19 September 2017

Reducing Wind Turbine Loads with Down-Regulation

Edited on 19 September 2017

Author(s)

D.C. van der Hoek
S.K. Kanev

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477.

Abstract

With the growth of wind energy worldwide, an increased interest in wind farm control has also 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 analyse their effect on the lifetime of certain wind turbine components.

Earlier research on down-regulation for wind farm control has resulted in several methods which were shown to reduce the fatigue loads of 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 work, different down-regulation strategies using the percentage reserve method are assessed based solely on their load reduction capabilities.

There exist several strategies for the down-regulation of wind turbines using the percentage reserve method. In partial load, the aerodynamic efficiency of the blades can be reduced by increasing or decreasing (until stall) the optimal Tip-Speed Ratio (TSR), or by increasing the pitch angle. In full load, down-regulation is achieved by reducing the rated generator torque or the rated rotor speed. This leads to a total of six down-regulation strategies which are implemented in ECN's controller. Besides the loads, the axial induction is also analysed for each down-regulation strategy. It was observed that decreasing the TSR and increasing the pitch angle in partial load result in a significant decrease of the axial induction factor, which is crucial for pitch based AWC.

The performance of the different control strategies is compared using aeroelastic simulations of the 10MW Innwind turbine and by comparing the Damage Equivalent Loads (DELs) of several components for the whole range of operational wind speeds. It is observed that decreasing the TSR results in increased fatigue loads at the tower for low wind speeds caused by prolonged operation at the cut-in rotor speed, where the 3P frequency excites the tower frequency. The strategies incorporating a higher TSR show a very positive effect on the tower fatigue loads. However, due to the higher rotor speed at very low wind speeds, blade root fatigue loads increase significantly in this region. The two strategies based on increased pitch angles show very stable behaviour over the whole range of wind speeds and result in a reduction of fatigue loads for both tower and blade roots. Additionally, it has to be noted that reducing the rated rotor speed results in an increase of the tower loads at higher wind speeds. This is caused by a decrease in aerodynamic damping resulting from operation at a lower rotor speed and increased pitch action. However, the fatigue loads of the blade roots decrease as a result of operation at a lower rated rotor speed.

Finally, lifetime fatigue load effects are analysed by combining the DELs that were computed for different wind speeds with a given wind distribution. The results show that all down-regulation strategies are successful in reducing the lifetime fatigue loads for some of the wind turbine components, with load reductions of up to 25% being achieved for some components when a 20% down-regulation level is selected.

Table of contents

1. **Introduction** **5**
2. **Down-Regulation Strategies** **7**
    - 2.1 Down-Regulation in Partial Load 7
    - 2.2 Down-Regulation in Full Load 8
    - 2.3 Down-Regulation Effects on Thrust Force 10
    - 2.4 Simplified Simulation Results 11
3. **Fatigue Load Analysis** **12**
    - 3.1 Simulation Setup 12
    - 3.2 Simulation Results 12
    - 3.3 Lifetime Load Reductions 15
4. **Conclusions** **16**
5. **Bibliography** **18**

1. Introduction

Recent years have seen a large increase in the number of (offshore) wind farms that have been installed or scheduled for installation, and it is expected that this increase will continue over the coming years. This rise in the number of wind farms has also led to increased interest in the subject of wind farm control. Two primary examples of wind farm control are given by Active Power Control (APC) and Active Wake Control (AWC) [1]. Both of these control types use the concept of down-regulation of wind turbines, i.e., operating wind turbines at sub-optimal power settings. 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. AWC refers to the optimization of a wind farm in terms of power production and fatigue loading using down-regulation 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.

There are several down-regulation methods which are often used for APC purposes [2], [3]. 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. In this way, the power output is reduced above rated wind speeds. Another method, called delta reserve, keeps a fixed amount of the available aerodynamic power in reserve. Above rated wind speed this is achieved in the same manner as with the de-rating approach. Below rated wind speeds down-regulation can be achieved by tracking a sub-optimal power coefficient C_p. In this case the sub-optimal C_p can be found by subtracting the desired power reserve from the available aerodynamic power. Clearly, this is only possible when the available aerodynamic power is greater than the desired power reserve. A third approach is called percentage reserve and it is able to maintain a percentage of the available power in reserve. This makes it very similar to the delta reserve method, the difference being that a fixed percentage of the optimal C_p is tracked. As a result, this method is able to achieve down-regulation 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, the down-regulation can be achieved by operating the wind turbine above the optimal tip-speed ratio. For pitch control the rated rotor speed 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 that have been performed using both these control methods indicate that down-regulation tends to decrease the fatigue damage of some of the structural components of a wind turbine [2], [3].

For the purpose of AWC, down-regulation is generally achieved through pitch control or yaw control. Pitch control is achieved by increasing the pitch angle above its nominal value in partial load, resulting in a decreased aerodynamic efficiency and hence decreased power production. Yaw control consists of misaligning upstream turbines such 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 report, down-regulation through yawing will not be considered.

The goal of this report is to investigate the effect of down-regulation on wind turbine loads over the entire range of operational wind speeds. Looking at the down-regulation methods that were discussed earlier, it seems that only the percentage reserve method can be applied at every wind speed and it will therefore be used for this research. In previous research concerning the effects of down-regulation on the loads this method was implemented by adjusting the torque controller in and by reducing the maximum torque. In this report some additional control strategies will be implemented and their effects on the loads will be assessed.

Chapter 2 will present all the down-regulation strategies which will be implemented in the wind turbine controller. A distinction is made between down-regulation methods in partial and full load.
In Chapter 3, different combinations of these strategies will be used in high-fidelity simulations of a wind turbine. Subsequently, their effect on the loads will be analysed by means of Damage Equivalent Loads (DELs). Finally, in Chapter 4 some conclusions are presented on which down-regulation strategy has the best performance in terms of fatigue loading.

2. Down-Regulation Strategies

In this Chapter several down-regulation strategies are derived from the nominal control strategy. Roughly speaking, a wind turbine has two different operational regions. The first region consists of operation below the rated wind speed and is referred to as partial load. The second region is called full load and consists of wind turbine operation above rated wind speed. Down-regulation strategies for both regions are discussed in Sections 2.1 and 2.2. In Section 2.3, the effects of down-regulation on the thrust force are examined. Finally, results from simplified simulations are presented in Section 2.4.

2.1 Down-Regulation in Partial Load

In partial load, the controller generally aims to maximize the power production of a wind turbine 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 θ. Consequently, the power production can be maximized by controlling the rotor speed through the generator torque so that the desired TSR is reached. 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 θ, the power coefficient 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 Figure 2.1, which depicts the contour curves of C_p as a function of TSR and θ.

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 Figure 2.1, the pitch angle is also increased below a certain TSR. The additional pitch action 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, and thus increasing the rotor speed at lower wind speeds. As a result, the rated rotor speed is reached sooner than normal.
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. If the power demand then suddenly rises again, it can be quickly met by simply increasing the generator torque. The first strategy on the other hand needs a recovery period to increase the rotor speed to the original level. In Figure 2.1 it is seen that the line for this strategy also introduces some pitching. This is done in order to prevent large deviations in the

pitch angle between two consecutive wind speeds, which would occur if only the TSR was increased initially. This is because if θ is kept constant for a given TSR, this would result in operation at the left hand side of the maximum power coefficient on the $C_p - \theta$ curve. When the rated wind speed is subsequently approached and the turbine starts pitching, this would actually lead to an initial increase in the power coefficient until the pitch angle has increased enough to get on the right hand side of the optimum.

The final strategy consists of increasing the initial pitch angle in order to reduce 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.

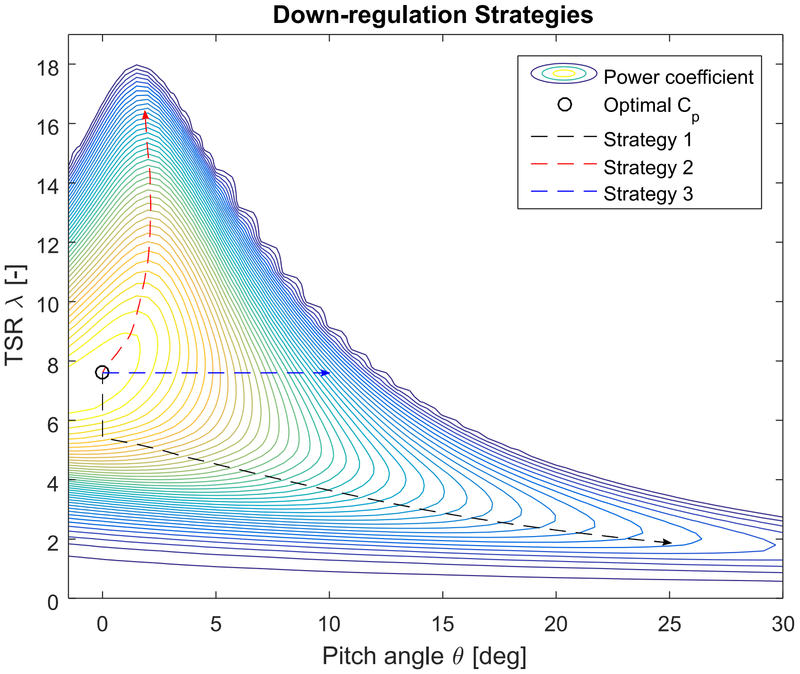


Figure 2.1 : Contour plot of a wind turbine's power coefficient data indication three down-regulation strategies in partial load.

2.2 Down-Regulation in Full Load

In full load, the wind turbine operates at the rated generator torque and now the rotor is controlled at its rated value through a pitch action of the blades. In the case of down-regulation at full load, three simple methods can be applied. The first method was presented in Chapter 1 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 desire percentage. The third method consists of a combination of torque and rotor speed reduction. 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. Furthermore, if the rotor speed is reduced, the turbine will operate in a narrower rotor speed region. This means it will become difficult to derate by reducing the rotor speed for higher down-regulation percentages, since the rotor speed cannot get lower than the cut-in rotor speed.

In this report the effect on the loads of both torque reduction (a) and rotor speed reduction (b) in combination with the three partial load down-regulation strategies will be evaluated. As a result a total of six down-regulation strategies are implemented in the wind turbine controller. An overview of these six strategies is presented in Table 2.1.

Table 2.1: Overview of down-regulation control strategies.

Strategy	**Partial Load**	**Full Load**
1a	$TSR\searrow, \theta\nearrow$	$\tau_g\searrow$
1b	$TSR\searrow, \theta\nearrow$	$\Omega_g\searrow$
2a	$TSR\nearrow, \theta\nearrow$	$\tau_g\searrow$
2b	$TSR\nearrow, \theta\nearrow$	$\Omega_g\searrow$
3a	$\theta\nearrow$	$\tau_g\searrow$
3b	$\theta\nearrow$	$\Omega_g\searrow$

The different down-regulation strategies are compared to the baseline controller in Figure 2.2 in terms of their torque-speed and pitch angle curves. These curves are generated beforehand and are fed to the controller as references. In this case, the operating curves were computed for 20% down-regulation and by using torque reduction at full load. Similar operating curves are obtained if rotor speed reduction is applied, the only difference is then that the curves end at 80% of the rated rotor speed. Looking at the figure containing the pitch angles, it is noticed that for the second down-regulation strategy additional pitch action is required a lot earlier than for the other 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. In order to compensate for this increased C_p, it is necessary to start pitching earlier.

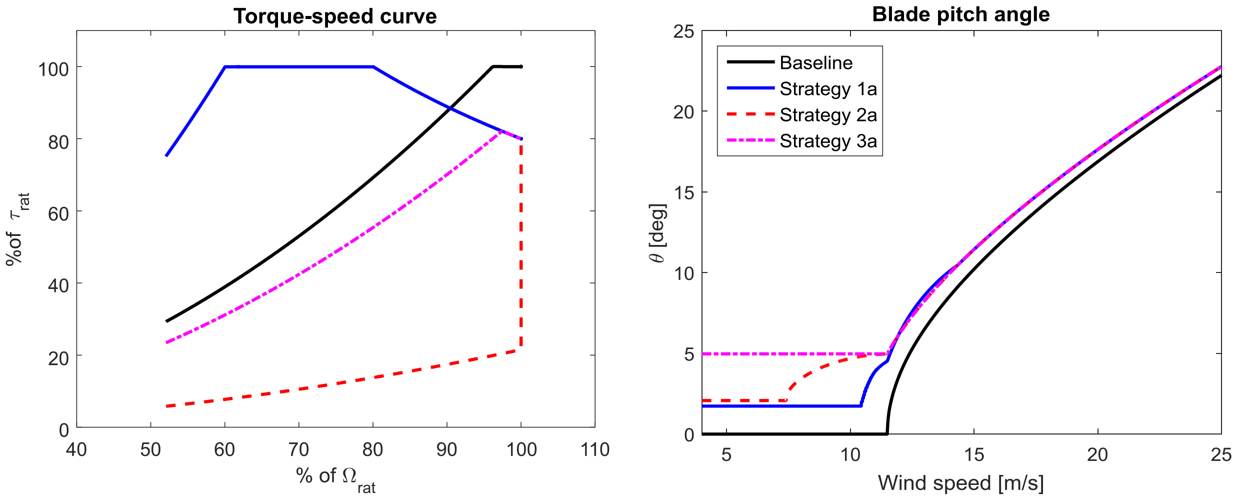


Figure 2.2: Torque-speed (left) and pitch angle (right) curves for the different derating strategies in combination with torque reduction at full load for 20% down-regulation.

2.3 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 [1]. As wind passes through the rotor of a wind turbine, the rotor experiences a force. As a result, the rotor exerts a reactive force on the wind, which is called the thrust force or axial force. This force gives an indication of the amount of energy left in the wind after it has passed the turbine. Induction control uses this fact 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.

Using available data on the thrust coefficient C_T, it is possible to compute the thrust force the wind turbine will be experiencing for 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 on the left-hand side of Figure 2.3 along with the three down-regulation strategies in partial load that were presented in Section 2.2. It can be observed that both strategies 1 and 3 will result in a lower C_T and hence a lower thrust force. However, the thrust coefficient does not change much when strategy 2 is used. The asterisks in the contour plot indicate the thrust coefficient when 20% down-regulation is desired. It can be seen that both strategy 1 and 3 result in approximately the same value of C_T.

In the right-hand plot of Figure 2.3, the expected thrust force is presented as a function of the wind speed. It can be observed that the maximum thrust force is reached at rated wind speed, after which it starts to decrease when pitch control is activated. As expected, strategies 1 and 3 both result in a significant decrease of the thrust force at every wind speed. By using strategy 2, the thrust force is initially the same as when the baseline controller is used. This strategy consists of increasing the desired TSR, which means that rated rotor speed is reached at lower wind speeds. This fact is also visible in Figure 2.3, when the thrust force for strategy 2 suddenly decreases with respect to the baseline controller and it starts following the other two down-regulation strategies. This can be explained using the pitch angles from Figure 2.2, where it is seen that the blades already start pitching at low wind speeds. Following this pitch action, the induction and thus the thrust force of the wind turbine is decreased.

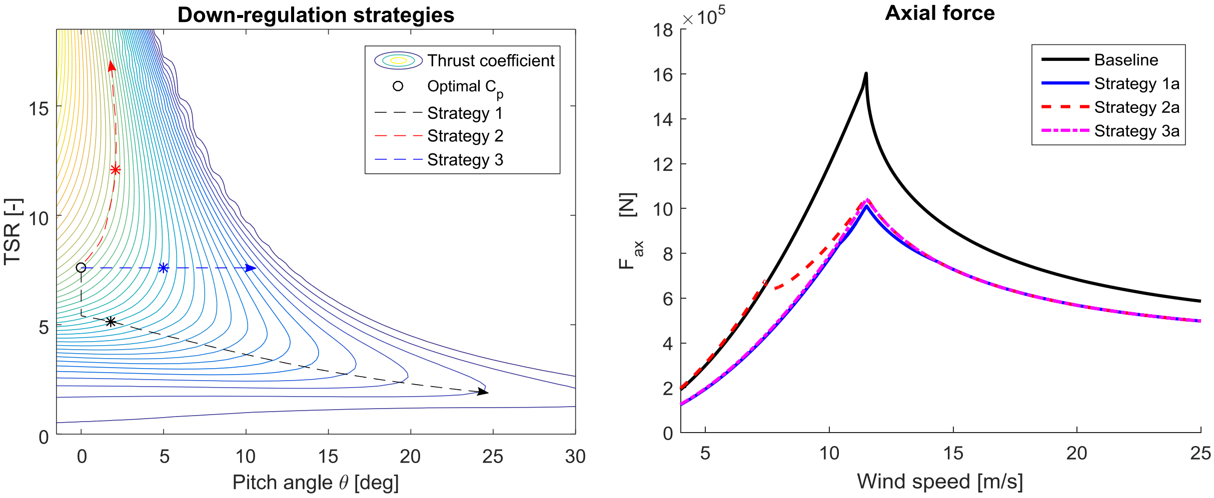


Figure 2.3: Contour plot of the thrust coefficient C_T along with the three down-regulation strategies in partial load (left) and a comparison of the thrust forces as a function of wind speed at 20% down-regulation (right).

In the right-hand plot of Figure 2.3 only the down-regulation strategies where the rated torque is reduced are shown. When the strategies where the rated rotor speed is reduced are used, this will lead to a small additional decrease in the thrust force after rated rotor speed is reached. Summarizing, when down-regulation strategies are considered for induction based AWC, the best result are expected to be achieved with strategies 1 and 3.

2.4 Simplified Simulation Results

Before the different down-regulation strategies are implemented in a high fidelity simulation model, their performance in terms of energy production is first evaluated using ECN´s in-house control tool ACT [4]. The considered wind turbine is the 10MW InnWind turbine equipped with a 180 diameter rotor [5]. The results of the simulations at different wind speeds for 20% down-regulation are presented in Figure 2.4. It can be observed that strategies 1a and 1b are not able to achieve the desired down-regulation percentage at very low wind speeds. These wind speeds are too low for the controller to follow the torque-speed curve given in Figure 2.2. The other down-regulation strategies achieve the desired power production well enough over the entire range of wind speeds.

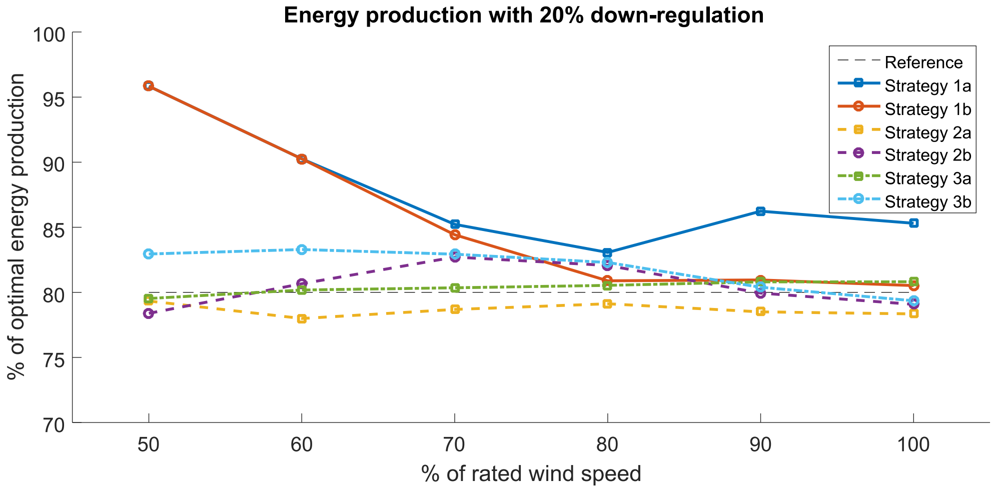


Figure 2.4: Energy production using different down-regulation strategies relative to the baseline controller performance. The results were obtained from 10 minute simulations using turbulent wind data.

3. Fatigue Load Analysis

In Chapter 2, six down-regulation strategies were presented and their derating capabilities were evaluated through simplified simulations. It was found that down-regulation using a lower TSR did not result in the desired effect at low wind speeds in terms of energy reduction, while the other strategies were able to achieve it well enough. The next step is to assess the effect of the different down-regulation strategies on the loads of the wind turbine, more specifically the aim is to reduce fatigue loads on the turbine.

3.1 Simulation Setup

In order to test the performance of the different controllers, they are used in the aeroelastic simulation tool PHATAS. Again the 10MW InnWind turbine with a 180 meter rotor diameter is used with a desired down-regulation percentage of 20%. Since the effect on fatigue loads are of primary interest, simulations are performed for normal operation with turbulent wind speeds ranging from 4-25 m/s with six realizations per wind speed. This corresponds to Design Load Case (DLC) 1.2.

The performances of the down-regulation strategies are subsequently 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. It has to be noted that the results for each part are given in the resultant direction. For the tower this means that DELs of the combined motion in the Fore-Aft and Side-Side direction are computed. Additionally, the actual energy production is compared with the desired reference. The results of the simulations are presented in Figures 3.1-3.4.

3.2 Simulation Results

The effects of the different down-regulation strategies on tower loads are depicted in Figure 3.1. It can be observed that there is an increase in fatigue loads at wind speeds around V = 10 m/s when down-regulation strategies 1a and 1b are used. In order to understand the cause of this increase in fatigue loads, the two time series plots given in Figure 3.5 are investigated. From the left-hand side plot it is observed that the absolute displacement of the tower bottom is many times greater when down-regulation strategy 1a is applied. Furthermore, by looking closely at the time period of the oscillations it can be seen that the tower moves at approximately the first tower frequency ($f \approx 0.25$ Hz), i.e., there is a lot of resonance occurring. By looking at both time series from Figure 3.5 side by side, it can be seen that the resonance behaviour occurs at Slow Shaft Equivalent (SSE) rotor speeds of around Ω = 5 rpm, for which the 3P blade passing frequency is right at f = 0.25 Hz. This causes the resonance and the increased fatigue loads in the tower bottom.

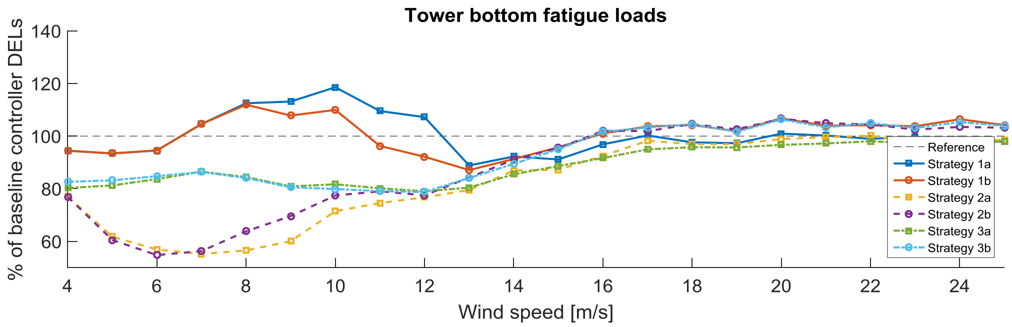


Figure 3.1: Average DELs of the tower bottom in the combined FA and SS direction over a range of wind speeds.

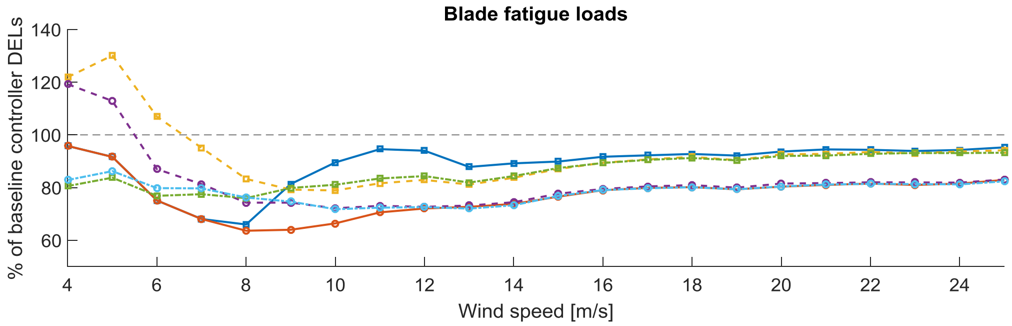


Figure 3.2: Average DELs of the blades over a range of wind speeds.

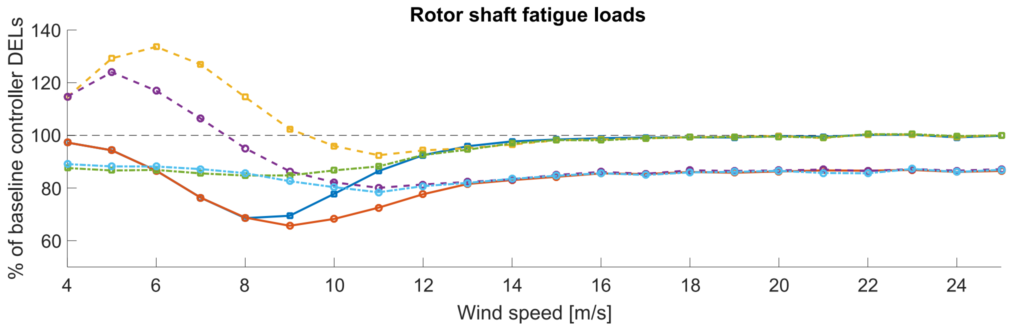


Figure 3.3: Average DELs of the rotor shaft over a range of wind speeds.

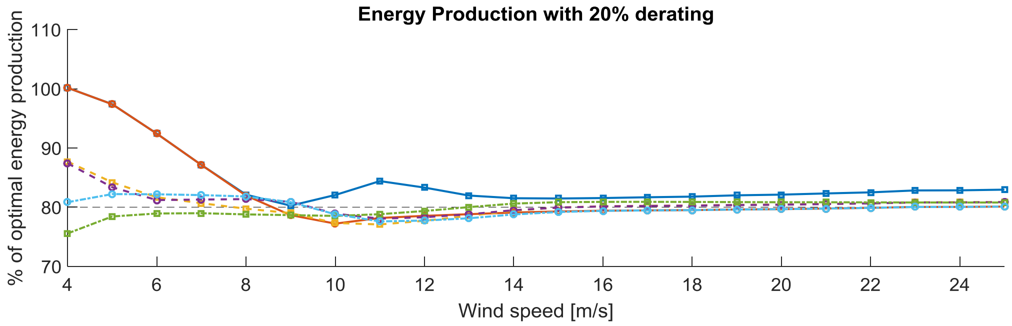


Figure 3.4: Wind turbine energy production over a range of wind speeds.

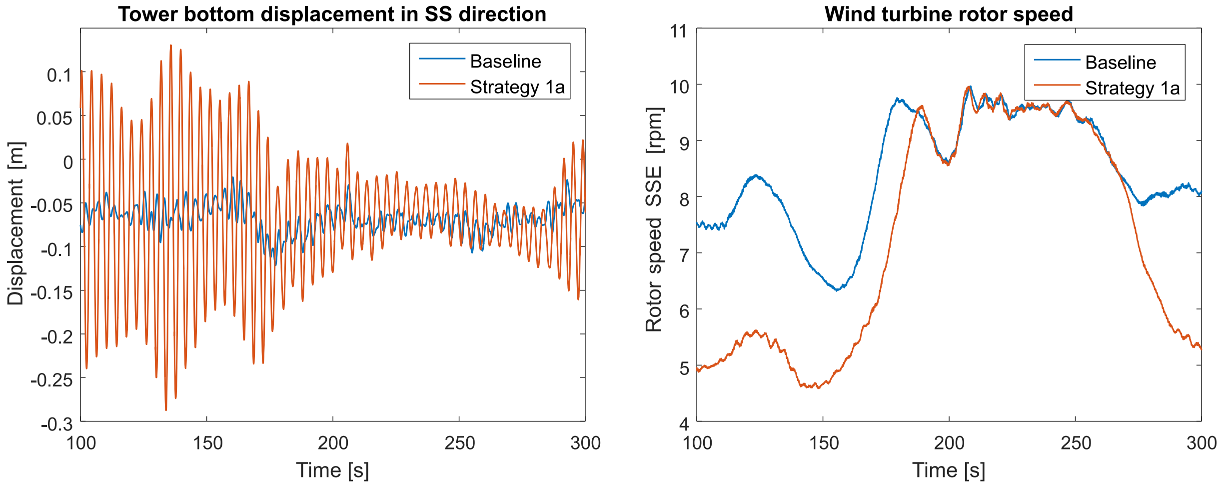


Figure 3.5: Time series of the InnWind turbines' tower bottom displacement (left) and Slow Shaft Equivalent (SSE) rotor speed (right).

Another interesting observation from Figure 3.1 is that strategies which reduce the rated rotor speed at full load result in slightly higher tower fatigue loads than in the case of reducing the torque. The increase in fatigue loads when the rated rotor speed is decreased, is thought to be the result of a decrease in aerodynamic damping. Aerodynamic damping results from the motion of the rotor blade relative to the wind velocity, thus this effect is reduced when the relative velocity is decreased. Furthermore, when the rated rotor speed is reduced the turbine requires a larger pitch action when operating in full load. This reduces the effective blade area and thus also results in a decrease of the aerodynamic damping and hence an increase in fatigue loads.

Figure 3.2 shows increased fatigue loads at very low wind speeds for strategy 2a and 2b. This is because the turbine operates at higher rotor speeds compared to the nominal controller at these wind speeds. This is also seen at higher wind speeds, when the strategies that limit the rotor speed show a larger decrease in blade loads. However, even the three strategies that reduce the generator torque at full load result in a (smaller) decrease of blade fatigue loads at higher wind speeds.
In Figure 3.3 it can be observed that the rotor shaft DELs increase at wind speeds around $V = 6$ m/s when using down-regulation strategies 2a and 2b. This is 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 maximum 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 nominal controller.

Figure 3.4 shows that with respect to power productions, the results are similar to those obtained using the simplified ACT model in Chapter 2. Again, strategies 1a and 1b are not capable of attaining the desired down-regulation level at very low wind speeds. 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 is done only by pitching, as can be seen by the lines referring to strategies 3a and 3b.

3.3 Lifetime Load Reductions

In Figures 3.1-3.4 the performance of the different down-regulation strategies were presented for a large range of wind speeds. However, the environmental conditions often differ for different turbines. It is therefore also interesting to see what the effect of down-regulation is for a given wind distribution. In doing so, the overall load reduction or increase over the entire lifetime can be estimated. The InnWind 10 MW turbine is a class 1A turbine with Rayleigh wind distribution given in Figure 3.6. Using this Rayleigh distribution, the lifetime fatigue loads of several turbine components are computed for each down-regulation strategy and compared to the fatigue loads resulting from the nominal controller. For a clear comparison it is assumed that the down-regulation strategies are used for the entire lifetime of a turbine. The results of this analysis are presented in Table 3.1.

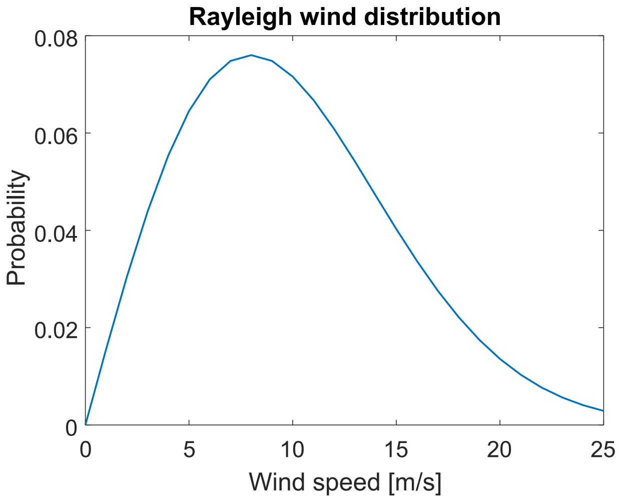


Figure 3.6: Rayleigh wind distribution with average wind speed $V_{avg} = 10$ m/s.

It is observed that for this particular wind distribution, only strategy 1a results in a small increase of tower lifetime fatigue loads. For the remaining down-regulation strategies it holds that all the fatigue loads have been slightly reduced and in many cases even significantly reduced. Overall it seems that strategy 2b, which incorporates operation at higher TSR and reduced rotor speed at full load, has the best load reduction performance. However, the load reduction of a particular component might have a higher priority and so the other strategies should not be cast aside immediately.

Table 3.1: DELs of several structural wind turbine components relative to the performance of the baseline controller.

	Strategy 1a	**Strategy 1b**	**Strategy 2a**	**Strategy 2b**	**Strategy 3a**	**Strategy 3b**
Tower bottom	+1.8%	-0.2%	-17.6%	-12.7%	-13.2%	-9.1%
Blade roots	-8.9%	-25.1%	-14.6%	-24.0%	-14.2%	-24.8%
Rotor shaft	-4.9%	-17.9%	-0.9%	-14.2%	-4.2%	-15.9%
Energy production	-17.1%	-20.1%	-20.8%	-20.3%	-20.3%	-20.7%

4. Conclusions

In this report several down-regulation strategies have been investigated using aeroelastic simulations with the InnWind 10MW turbine. Three different approaches were devised that can be used for down-regulation during partial load. The first one consisted of reducing the desired TSR of the turbine until stall is reached, after which the pitch angle of the blades is increased. The second approach did the opposite by increasing the desired TSR (and slightly increasing the pitch angle in order to remain at the peak of the $C_p - \theta$ curve). The final approach consisted of increasing the pitch angle and keeping the TSR constant. In full load operation, two methods are implemented to achieve derating: the rated generator torque or the rated rotor speed is reduced. By combining all these approaches, a total of six down-regulation strategies were assessed with respect to their effect on fatigue loading.

In order to test the down-regulation strategies, they were first implemented in the wind turbine controller developed at ECN. It was shown that decreasing the desired TSR or increasing the pitch angle resulted in a significant decrease in thrust force. This is a useful aspect when down-regulation strategies are considered for induction based AWC. Subsequently, simplified simulations were performed in the Simulink environment to find out if the desired down-regulation percentages could be achieved in terms of energy production. It was found that decreasing the TSR results in some issues in tracking the desired down-regulation level at very low wind speeds. However, the overall performance of all six strategies was considered to be good enough. Subsequently, the effects of the down-regulation strategies on fatigue loads were analysed using detailed aeroelastic simulations using PHATAS.

The fatigue of several structural wind turbine components was analysed 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 the DELs resulting from operation using the baseline controller. It was found that the strategies consisting of lowering the TSR had a significant fatigue load increase at the tower for low wind speeds. This was the result of prolonged operation at the cut-in rotor speed, where the 3P frequency excites the tower frequency. The strategies incorporating a higher TSR showed a very positive effect on the tower fatigue loads. However, due to the higher rotor speed at low wind speeds, the blade and rotor shaft fatigue loads increased significantly in this region. The final two strategies based on increased pitch angles showed very stable behaviour over the whole range of wind speeds and resulted in a reduction of fatigue loads for all components. Additionally, it has to be noted that reducing the rated rotor speed resulted in an increase of the tower loads at higher wind speeds. This is caused by a decrease in aerodynamic damping resulting from operation at a lower rotor speed and increased pitch action. However, the fatigue loads of the blades and rotor shaft were decreased as a result of this strategy.

Finally, the performance of the six down-regulation strategies was compared by computing the lifetime fatigue loads for the considered wind class. Apart from strategy 1a, which consists of decreasing the TSR in partial load and reducing rated generator torque in full load, all the down-regulation strategies resulted in a decrease of fatigue loads for all the selected components. The highest load reductions were seen at the blade roots, where fatigue load reductions of up to 25% were achieved. The best load reductions overall are achieved by increasing the TSR in partial load and decreasing the rated rotor speed in full load, i.e., using strategy 2b. However, this strategy limits the percentage of down-regulation that can be achieved. If higher percentages of down-regulation are required, strategy 3a is recommended. By increasing the pitch angle in partial load and reducing the rated generator torque, significant load reductions are achieved.

For future work, it is recommended that the down-regulation strategies that were discussed in this report are subjected to aeroelastic simulations using additional load cases. Further research should also focus on the implementation of the down-regulation strategies in wind power plants. Down-regulation can be used in wind power plants for several different purposes. First, it can be used for induction based AWC by optimizing the AWC settings using a cost function that also includes fatigue loads. Second, down-regulation might prove useful for some operations and maintenance strategies which aim to reduce wind turbine downtime. By operating a turbine using one of the strategies and thereby decreasing the loads, the moment of failure of a component can be delayed. Finally, the down-regulation strategies discussed in this report should be analysed in terms of ancillary APC services, which are essential for grid reliability.

5. Bibliography

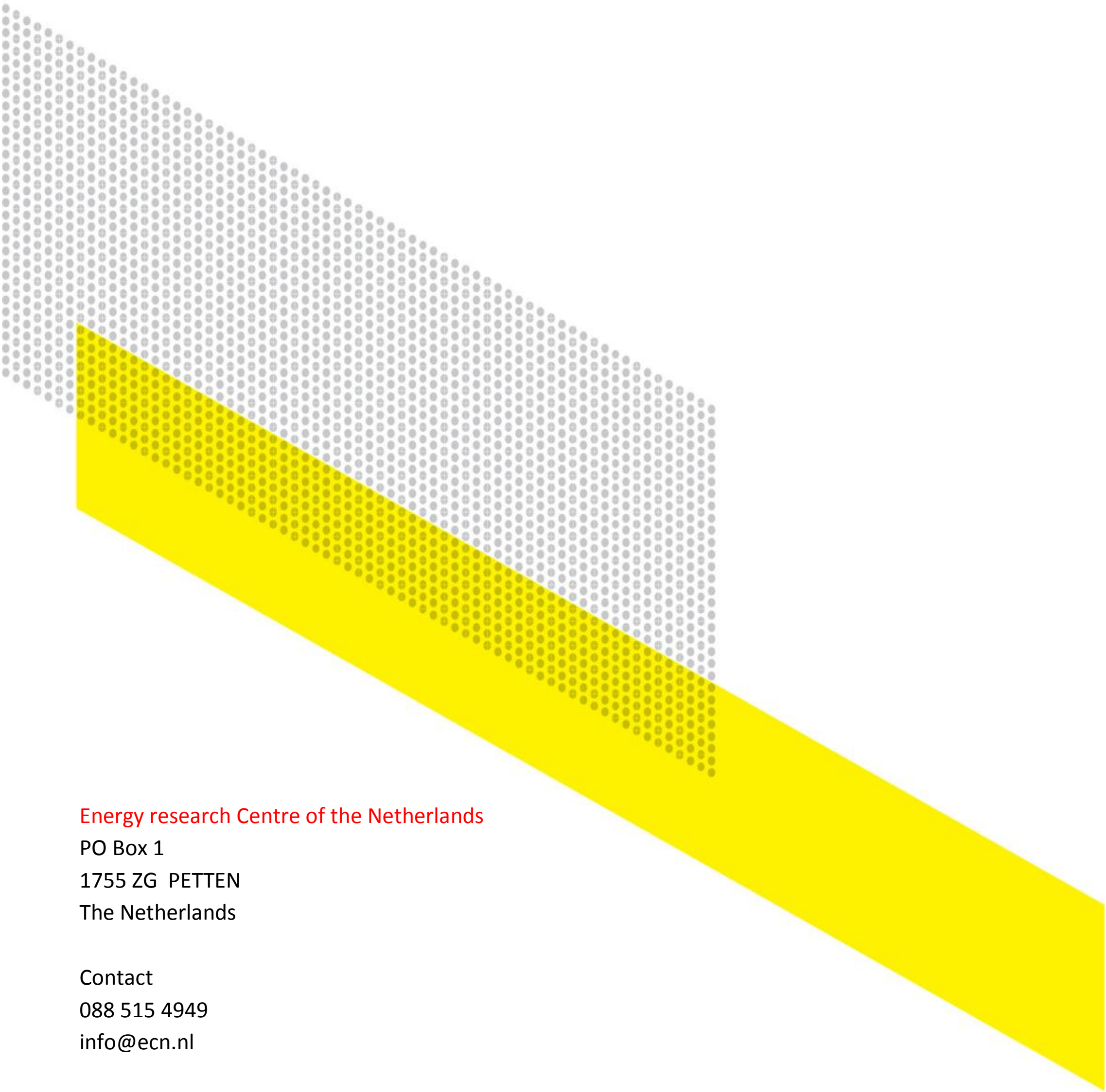
[1] S. K. Kanev, F. J. Savenije and W. P. Engels, “Active Wake Control: an approach to optimize the lifetime operation of wind farms,” *Wind Energy,* p. 13, 2017.

[2] J. Aho, P. Fleming and L. Y. Pao, “Active Power Control of Wind Turbines for Ancillary Services: A Comparison of Pitch an Torque Control Methodologies,” in *American Control Conference (ACC)*, Boston, 2016.

[3] P. A. Fleming, J. Aho, A. Buckspan, E. Ela, Y. Zhang, V. Gevorgian, A. Scholbrock, L. Y. Pao and R. Damiani, “Effects of power reserve control on wind turbine structural loading,” *Wind Energy,* vol. 19, p. 17, 2016.

[4] S. Kanev and F. Savenije, “Technical documentation of wind turbine control desing tool ACT,” ECN, Petten, 2014.

[5] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. Henriksen, A. Natarajan and M. Hansen , “Description of the DTU 10 MW Reference Wind Turbine,” Technical University of Denmark (DTU), 2013.



Energy research Centre of the Netherlands
PO Box 1
1755 ZG PETTEN
The Netherlands

Contact
088 515 4949
info@ecn.nl

www.ecn.nl