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Derating a single wind farm turbine for reducing its wake and fatigue

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Abstract. Derating of individual turbines is one of the options to implement wind farm performance optimization, although there are different ways to proceed with such derating at the turbine control level. The present paper develops an option based on the minimal thrust coefficient in accordance with the C_p and C_t contour levels. This strategy is compared for the region below rated wind speed with two other strategies where either the pitch or the tip speed ratio are maintained at their maximum C_p values from normal operation. The study concludes that maintaining the pitch at the optimal value from normal operation produces poorer performance from the thrust and the loads perspective. Practical implementation issues have also been detected.

1. Introduction

Presently, and in the foreseeable future, the expansion of wind turbine capacity is in farms, onshore and especially offshore. The turbines interact through their wakes in the flow field they are sharing. Therefore it is of major importance to optimize performance of the collection of turbines instead of optimizing each individual turbine performance.

When a wind turbine is placed in an air flow, forces on the rotor blades can be decomposed into: 1) thrust in the wind direction bending the tower and 2) torque driving the rotor to produce useful energy. However, reaction forces from the rotor to the air flow also changes the flow both 1 to 2 diameters upwind of the turbine and up to at least 10 diameters downwind of the turbine. The effect downwind is called the wake and this is more important as it can cover other turbines in a farm. In the wake wind speed will be reduced and the turbulence intensity increased. The operation of the turbine affects the aerodynamics and changes the wake from full wake at full load to virtually no wake at freewheeling with 90 degrees pitch.

Wind farm control can be structured in a top level where set points are sent to the single turbines to control the flow in the wind farm and a single turbine level where the turbine controller implements these set points [1]. The wake can be controlled by a combination of wake steering and derating of the turbine [2], [3]. Here only the latter is considered. Derating the turbine means operating the turbine at a lower power than it could deliver based on the wind conditions and its power curve [4].

A large part of the literature in this area focuses on the farm top level without explaining in detail how the single turbines can implement the set points from such top level [1]. As an example, [5] uses the induction factor on the single turbine as control handle without explaining how it will be achieved on the turbines.

In the literature on control for derating a single turbine, there is focus on derating for ancillary services such as primary frequency control [6], [7], [8], power curtailment [9], providing reserve power [10] and surviving extreme turbulence [4]. For these applications the solution is to follow a specific power reference for the single turbine throughout the whole wind speed range.

In this paper the purpose of derating the single turbine is to be able to maximize wind farm power while minimizing fatigue. Control at the farm level is however not considered here. The contribution of the paper is firstly to suggest the operation at minimum C_t for given relative derating, focusing on operation for wind speeds below rated, and based on relative power (fraction of produced over available power) as the best interface between farm and turbine controller. Secondly, to access the performance effect of this for the INNWIND.EU 10MW virtual turbine (also called DTU10MW).

2. Derating control strategy

Axial induction control refers to the optimization of a wind farm in terms of power production and fatigue loading using derating of several wind turbines. This results in less turbulent wakes from these turbines while leaving more energy in the wind for downstream turbines to extract. The operation of a turbine can be characterized by the tip speed ratio (TSR) and pitch angle. From simple theory this gives the power and thrust given by

$$P = \frac{1}{2}\rho A v^3 C_p(\beta,\lambda)\ ,\ T = \frac{1}{2}\rho A v^2 C_t(\beta,\lambda)\ ,\ \lambda = \frac{\omega_r R}{v} \tag{1}$$

where β is the pitch angle, λ is the TSR, ρ is air density, A is rotor area, ω_r is the rotor speed, R is the rotor radius and v is ambient wind speed. The thrust is the sum of blade forces in the wind direction. It is fair to assume that decreased mean thrust also generally decreases thrust variation, and thereby standard deviation, which in turn decreases blade and tower fatigue.

The power coefficient C_p and thrust coefficient C_t functions for the INNWIND.EU 10MW turbine are shown by contour curves in Figure 1. When the turbine is operating at some (β,λ) point, it can be derated by moving to a lower C_p contour. However, there is some freedom in choosing the particular operating point on this contour. Depending on the wind speed, the admissible points can be limited by minimum and maximum rotor speed. Stall should also be avoided.

To characterize the operation points effect on the wake generated by the derated turbine, static models from the literature are used.

A simple expression for the center wake wind speed v_w is given by the "Jensen" model as follows [11]:

$$v_w = (1 - kC_t)v\ ,\ k = \frac{1}{2\left(1 + \frac{d}{2D}\right)} \tag{2}$$

where v is the ambient wind speed, D is the rotor diameter and d is the distance downwind from the wake generating turbine to the location for v_w. Notice that $0 \leq k \leq 1/2$ and it can be assumed that $0 \leq C_t \leq 1$ in normal operation. Therefore the factor $(1 - kC_t)$ will be in the range $[1/2, 1]$ which complies with it being positive from a physical point of view as the wake wind speed will not be negative.

In the wake from the turbine the total wind speed variance σ_w^2 can be expressed as [12, 13]

$$\sigma_w^2 = \left(t_{ad}^2 + t_a^2\right) v_w^2 \tag{3}$$

where t_a is the ambient wind speed turbulence intensity and

$$t_{ad} = \left(1.5 + \frac{0.8d}{D\sqrt{C_t}}\right)^{-1} \tag{4}$$

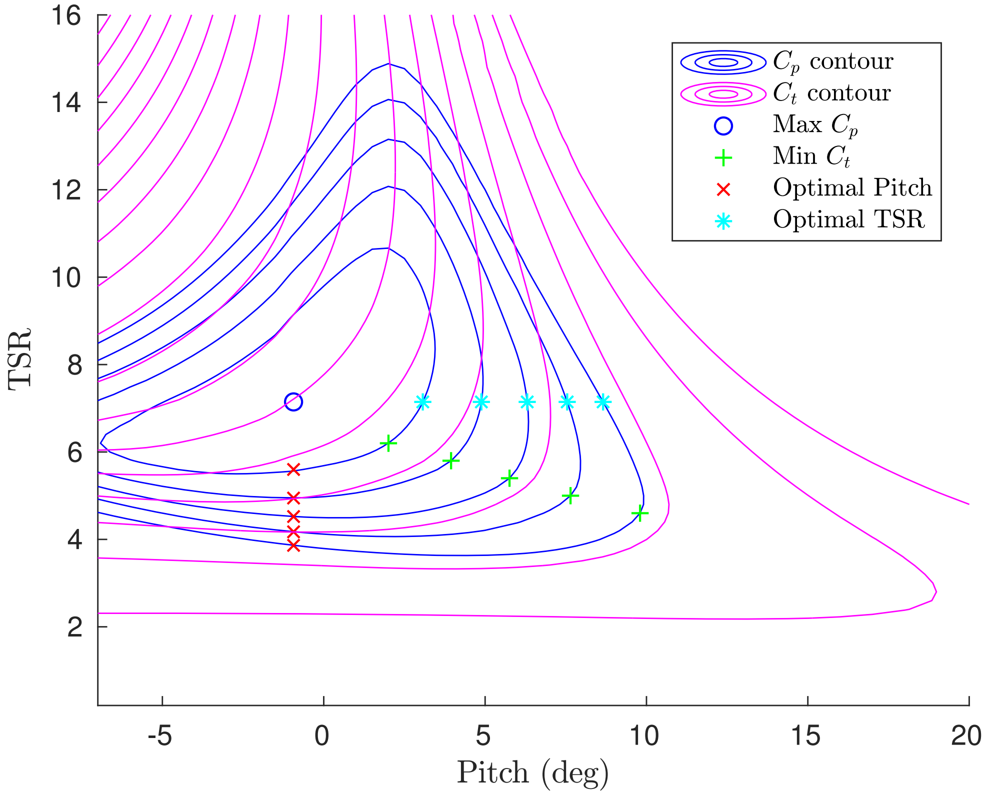


Figure 1. C_p and C_t contours for INNWIND.EU 10MW. The levels for the C_t contours is decreasing from the upper left towards the lower right of the figure. The relative C_p contour levels are 0.5, 0.6, 0.7, 0.8 and 0.9. Different strategies for derating in cyan (optimal TSR), green (minimum C_t) and red (optimal pitch).

Because of (3) t_{ad} can be interpreted as added turbulence intensity.

It follows from (2) that decreasing C_t increases wind speed in the wake, and decreases the added turbulence intensity according to (4). The question is then what happens to the total turbulence in the wake σ_w^2 when decreasing C_t.

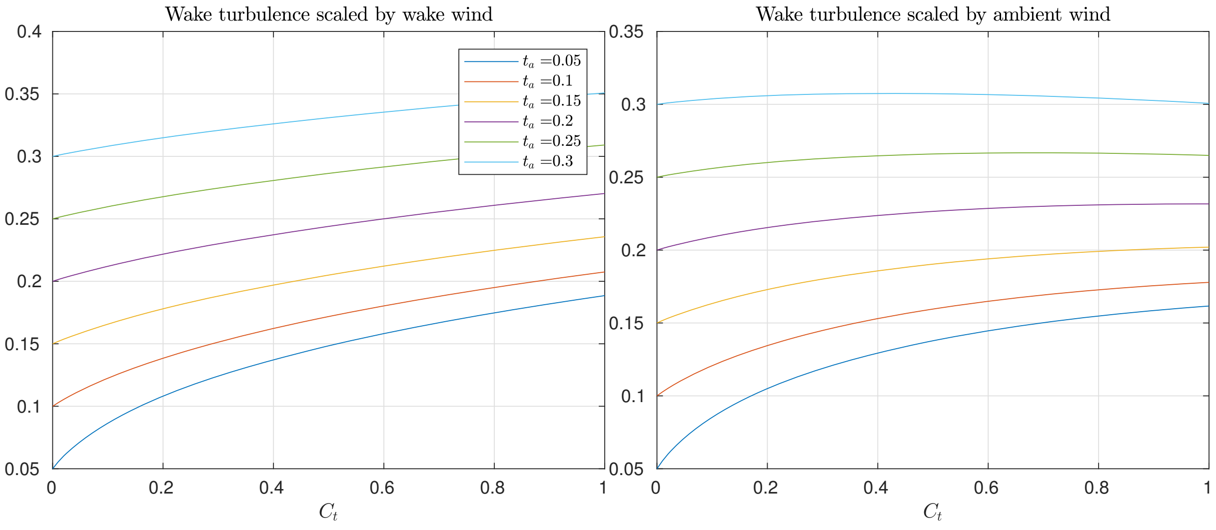
Inserting (2) and (4) into (3) gives the wake wind speed variance and standard deviation as follows

$$\sigma_w^2 = \left(\left(1.5 + \frac{0.8d}{D\sqrt{C_t}}\right)^{-2} + t_a^2\right)(1 - kC_t)^2 v^2 \Leftrightarrow \tag{5}$$

$$\sigma_w = \sqrt{\left(\left(1.5 + \frac{0.8d}{D\sqrt{C_t}}\right)^{-2} + t_a^2\right)}(1 - kC_t)v \tag{6}$$

Clearly, the relation between σ_w^2 and C_t is given solely by the first two factors in (5). Differentiating this with respect to C_t gives a rather complicated expression which cannot be proved to be positive always. Moreover, it is clear from (5) that if t_a is so large that it dominates the first factor then σ_w^2 will decrease with C_t due to the second factor. Figure 2 shows (a) plot of the first factor in (6) and (b) the product of the first two factors in (6) for ambient turbulence intensity from 5 to 30%. Subplot (a) only verifies that the first factor always increases with C_t. More interesting subplot (b) shows that the product of the first two factors, and thereby the standard deviation σ_w, and thus also the variance σ_w^2, increases with C_t as long as the ambient turbulence intensity is below 25% which it normally is, especially for offshore. Moreover, high ambient turbulence reduces the potential gains from using derating for farm control [14]. The above calculations are made for $d/D = 5$ but the results for $d/D \in [3-9]$ are similar.

In conclusion: a low value for C_t for an upwind turbine is good for both power production and fatigue for a turbine in the wake.



(a) (b)

Figure 2. (a) first factor in (6) i.e. wake turbulence scaled by wake wind; (b) product of the first two factors in (6) i.e. wake turbulence scaled by ambient wind. $d/D = 5$.

2.1. Operational points

The strategy put forward here is to choose the point on the derated C_p contour that has the smallest C_t as this is expected to reduce fatigue on both the wake-generating turbine and the turbines affected by the wake given that the turbulence is reduced while wind speed in the wake is increased as explained above. Mathematically this strategy can be formulated as: for a given relative derating δ use the β, λ solving the minimization problem:

$$\min_{\beta,\lambda} C_t(\beta,\lambda) \tag{7a}$$

subject to

$$C_p(\beta,\lambda) = \delta C_p(\beta_m,\lambda_m) \tag{7b}$$

where β_m, λ_m correspond to maximum C_p operation that is usually applied in this control region below rated. The resulting point can be found using numerical methods. Additionally, the point on the same contour but where either β or λ are fixed at max C_p values can be found numerically by solving respectively

$$C_p(\beta_m,\lambda) = \delta C_p(\beta_m,\lambda_m) \tag{8}$$
$$C_p(\beta,\lambda_m) = \delta C_p(\beta_m,\lambda_m) \tag{9}$$

All the above are illustrated in Figure 1.

2.2. Achieving this with a standard wind turbine controller in partial load

The problem is now how to achieve the desired (β,λ) using a standard turbine controller. In partial load the pitch can directly be set to the desired β. The standard generator torque controller for this region is $Q_g = K\omega_g^2$. As shown below the solution consists in simply adjusting the gain K in this torque controller, particularized for the derated operating point at $\delta C_{p,max}$:

$$Q_r = \frac{P}{\omega_r} = \frac{1}{2}\rho A v^3 C_p(\beta,\lambda)\frac{1}{\omega_r} \tag{10}$$

using

$$\lambda = \frac{\omega_r R}{v}\ ,\ C_p(\beta,\lambda) = \delta C_{p,max} \tag{11}$$

gives

$$Q_r = \frac{1}{2}\rho A\left(\frac{\omega_r R}{\lambda}\right)^3 \delta C_{p,max}\frac{1}{\omega_r} = \frac{1}{2}\rho A\left(\frac{R}{\lambda}\right)^3 \delta C_{p,max}\omega_r^2 \tag{12}$$

using generator values

$$Q_g = \frac{1}{N}Q_r\ ,\ \omega_g = N\omega_r \tag{13}$$

where N is the gearbox ratio, the below is obtained

$$Q_g = K\omega_g^2\ ,\ K = \frac{1}{2}\rho A\left(\frac{R}{\lambda N}\right)^3 \delta C_{p,max} \tag{14}$$

Notice that a wind speed estimate is not needed using this method for relative derating when referring the derated point to the maximum power coefficient point. It will require however proper characterization of the $C_p(\beta,\lambda)$ and $C_t(\beta,\lambda)$ surfaces through suitable modeling of the rotor characteristics.

The implementation for example of the minimum C_t control strategy is as follows:

- Offline:
  - Calculate the table relating δ to β,λ by numerically solving (7) as illustrated in figure 1.
- Online at every sample time as long as $\omega_{g,min} \leq \omega_g \leq \omega_{g,max}$:
  - Low pass filter δ commands to make sure it is slowly varying.
  - Look up the corresponding (β,λ) point.
  - Directly set pitch to β.
  - Calculate K from δ and λ (14) and set it in the torque controller.

The above can also be used for the other strategies as (8) for the optimal pitch strategy and (9) for the optimal TSR strategy if the corresponding tables are used in the offline step. If the generator speed meets a limit the above must be modified.

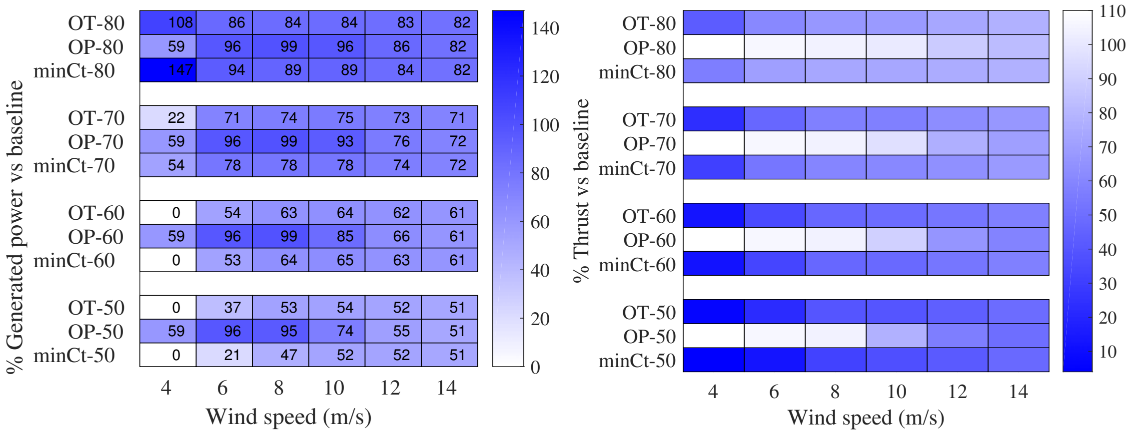
3. Simulations and discussion

The wind turbine control strategies described in Section 2 have been implemented in the INNWIND.EU 10MW reference wind turbine by means of the open access controller developed within CL-Windcon project [15], which was used as a baseline. Simulations have been performed by using the aeroelastic code FAST v8.16 for the design load case DLC 1.2 in order to assess the related fatigue loads with normal operation production and turbulent wind speeds. Each particular derating is applied during all the simulation. To focus on the region below rated, the results concentrate on the range of wind speeds from 4 m/s to 12 m/s each 2 m/s. Excursions above rated are covered by a derated torque implementation, in which reference torque set point is reduced not to exceed the targeted derated power. In region 3, pitch angle is used to control generator speed.

For each wind speed, three derating strategies have been analyzed, namely (β, λ) operating points corresponding to:

- $\min C_t$ strategy provided by (7)
- optimal pitch strategy - OP (8)
- optimal TSR strategy - OT (9)

The analysis is performed for δ power ratios of 0.5, 0.6, 0.7 and 0.8 with respect to the $C_{p,max}$ normal operating point. DEL (damage equivalent load) variation for different components is computed and presented in the following figures.

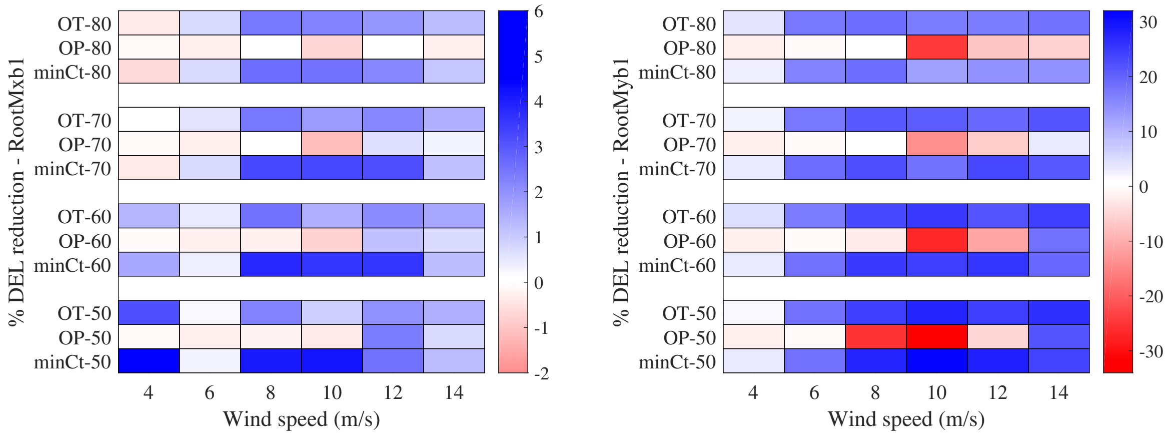


(a) (b)

Figure 3. (a) Percentage of generated power vs baseline; (b) Percentage of mean thrust variation with respect to baseline.

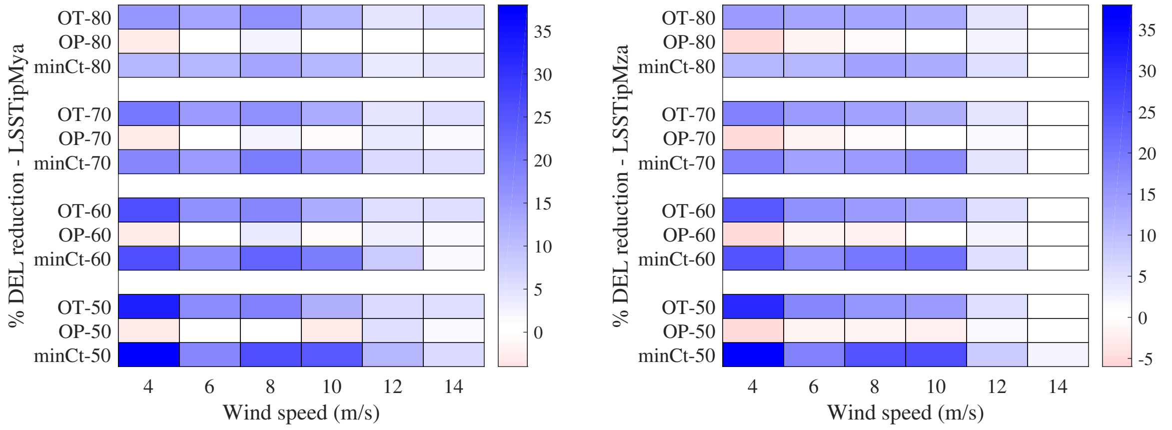
It has to be noticed that the offline computation of the $C_p(\beta, \lambda)$ and $C_t(\beta, \lambda)$ surfaces is based on TSR and not the exact wind speeds through dynamic computation. This may have impeded achieving the exact targeted values for the whole range of wind speeds.

Figure 3 (a) shows the percentage of generated power with respect to the baseline controller for each wind speed and each derating strategy and power ratio combination. At 4 m/s and low power ratios (0.5 and 0.6), it has been found that $\min C_t$ and OT strategies are not able to provide the required derating due to the large value of targeted pitch angle. This causes the turbine to stop due to insufficient aerodynamic power. For the same strategies ($\min C_t$ and OT), low wind speed and 0.8 power ratio, the derated power objective is neither achieved, in fact the power is increased, due to the impossibility to get the chosen TSR because of the minimum rotor speed limitation of the wind turbine (6 rpm). For the OP strategy the pitch angle is maintained at the optimal pitch value and the TSR is modified accordingly. However, the targeted TSR points are not achieved due again to the rotor speed limitations. Also, the sensitivity of C_p at the TSR points achieved in practice is quite high.



(a) (b)

Figure 4. Percentage of DEL variation (reduction positive) vs baseline for: (a) blade root edgewise moment; (b) blade root flapwise moment.

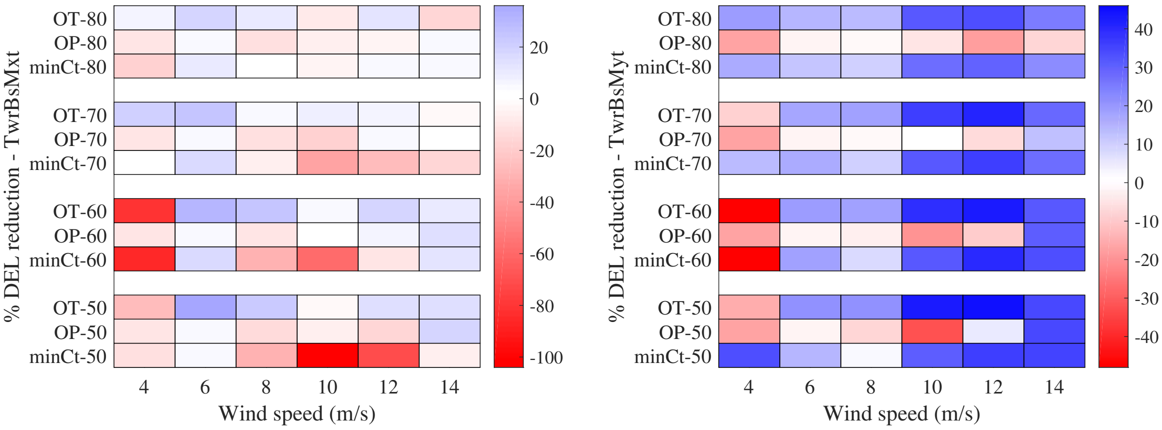


(a) (b)

Figure 5. Percentage of DEL variation (reduction positive) vs baseline for bending moments at rotating hub: (a) LSSTipMya; (b)LSSTipMza.

Figure 3 (b) depicts for each wind speed and strategy combination the relative variation in percentage of thrust with respect to the baseline. It is clear how the OP strategy either increases the thrust or decreases it to a lesser extent than the two other strategies. According to Section 2, this would imply more wake generation, which is counterproductive for derating from the perspective of power maximization and load minimization.

In Figure 4 , Figure 5 and Figure 6, the percentage of DEL variation (reduction positive, shown in blue) with respect to the baseline is presented for different components, namely blade root, rotating hub and tower base moments. For the min C_t and OT strategies load reduction is generally obtained. Side-side loads are significantly increasing in Figure 6 (a) when the minimum generator speed is reached in region 2 while keeping the pitch angle constant. The generator torque is then acting strongly to maintain this minimal speed constraint. OT strategy presents better results in terms of side-side moment reduction. By contrast, OP strategy behaves again



(a) (b)

Figure 6. Percentage of DEL variation (reduction positive) vs baseline for: (a) tower base side-side moment; (b) tower base fore-aft moment.

in a poorer way compared to the two other strategies, both for side-side and fore-aft tower base moments.

4. Conclusions and future work

Controlled derating of individual turbines in a wind farm is a way to pursue optimized farm performance in terms of power and fatigue. Therefore it is crucial that the derating is done in the best way. The present paper focuses on the derating of a single turbine and the effect on the derated turbine and the wake behind it which could cover other farm turbines.

Based on simple modelling and arguments derated operation where the thrust coefficient is minimized is suggested. Further realization of this strategy using “standard” wind turbine controllers is developed.

The “minimal thrust coefficient” strategy is compared with two others where pitch or TSR is fixed at their maximum C_p values from normal operation. Focus is on the below rated wind speed range. From the results, it is concluded that the strategy maintaining the pitch at the optimal value from normal operation behaves in a poorer way not only from the thrust aspect but also from the loads perspective. The strategies of $\min C_t$ and optimal TSR behave in quite a similar manner.

However, some issues for practical implementation have been detected and will need further consideration. Firstly, the characterization of the $C_p(\beta, \lambda)$ and $C_t(\beta, \lambda)$ surfaces requires suitable modeling effort and dynamical computation of the rotor characteristics. Secondly, low wind speeds may become problematic due to the generator speed low limit constraint, which may lead the turbine to stop or provoke some undesired load increase. It will be interesting to see the effect of lowering the minimum generator speed limit, although this may create interaction with the tower modes. Finally, the authors consider that the real effects on the wake for the turbine control strategies need to be further explored through farm simulations.

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