A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine.

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Abstract. Wind turbines mounted on floating platforms is subjected to completely different and soft foundation properties, than seen for onshore wind turbines. This leads to much lower natural frequencies, related to the rigid body motion of the structure which again leads to an unfavorable coupling between tower motion and the pitch control of the turbine. The tower motion in combination with the aerodynamics and the pitch control will be poor or even negative damped which causes large transient loads if not accounted for. The reason for this low damping is shown to be caused by a too fast pitch regulation compared to the motion of the tower or in other words the lowest control-structure natural frequency must be lower than the lowest critical tower frequency. A control algorithm is presented including the tuning method (pole-placement) to ensure the desired control frequency which provides stable tower vibration modes.

1. Introduction

Within the last years a lot of focus has been on offshore turbines mounted at water depths up to 20 m. However, for a lot of coast sites, especially in Norway, Spain or the eastern coast of USA water depths are significantly larger. This has caused attention to the possibility of floating offshore wind turbine foundation. Norsk Hydro has developed a concept – the HYWIND concept, illustrated in Figure 1, which is a slender draft hull with ballast in the lower part. It is supported by three mooring lines consisting of steel wires and clump weights. This design, which is designed for water depths between 200 and 700m is described in more details in [3]. In this paper a 5 MW pitch regulated wind turbine has been mounted on top of the foundation. The rotor diameter is 123m with a hub height of 81.5m above mean sea level.

In order to be able to simulate loads and dynamics of the system including the highly non-linear interaction between aerodynamics, hydrodynamics, structure and control a special simulation tool was developed. This is a combination of SIMO/RIFLEX developed by MARINTEK and HAWC2 developed by Risoe National Laboratory. SIMO is a computer code designed for simulations of motions and station-keeping behaviour of floating vessels, whereas RIFLEX is a program for static and dynamic analysis of slender marine structures. HAWC2 is a code developed for calculation of dynamic wind turbine load and response including coupling to control. It is based on a multibody
formulation which makes it especially suited for investigations of new turbine concepts. More information of the two codes, the integration and verification to measurements can be found in [3].

When the turbine is mounted on the floating foundation the lowest natural frequencies decrease significantly. The 1st tower frequency for the turbine mounted on-shore is close to 0.4Hz, which is a lateral bending mode. Mounted on the floating foundation some new vibration modes appear. The 1st mode is a horizontal translation mode of the tower with a natural frequency of 0.01Hz. The second mode is a rigid body tilt rotation with a frequency of 0.035Hz and the third mode is a vertical translation mode of 0.037Hz. The purpose of such low frequencies is to avoid any structural vibration modes in the frequency range of wave excitation in order to minimize dynamic load amplification, but it is also the source for some new vibration problems that is treated within this paper.

![Figure 1. The HYWIND concept. The turbine is mounted on a floating spar attached to three mooring lines. The concept is intended for water depths between 200 and 700m.](image-url)
2. The stability problem

Very early in the project it became clear that special stability problems could occur when a turbine with very low natural frequencies is combined with a traditional pitch controller. This can be seen in the simulation results in Figure 2. In these simulations a linearly increasing wind velocity up to 18m/s is submitted to a turbine with three different characteristics. The first simulation is a turbine mounted on a typical on-shore foundation which leads to a tower frequency of 0.5Hz. The natural frequency of the controller (explained in more details later in the paper) is typical 0.1Hz. This means that the pitch control is slow related to the tower motion. It can be seen that this approach leads to a stable response. In the center figure of Figure 2 the same control is applied to an off-shore configuration with a tower tilt rotation frequency of 0.05Hz. A severe instability is seen related to unfavorable coupling between tower motion and pitch control. In this case the control frequency was still 0.1Hz which is fast compared to the tower motion. In the last figure of Figure 2 it is seen that the tower motion is again stable if the control frequency is reduced to a value lower than the first tower frequency.

The reason for the instability is the influence of thrust force on the tower motion as it contributes directly as damping. If the change in thrust related to change in wind speed $dT/dU$ is positive the aerodynamic damping on the tower motion is positive (since tower motion leads to a direct change in effective wind speed). In Figure 3 the typical thrust characteristic for a pitch regulated turbine can be seen. From a quasistatic point of view where everything is in equilibrium for each wind speed the gradient is positive at wind speed below rated but negative above rated. The negative gradient at high wind speeds are primarily caused by the changed pitch angle setting which reduces the loads and changes the effective force direction. This means that the damping is positive at low wind speeds but negative at high wind speeds. This is however not the case since the time constants in the aerodynamics are large and that the pitch controller is normally slow compared to the changes in wind speed induced by structural vibrations. For instantaneous changes in wind speed the induced velocities and the pitch setting remain constant leading to positive $dT/dU$ gradients, hence positive damping.

For the turbine mounted off-shore so the 1st tower frequencies decrease significantly and becomes more low frequent than the pitch action, the effect is opposite. The thrust gradient will more or less follow the negative slope of the quasistatic thrust curve leading to a negatively damped tower motion.
The PSD of the tower bending moment of the floating turbine with a on-shore controller is shown in Figure 4. What is interesting to notice is that the main energy content is at the 0.035Hz frequency. This is the 1st tilt mode of the floating turbine. It seems that the reason why the translational modes of the tower at 0.01Hz was not significant is the high damping from the catenary lines. These lines also provides high damping in the heave mode at 0.037Hz, but almost nothing at the tilt mode a 0.035Hz.

3. The controller and the tuning procedure
The controller used in the simulations has three working regions; variable speed at low wind speed, constant speed just below rated power and constant torque with active pitch above rated. The reason for using constant torque instead of constant power above rated wind speed is first of all to minimize drive train loads in general, but secondly to provide the possibility for reduced pitch activity which is especially important for the floating turbine concept. The control content is shown in Figure 5. The most essential input signal to the controller is the rotational speed of the generator \( \omega_{\text{mea}} \). This signal is first of all filtered by a low pass filter to avoid any high frequent excitation of the blade pitch and generator control. The reference pitch angle is set by a PI-regulator provided with gain scheduling to account for the increased effect of pitch changes at high pitch angles, see [1],[2]. The generator torque is controlled by another PI-regulator provided with an upper maximum limitation and a low limitation depending on the rotational speed and pitch angle. The transitions between the different control regions (variable speed, constant speed and constant torque) are achieved using variable max-min limits on the different PI-regulators handled by simple logic switches. This may appear a little complicated at first hand but it is highly effective to provide smooth transients. E.g. when the measured pitch angle is above minimum both limits on the torque controlling PI regulator will be reference torque; hence the output to the generator will be constant no matter the rotational speed. This is the operation above rated power. When the wind speed decrease, the rotational speed decreases and so does the reference pitch angle until the pitch angle is less or equal to the minimum (optimal) pitch angle \( \theta_{\text{opt}} \). At this stage switch 1 will change instantaneously from \( M_{\text{ref}} \) to a lower tabulated value. The effect of this change is low pass filtered to ensure the smooth transition from constant torque to
constant speed. Similar approaches are used for the change between the other regions. All information of the controller can be deducted from Figure 5 but it might be nice to know that Table 1 in the figure is the optimal relation between generator torque and rotational speed for the variable speed region up to rated rotational speed. Table 2 is the optimal relation between pitch angle and wind speed used below the constant torque region. The performance of the regulator can be seen in Figure 17 where step changes of a broad range of wind speeds are performed.

**Figure 5:** Control diagram of the used controller

**Figure 6.** Step response using the tuned controller
3.1. Tuning of the high wind speed region

In this section particular attention to the above rated wind speed area is made. The basic principle of the controller is a simple PI-regulator on the rotational speed to provide a reference pitch angle for the servo system as shown in Figure 7. The basic equations for the control system illustrated in Figure 7 is originally described in [2] and [1] but is repeated here since [2] is not published and the description in [1] is a little short regarding the deduction of equations.

The dynamic system we consider includes only one degree of freedom (DOF); the rigid body rotation of the rotor coupled to the aerodynamics and the PI-control of the pitch angle, see Figure 7. What we seek is the equation of motion including the terms of the PI gains in order to determine the natural frequency and damping of this system by adjusting the gains. The basic equation of motion is derived based on Newton’s second law as shown in equation (1).

\[ I \ddot{\varphi} = M_{aero} - M_{gen} \]  

where \( M_{aero} \) is the aerodynamic torque from the rotor and \( M_{gen} \) is the generator torque transformed to the low speed shaft. The state \( \varphi \) is the integrated angle difference from the actual rotational speed and the synchronous angle speed.

\[ \varphi = \int_0^t (\Omega - \Omega_0) dt \Rightarrow \dot{\varphi} = \Omega - \Omega_0 \]  

A small difference from the control system formulated here to the system described in [2],[1] is that constant torque in the region above rated power is used.

\[ M_{gen} = M_0 = \frac{P_0}{\Omega_0} \]  

The aerodynamic torque is linearized using a 1st order Taylor expansion, where it is assumed that for a given equilibrium state above rated, the influence is primarily caused by variations in pitch angle (variations in rotational speed is assumed small and negligible).

\[ M_{aero} = \frac{1}{\Omega} P(V, \theta) \approx \frac{P_0}{\Omega_0} + \frac{1}{\Omega_0} \frac{\partial P}{\partial \theta} (\theta - \theta_0) \]  

The pitch angle contribution is the output from the PI-controller (proportional term and an integral term), where each term is related to the state variable \( \varphi \).
\[ \theta = \theta_i + \theta_p \]  
\[ \theta_i = \int K_i (\Omega - \Omega_{ref}) \, dt = K_i \phi, \quad \Omega_{ref} = \Omega_0 \]  
\[ \theta_p = K_p (\Omega - \Omega_{ref}) = K_p \dot{\phi} \]  
Based on the equations (1) to (7) the constants of (8) are derived.

\[ I \ddot{\phi} + D \dot{\phi} + K \phi = 0 \]  
\[ I = I_{\text{rotor}} + n^2 I_{\text{gen}}, \]  
\[ D = \frac{1}{\Omega_0} \frac{\partial P}{\partial \theta} K_p, \quad K = \frac{1}{\Omega_0} \frac{\partial P}{\partial \theta} K_I \]  

From this ordinary 2nd order differential equation system characteristic in shape of natural frequency and damping is standard solutions, see equations (11). The natural frequency of the undamped system is \( \omega_0 \), the relative damping \( \zeta \) and the damped frequency \( \omega_d \)

\[ \omega_0 = \sqrt{\frac{K}{I}}, \quad \zeta = \frac{D}{2I\omega_0}, \quad \omega_d = \omega_0 \sqrt{1 - \zeta^2} \]  

This allows to design the control parameters in a way that the total systems behaves as desired with input of damped natural frequency and damping ratio.

\[ \omega_0 = \frac{\omega_d}{\sqrt{1 - \zeta^2}}, \quad K_I = \frac{\Omega_0 I \omega_0^2}{\frac{\partial P}{\partial \theta}}, \quad K_p = \frac{2\zeta K_I}{\omega_0} \]  

When introducing a differential term in the controller it is possible to adjust the efficient inertia in the system. An extra equation (13) is introduced, which modifies the expression for aerodynamic torque and the controller constants need to be updated.

\[ \theta_d = K_d \frac{\partial (\Omega - \Omega_{ref})}{dt} = K_d \dot{\phi} \]  

This extends the linearized expression for the aerodynamic torque in equation (4) to the expression in equation (14), hence the expressions for proportional and integral gain is modified.

\[ M_{\text{aero}} = \frac{P_0}{\Omega_0} + \frac{1}{\Omega_0} \frac{\partial P}{\partial \theta} (K_i \phi + K_p \dot{\phi} + K_d \dot{\phi}) \]  

\[ K_I = \frac{\omega_0^2 \Omega_0 (I_R + n^2 I_G + \frac{1}{\Omega_0} \frac{\partial P}{\partial \theta} K_d)}{\frac{\partial P}{\partial \theta}}, \quad K_p = \frac{2\zeta K_I}{\omega_0} \]  

A new parameter is introduced, which is the ratio between system inertia with and without \( K_d \) contribution.

\[ \eta = \frac{I_{\text{new}}}{I_{\text{old}}} \]  

And the final expression for \( K_d \) is

\[ K_d = \frac{\Omega_0 (I_R + n^2 I_G)(1 - \eta)}{\frac{\partial P}{\partial \theta}} \]
In the actual tuning procedure of the control gains four different control natural frequencies in the range between 0.01 and 0.1Hz with a damping ratio 0.7 was investigated with respect to the dynamic response at different load situations at different wind speeds. It was found that a control frequency of 0.02Hz had superior performance. An example of the different behaviour can be seen in Figure 8. Large tower transient occurs with a fast control, where a poor performance of the rotational speed was seen with a very slow controller. The extra benefits from changed inertia through the control was minimal and only seemed to decrease the robustness off the controller.

![Figure 8: Different response depending on the control natural frequency.](image)

3.2. Tuning of the constant speed region

Since the new controller is equipped with a PI-regulator to handle the constant speed region some tuning of these PI gains must be performed. A similar approach to the tuning procedure of the pitch PI-regulator of the constant torque region has been chosen. The control system is illustrated in Figure 9. The aerodynamic torque in this region is almost constant since the turbine partly operates in stall.

\[ M_{aero} = M_g \quad (18) \]

\[ M_{gen} = K_p (\Omega - \Omega_{ref}) + K_i \int (\Omega - \Omega_{ref}) dt = K_p \dot{\phi} + K_i \phi \tag{19} \]

Based on the equations (1), (2), (9), (18) and (19) the constants of (20) are derived.

![Figure 9: Control of the intermediate wind speed region](image)
The performance of the new controller tuned for the floating concept is shown in the following figures. The simulations are with stochastic turbulence with an intensity of 20% at different wind speeds. A selected number of results is shown in Figure 10. It seems that the total response is OK, but maximum rotational speed is up to 30% higher than the nominal speed. The variation in electrical power is also in the size of 30% above rated which is significantly worse than for a similar onshore turbine. The mechanical loads on the structure appear however reasonable and there are no indications of stability problems.

4. Results

The performance of the new controller tuned for the floating concept is shown in the following figures. The simulations are with stochastic turbulence with an intensity of 20% at different wind speeds. A selected number of results is shown in Figure 10. It seems that the total response is OK, but maximum rotational speed is up to 30% higher than the nominal speed. The variation in electrical power is also in the size of 30% above rated which is significantly worse than for a similar onshore turbine. The mechanical loads on the structure appear however reasonable and there are no indications of stability problems.

\[ I \ddot{\phi} + D \dot{\phi} + K \phi = 0 \]
\[ D = K_{pg}, \quad K = K_{lg} \]

From this ordinary 2nd order differential equation system characteristic in terms of natural frequency and damping is standard solutions, see equations (11). The natural frequency of the undamped system is \( \omega_n \), the relative damping \( \zeta \) and the damped frequency \( \omega_d \). This allows us to design the control parameters in a way that the total system behaves as desired with input of damped natural frequency and damping ratio. The design variables used for this controller is chosen to be \( \omega_n = 0.07 \) Hz and \( \zeta = 0.8 \)

\[ K_{lg} = I \omega_n^2, \quad K_{pg} = \frac{2 \zeta K_{lg}}{\omega_n} \]

\[ (21) \]

\[ (22) \]
5. What about active stall control?
During the process of tuning the constant torque control for the pitch controlled turbine a sign error in the pitch angle occurred. This caused the controller to pitch the blades into stall – towards high angles of attack, which is opposite normal pitch control. The behavior of the system was however surprisingly good. The tower motion was highly damped hence stable and the overall performance of all other sensors also seemed good. A selection of simulation results can be seen in Figure 11. This could very well be a feasible solution for a floating concept and deserve further investigations if active stall controlled turbines can be made in the 5MW size.

6. Conclusion
The wind turbine concept is a 5MW pitch controlled turbine mounted on a floating foundation, a spar buoy anchored by 3 catenary lines. This foundation makes the lowest structural frequencies very low compared to a normal bottom mounted turbine. The three lowest vibration modes, which basically are rigid body motions, are:

- Translation, tower, horizontal \(0.01\)Hz
- Rotation, tower, tilt \(0.035\)Hz
- Translation, tower, vertical \(0.037\)Hz

The vibration mode with the lowest frequency of \(0.01\)Hz has a positive damping from the hydrodynamic loads and the catenary lines. The vertical mode is also positive damped by the catenary lines, but the rotational mode of the tower at \(0.05\)Hz has no damping from the catenary lines and very little damping from the hydrodynamic loads. Since the natural frequency is very low compared to a traditional bottom mounted turbine the pitch controller will adjust the pitch angle during the motion and thereby reduce the thrust when the motion is towards the wind and vice versa. The aerodynamic damping is therefore negative when the pitch control is fast.

Figure 11: Performance of an active stall controlled turbine on the floating foundation at 12m/s with 20% turbulence intensity.
The solution presented in this paper is an adjustment of control parameters to reduce the control activity, or in more precise words, a reduction of the controllers natural frequency combined with the free rotation of the rotor. This makes the aerodynamic damping positive, but at the same time causes a significant increase in rotational speed variations. To limit these variations the generator control has been changed from a constant power approach to constant torque.

The new controller seem to perform well, especially regarding tower motion stability, but the variations in rotational speed and electrical power are up to 30% higher than nominal speed where a bottom mounted turbine typically has a variation up to 10%. Structural loads was however reasonable and showed no sigh of instability problems. The significant variation in electrical power might be less important if the turbine is intended for park configuration which enables a smoothing of park production since the different turbines contribution is averaged.

An alternative control method is to use a stall controlled turbine. By accident the pitch controlled turbine was run with opposite sign in pitch angle causing it to operate in stall and the performance was very fine related to tower stability, rotor speed variations and power production. This could be a feasible solution as well, but must be investigated further for a real stall controlled turbine before final conclusions can be made.

References
[1] Morten H. Hansen, Anca Hansen, Torben J. Larsen, Stig Øye, Poul Sørensen and Peter Fuglsang. Control design for a pitch-regulated, variable speed wind turbine. Risø-R-1500(EN). Risø National Laboratory Denmark. January 2005.
[2] Øye S. Pitchregulering af omdrejningstal ved fastholdt generatoreffekt. Hand written notes, not published. Technical university of Denmark.
[3] Skaare B, Hanson T D, Nielsen F G, Yttervik R, Hansen A M, Thomsen K, Larsen T J. Integrated Dynamic Analysis of Floating Offshore Wind Turbines. In proceedings (online) of 2007 European Wind Energy Conference and Exhibition, Milan (IT), 7-10 May 2007.