Balancing rotor speed regulation and drive train loads of floating wind turbines

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Abstract. The interaction of the blade pitch controller with structural motion is particularly important for wind turbines mounted on floating platforms. A controls-based approach to overcome the related technical challenges is to feed back the nacelle’s motion to the demanded generator torque. This work aims to further improve this approach by feeding back only a narrow fraction of the available frequency range. Simulations show that, in doing so, unrealistically high torque magnitudes are avoided, and better a trade-off between rotor speed regulation and drive train loads is achieved.

1 Introduction
The placing of wind turbines on floating platforms poses an especially interesting control engineering problem. First, consider regular on-shore wind turbines. To put it simply, the “classical” speed control loop above rated wind speed is usually designed in such a way that the loop bandwidth rolls off before the first eigenfrequency of the turbine tower. This way, a possibly unstable interaction of the blade pitch controller with structural motion is avoided. Thus, the natural frequency of the first tower mode forms a natural upper barrier for the closed-loop bandwidth.

In the case of floating wind turbines however, the available literature suggests that the eigenfrequency of a rigid body mode associated with the platform limits the achievable bandwidth of the speed control loop. This frequency is much lower than the first tower eigenfrequency and, in turn, the speed regulation capability above rated wind is deteriorated.

This was observed in early works on the control of floating wind turbines, see e.g. [1, 2]. Both references propose to reduce the bandwidth of the speed control loop as a solution to avoid unstable interaction between the platform mode and the control system. In [2] this control design strategy is denoted as “detuning” the controller gains, where “detuning” refers to the original parameters of the fixed-foundation turbine. However, the pitfall of this strategy is that it simultaneously degrades the speed regulation. Without substantial hardware modifications, the resulting increase in rotor speed variations would cause numerous overspeed-induced turbine shut-downs.

Another control strategy has been proposed in [3] where an additional control loop is added in parallel to the speed control loop in above-rated operation: A measurement of the nacelle’s motion is fed back to the demanded generator torque, see Figure 1. This second control loop is designed to increase the upper barrier for the closed-loop bandwidth of speed control loop and thus regain the speed regulation capabilities of fixed-foundation turbines. A rather broad frequency range has been fed back in the original work leading to heavy usage of the demanded generator torque and high drive train loads.

In this study, we improve the method proposed in [3]. It is demonstrated that by feeding back a much narrower frequency range a similar speed regulation is achieved – with feasible duty cycles of generator torque.
The next section briefly reviews the challenges associated with the control of floating wind turbines and what has been proposed in the literature to overcome them. Then, the improved method is described. The fourth section presents the results from a reduced load analysis that compares the new method with existing solutions and shows the improved trade-off between rotor speed regulation and drive train loads.

![Figure 1](https://example.com/image.png) **Figure 1.** Block schematic of the general controller structure above rated wind speed with speed control loop and RHP zero compensator.

## 2 Control of floating wind turbines

Why can the interaction of control system and structural motion lead to an unstable overall system? The speed regulation above rated wind speed is typically realised by feeding back the rotor speed error to the blade pitch angles. When the rotor speed increases, the controller pitches to feather in order to reduce the aerodynamic torque and recapture the rotor. There is, however, a second physical effect. Pitching the blades to feather also reduces the thrust force on the rotor. Consequently, the nacelle will move upwind. This motion affects the blades as a locally increased wind speed that in turn would lead to a higher rotor speed.

It depends on the operating point and the considered frequency range which of the two competing effects dominates. As a rule of thumb it can be said that the thrust force pathway dominates the aerodynamic torque pathway for operating points near rated wind speed and in the frequency range where there is significant motion of the nacelle. For floating wind turbines, the latter is typically a rigid body mode associated with the platform motion, which is considerably slower than the first relevant natural frequency of fixed-foundation turbines usually associated with the first tower bending mode.

Please note that this explanation is somewhat simplified. There are further effects to completely describe the mechanisms that are associated with the interaction between control and turbine, e.g. regarding lateral modes and blade flap-wise modes. For more detailed information, the interested reader is referred to the excellent in-depth study [4].

How do the competing pathways challenge the control design? Two competing pathways can lead to the emergence of right half plane zeros (RHP zeros). That is, the transfer function of the linearised single-input single-output (SISO) plant exhibits a zero in the open right half of the complex plane. Plants with RHP zeros exhibit so called non-minimum phase or allpass behaviour and suffer from a fundamental limitation on the achievable closed-loop bandwidth below the frequencies of the zeros. By means of control, the limitation cannot be overcome without using at least one appropriate additional input and one appropriate additional output, see e.g. the excursus in [5].

The deliberate compensation of the non-minimum phase behaviour can be denoted “parallel path modification” and goes back to [6]. It has firstly been proposed for fixed-foundation turbines in [7] where the term “coordinated control” is also used. The specific application to floating turbines is found in [3]. The common above-rated controller structure is amended by a simple filter that feeds back the tower top acceleration to the generator torque. Thus, the RHP zeros are counter-acted. Once the non-minimum phase behaviour is compensated, the actual speed control loop can be designed without the limitations imposed by the RHP zeros. This additional degree of freedom is useful especially to improve the rotor speed regulation capability.
In addition to stability and rotor speed regulation there are, however, further criteria to be evaluated regarding the control performance. These include for example the variation of the electrical power output, the motion of the platform, and, more generally, the structural loads. Several controls-based solutions have been proposed in the literature for modifying the control system to allow for operation on a floating platform.

2.1 Brief classification of methods for controlling floating wind turbines

A general classification might distinguish between “classical” and “advanced” control methods. Because the latter are only slowly making their way from science to industry, we focus on the “classical” methods. These share the property that there are different SISO control loops dedicated to different control tasks. Usually the tasks are related to separate frequency ranges and can, more or less, be considered to be uncoupled. This allows for an iterative control design. The advantage of this approach is its transparency and that it is relatively simple to include ad-hoc measures for troubleshooting.

Three different solutions can be classified:
1. Detuning of controller gains.
2. Feeding back motion measurements to the demanded pitch angle.
3. Feeding back motion measurements to the demanded generator torque.

“Detuning” has already been mentioned in the introduction. It means reducing the bandwidth of the speed control loop and accepting the poorer speed regulation. The second type includes different approaches. For example, the nacelle acceleration is additionally fed back to the pitch angle in the manner of an active tower damping, see e.g. [8]. Another example is [9], where the platform pitch velocity is used to manipulate the set-point of the speed control loop.

However, all the approaches of type 2 cannot overcome the fundamental bandwidth limitation of the speed control loop because they share the same control input with the speed regulation. In [5] it is demonstrated that using the same control input means adding a series block to the control plant that cannot overcome the RHP zero. Therefore, we think that it is misleading to use the terminology proposed in [10], where these methods are termed “parallel compensation” although they actually exhibit a pure serial nature.

The third type would more rightly be named parallel compensation since feeding back a second output to a second control input can result in a block in parallel to the plant, see [5]. This case is considered in this work, where the additional measurement is either the nacelle or the platform pitch velocity, and the additional input is the generator torque. Please note that the actual measurement value might be acceleration. Velocity is then obtained from numerical integration. We use only “velocity” for the sake of simplicity.

3 Control design for improved RHP zero compensation

After a brief recapitulation of the original method, we describe its improvement and the specific control design that has been used in this study.

3.1 RHP zero compensation for floating wind turbines

Fortunately, for wind turbines the RHP zero compensation is possible without introducing new actuators. A simple filter has been used in [3] to feed back the nacelle velocity to the generator torque, see bottom path in Figure 1. Thus, the design of the top path, i.e. the speed control loop, is no longer constrained by the RHP zeros.

The filtered signal must contain the frequencies around the frequency of the RHP zeros to achieve compensation. This is around the natural frequency of the platform pitch mode for the turbine considered below. Low-pass characteristics are necessary to attenuate high frequency content. High-pass characteristics are necessary to remove sensor offsets.
In [3] it is demonstrated that with the RHP zero compensation it is possible to even use the pitch controller parameters of the fixed-foundation turbine for the corresponding floating system. This is somewhat academic because it would make sense to redesign the speed controller taking into account the effect of the compensator. Furthermore, the generator torque amplitudes for counter-acting the RHP zeros are rather high. This leads to considerable drive train loads.

We aim to show that it is possible to achieve an improved compromise between rotor speed regulation and drive train loads in this work.

Before the main improvements to [3] are described in the subsequent section, we would like to endorse the “classical” approaches again. It can be argued that using additional inputs and outputs allows for the application of multivariate control design methods. These methods offer a greater flexibility for the design. However, as mentioned in the previous section, the transparency of iteratively closing several SISO control loops is appealing from a practical point of view. Hence, an increase in flexibility from multivariate methods must be balanced against the increase in complexity. Therefore, we think that using advanced multivariate control should always be the last resort.

3.2 Broad-band vs. narrow-band compensation

One of the reasons for the high generator torque duty cycles observed in [3] is that the wave frequencies are not sufficiently attenuated. We denote this as “broad-band compensation”. It leads to unnecessary control actuation in frequency ranges that do not contribute to the compensation task. This is of special interest when considering wave-induced frequencies of the nacelle or pitch velocity, see Section 4.2 for further details.

Thus, a narrow band-pass filter designed to transmit only the critical frequency range is the logical solution to this problem. Furthermore, we propose the usage of the platform pitch angular velocity instead of the nacelle fore-aft velocity, which provides further filtering of the feedback signal, see Figure 2. The wave frequency range is centred around 0.1 Hz, which is far above the platform pitch eigenfrequency at 0.033 Hz. Thus, an attenuation of almost 10 dB is achieved when switching from the nacelle velocity to the platform pitch angular velocity as a measurement for the feedback to the generator torque.

With the usage of the afore-mentioned narrow-band filter and the platform pitch angular velocity, we achieve improved controller performance for the RHP zero compensation. The required maximum generator torque is reduced from 120% to 110% of its rated value compared to the broad-band feedback compensation. In turn, the drive shaft loads are reduced considerably. The details are demonstrated in Section 4.2.

![Figure 2. Comparison of the normalised magnitude response from generator torque \((T_G)\) to nacelle fore-aft velocity \((v_{\text{NAC}})\) and platform pitch angular velocity \((v_{\text{PP}})\).](image)

3.3 Control design

This subsection describes the model-based design of the compensator filter. It has been pointed out in [3] that the simple model that has been used there to explain the occurrence of the RHP zeros is not sufficient for a model-based controller design. Hence, we used a model of the 5MW NREL baseline turbine linearized with our in-house tool chain “WTsim”, see e.g. [11], including the following structural degrees of freedom:
- platform surge, sway, heave, roll, pitch and yaw,
- tower 1st and 2nd modes, both fore-aft and side-side,
- blade 1st and 2nd modes, both edge-wise and flap-wise,
- drive train 1st mode.

The two control loops shown in Figure 1 are closed consecutively. First, the filter for the RHP zero compensation is designed. We used a second order band pass filter with the transfer function

$$F(s) = \frac{K \cdot s}{\omega_{pp}^2 \cdot s^2 + 2\theta \omega_{pp} \cdot s + 1}$$

where $\omega_{pp}$ is the natural frequency of the platform pitch mode in rad/s and the parameters $K$ and $\theta$ are used to specify the gain and the bandwidth of the filter. Bandwidth and gain must be chosen high enough to effectively counter-act the RHP zero but not too high in order to avoid heavy usage of the actuator.

Second, the PI-controller is designed for the compensated speed control plant. Unsurprisingly, the bandwidth of the speed control loop cannot be increased further than the bandwidth of the land-based system. This is because we only compensate for the RHP zeros due to the platform pitch mode; it is beyond our scope to compensate for RHP zeros at higher frequencies.

Hence, we can use the parameters of the fixed-foundation system given in [12]. This leads to a tight speed regulation comparable with those of the fixed-foundation system. To further illustrate the flexibility offered by the compensator method, we used a second speed controller with an integral gain reduced to 20% of the original value. Although this controller leads to a slightly degraded speed regulation, the overall behaviour of the system is improved.

The standard control structure from [12] is amended by simply adding the compensator torque to the torque demand of the controller. The control action of the compensator is limited by saturation blocks in both magnitude and rate. This reduces the compensator-induced actuator duty cycle above rated wind speeds and provides a smooth transition between the operation regions below and above rated conditions. The fading in and out of the compensation scheme is carried out in the transition region 2 ½, since it is only required when the turbine operates above rated wind speeds. Also, the compensator may be turned off during wind conditions that are far above rated conditions as well. However, this is not considered in this work.

It should be noted that using the generator torque in the manner of the RHP zero compensator is not common in industry. Nevertheless, we see no principle technical reason that impedes overcoming this acceptance barrier.

4 Simulation with the 5MW NREL baseline turbine model

The performance of the two controllers is systematically evaluated below by means of a reduced load analysis.

4.1 Simulation setup

We use fully coupled, non-linear simulations of the 5 MW NREL offshore wind turbine installed on the OC3-Hywind spar buoy [13] for the control system evaluation. All simulations have been carried out in Matlab/Simulink with the FAST module [14].

A reduced fatigue load analysis has been carried out following DLC1.2 of the IEC 61400-3 standard (normal operation). The different simulated environmental conditions are:

- 4, 6, 8, ..., 24 m/s mean wind speeds (IEC I, B; power law exponent 0.14), no yaw misalignment, and
- site-specific metocean data according to [15], a location in the northern North Sea.

Each simulation run takes 850s, whereas the first 250s are omitted for the analysis to exclude transients because of initialization effects. Five different random seeds are used for each wind speed.

Four different control configurations are considered. The narrow-band compensator described above with two sets of speed control parameters; the first one being the fixed-foundation controller
according to [12] leading to a high bandwidth of the speed control loop, denoted case ‘narrow-band A’, and the second one being the same except for the integral gain being reduced to 20% of its original value, which leads to a medium bandwidth speed control loop, denoted case ‘narrow-band B’.

Two other configurations are used for comparison: the ‘detuned’ control system with low bandwidth according to [13] without RHP zero compensator, and the control system from the earlier work [3] with ‘broad-band’ compensator and speed control parameters according to [12]. The control configurations are summarised in Table 1.

| Case            | Speed controller | Compensator       |
|-----------------|------------------|-------------------|
| ‘detuned’       | low bandwidth    | none              |
| ‘broad-band’    | high bandwidth   | broad-band        |
| ‘narrow-band A’ | high bandwidth   | narrow-band       |
| ‘narrow-band B’ | medium bandwidth | narrow-band       |

### 4.2 Simulation results

This subsection includes the results from the simulations. The comparison of the four control configurations is carried out with the help of

- sample time series from a simulation run with 14 m/s mean wind speed (Figure 3 to Figure 7),
- a statistical analysis of all simulation runs (Figure 8), and
- fatigue load analysis of all simulation runs (Figure 9).

We start by separately commenting the main features of individual signals. An overall evaluation is given in the next section.

**Generator speed.** Figure 4 shows the heavy variations of the generator speed in the sample time series for the detuned case in the top row. At approx. 350 s, the turbine drops into the operating region below rated wind speed. It returns to above-rated shortly after, where the slow pitch controller only maintains rated generator speed rather poorly. The statistical analysis results in Figure 8 confirm these variations. They are up to around 30% overspeeds over all simulations.

Because of the increased bandwidth of the rotor speed control loop, the variations of the cases with original onshore parameters, i.e. ‘broad-band’ and ‘narrow-band A’, are reduced to “onshore” values, which are below 15% overspeed. The variations are again slightly increased for the case ‘narrow-band B’, where the medium bandwidth speed loop leads to maximum overspeeds around 20% above rated, see also Figure 8.

**Generator torque.** The constant torque maxim for above rated wind speed is clearly visible for the detuned case in the top row of Figure 5. Only around 350 s, the torque drops below the nominal value for a short period. In contrast, the torque fluctuates in the other three cases because of the compensator.

All these other signals share the presence of motion due to the platform pitch mode with a period of approx. 30 s. The broad-band compensator exhibits the strongest usage of the generator torque. This is mainly because of i) the increased maximum amplitude, 120% instead of 110% of nominal, and ii) the additional spectral content due to the wave induced motion, compare the time series of the wave elevation in Figure 3.

The narrow-band compensators require much lower control amplitudes. These amplitudes are concentrated around the natural frequency of the platform pitch mode. While case B with the medium bandwidth speed loop stays well inside the allowed control range, case A with the high-speed bandwidth loop saturates repeatedly.

**Generator power.** Since the control maxim above rated wind speed is constant torque and not constant power, the generator power fluctuates in all four cases in Figure 6. The strongest variations are observed for the broad-band case, where the wave frequency range is clearly present.
Figure 3. Time series of hub-height wind speed and wave elevation for a sample simulation run with 14 m/s mean wind speed.

Figure 4. Sample time series of generator speed for the four control cases.

Figure 5. Sample time series of generator torque for the four control cases.

This is confirmed by the statistical analysis shown in the centre row of Figure 8. With detuned speed control loop, the overall power maximum is 6576 kW, which lies below the 6833 kW of the broad-band case and above the 6385 kW and 6338 kW of the narrow-band cases A and B, respectively.

Platform pitch. Figure 7 shows time series of the platform pitch motion. The natural frequency of the platform pitch mode is visible in all signals. Most noticeable are the pronounced oscillations for the case ‘narrow-band A’. Additional simulations, which are not presented here in detail, have shown that the oscillations can be reduced to the levels of the cases ‘broad-band’ and ‘narrow-band B’ by increasing the compensator gain and the control range of the compensator, so as to avoid generator torque saturation. This suggests that the compensator does not sufficiently compensate the non-minimum phase behaviour of the speed control path for the combination of compensator and speed controller chosen in case ‘narrow-band B’.
Figure 6. Sample time series of generator power for the four control cases.

Figure 7. Sample time series of platform pitch angle for the four control cases.

Figure 8 shows the results from the statistical analysis of the platform pitch angle in the bottom row. Both broad-band and ‘narrow-band A’ cases exhibit larger platform movement than the detuned case. However, ‘narrow-band B’ leads to the lowest platform pitch motion of all considered cases.

**Fatigue loads.** Fatigue load calculations have been performed for each case. The resulting damage equivalent loads (DELs) of the floating turbines are divided by the DELs of the land-based turbine. Thus, a DEL ratio of 1.05 means that the corresponding DEL of the floating system is increased by 5% with respect to the land-based system. The reference to the land-based values has been kept to maintain comparability to the earlier work [3].

Figure 9 shows a bar plot of the DEL ratios for the main shaft torque and the bending moments of blade roots and tower base. In general, the bar heights are very similar with the exception of the main shaft torque. The main shaft torque DEL is considerably higher for the case with broad-band compensator. With the narrow band compensators this value is, however, only 5% higher than in the detuned case. This is because the narrow band compensators lead to less load cycles and reduced torque amplitudes. Minor differences occur for the other four load signals, where the case ‘narrow-band B’ leads to the lowest DEL values.

5 **Discussion and conclusion**

Earlier work has shown that using a broad-band compensator enables us to regain bandwidth of the speed control loop and, in turn, effectively reduce rotor speed variations [3]. The main result of the work presented above is that the drawback of the broad-band compensator, that is the unrealistically high duty cycle of the demanded generator torque, has been overcome by a very simple means.
Figure 8. Statistical analysis for the four control cases. Maximum and minimum for each seed, mean and standard deviation across all seeds. Top row: Generator speed. Centre row: Generator power. Bottom row: Platform pitch angle.

Figure 9. Damage equivalent load ratios for the four control cases. The values of the floating turbines are divided by those of the land-based turbine.

Implementing a narrow-band compensator significantly reduces the necessary control range and activity; see the time series in Figure 5 and the main shaft torque DELs in Figure 9, where the DEL ratio is reduced from 144% to 110%. The narrow band-bass filter transmits only frequencies around the natural frequency of the platform pitch mode and cuts off wave-induced content that would lead to large, unhelpful control amplitudes. Another feature is the reduced fluctuation of generator power (Figure 8).

These benefits come at the expense of either low damping of the platform pitch motion or slightly degraded speed regulation. The two investigated cases with narrow-band compensator demonstrate this trade-off.

Although the relatively low damping of the platform pitch motion in case ‘narrow-band A’ does not destabilise the system, the platform pitch amplitudes are the highest of all considered cases. On the other hand, it maintains the level of speed variation that is characteristic for fixed-foundation turbines (Figure 8). The speed variations are slightly higher than typical fixed-foundation values in case ‘nar-
row-band B’. However, it exhibits the lowest platform motions of all. This, in turn, leads most likely to the lowest DEL ratios of tower and blade loads (Figure 9).

In sum, the results suggest that both cases with narrow-band compensator have their advantages and disadvantages. It depends on the design of the turbine’s components how to optimally balance rotor speed regulation, drive train loads, and other criteria. A general statement regarding this optimum is unreliable for the turbine used in the numerical study because its components are not specified in detail.

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