The effect of a speed exclusion zone and active tower dampers on an upwind fixed-hub two-bladed 20 MW wind turbine

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Abstract. Large two-bladed offshore wind turbines possess cost-saving potentials in their complete life-cycle, together with general structural blade advantages, compared to similar three-bladed machines. However, the general dynamics and tower-eigenfrequency interactions are challenging. Therefore, a speed exclusion zone for the partial load region and two straightforward pitch- and generator-driven tower dampers for the whole power production region are introduced. They enable the incorporation of a reasonable controller for a two- and a three-bladed baseline reference to facilitate a fair and objective turbine comparison. The outlined control features significantly reduced tower fatigue loads by 18% and 70% in the case of a three-bladed 20 MW and a two-bladed 20 MW turbine, respectively.

1. Introduction
Occasionally the question arises in scientific research and the wind industry if two-bladed offshore turbines are a more economical (and eco-friendlier) alternative to three-bladed wind energy conversion systems. The answer to this question is manifold: On the one side, the missing blade together with the corresponding pitch system does not only lead to potential cost benefits during manufacturing, but also during the turbine’s erection and operation [1, 2], and reduces effort and recycling issues during decommissioning. On the other side, structural advantages of a larger blade chord and thickness permit the usage of cheaper or eco-friendlier materials with less rigidity, and reduce tip tower clearance issues for huge turbines [3, 4]. However, the focus of the paper at hand is on the typically more harmful dynamics of two-bladed turbines and about three straightforward strategies for a decent reduction of tower loads when designing a two-bladed, variable-speed, fixed-hub, upwind machine. The controller features mainly act on two tower issues:

(i) Tower-eigenfrequency excitation by a matching multiple of the rotation speed during partial load conditions (e.g., 2P or 3P).

(ii) Higher tower loads due to an even number of blades and a less uniform distribution of blade forces in the entire wind range [5].

In the following, three controller modifications will be introduced, tuned, and evaluated for both, a 20 MW three-bladed and a 20 MW two-bladed wind turbine, likewise. The baseline
for the modifications is a standard controller that consists of a pitch-driven PI speed regulator for full load operation and a quadratic $K_{opt}$ torque regulator for partial load operation [6]. The first addition mainly utilizes a PI-torque controller for constant rotor speed that is only active in a specific region during partial load conditions. The remaining two modifications are straightforward active tower dampers. One reduces fore-aft (FA) tower oscillation with the pitch, and the other reduces side-to-side (StS) tower movement by the generator torque. Both are active during the entire wind range to a varying extent.

2. Issues with the tower-eigenfrequency and the speed exclusion zone

Large three-bladed turbines are often designed with a soft-stiff tower configuration [5]. The term refers to the tower-eigenfrequency being placed between the once-per-revolution (1P) and the three-per-revolution (3P) frequency at the design rotation speed. This introduces the issue that the 3P-frequency of the turbine has to pass the tower-eigenfrequency during start-up and shut-down. Nevertheless, the frequency gap $f_{gap,3B}$ between 1P and 3P mostly leaves enough space for power production without rotation and tower frequency interaction. In contrast, the typical rotational excitation of a two-bladed turbine occurs at the twice-per-revolution (2P)- instead of the 3P-frequency. It reduces the frequency design gap $f_{gap,2B}$ to such an extent that the power production without a tower interaction in the partial load region is challenging at best or even uneconomical. For a better overview of the link between the lowest turbine frequencies, the wind speed, and the operating region, a Campbell diagram with the wind speed on the x-axis is plotted in Figure 1. Blue refers to a three-bladed turbine and green to a two-bladed one.

![Campbell diagram](image)

**Figure 1.** Campbell diagram with 1P, 2P, and 3P frequencies for a three-bladed 20 MW turbine with 90 m/s rated tip speed and a two-bladed 20 MW turbine with 101 m/s tip speed and a -2% longer rotor.

While Figure 1 illustrates the soft-stiff configuration in general, the actual values belong to the turbines described in Chapter 4 and utilized later on. It highlights that the tower eigenfrequency excitation of the two-bladed turbine occurs at a higher wind speed of 7.57 m/s instead of 5.4 m/s, even though the turbine is rotating 10% faster. This alone indicates higher (dynamic) loads since the aerodynamic forces increase cubically with the wind speed until the turbine starts pitching out. The two-bladed turbine would have to rotate 50% faster to achieve an overlap of both turbines’ critical zones (marked in diagonal patterns), which would then drastically increase erosion, flutter, and would cause higher blade material usage [4, 5]. Nonetheless, rotating slightly faster already proved to reduce tower fatigue loads of the later analyzed two-bladed turbine in full load conditions [7].

Another, more popular, approach would be to shift the tower eigenfrequency by designing a new tower and foundation. The eigenfrequency could be decreased by reducing the jacket width and tower diameters and increasing the wall thicknesses. However, it has the disadvantage of
higher costs due to more material being necessary for equal structural strength. The reciprocal option is to increase the tower-eigenfrequency by increasing jacket width and tower diameters and reducing the wall thicknesses. While the resulting stiff-stiff configuration would be easier to achieve with a two-bladed turbine compared to a similar three-bladed one (see Figure 1), the structure might tend to have stability issues since the thinner wall panels tend to buckle earlier. This could lead to a conflict of stability and strength design criteria or to a significant increase of masses. The latter option might still be the more suitable one [8, 9]. However, the focus of the work at hand is on a good comparability and thus includes only necessary changes when designing a two-bladed turbine out of a three-bladed turbine [10]. Tower and jacket will therefore stay unchanged, bearing in mind that the comparison is more conservative for the two-bladed turbine due to more unfavorable initial conditions.

The approach presented here is to avoid the tower and rotation speed interaction by introducing a safety zone, marked with diagonal patterns in Figure 1. Its aim is to exclude, as much as possible, the respective rotation speed \( \Omega_{\text{avoid}} \), where the 2P- or 3P-frequency, depending on the number of blades \( n_{\text{blades}} \), interacts with the tower frequency \( f_{\text{tower}} \) during partial load.

\[
\Omega_{\text{avoid}} = \frac{f_{\text{tower}}}{n_{\text{blades}}}
\]

It is basically an extension of a quadratic \( K_{\text{opt}} \) torque control algorithm for partial load conditions [6] that shifts the rotation speed around the critical zone indicated by the arrows in Figure 1. Implemented efficiently, this option might result in a more economical overall turbine other than the mentioned design of a new tower and jacket with another eigenfrequency and more material [11]. It differs from a more straightforward torque look-up table [3, 12] by utilizing a constant speed PI-torque controller for an aerodynamically more efficient turbine operation. The method is thus closer to the procedure scripted in [13], but it uses another strategy to exit the speed exclusion zone when crossing \( \Omega_{\text{avoid}} \) by utilizing a wave-like spline function instead of ramping up the PI-controller’s reference speed. Furthermore, even more sophisticated model predictive approaches have been introduced to tackle the challenge of eigenfrequency interaction and to enable a real-time trade-off between power losses and loads [11].

A flow-chart of the utilized speed exclusion zone algorithm is sketched in Figure 2 to offer better insight and facilitate adoption. It starts with checking whether the rotation speed \( \Omega_k \) of the current time step \( k \) is within a pre-defined relative distance \( x_{\text{rel exZone}} \) to the rotation speed that is supposed to be avoided \( \Omega_{\text{avoid}} \). If it is not the case, the controller continues as usual and sets the sign variable \( x_{\text{sign}} \) to 0. The important role of \( x_{\text{sign}} \) is not only to indicate whether the current rotation speed is below or above \( \Omega_{\text{avoid}} \), but it is also used as a switch to reduce \( x_{\text{rel exZone}} \) to the relative width of the exclusion zone \( e_{\text{rel exZone}} \). Once \( \Omega_k \) enters the safety zone, \( x_{\text{sign}} \) will be defined as \( \pm 1 \) initially to increase \( x_{\text{rel exZone}} \) by a relative switch width \( c_{\text{switch}} \) to prevent the excessive transition between constant speed PI-torque control and the usual quadratic \( K_{\text{opt}} \) control, as part of a hysteresis. Afterwards, there is a chain of decisions. Firstly, it is checked if the current time \( t_k \) is outside the time period \( t_{\text{to exit}} + t_{\text{exZone}} \) necessary to exit the speed exclusion zone by crossing \( \Omega_{\text{avoid}} \). Secondly, it is monitored whether the demanded generator torque of the last time step \( Q_{k-1} \) reached the upper or lower torque limit of the exclusion zone \( (Q_{\text{upper}} \text{ or } Q_{\text{lower}}) \) depending on the rotation speed being below or above \( \Omega_{\text{avoid}} \), respectively. If this is not the case, the rotation speed error \( \Omega_0 \) will be calculated by

\[
\Omega_0 = \Omega_k - \Omega_{\text{avoid}}(1 + x_{\text{sign}}c_{\text{rel exZone}})
\]

as control variable for the constant speed PI-torque controller, which will be used instead of the normal quadratic \( K_{\text{opt}} \)-control. However, if the rotation speed \( \Omega_k \) is kept, e.g., above \( \Omega_{\text{avoid}} \) by reducing the generator torque \( Q_k \) for a while until it is close to the lower limit \( Q_{\text{lower}} \), or vice versa, this indicates that \( \Omega_{\text{avoid}} \) needs to be crossed by the rotation speed. In this case, the
\[
\Omega_k - \Omega_{\text{avoid}} < x_{\text{rel exZone}}
\]

\[
x_{\text{sign}} = 0 \quad (\text{speed exclusion zone will not be used})
\]

\[
Q_k = K_{\text{opt}} \Omega_k^2
\]

\[
Q_{k-1} < Q_0 < Q_{\text{upper}}
\]

\[
x_{\text{sign},k+1} = -x_{\text{sign}}
\]

\[
set \Omega_0 = \Omega_k - \Omega_{\text{avoid}}(1 + x_{\text{sign}}c_{\text{rel exZone}})
\]

as control variable for constant speed PI-torque control via \(Q_k\). Limits are \([Q_{\text{lower}}; Q_{\text{upper}}]\). Crossing process will be initiated by setting \(t_{\text{exZone}}\) to the current time, remembering the latest generator torque by \(Q_0\), and switching the sign parameter \(x_{\text{sign}}\) to enable a good transition after passing \(\Omega_{\text{avoid}}\). For the period of \(t_{\text{to exit}}\), the demanded torque \(Q_k\) will be ramped in the form of a spline [6] from \(Q_0\) to the variable outcome of \(K_{\text{opt}} \Omega_k^2\). The variable term is used instead of a preliminary fixed value to in- or decrease the rotation speed more aggressively if required in case of a slower rotation speed response during adverse wind speed propagations. However, if \(\Omega_{\text{avoid}}\) does not need to be crossed to leave the speed exclusion zone, the PI-torque controller will simply be limited by the respective \(Q_{\text{upper}}\) or \(Q_{\text{lower}}\) boundary, and the rotation speed will drift outside the zone eventually. The utilized spline function and the PI-torque controller with an upper and lower limit are part of the basic DTU wind energy controller [6]. Also, diverging PI boundary values are used during the first \(t_{\text{to exit}}\) seconds of every exclusion zone initiation.
3. Straightforward active tower dampers

The lower number of blades of a two-bladed turbine causes higher unbalances of the rotor. Additionally, the even number of blades results in blades being placed in the lowest and highest wind speed region simultaneously and periodically. The results are higher dynamic (tower) loads, in all power production regions, if no countermeasure is applied. Fortunately, there is a variety of solutions available, e.g., individual pitch control (IPC) [2], free-yaw control [14], and teetering [15]. Simply stated, a two-bladed turbine without any controller extension or passive damping technique would not serve as a reasonable design or benchmark. Therefore, the main idea has been to create straightforward and easy-to-implement controller extensions applicable to three- and two-bladed wind turbines, likewise, that could serve as an adequate and fair baseline to evaluate those more advanced (control) techniques. The solution described herein is a much simpler active damping of the tower fore-aft (FA) and side-to-side (StS) movement by the pitch and generator, respectively, similar to the methods of [16]. Both have a surprisingly decent effect of mitigating tower loads, depending on the wind region, and utilize the same basic idea:

\[ \beta_{FA \text{ damper}} = \beta_{ref} + v_{nacelle,FA} g_{v,FA} \]

\[ Q_{StS \text{ damper}} = Q_{ref} + \Phi_{roll} Q_{rated} g_{v,StS} \] (3)

The authors like to note that filters, as used in [16], might have improved the power quality and the damper efficiency, or reduced the pitch movement, but have been omitted due to the sake of simplicity. Both gains can vary with the wind speed \( v \), depending on the respective optimal trade-off between conflicting objectives such as blade and tower loads.

**Figure 3.** Sketch of nacelle fore-aft (left) and roll velocity (right) together with the respective signals, pitch and generator torque responses (middle) for a two-bladed 20 MW turbine at 15 m/s.

To reduce the fore-aft tower movement, the fore-aft nacelle acceleration is measured and integrated to the velocity \( v_{nacelle,FA} \), depicted red in Figure 3. Afterwards, the signal is applied with a specific gain \( g_{v,FA} \) to the demanded pitch signal (green) at the end of the control algorithm for normal power production.

Analogously, the side-to-side tower damper starts by measuring the nacelle roll acceleration and integrating the acceleration to the roll velocity \( \Phi \) (blue). The signal is then added with a pre-defined gain \( g_{v,StS} \) to the demanded generator torque (yellow) during normal power production.

\[ \beta_{FA \text{ damper}} = \beta_{ref} + v_{nacelle,FA} g_{v,FA} \]

\[ Q_{StS \text{ damper}} = Q_{ref} + \Phi_{roll} Q_{rated} g_{v,StS} \] (3)
4. Baseline turbines and simulation setup

A two- and a three-bladed turbine are analyzed in the following simulations, each with and without the described control features. One is the three-bladed INNWIND 20 MW reference turbine [17]. The other one is a thereof derived two-bladed 20 MW turbine, featuring the same up-wind, fixed-hub, max-Cp, variable-speed concept, and similar aerodynamics due to the same aerofoils, relative chord layout, and local angles-of-attack [10]. Nevertheless, the chords and thicknesses are 19% broader, and the design tip speed is increased from 90 m/s to 101 m/s [18]. Each blade is about 2% longer to counterbalance the ~4% decreased aerodynamic efficiency and enable the same absolute static power curve [10]. The structure has been adapted to ensure equal material stresses and an equal buckling resistance for 50% higher blade loads in flapwise direction and gravity-scaled edgewise blade loads [4]. The utilized controller is based on the Basic DTU wind energy controller [6]. The pitch PI gains are tuned with a control cost criterion (CCC) [7], resulting in comparatively low integral gains. Moreover, the CCC has been used to tune the damper gains $g_{\text{FA}}$ and $g_{\text{StS}}$, and the speed exclusion zone parameters $\Omega_{\text{avoid}}$, $c_{\text{rel exZone}}$, and $t_{\text{to exit}}$. The CCC aims to evaluate and find an optimal trade-off between conflicting objectives such as power-loss, component loads of e.g. blades or tower, and pitch activity. It is noted that the CCC has been updated to include the additional jacket material costs required to withstand higher tower loads. Likewise, the actuator-duty-cycle is replaced by the pitch load duty cycle described in [19] for higher accuracy. Nonetheless, the pitch movement has not been part of the CCC for the FA damper tuning due to high relative differences in the pitch movements and respective limitations of the linear CCC’s approach. The simulation environment is Bladed 4.10, and the evaluated time series are either the complete DLC 1.2 from the IEC-61400, or parts of it if labeled, with a wind bin step width of 2 m/s, a yaw error of 0°, and ±8° and six seeds each. Damage equivalent loads (DEL) are calculated with Bladed’s post-processor and a Wöhler coefficient of 10 for the blades and 4 for the tower. The loads are distributed over the wind range by a Rayleigh distribution with a design wind speed of 11.4 m/s. It is presumed that tower and jacket are primarily design driven by fatigue. Thus extreme loads will not be investigated herein.

5. Results – the effect of a speed exclusion zone and active tower dampers

The results of applying the control features will be presented in two consecutive steps. In the first step, the successful operation of the speed exclusion zone will be shown. The second step

![Figure 4](link)

Figure 4. Influence of the speed exclusion zone and active FA and StS tower dampers on the tower base moment of the two-bladed turbine (2B101) compared to the three-bladed reference (3B.ref) including all extensions for DLC 1.2 with six seeds and ±8°, 0° yaw per wind bin
will describe the impact of the dampers for different gains. The respective effects of the control features $i$ on the tower fatigue loads of the two-bladed turbine 2B101 are illustrated in Figure 4 in relation to the three-bladed turbine 3B$\text{ref}$ which already utilizes all three features. The chapter will conclude with a summarized comparison of both turbines with and without all features.

**The speed exclusion zone** is showcased in Figure 5, exemplarily for the three-bladed turbine for a normal turbulence model (NTM) at 5 m/s mean wind speed. Compared to the baseline controller (yellow), the speed exclusion zone is clearly visible in the rotation speed plot, where the blue line shifts quickly above or beneath $\Omega_{\text{avoid}}$ and mostly maintains a safety gap that has the relative width of $c_{\text{rel exZone}} = 15\%$. The shift of the controller’s reference rotation speed is initiated with a $t_{\text{to exit}} = 25s$ long spline function, after the demanded generator torque $Q$ has reached its threshold, the upper $Q_{\text{upper}}$ or lower limit $Q_{\text{lower}}$. Subsequently, the constant speed PI-torque-controller starts again twice, until the rotation speed slides out of the speed exclusion zone at 455 seconds. The load mitigating effect of the control feature is demonstrated in the plot of the tower base side-to-side moment $M_{\text{StS}}$ where large oscillations have been avoided. In this specific case, the damage equivalent load (DEL) of $M_{\text{StS}}$ has been reduced by 45%. The DEL of the tower base bending moment in the worst direction $M_{y'}$, representing the worst combination of $M_{\text{StS}}$ and $M_{\text{FA}}$, has been decreased by 38%. For the overall fatigue load case DLC 1.2, $M_{y',\text{DEL}}$ has been reduced by 9.2%, even though the control feature is only active at the 5 m/s wind bins. For the two-bladed turbine, the tower eigenfrequency excitation by the rotation speed $\Omega_{\text{avoid}}$ occurs at higher wind velocities (see Figure 1). There, $M_{y',\text{DEL}}$ could thus be mitigated even more effectively by 34%. Yet, the loss in energy yield has also been higher (-0.14% instead of -0.03%).

![Figure 5](image-url)

*Figure 5.* Example for the three-bladed turbine at 5 m/s wind speed with the speed exclusion zone (blue) and without as a baseline (yellow), showing the wind speed at hub height $v_w$, generator torque $Q$, rotation speed $\Omega$, and tower base side-to-side moment $M_{\text{StS}}$. 
The active FA and StS tower dampers enable another decent tower DEL reduction. Nonetheless, the respective gains have to be tuned carefully. For the side-to-side damper, the upper plots of Figure 6 illustrate that the effect of a higher gain $g_{\text{StS}}$ is almost the same for both turbines and that the tower StS DELs are efficiently reduced with an increased constant gain value over the whole wind range. Fine-tuning the damper by applying the control cost criterion [7] leads to a varying gain over the wind speed in the form of the look-up Table A1, which has been linearly interpolated inside the controller with a highly low-pass filtered wind speed signal. The two-bladed turbine uses the StS damping more aggressively because the side-to-side moment $M_{\text{StS}}$ has a more significant influence on the tower bending moment in the worst direction $M_y'$. It is noted that its effect on $M_y'$ increases from 1% to 8% if the FA damper actively reduces $M_{\text{FA}}$ as well. The relative difference of $M_{\text{StS}}$ remains similar. For the three-bladed turbine, the DEL of $M_y'$ has only been reduced by 0.5%, while the $M_{\text{StS}}$ DEL has been 9% lower, which is quite similar to the 11% $M_{\text{StS}}$ reduction of the two-bladed turbine. A power loss is almost not existent for both turbines. The power quality had not been analyzed.

![Figure 6. Effect of fore-aft (FA) and side-to-side (StS) dampers for wind speed optimized and constant gain values on damage equivalent loads of the blade root flapwise moment, the tower base StS, FA, and worst direction ($y'$) bending moment, and the energy yield for the complete wind range with 0° yaw.](image)

The fore-aft damper, in turn, performs significantly better for the two-bladed turbine, where higher gains also lead to a decent tower fatigue load reduction, as shown in the lower plots of Figure 6. Even though it approximates a cost-optimum by the CCC, the $g_{v,\text{FA}}$ optimized case reduces $M_y'$ by 28%, while the blade flapwise moment DEL is increased by 11%. The pitch load duty cycle is even increased by its 12 fold because there has been only little pitch usage before. The energy yield has been reduced by 0.07%. The three-bladed turbine achieves a higher tower load reduction in the optimized case with the $g_{v,\text{FA}}$ values of Table A1 than any constant gain in Figure 6. The three-bladed turbine’s FA damper thus reduces tower fatigue by 8%, with only a small influence on blade fatigue (1%) and energy yield (-0.003%). Yet, the pitch’s small cyclic usage increases the pitch load duty cycle by its six fold.
Figure 7. The respective combined influence of speed exclusion zone, fore-aft and side-to-side damper on a three- and a two-bladed turbine. 2B blade loads are scaled to equal rotor length.

The combined effect of all three control features is illustrated in the bar chart of Figure 7. The most striking is that the tower fatigue of the two-bladed baseline turbine without the control features is 163% and 219% higher compared to the three-bladed turbine without and with all control features, which is still in-between the findings of [9] and [20]. Implementing the control features into the two-bladed turbine reduces these values to 11% and 35%, respectively. As mentioned before, the FA damper increases blade fatigue if used aggressively. However, the two-bladed turbine’s blades have been designed to withstand 50% higher loads per blade [4, 10, 18], which has not yet been reached by the fatigue values. Quite surprisingly, the flapwise fatigue blade loads are only 31% higher compared to the three-bladed turbine if both turbines are operating without the control features. This underscores the quasi-static load assumption of 50% higher loads per blade, even though two-bladed turbines are dynamically more demanding. Thus, the main issue remains the tower fatigue loads, which have been effectively reduced by 70%, mainly to the costs of a much higher pitch activity and a 0.2% lower energy yield.

6. Conclusion and outlook
Three tower load reducing controller enhancements have been introduced, tested, and evaluated. They are applicable to three- and two-bladed wind turbines, likewise. In general, the features exhibit a higher effect on the loads of the two-bladed turbine. This can be related to a more uneven aerodynamic load distribution as well as the tower eigenfrequency and rotation speed interaction occurring in higher wind speed regions. Nonetheless, the two-bladed turbine’s tower fatigue load has been reduced from 163% to 11% above the loads of the three-bladed turbine without these control features. With all three features, the three-bladed turbine’s tower load has been reduced by 18%, which is then 38% beneath the two-bladed turbine with an equal controller setup, but with only minor impacts on energy yield or blade loads. All three control features combined transform a most likely uneconomical two-bladed turbine into an economically compatible design. While the speed-exclusion zone already represents a sophisticated method, the pitch- and generator-torque-driven active tower dampers are straightforward to implement. They can now serve as a baseline reference for even more advanced load mitigating techniques like teetering, individual pitch, free-yaw, sliding mode, or model predictive control. While open issues remain, this contribution represents another basis to answer the general question of whether two-bladed turbines might be the more economical turbine alternative for the future offshore wind energy market.
Acknowledgments
The presented work is part of the four-year research project “X-Rotor – two-bladed wind
turbines” funded by the German Federal Ministry of Education and Research and Siemens
Gamesa Renewable Energy (reference 13FH1I04IA), whom we would here like to thank.

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Appendix A.

Table A1. Variation of the gains for FA and StS dampers over the complete wind range.

| wind speed in m/s | 5  | 7  | 9  | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|
| $g_{StS,2B}$ in s/rad | 10 | 10 | 10 | 10 | 10 | 05 | 05 | 05 | 05 | 00 |    |
| $g_{StS,3B}$ in s/rad | 10 | 05 | 05 | 10 | 00 | 00 | 00 | 05 | 05 | 05 | 05 |
| $g_{FA,2B}$ in rad/s/m | 0.20 | 0.15 | 0.15 | 0.20 | 0.20 | 0.20 | 0.20 | 0.15 | 0.15 | 0.10 | 0.10 |
| $g_{FA,3B}$ in rad/s/m | 0.15 | 0.15 | 0.00 | 0.00 | 0.00 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |