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The effect of minimum thrust coefficient control strategy on power output and loads of a wind farm

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Abstract. The use of down-regulation control strategies for wind turbines potentially optimises the wind farm performance. One of the promising strategies to minimise the wind farm loads and maximise the energy production is by down-regulating the upstream turbine with minimum thrust coefficient ($C_t$). Nonetheless, a majority of minimum $C_t$ control studies is confined to fatigue load analysis of a single turbine. Therefore, this paper focuses on the investigation of the fatigue loads when operating turbines in a wind farm using a minimum $C_t$ control strategy, as well as extreme loads and energy production. The control strategy is implemented in the DTU Wind Energy controller coupled with the aero-elastic code, HAWC2. The Dynamic Wake Meandering model in HAWC2 is used so that the wake deficits generated from the upstream turbines realistically represent the minimum $C_t$ control strategy, as well as the interactions between wakes. The main contribution of this paper is to investigate the possible wind farm operating strategy using minimum $C_t$ control that leads to decrease the lifetime fatigue loads and increase the overall energy production of a wind farm due to the potential extended lifetime of certain wind turbine components.

1. Introduction

Although the control of modern variable-speed pitch-regulated wind turbines has achieved a high level of maturity in the industry, new control strategies and functionalities are in demand to increase the efficiency of wind farm operation while adhering to stricter grid code compliance [1] and the demands of the grid operator. In order to satisfy new requirements, such as grid curtailment, changes should be made in the control strategy from optimizing the performance of a single wind turbine with respect to power production and load alleviation, to considering the loads and overall energy production of a wind farm.

There exists several types of down-regulation strategies (see [2, 3]). To increase the overall energy production in a wind farm, one of the promising strategies is the minimum thrust coefficient control [4, 5, 6]. By down-regulating the upstream turbine in the minimum thrust coefficient operation, the wake deficits from upstream turbine are minimised, thus, resulting a potential increase in the wind farm power output. Nonetheless, the literature in this area typically focuses on the effect of down regulation control and the dynamic performance of the single de-rated wind turbine with respect to fatigue and extreme loads rather than considering the effects on a full wind farm due to down-regulation control. For example, the study by Mirzaei [7] investigated the fatigue loads of a single turbine under several down regulation strategies. Similar studies on fatigue loads by additional down-regulation methods were conducted in [2, 3, 4, 5, 6]. In the work of Fleming [8], load analysis and field tests on a single turbine...
were performed based on torque-based down-regulation strategies. In terms of load analysis in a wind farm setting, a down-regulation study by Galinos [9] investigated the fatigue load for two turbines in a row. Clearly, there has been limited research on the effect of down-regulating wind turbines, which follow minimum thrust coefficient control strategy, on the loads and energy production of a wind farm.

Therefore, this paper is to investigate the possible wind farm operating strategy based on minimum $C_t$ control. Furthermore, a further key focus of this paper is to understand that the fatigue and extreme loads and overall energy production of a wind farm under the minimum $C_t$ control strategy. Such a wind farm operating strategy could potentially lead to decrease the lifetime fatigue loads and increase the overall energy production of a wind farm due to the potential extended lifetime of certain wind turbine components. For this purpose, a dummy small-scale wind farm consisting three turbines standing in a row is used in the simulation. The analysis is based on high fidelity aero-elastic simulations using the HAWC2 [10] with the Dynamic Wake Meandering (DWM) model [11]. The simulations focus on different combinations of wind classes and down regulation levels using the minimum $C_t$ control strategy. Based on the simulation results, an useful information of selecting possible wind farm operating strategy, which optimises the wind farm performance, is given. A short description of DWM model and the minimum $C_t$ control strategy implementation are presented in section 2. The detailed simulation setup is presented in section 3. In section 4, lifetime fatigue loads, extreme loads and Annual Energy Production (AEP) are analysed and discussed.

2. Modelling and methodology

2.1. Dynamic Wake Meandering model

The Dynamic Wake Meandering model as implemented in HAWC2 calculates the wake deficit from Blade Element Momentum (BEM) theory coupled with a 2D axisymmetric boundary layer approximation of the Navier-Stokes equations [12]. The DWM model utilizes the steady-state minimum thrust operation point (rotor speed and blade pitch angle) of the upstream turbine to compute the quasi-steady velocity deficit experienced by the downstream turbine. The wake meandering part is based on a fundamental presumption stating that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures [11]. The added wake turbulence is modelled based on a homogeneous Mann turbulence field [13] driven by small-scale turbulence structures with the cross section covering one rotor diameter. The added turbulence is approximated by scaling the created homogeneous Mann turbulence field depending on the quasi-steady velocity deficit and the velocity deficit gradient at the considered downstream location [14]. Multiple wake sources interact with each other by adjusting the steady-state operation point of a wake generation turbine when it is in the wake of another turbine.

In the current implementation of DWM model, the wake sources can operate at different combinations of rotor speed and blade pitch angle during down-regulation which have different impact on loads. Thus, the generated wakes can be altered to determine the optimal control solution for maximizing the overall AEP while minimizing lifetime fatigue loads and extreme loads.

2.2. Down regulation control strategy

The standard control strategy of an individual wind turbine under normal operating conditions is to maximise the power output below rated wind speed by tracking the optimum tip-speed ratio, and to track the rated power set point above the rated wind speed. When turbines operate in a wind farm, different control strategies should be considered. For example, down regulation of the upstream turbines such that the generated velocity deficits are minimized, allowing the downstream turbines to capture more energy while alleviating the fatigue and extreme loads of
both upstream and downstream turbines.

One type of down regulation control is the minimum $C_t$ control strategy, which minimizes the thrust coefficient of a turbine for a given power output. This control strategy, although reducing the power output of the de-rated turbines, results in an overall increase in power output in the wind farm due to attenuated wake effects. An additional benefit of minimum $C_t$ control is a reduction of fatigue loads farm-wide due to a reduction of the wake deficit and added wake turbulence mentioned in [6, 11].

The concept of minimum $C_t$ control strategy is described in the optimisation problem (1). For a given down regulation percentage, $\Delta P$, the following minimization problem is solved to find the solution of tip-speed-ratio, $\lambda$, and pitch angle, $\beta$. The power coefficient, $C_p$, and thrust coefficient, $C_t$, of the DTU 10MW reference turbine [15] are illustrated in contour plots as functions of $\lambda$ and $\beta$ in Figure 1.

$$\lambda_d, \beta_d = \arg \min_{\lambda, \beta} C_t(\lambda, \beta)$$

Subject to:

$$\begin{cases} 
C_{p,d}(\lambda_d, \beta_d) = \Delta P C_{p,max} \\
\lambda_{min} \leq \lambda_d \leq \lambda_{max} \\
\beta_{min} \leq \beta_d \leq \beta_{max}
\end{cases}$$

(1)

In this work, we utilize the same terminology as defined in literature [16], where the control regions are referred to as Regions 2, 2.5 and 3. The implementation of this control strategy in Region 2 is simply re-calculating the generator constant, $K$, tracking the minimum $C_t$ instead of the traditional way that tracks the optimal power coefficient $C_{p,max}$ using the equation

$$K = \frac{1}{2} \rho \pi R^5 \left( \frac{1}{N \lambda_d} \right)^3 C_{p,d}(\lambda_d, \beta_d)$$

(2)

where, $N$ is the gearbox ratio, $R$ is the rotor radius, $\rho$ is air density and $C_{p,d}$ is the power coefficient value associated with down regulation percentage. In Region 2.5, a PI generator torque controller with torque limits is implemented. We assume the rated wind speed ($V_r$) is
the same as the designed value. Then, the lower limit of generator speed in Region 2.5, \( \Omega_{2.5} \), is calculated as

\[
\Omega_{2.5} = \frac{V_r \lambda_d}{R}
\]

(3)

where, \( \lambda_d \) is the tip-speed-ratio value as the solution of the minimization problem mentioned before. The upper limit generator speed in Region 2.5 during down regulation, which is the de-rated generator speed in Region 3, is defined as \( \Omega_{r,d} = \Omega_{2.5}/\gamma \). Here, the \( \gamma \) is an user selected parameter. In this study, a value of 95% is used for generalizing the minimum \( C_t \) control strategy to match the behavior of the DTU Basic Controller when the down-regulation level is at 100%.

A linear interpolation factor, \( \sigma \), is defined as

\[
\sigma(\Omega_{2.5}, \Omega_{r,d}, \Omega) = \begin{cases} 
0 & \Omega < \Omega_{2.5}, \\
\frac{\Omega - \Omega_{2.5}}{\Omega_{r,d} - \Omega_{2.5}} & \Omega_{2.5} \leq \Omega \leq \Omega_{r,d}, \\
1 & \Omega > \Omega_{r,d},
\end{cases}
\]

(4)

where, \( \Omega \) is the current generator speed. Then, the torque limits used by the PI generator torque controller in Region 2.5 is expressed as

\[
Q_g \in \begin{cases} 
[K\Omega^2, K\Omega^2] & \Omega < \Omega_{2.5}, \\
[K\Omega_{2.5}^2, (1 - \sigma)K\Omega^2 + \sigma Q_{g,r}^d] & \Omega_{2.5} \leq \Omega \leq \Omega_{r,d}, \\
[Q_{g,r}^d, Q_{g,r}^d] & \Omega > \Omega_{r,d},
\end{cases}
\]

(5)

where, \( Q_{g,r}^d \) is the de-rated generator torque.

In Region 3, The generator speed and torque set-points are determined by \( \Omega_{r,d} \) and the de-rated generator power. The implementation of the switch between Region 2.5 and 3 follows the same method as described in the report of DTU Wind Energy controller [17].

3. Simulation setup

In this study, simulations are performed on the DTU 10MW reference turbine [15] using the high fidelity aero-elastic simulation code, HAWC2. Three different wind classes, namely IA, IB and IC representing different turbulence intensity values 0.16, 0.14 and 0.12 defined in IEC standard [18], are used in the simulation. The wind speed range is from 4 m/s to 24 m/s in 2 m/s increments, and 6 random turbulent seeds are used per wind speed. We select five different down regulation levels for the upstream turbine (WT-1), three down regulation levels for the second row turbine (WT-2) and two down regulation levels for the third row turbine (WT-3) in this work. They are combined with all three wind classes. The 20 years lifetime equivalent loads on the blade root, the tower bottom, the yaw bearing and the main shaft bearing are evaluated for all turbines assuming that power production period occurs with a probability of 97.5%, and the wind speed conforms to a Weibull distribution. Wöhler exponent values of 3, 4 and 10 are chosen for the bearings (yaw and shaft), the tower and the blade respectively. The absolute values of maximum loads on the mentioned components are extracted from the time series to get the extreme loads. The AEPs are evaluated on overall wind farm composed by the three turbines for different down regulation levels.

3.1. Wind farm setup

For the purpose of this investigation, a simplified wind farm layout with three turbines in a row is formulated. The space distance, which is four rotor diameters (4D) in length, is chosen, which represents a tight wind farm layout similar to the Lillgrund wind farm. The ambient
wind direction is set to zero degrees, which means yaw misalignment is not considered in this study. Only one dominating direction in the wind rose is considered in the simulation, while other directions can be treated in a similar way. WT-1 is down regulated to produce 60%, 70%, 80%, 90% and 100% of the available power. WT-2 is down regulated to produce 70%, 80% and 100% of the available power. For WT-2 the 90% down regulation level is not simulated in order to reduce the number of load cases. The results at 90% down regulation level can be obtained by interpolation based on the simulated de-rating levels. For the turbine in the last row, WT-3, only two different down regulated levels, 80% and 100%, are considered in this work. The 80% de-rating level is kept for checking the fatigue and extreme loads, and the 100% de-rating level is for giving the reference value of AEP.

4. Results and discussion
The lifetime fatigue loads and extreme loads of each turbine have been normalized with respect to the loads when the turbines are not down-regulated. AEP is normalized by all 3 turbines operated normally. For the loads on WT-1, a bar plot is used. Different colors represent different down regulation levels in the figure, and the load channel names are plotted on the x-axis. For the loads on WT-2 and WT-3 which are affected by the operational points of the upstream turbines, a color matrix plot is used. The numbers in the colored cells, rounded to have 2 decimal places, represent either the normalized lifetime DELs or extreme loads. The load channel names are shown on the top of each sub-figures.

4.1. Lifetime fatigue loads
Figure 2 shows the 20 years lifetime fatigue loads of the WT-1 operating at wind class IC. As it is shown, most of the fatigue loads are reduced for different down regulation levels compared with normal operation case except for tower bottom fore-aft and side-to-side loads described by channel name TBFA and TBSS, and the yaw bearing roll moment and main bearing torsional moment described by channel name YBRoll and MBTor, which are related to the drive train loads. The blade root edgewise bending moment is mainly driven by the gravity, therefore, the edgewise fatigue load reduction is smaller compared to the flapwise fatigue load.

A further investigation on the time series and the Fast Fourier Transformed (FFT) signal of tower bottom fore-aft bending moment (see Figure 3) shows that the fatigue load increase at the tower bottom for fore-aft bending moments is due to higher oscillation when the turbine is de-rated. This is caused by the 3P frequency (0.255 Hz) interaction with the tower fore-aft (0.25 Hz) frequency of this DTU 10MW turbine when the turbine is de-rated to 70% with the rotor speed at 5.1 rpm. Figure 3 shows, at 10 m/s, when the turbine is running without de-rating, the 3P frequency is 0.4 Hz. The 3P frequency is reduced to 0.281 Hz and 0.255 Hz when the turbine is de-rated at 90% and 70% respectively. Therefore, when the turbine is de-rated, for example, at 90% and 70%, the tower fore-aft mode is excited and a higher amplitude as it is shown in Figure 3 is observed. Similar resonance phenomena is observed for the tower side-to-side mode in Figure 4. Further more, the excited tower side-to-side vibration couples with the drive train torsional mode and leads to higher drive train torsional oscillation, which is closely related to the main bearing torsional moment (MBTor) and the yaw bearing roll moment (YBRoll). This explains the fatigue loads increase on channels YBRoll and MBTor.

This finding suggests that for the turbines designed with narrow rotor speed range, like the DTU 10MW reference turbine, with the range from 6 rpm to 9.6 rpm, the rotor speed exclusion should be implemented in the down regulation control algorithm to avoid resonance. It also suggests that the drive train damping parameters need to be re-tuned in order to damp the drive train vibration under the down-regulated control. Re-tuning of the drive train damping parameters for down regulation is out of the range of this investigation.

Similar results have been found for WT-2 when WT-1 is operated at different down regulation
levels. Figure 5 shows the lifetime DELs loads of WT-2 operated at 70%, 80% and 100% of the available power indicated in x-axis, in the meantime WT-1 is running at different down regulation levels indicated in y-axis. The flapwise and torsional fatigue loads on the blades of WT-2 are all reduced with different combination of de-rating levels of WT-1. The same fatigue loads reduction are found at load channel, namely, TBTor, YBTilt, YBYaw, MBTilt and MBYaw. The edgewise fatigue loads are reduced if the WT-2 is under down regulation but the reduction is smaller than the flapwise and torsional loads due to the loads are mainly driven by the gravity force. The loads at tower bottom described by TBFA and TBSS, and the loads related to the drive train described by YBRoll and MBTor are increased when the WT-2 is de-rated.
The fatigue loads on the WT-3 are more complicated because they are affected by the combination of the operational points of the two upstream turbines. Therefore, they are shown in two separated plots (Figure 6 and 7) representing the de-rating levels of 80% and 100% on WT-3. The fatigue loads on WT-3 described by BRFlap, BREdg, BRTor, TBTorr, YBYaw, MBTilt and MBYaw are all reduced when WT-3 is de-rated at 80% regardless of the de-rating combination of WT-1 and WT-2. The tower bottom side-to-side fatigue loads (TBSS) is largely increased when WT-3 is de-rated at 80% regardless of the de-rating combination of WT-1 and WT-2 but it is decreased when WT-3 is de-rated at 100% (See Figure 6 and 7) in the combination of 70% and 80% de-rating on WT-2. Further more, the results indicate that there is very little effect of down regulating WT-1 on the fatigue loads on WT-3, which means the fatigue loads on WT-3 are dominated by the operational points of WT-2. Similar results are also found for wind class IA and IB.

Figure 6: 20 years normalized DELs on WT-3 when de-rating at 80%.

4.2. Extreme loads

Figure 8 shows the extreme loads of WT-1 operating under different down regulation levels at wind class IC. Most of the extreme loads are reduced considerably for different down regulation
levels except for the tower bottom side-to-side bending moment (TBSS), the yaw bearing roll moment (YBRoll) and the main bearing torsional moment (MBTor). The reason for the increased extreme loads is similar to fatigue loads, which has been explained in the previous section. One noticeable difference compared to the fatigue loads is that the extreme bending moment at the tower bottom in fore-aft direction is not increased. This is because the mean value of tower bottom fore-aft bending moment during the down-regulated control is reduce largely (see Figure 3), which is able to compensate the high vibration amplitude due to the excited tower first fore-aft mode. Another difference is that the extreme yaw bearing roll moment (YBRoll) and the main bearing torsional moment (MBTor) are increased only when down regulating the turbine to produce 80% and 90% of the available power.

Figure 8: Normalized extreme loads on WT-1 for wind class IC.

Figure 9 shows the extreme loads of WT-2 operating at 70%, 80% and 100% de-rating levels, in the meantime WT-1 is running at different down regulation levels as it is displayed on y-axis. It shows that all the extreme loads are largely reduced when the WT-2 is operating at 70% and 80% de-rating levels except for Tower bottom side-to-side moment (TBSS), yaw bearing roll moment (YBRoll) and main bearing torsional moment (MBTor). These loads are closely related with drive train vibration which has been discussed in the previous section.

Figure 9: Normalized extreme loads on WT-2 for wind class IC.

The extreme loads on WT-3 are presented in two separated figures, which are Figure 10 and 11. When the WT-3 is operating at 80% de-rating level, all the extreme loads are reduced
regardless of the operational condition of the WT-1 and WT-2 except for the extreme loads represented by TBSS, YBRoll and MBTor. Figure 11 shows when the WT-3 is operating at 100% de-rating level, only the extreme loads represented by BRFlap, TBTor, YBTilt, YBYaw and MBTilt are decreased, the rest of the extreme loads are slightly increased. Similar as the fatigue loads, the extreme loads on WT-3 are dominated by the operational points of WT-2. For wind class IA and IB, similar extreme loads are also found.

Figure 10: Normalized extreme loads on WT-3 when de-rating at 80%.

Figure 11: Normalized extreme loads on WT-3 when de-rating at 100%.

4.3. Wind farm AEP
The normalized AEPs of the wind farm based on different combinations of the operational strategies on each turbine are shown in Figure 12. The result shows that the AEPs of wind farm are reduced for all the operational strategies, which indicates, in terms of wind farm AEP, the minimum $C_t$ control strategy for down regulating the turbines in a wind farm gives a lower AEP. On the other hand, it gives lower fatigue and extreme loads on the turbines. Three operational strategies, namely, CASE1, CASE2 and CASE3 are selected for further investigation based on fatigue loads and AEP discussed in Section 4.1 and 4.3. The Baseline case is defined as all 3 turbines are running without down regulation over their lifetime. CASE1, CASE2 and CASE3 are described as the following:

- **CASE1**: WT-1 at 90%, WT-2 at 100% and WT-3 at 100%.
4.4. Lifetime extension application

This investigation focuses on the technical feasibility of lifetime extension on some components of wind turbines. Therefore, some assumptions regarding wind farm operation are made for the calculations without using the real wind farm operation data. Beside this, only fatigue loads are considered as the main factor of the lifetime extension.

According to the Miner’s linear damage hypothesis [19] the total damage as the function of $t_n$ and $t_d$ after 20 years with combined normal operation and down-regulated operation is calculated as

$$D_t(t_n,t_d) = \frac{t_n}{T_l} + \frac{t_d}{T_l} \left( \frac{L_{eq,d}}{L_{eq,n}} \right)^m$$

(6)

where, $D_t$ is the total fatigue damage, $T_l$ is complete lifetime, $L_{eq,n}$ and $L_{eq,d}$ are the lifetime equivalent loads at normal operation and at down-regulated operation, $t_n$ and $t_d$ are the time periods of the turbine running at normal operation and at down-regulated operation, $m$ is the material Wöhler coefficient. Substituting the values of $t_n$ and $t_d$, the total fatigue damage can be calculated. The difference between the reference case and any other case, $i$, are defined as damage margin, $\Delta D_t = D_t,ref - D_t,i$, which is used in Equations 7 to calculate the lifetime extension, $T_{l,ext}$.

$$T_{l,ext} = \Delta D_t T_l \left( \frac{L_{eq,d}}{L_{eq,n}} \right)^{-m}$$

(7)

In this study the evaluation is performed on the component level of three turbines. we assume $t_n = 0$ and $t_d = 20$ years for the down regulated turbines. The normalized lifetime extension on the main components of three turbines are shown in Figure 13. Among the three selected operational cases, the lifetime of the evaluated load channels are increased except for load channels, namely, TBFA, TBSS, YBRoll and MBTor when the turbine is under down regulation control. Consistent result is found from CASE3, in which the WT-2 is down-regulated at 80% while the WT-1 and WT-3 are under normal operation. Although WT-1 is not down-regulated, the extended lifetime of WT-3 is nearly the same as CASE2. This is because the fatigue loads on the WT-3 are dominated by the operational point of WT-2, which has been discussed in...
Section 4.1. The benefit of CASE3 is that the wind farm AEP is about 2.8% higher than CASE2. Another noticeable result is found that a larger lifetime extension happens on the blades for all three cases. It shows the effect of the material. For the material with a steep S-N curve, a small fatigue load reduction contributes to large a lifetime extension. This investigation is a rough attempt to quantify the contribution of minimum \( C_t \) control strategy to the lifetime extension showing that there is some potential while more specific control parameter tuning is needed.

5. Conclusions and future work
In this paper, a minimum \( C_t \) control strategy for down regulating wind turbines in wind farm is implemented in the basic DTU Wind Energy controller, which couples with the aero-elastic code, HAWC2. The results show that a minimum \( C_t \) control strategy attenuates the wake deficit generated by upstream turbines, and results in both lower fatigue and extreme loads on most of the components of both upstream and downstream turbines. Three possible wind farm operational strategies are investigated and the results indicates that CASE1 and CASE3 can extend the lifetime of the wind turbine main components if the control parameters were fine tuned based on the down regulation conditions and the overall energy production of a wind farm can be increased.

The results also show that the minimum \( C_t \) control strategy might result in a sub-optimal performance or poor robustness (deteriorate the system stability), for example, the possibility of exciting the tower first fore-aft and side-to-side modes if certain control functionality, such as rotor speed exclusion, is not considered, or the control parameters are not adjusted accordingly based on the down regulation conditions, which will lead increased fatigue and extreme loads. Therefore, when implementing a down regulation control strategy on the original turbine controller, the changes due to down regulation control such as the rotor speed, initial pitch angle and aerodynamic performance need to be investigated in the future work.

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