control (APC) and Active Wake Control (AWC) being two primary examples. Both these methods rely on the down-regulation (i.e., operation using sub-optimal power settings) of wind turbines in order to provide such services. Apart from these services, down-regulation also affects the loads acting on a wind turbine. Hence, it is important to analyze the effects on the lifetime of wind turbine components, e.g., the tower, blades and rotor shaft.**

Earlier research on APC for wind farms has resulted in several down-regulation methods which were shown to reduce fatigue loads for some wind turbine components. One of these methods is called the percentage reserve method, which makes it possible for the wind turbine to generate a desired percentage of the available power at every wind speed. In this paper, different down-regulation strategies using the percentage reserve method are assessed on their capability of reducing fatigue loads.

The performance of the different control strategies is compared using aeroelastic simulations and by comparing the Damage Equivalent Loads (DELs) of several components for the whole range of operational wind speeds. The fatigue lifetime is analyzed by combining the DELs with a wind speed distribution for the turbine specific wind class. The results show that all down-regulation strategies are capable of achieving significant lifetime fatigue load reductions for some wind turbine components. Whichever strategy provides the best performance, depends on the user's wishes as well as the environmental conditions and the wind turbine in question.

I. INTRODUCTION

Recent years have seen a large increase in the number of installed and planned (offshore) wind farms, and it is expected that this increase will continue over the coming years. The rise in the number of wind farms has also led to an increased interest in wind farm control. Two primary examples of wind farm control are given by Active Power Control (APC) [1] and Active Wake Control (AWC) [2]. Both control types use the concept of down-regulation of wind turbines. The former example refers to the ability of having a wind farm follow a power set point supplied by the grid operator and providing ancillary power services such as grid stability. In case of AWC, down-regulation of the most upstream wind turbines can be used to reduce the wake deficit and decrease turbulence intensity in the wake in order to increase overall power capture and possibly reduce fatigue loads of downstream turbines.

There are several down-regulation methods which are often used for APC purposes [1], [3], [4]. One of these approaches is called de-rating and consists of controlling the maximum power output by reducing the rated generator torque while keeping the rated rotor speed unchanged. Another method, called delta reserve, keeps a fixed amount of the available aerodynamic power in reserve. A third approach is called percentage reserve and it is able to capture a percentage of the maximum available power over the entire range of operational wind speeds.

Both the delta reserve and percentage reserve methods use either torque control or pitch control in order to achieve the down-regulation. Using torque control, down-regulation can be achieved by operating the wind turbine above or below the optimal tip-speed ratio. For pitch control the rotor speed set point is decreased in order to start pitching below rated wind speeds. The working principle behind both torque and pitch control is that the aerodynamic efficiency of the wind turbine drops as a result of a sub-optimal tip-speed ratio or pitch angle. Wind turbine simulations using both these control methods indicate that down-regulation tends to decrease the fatigue loads on some of the structural components of a wind turbine [1], [4].

For the purpose of AWC, down-regulation is generally achieved through pitch control or yaw control. Pitch control is achieved by introducing a pitch offset in partial load, resulting in a decreased aerodynamic efficiency and hence decreased power production. Yaw control consists of misaligning upstream turbines so that the wake is (partially) redirected from downstream wind turbines. Subsequently, the yawed turbines will generate less power than in the nominal case, but the downstream turbines and the overall wind farm will generate more power. In this paper, down-regulation through yawing will not be considered.

The goal of this paper is to investigate the effect of down-regulation on wind turbine fatigue loads over the entire range of operational wind speeds. Only the loads of the down-regulated wind turbine are considered, and not those from wind turbines situated in the wake. The percentage reserve method is selected for this research, since it is able to track a percentage of the optimal power coefficient C_p and can therefore be applied at every wind speed. In previous research concerning the effects of down-regulation on the loads, this method was implemented by adjusting the torque controller and by lowering the torque limit [4]. In this paper some additional control strategies will be implemented and their effects on the loads will be assessed.

This paper is organized in the following way. Section II

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presents all the down-regulation strategies which are added to the baseline wind turbine controller. A distinction is made between down-regulation methods for partial and full load. In Section III, different combinations of these strategies will be used in aeroelastic simulations of the DTU 10 MW reference wind turbine [5]. Subsequently, their effects on the loads are analyzed by means of Damage Equivalent Loads (DELs). Finally, Section IV provides some conclusions on down-regulation strategies.

II. DOWN-REGULATION STRATEGIES

The operation of a wind turbine can roughly be divided into two regions, one where the turbine operates below the rated wind speed (partial load) and another where it operates above the rated wind speed (full load). Separate down-regulation strategies for both these regions are discussed next.

A. Down-Regulation in Partial Load

The power generated by a wind turbine can be expressed by the following equation

$$P = \frac{1}{2}\rho C_P A V_w^3, \tag{1}$$

with ρ being the density, C_p the power coefficient and A the effective rotor area. In partial load, the controller aims to maximize the power production by tracking the optimal power coefficient $C_{p,opt}$ until rated power is reached. This optimal C_p is a function of the tip-speed ratio (TSR) and the pitch angle. Consequently, the power production can be maximized by controlling the rotor speed through the generator torque such that the wind turbine is operating at the desired TSR. The pitch angle is generally held constant during this process.

Down-regulation through the percentage reserve method simply consists of tracking a sub-optimal C_p, being an arbitrary percentage of $C_{p,opt}$. Since the power coefficient is a function of the TSR and the pitch angle, it can be decreased by changing one or both of these parameters. Three different down-regulation strategies in partial load will now be discussed with the help of Fig. 1, which depicts the contour curves of the power coefficient C_p as a function of TSR and pitch angle.

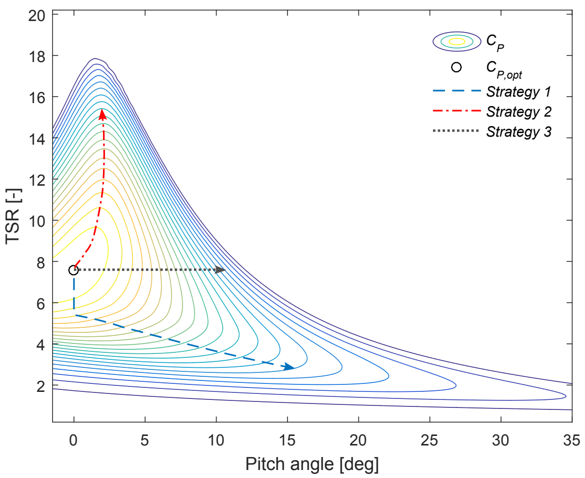

Fig. 1. Contour plot of the power coefficient C_p indicating the three down-regulation strategies in partial load for the DTU 10 MW turbine.

The first down-regulation strategy in partial load consists of operating the wind turbine at a lower TSR, i.e., the wind turbine is operated at a lower rotational velocity at wind speeds below rated. However, as can be seen in Fig. 1, a pitch offset is also introduced below a certain TSR. This pitch offset is necessary in order to prevent that the wind turbine starts operating in the stall region, which is undesirable.

The second strategy reduces the power coefficient by increasing the TSR, thus increasing the rotor speed at lower wind speeds. As a result, the rated rotor speed is reached at a lower wind speed than usual. An advantage of this strategy compared to the first strategy is that due to the higher rotor speed more kinetic energy is stored in the rotor, making it possible to quickly return to a higher power level. A disadvantage is the fact that the rotor shaft has more rotations over the lifetime, which may negatively affect the bearings. In Fig. 1, it can be seen that this strategy also introduces a small pitch offset. This is done in order to prevent operation at the left hand side of the maximum C_p on a C_p curve as function of the pitch angle, which would initially lead to an increase in power if the blades need to be pitched at a higher wind speed.

The final strategy consists of increasing the initial pitch angle in order to reduce the C_p by an arbitrary percentage while keeping the TSR constant. A disadvantage of down-regulation through pitch control is that the response is slower compared to the first two strategies which use torque control.

B. Down-Regulation in Full Load

In full load, the wind turbine operates at the rated rotor speed and now the rotor is controlled through a pitch action of the blades. In the case of down-regulation at full load, two simple methods can be applied. The first method was presented in Section I as de-rating and consists of decreasing the rated generator torque by a desired percentage. The second method reduces the rated rotor speed by the desired percentage. With respect to the dynamics of the response, the first method is preferred since this allows for a quicker recovery of the turbine's production when down-regulation is no longer required. Additionally, if the rotor speed is reduced the turbine will operate in a narrower rotor speed region making it difficult to achieve high down-regulation percentages. Both methods require an additional pitch offset compared to the baseline controller.

In this paper the effects on the loads of both rated torque reduction (a) and rated rotor speed reduction (b) in combination with the three partial load down-regulation strategies are evaluated. As a result, a total of six down-regulation strategies are added to the baseline controller. An overview of these six strategies is presented in Table I.

TABLE I

OVERVIEW OF THE DOWN-REGULATION CONTROL STRATEGIES.

Strategy	Partial Load	Full Load
1a	TSR$\searrow$, $\theta \nearrow$	$\tau_{gen} \searrow$
1b	TSR$\searrow$, $\theta \nearrow$	$\Omega_{gen} \searrow$
2a	TSR$\nearrow$, $\theta \nearrow$	$\tau_{gen} \searrow$
2b	TSR$\nearrow$, $\theta \nearrow$	$\Omega_{gen} \searrow$
3a	$\theta \nearrow$	$\tau_{gen} \searrow$
3b	$\theta \nearrow$	$\Omega_{gen} \searrow$

The different down-regulation strategies are compared to the baseline controller in Figs. 2 and 3 in terms of their torque-speed and pitch angle curves. These curves are generated in advance and are fed to the controller as reference set points. In this case, the operating curves were computed at 20% down-regulation and by using torque reduction at full load. Looking at Fig. 3, it can be noticed that for the second down-regulation strategy an additional pitch offset is required at lower wind speeds than for the other two down-regulation strategies. This is due to the fact that the rated rotor speed is reached relatively fast, at which point the TSR will start dropping and thus the power coefficient will increase (see Fig. 1). In order to compensate for this increased C_p, it is necessary to increase the pitch angle at lower wind speeds.

C. Down-Regulation Effects on Thrust Force

In addition to investigating the effects of the different down-regulation strategies on the loads of the wind turbine, it is also interesting to analyse the effects on the thrust force. The thrust force is an important aspect for induction based AWC [2], as it provides an indication of the amount of energy left in the wind once it has passed the rotor. Induction based AWC uses this aspect to increase the amount of energy in the wake so that there is more energy available for downstream turbines. Even though upstream turbines generate less energy, the overall energy production of a wind farm can be increased in this way.

Using the thrust coefficient C_T, it is possible to estimate the thrust force the wind turbine will be experiencing at each wind speed. In this way the effects of down-regulation on the thrust force can be investigated. A contour plot of C_T is provided in Fig. 4 along with the three down-regulation strategies in partial load that were presented in Fig. 1. It can be observed that both strategies 1 and 3 will result in a lower C_T value and hence a lower thrust force. However, the thrust coefficient does not change much when strategy 2 is used.

The thrust force can be computed for the entire range of wind speeds using

$$T = \frac{1}{2}\rho C_T A V_w^2. \tag{2}$$

The static thrust force is presented as a function of the wind speed in Fig. 5 for the strategies that limit the generator torque. It can be observed that the maximum thrust force is reached at rated wind speed, after which it starts to decrease when the pitch controller is activated. As expected, strategies 1a and 3a both result in a significant decrease of the thrust force at every wind speed. By using strategy 2a, the thrust force is initially the same as when the baseline controller is used. However, once the rated rotor speed is reached, the thrust force starts approaching the other two strategies. This is the result of the early pitch action seen in Fig. 3, which decreases the axial induction. In the case that the maximum rotor speed is lowered an even larger decrease in thrust force is expected at above rated wind speeds, since a lower TSR gives an additional decrease in C_T.

III. FATIGUE LOADS ANALYSIS

The effects of the different control strategies on fatigue loads are assessed using aeroelastic simulations with Focus/Phatas. For this purpose, the DTU 10 MW reference wind turbine is used with a desired down-regulation percentage of 20%. This turbine has a rotor diameter of $D = 178.3$

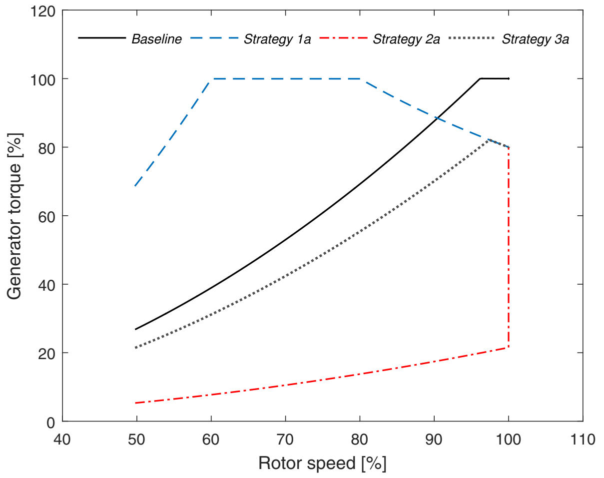

Fig. 2. Torque-speed curves for different partial load strategies in combination with rated generator torque reduction at 20% down-regulation.

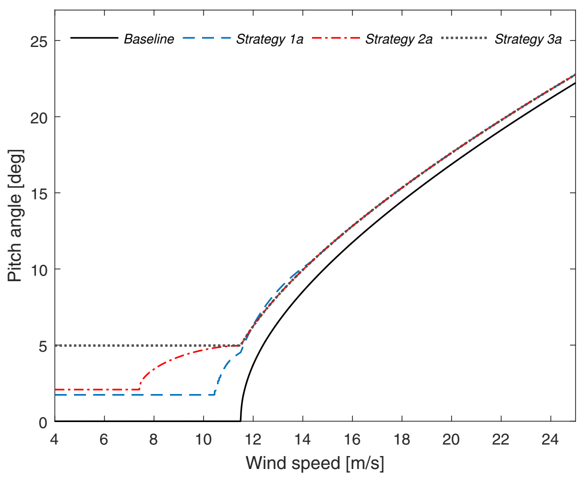

Fig. 3. Pitch angle curves for the different partial load strategies in combination with rated generator torque reduction at 20% down-regulation.

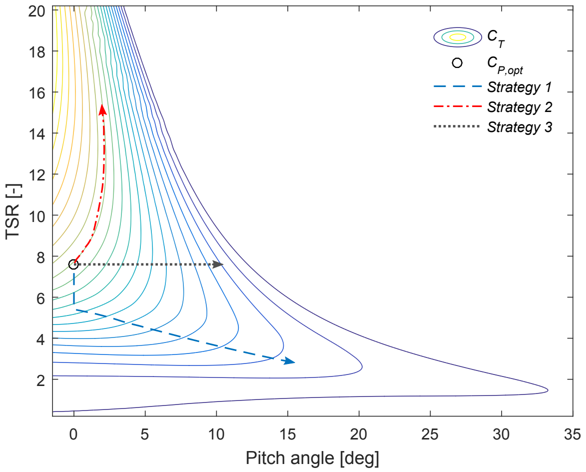

Fig. 4. Contour plot of the thrust coefficient C_T along with the three down-regulation strategies in partial load.

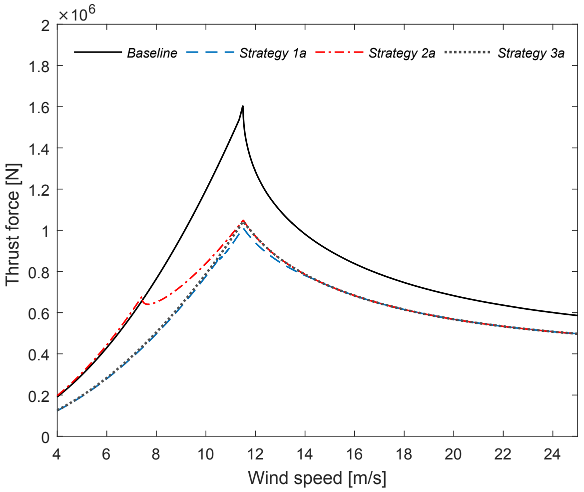

Fig. 5. Comparison of the (static) thrust force as a function of wind speed for the partial load strategies in combination with rated generator torque reduction at 20% down-regulation.

m and rated rotor speed of $\Omega = 9.6$ rpm. Since the effects on fatigue loads are of primary interest, the simulations are performed for normal operation with wind speeds ranging from $V = 4 - 25$ m/s, using a normal turbulence model with turbulence intensity of 16% and six realizations per wind speed corresponding to Design Load Case 1.2 for a wind turbine of class 1A [6].

A. Simulation Results

The performance of the down-regulation strategies is compared to the case of the baseline controller in terms of fatigue loading on a number of selected structural wind turbine components, i.e., the tower (bottom), the blade roots and the rotor shaft. The DELs are computed through a rainflow count and using Wöhler exponents $m = 3$ and $m = 10$ for the steel components and blades, respectively. The DELs consist of the 1 Hz equivalent fatigue loads, i.e., the single load amplitudes with a frequency of 1 Hz that represent the fatigue loading of the sum of all the different amplitudes during the considered time series. The results of the simulations for several components are presented in Figs. 6-8 as an increase or decrease in loads relative to the baseline controller case.

The effects of the different down-regulation strategies on tower loads are depicted in Fig. 6. It can be observed that by increasing the TSR or by pitching the blades in partial load, a significant decrease in fatigue loads can be achieved at below rated wind speeds. In the case where the TSR is lowered, an increase in fatigue loads at wind speeds around $V = 8$ m/s is visible. In order to understand the cause of this increase in fatigue loads, the two time series given in Figs. 10 and 11 are investigated. In Fig. 11, it is observed that the absolute displacement of the tower top is many times greater while down-regulation strategy 1a is applied. This was caused by some resonance occurring due to prolonged operation at a rotor speed of approximately $\Omega = 5$ rpm, for which the $3P$ blade passing frequency is very close to the first tower frequency.

Another interesting observation from Fig. 6 is that strategies which reduce the rated rotor speed at full load result in slightly higher tower fatigue loads than in the case of baseline controller. This increase in fatigue loads is thought to be the result of a decrease in aerodynamic damping, which is the result of lower relative velocities between the blades and the wind as well as higher pitch angles when the rated rotor speed is reduced.

Increased fatigue loads at the blade roots are observed in Fig. 7 at very low wind speeds for strategies 2a and 2b. This is the result of operation at higher rotor speeds compared to the baseline controller at these wind speeds. The other strategies operate the turbine at lower rotor speeds and hence achieve a decrease in fatigue loads at low wind speeds. At higher wind speeds the strategies which limit the maximum rotor speed are able to reduce the loads.

In Fig. 8, it can be observed that the DELs of the rotor shaft bending moment increase at wind speeds around $V = 6$ m/s when using down-regulation strategies 2a and 2b. This is also due to the higher rotational velocity of the rotor which results in higher bending moments of the blades. In turn, this also leads to higher bending moments and thus fatigue loads in the rotor shaft. At higher wind speeds it is observed that reducing the rated rotor speed has a positive influence on the fatigue loads on the shaft, while reducing the maximum generator torque results in similar loads as in the case of the baseline controller.

Finally, the relative energy production of each strategy is presented in Fig. 9. It is seen that strategies 1a and 1b are not capable of attaining the desired down-regulation level at very low wind speeds. These wind speeds are too low for the controller to follow the torque-speed curve given in Fig. 2. To a lesser degree this can also be said about strategies 2a and 2b, but the desired down-regulation level is achieved at low wind speeds. The most stable performance is given when down-regulation through pitching is used.

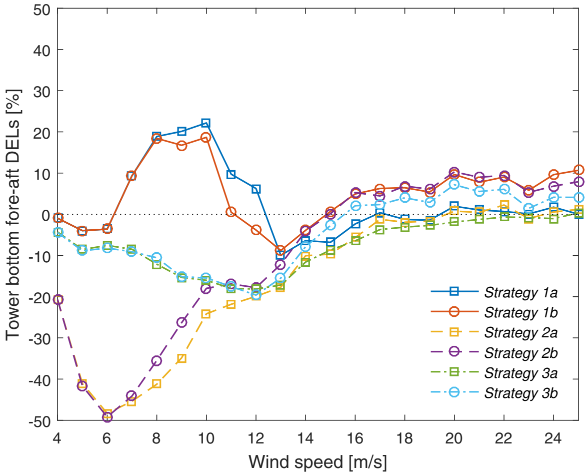

Fig. 6. Average DELs of the tower bottom in the fore-aft direction over a range of wind speeds for 20% down-regulation using proposed down-regulation strategies.

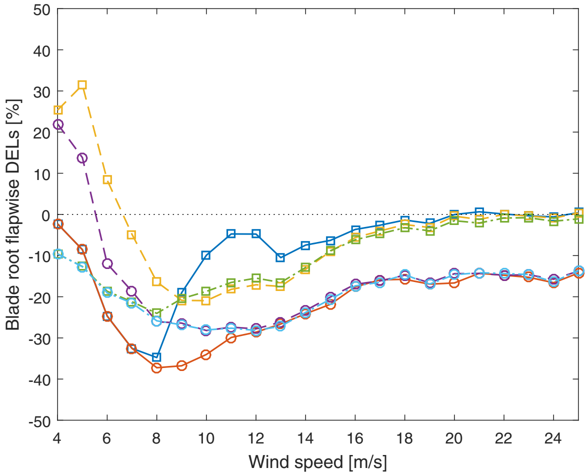

Fig. 7. Average DELs of the blade root in the flapwise direction over a range of wind speeds for 20% down-regulation using proposed down-regulation strategies.

B. Lifetime Fatigue Loads

Besides evaluating the fatigue loads at different wind speeds, it is also interesting to see what the effect of down-regulation is on the lifetime fatigue loads of a wind turbine. This is done by weighting the DELs that were computed earlier with a given wind distribution. The DTU 10 MW turbine is designed as a class 1A wind turbine [5], for which a Rayleigh wind distribution with average wind speed $V_{avg} = 10$ m/s is taken [6]. Using this wind distribution, the lifetime fatigue loads of several wind turbine components are computed for each down-regulation strategy and compared to the fatigue loads from the baseline controller. In order to have a clear comparison, it is assumed that the down-regulation strategies are used for the entire 20 year lifetime of the turbine. The results of this analysis are presented in Table 2.

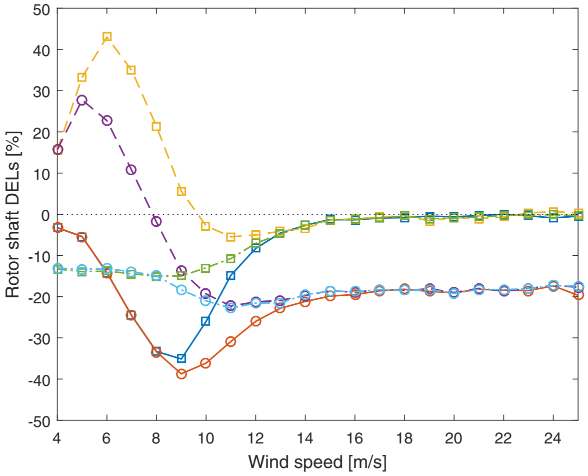

Fig. 8. Average DELs of the rotor shaft bending moment over a range of wind speeds for 20% down-regulation using proposed down-regulation strategies.

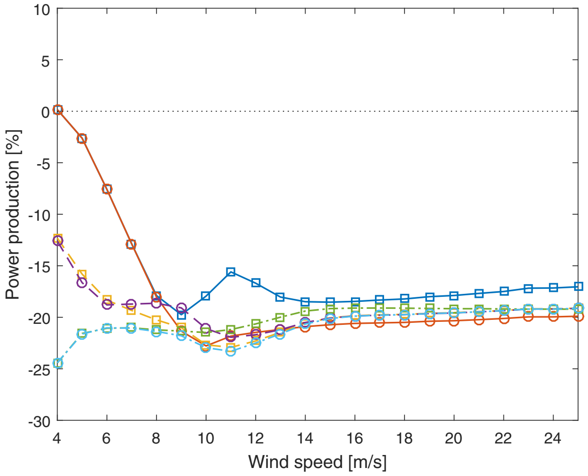

Fig. 9. Average power production of the wind turbine over a range of wind speeds for 20% down-regulation using proposed down-regulation strategies.

It is observed that strategies 1a and 1b, as well as strategies that limit the maximum rotor speed, result in increased tower loads. Especially the loads in the sideward direction see a large increase, although these loads are a lot smaller compared to the loads in fore-aft direction and might not necessarily be an issue. For the remaining components most of the down-regulation strategies are able to reduce the fatigue loads. It seems that strategy 2a is able to reach the highest load reductions, while strategy 3a reduces the lifetime loads of every component. In the end, selecting the right down-regulation strategy will depend on the type of turbine, the environmental conditions at the turbine site and the priority of certain wind turbine components.

IV. CONCLUSIONS

For this paper, multiple down-regulation strategies for wind farm control were compared using aeroelastic simula-

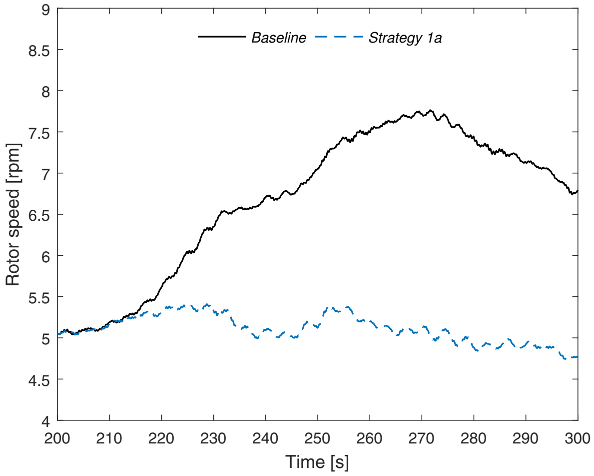

Fig. 10. Time series of the wind turbine's rotor speed for 20% down-regulation and average wind speed of $V = 8$ m/s.

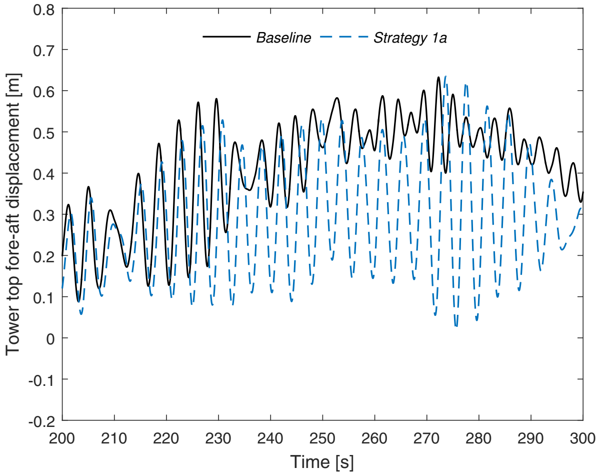

Fig. 11. Time series of the wind turbine's tower top displacement in the fore-aft direction for 20% down-regulation and average wind speed of $V = 8$ m/s.

tions with the DTU 10 MW wind turbine. Three approaches were used during partial load by altering the optimal TSR or pitch angles. In full load operation, either the rated generator torque or the rated rotor speed was reduced. By combining all these approaches, a total of six down-regulation strategies were assessed with respect to their effect on fatigue loading.

Initial analysis of these strategies focused on the pitch activity and thrust force of the wind turbine. It was observed that strategies adjusting the desired TSR, required a pitch offset at lower wind speeds compared to the baseline controller. It is expected that this will have a negative impact on the fatigue of the pitch bearings. When down-regulation is performed by pitching this will not be the case, since it only introduces an additional offset and pitching at lower wind speeds is not required. Using the C_T coefficients, the expected thrust force could also be determined. It was seen that all down-regulation strategies will result in an overall decrease in thrust force.

The fatigue loads of several structural wind turbine components were analyzed by computing the DELs over the entire range of operational wind speeds for each strategy at 20% down-regulation. These DELs were then compared to those resulting from operation using the baseline controller. It was found that all strategies are capable of reducing the loads for some wind turbine components. By lowering the desired TSR, the loads at both the blade roots and the rotor shaft could be decreased. Increasing the TSR resulted in a significant decrease of tower loads. However, the most stable performance was seen when the pitch angle was increased, which leads to a reduction of fatigue loads at all the selected components. Subsequently, the lifetime fatigue loads were computed using an arbitrary wind distribution. Load reductions in the order of 20% were observed for some components. Depending on the wind turbine and environmental conditions, any of these down-regulation strategies can be applied in order to achieve fatigue load reductions.

TABLE II

COMPARISON OF THE LIFETIME DELS RELATIVE TO THE BASELINE CONTROLLER OF SEVERAL STRUCTURAL WIND TURBINE COMPONENTS AND ENERGY PRODUCTION USING DOWN-REGULATION STRATEGIES.

	Strategy					
Component	1a	1b	2a	2b	3a	3b
Tower bottom fore-aft	+3.3%	+3.9%	-18.5%	-12.3%	-9.3%	-6.7%
Tower bottom sideward	+37.5%	+52.4%	-21.0%	+7.8%	-6.6%	+11.9%
Blade root flapwise	-3.0%	-18.2%	-4.7%	-17.7%	-5.3%	-17.9%
Blade root edgewise	-0.4%	+0.6%	+0.4%	+1.2%	-0.1%	+0.8%
Rotor shaft	-6.5%	-22.8%	+0.4%	-17.0%	-4.5%	-19.3%
Energy production	-17.1%	-20.1%	-20.8%	-20.3%	-20.3%	-21.3%

Further research should focus on the implementation of these strategies in a wind farm setting, in order to analyze the effects of down-regulation on the loads of wind turbines situated in the wake of the down-regulated turbine.

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