Control development for floating wind

Feike Savenije and Johan Peeringa

ECN Wind Energy, Westerduinweg 3, 1755 LE Petten, The Netherlands

E-mail: savenije@ecn.nl

Abstract. Control of a floating wind turbine has proven to be challenging, but essential for lowering the cost of floating wind energy. Topic of a recent joint R&D project by GustoMSC, MARIN and ECN, is the concept design and verification with coupled simulations and model tests of the GustoMSC Tri-Floater. Only using an integral design approach, including mooring and control design, a cost effective system can be obtained. In this project, ECN developed a general floating wind turbine control strategy and applied this in a case study to the GustoMSC Tri-Floater and the OC3Hywind spar, both equipped with the NREL 5MW RWT. The designed controller ensures stable operation, while maintaining proper speed and power regulation. The motions of the floating support are reduced and substantial load reduction has been achieved.

1. Introduction
Energy is a very important resource in today's modern world. For deep water regions offshore, floating wind turbines might be feasible from economic perspective. As shown in [7] and [1], there are three main concepts for the floating platform supporting the wind turbine, all having their strengths and weaknesses:

(i) spar; gravity balanced
(ii) tension leg; mooring balanced
(iii) semi-submersible; buoyancy&ballast balanced

Several prototypes are already installed (i.e. Statoil's HyWind [22], Principle Power's WindFloat [21]). Also other initiatives for prototype development are currently ongoing.

GustoMSC, MAritime Research Institute Netherlands (MARIN) and Energy Research Center of the Netherlands (ECN) joined in the R&D project 'Floating Wind Offshore Structures' supported by the Dutch government in the Maritiem Innovatie Programma (MIP).
The first phase of this project (2011) focussed on establishing a tool for analysis and simulation of floating wind turbines. ECN's code for wind turbine simulation PHATAS [18] has been coupled to the hydrodynamic codes aNySIM (developed at MARIN) and AQWA (used by GustoMSC). Both coupled codes have been benchmarked ([6], [2]) against the OC3 results [12].
The second phase of the 'Floating Wind Offshore Structures' project is about the concept design of the GustoMSC Tri-Floater [8]. This paper reports the findings from the controller impact study.

1.1. background

While there exist several other control strategies, most modern wind turbines are of the variable speed, pitch regulated type. At ECN, wind turbine control development was a main topic during the DOWEC research project [3], which resulted in the development of the Control Design Tool (CDT, see [24] and [27]). Since then, the tool is used as a container for knowledge developed in various research projects. In the past, speed and power regulation was the main task of the wind turbine controller. Nowadays, with wind turbines increasing in size above 5MW, more and more emphasis is on reducing loads (see [15] and [14]), using advanced control strategies like Individual Pitch Control (IPC) and active tower damping.

Control of a floating wind turbine has proven to be a challenging problem; placed on a floating platform, the controlled wind turbine can become unstable. The mechanism behind this is clearly described in [10]. For a pitch to vane controlled wind turbine, the thrust force on the rotor decreases with increasing wind speed and vise versa. This can lead to instability when (lightly) damped modes are within the controller bandwidth, such as the low frequent rigid body modes of the floating support.
In the floating part (phase IV) of the OC3 project [12], a modified controller has been developed, based on the approach to limit the controller bandwidth to the lowest (unstable) mode in the system ([16]). The downside to this reduction in control bandwidth is worse tracking performance (i.e. large power fluctuation in turbulent wind and rotor overspeed during wind gusts).
Some more recent studies ([25] and [5]) suggest combining pitch and generator control (MIMO approach) to improve regulation.

Another key aspect of floating wind turbines is the increase of the loads. This subject has not been touched much in the literature to the best of the authors knowledge, at least not in relation to the wind turbine controller. In [10], the topic is only briefly mentioned. In [17], a model predictive control approach is used, where the issue of loading is adressed in short. Namik et.al. ([19] and [20]) do include loading in the discussion, mainly focussing on individual pitch control for floating wind turbines. The approach in this paper is based on collective pitch control with conventional measurements.

1.2. goal and scope

This paper first adresses the impact of control on a floating wind turbine system and identifies points for improvement. A general control strategy has been developed and applied in a case study on control design for the GustoMSC Tri-Floater and the OC3Hywind spar. The main task of the wind turbine controller is speed and power regulation, i.e. optimal power production while assuring stable operation of the wind turbine. Secondly, the controller should reduce loads as much as possible. These will be the two main focus points for the floating wind turbine control develepment.

1.3. paper outline

The main body of this paper consists of four sections. Section §2 introduces the control related issues that arise when a wind turbine is put on a floating support. The next section (§3) presents the algorithms for developed for floating wind turbine control. The focus is on stable operation of the floating wind turbine system and reduction of the loads due to wave excitation. Section §4 shows results of the evaluation of the floating wind turbine controller with a nonlinear time domain code. The report finishes with a discussion of the results in section §5.

2. Controller impact

2.1. control related dynamic behavior

As shown in several previous studies ([10], [16], [25]), the causes of pitch controller induced instability are:

(i) negative thrust sensitivity to wind speed variations $\frac{dF_{ax}}{dV_w}$, due to pitch control feedback on rotor speed variations
(ii) lightly damped eigenmode of floating support within the control bandwidth

These two combined lead to an instable system, involving the aero-hydro-structural behavior and control of the system. This is shown below, comparing the behavior of (a control oriented model) of the OC3Hywind spar to that of the bottom fixed turbine, both using a conventional land based controller. From the Nyquist plot in figure 1, the effect of the floating platform eigenmotion on stability of the system is clearly visible; with the floating system, the $(-1 + 0i)$ point is Clock Wise (CW) encircled a single time, which indicates that the feedback loop would be destabilizing when closed. The pole zero map in figure 2 shows the location of the system poles (and zeros) for the bottom fixed and floating wind turbines. For floating wind turbines, having a structural eigenmode well below the control bandwidth, a pole and zero pair has moved into the Right Half Plane (RHP).
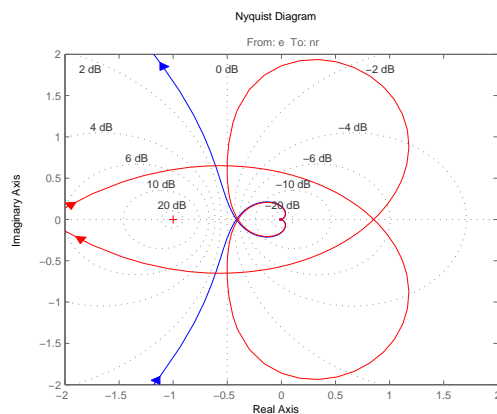

Figure 1. Nyquist plot of the floating wind turbine pitch control loop (b:bottom fixed, r:floating)
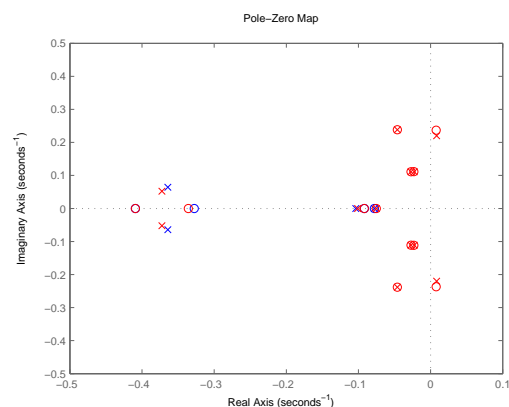
Figure 2. Pole zero map of the floating wind turbine pitch control loop (b:bottom fixed, r:floating)

2.2. evaluation of the OC3 floating controller

As mentioned in the introduction, control of a floating wind turbine has proven to be challenging. In the floating part (IV) of the OC3 project [12], the instability with a controlled floating wind turbine has been identified and a method for stabilising the system has been proposed. This section analyses the (reproduced) OC3 results, to show the controller impact and evaluate the proposed method. For this purpose, the OC3Hywind spar system has been analysed with aNySIM+PHATAS using the two different controllers both developed in the OC3 benchmark project; the bottom fixed controller [13], and a modified controller for floating wind turbines [11].

The design of the bottom fixed OC3 wind turbine controller follows the conventional approach; generator torque control with QNcurve for variable speed optimal power below rated wind speed and blade pitch control for constant speed and rated power above rated wind speed. Rotor speed filtering is used to suppress 3P effects and gain scheduling is applied to handle the nonlinear behavior due to changing operating point. In the floating part (phase IV) of the OC3 project, a modified controller has been developed, based on the approach to limit the controller bandwidth to the lowest (unstable) mode in the system (see also [16]). The downside to this reduction in control bandwidth is lower (regulating) performance (i.e. power fluctuation in turbulent wind, rotor overspeed in wind gusts). This has only partially been solved with constant torque control above rated (iso).

The controllers are compared for a normal production case above rated using stochastic wind ($V_w = 14m/s$) and regular waves ($H = 3m, T = 6s$). Figure 3 shows the wind turbine operation and figure 4 shows the motion of the floating support. The excessive pitch motion of the floating support and limit cycling of the blade pitch angle clearly show the instable operation with the fixed base controller. Due to the reduced bandwidth, the modified controller is able to maintain stable operation. However, generator power regulation clearly suffers from this approach.
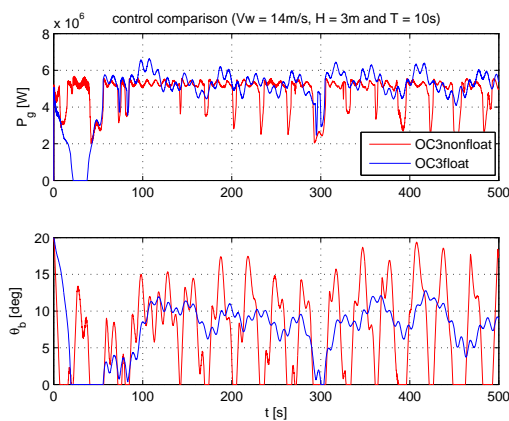

Figure 3. Wind turbine operation for normal production above rated ($V_w = 14m/s, H = 3m, T = 10s$)

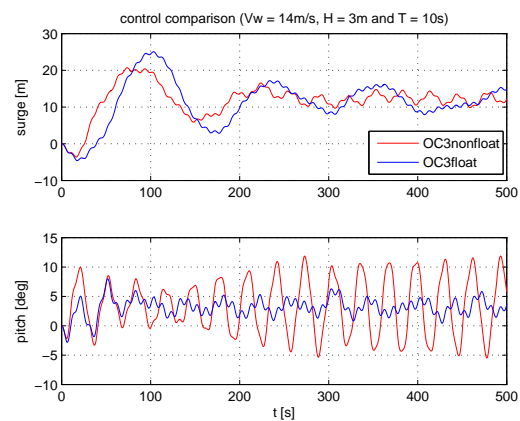**Figure 4.** Floating support motion for normal production above rated ($V_w = 14m/s, H = 3m, T = 10s$)

Although the method described in [16] is effective in stabilising the floating wind turbine system, the decrease in tracking performance is unwanted. This paper presents a control design strategy that stabilises the floating system, while keeping performance (ie regulation, and if possible load reduction) up. Key aspect for this approach is to act *only* on the relevant components of the apparent wind.

3. Algorithm development

3.1. damping of the platform (eigen)motion

The approach for stabilising the floating support relies on wind speed estimation, an observer to find the platform eigenmotion and a state feedback loop to damp that eigenmotion.

<u>A</u> wind speed estimation

The problem of obtaining a proper wind speed signal is not trivial. Point measurement (nacelle anemometer) will not give a good representation of the rotor effective wind speed. Instead, the wind speed can be estimated.

The wind speed estimation (WSE) method in the CDT (see also [23]) uses conventional measurements (i.e. generator speed and power, pitch angle) and the known aerodynamic rotor characteristics to derive the rotor effective wind speed. It performs the following steps:

1. find the aerodynamic torque

The aerodynamic torque T_a is estimated from the measured generator power P_g and speed Ω_g and the (known) losses:

$$T_a = J_{sse} \cdot \dot{\Omega}_r + \frac{P_g}{\Omega_g} + T_{loss} \tag{1}$$

with the slow shaft equivalent inertia J_{sse} of rotor and generator combined. Neglecting the (relatively fast) drive train dynamics, the rotor speed Ω_r follows directly from the measured generator speed. As the torque actuator is fast enough, the torque setpoint can also be used instead of the measured generator power. Obviously, appropiate filtering needs to be applied the used inputs.

2. reconstruct the (relative) wind speed

The relation between aerodynamic torque T_a and wind speed V_w is:

$$T_a = C_q(\theta, \lambda) \cdot \frac{1}{2} \rho_{air} \pi R_r^3 \cdot V_w^2 \tag{2}$$

with the tip speed ratio $\lambda = \frac{\Omega_r R_r}{V_w}$. As this relationship is nonlinear in V_w, there exist multiple solutions for some operating points. Restricting the search area to the likely operating region of the wind turbine (i.e. (T_a, Ω_r, V_w) on the interval $(0, \infty) = \{x \in \Re \mid 0 > x > \infty\}$), two solutions (at most) remain. One of the solutions is in attached flow, the other in stall. Ignoring the stall solutions (valid assumption for a 'pitch to vane' regulated wind turbine), a unique V_w is computed for each operating point (θ, T_a, Ω_r). As discussed in [23], the CDT uses a tabular implementation of this relation, which is calculated offline. Real time interpolation is used to reduce the size of the 3D table for a given accuracy.

<u>B</u> observer of the floating support

The observer estimates the floating support motions from estimated aerodynamic loads and measured tower top acceleration using a Kalman filter.

The model is derived from the full 6DOF rigid body floating support model selecting the relevant degrees of freedom. The foreaft motion of the tower top includes platform surge and pitch modes, while the sideways motion of the tower top includes sway and roll.

$$\begin{aligned} \begin{bmatrix} x(k+1) \\ \dot{x}(k+1) \end{bmatrix} &= AA_f \begin{bmatrix} x(k) \\ \dot{x}(k) \end{bmatrix} + BB_f Q_f(k) \\ \ddot{x}(k) &= CC_f \begin{bmatrix} x(k) \\ \dot{x}(k) \end{bmatrix} \end{aligned} \tag{3}$$

This system is observable. To estimate the state, the input (load vector Q_f) needs to be given. The tower top loads are not measured and neither are the wave loads. However, the aerodynamics loads can be estimated using the estimated wind speed and the known rotor coefficients. The

wave loads are assumed neglegible around the eigenfrequency of the floating support modes. Thus, a Kalman filter can be used to estimate the motions of the floating support given the estimated load $\hat{Q}_f$ and the measured acceleration $\ddot{x}$:

$$\left[\begin{array}{c} \hat{x}(k+1) \\ \hat{\dot{x}}(k+1) \end{array} \right] = (AA_f - L_f CC_f) \left[\begin{array}{c} \hat{x}(k) \\ \hat{\dot{x}}(k) \end{array} \right] + BB_f \hat{Q}_f(k) + L_f \ddot{x}(k) \tag{4}$$

with L_f the Kalman filter gain.

The Kalman filter is designed using white noise assumption on both the process and measurement. The performance of the state estimation is sufficient, with a good match of both phase and amplitude of the low frequent rigid body floater motion.

<u>C</u> damping of the platform (eigen)motion
First focus has been on the foreaft damping loop, causing the instable behavior above rated as discussed in §2.2. Several feedback laws have been examined. One possible solution can be obtained by solving the optimal Linear Quadratic Regulator (LQR) problem, which combined with the Kalman filter forms a Linear Quadratic Gaussian (LQG) controller. The LQG approach balances performance and actuator effort (using weighting factors W_Q and W_R on fore aft tower top motion x_{fa} and blade pitch angle θ_b):

$$K_{fsd|fa} = \arg\min \int_0^\infty \left\{ W_{Q|fa} \cdot (\delta\hat{x}_{fa})^2 + W_{R|fa} \cdot (\delta\theta_b)^2 \right\} dt \tag{5}$$

However, good results with respect to stability are obtained with simple tower top velocity feedback with a (scheduled) multiplication factor. The proposed state feedback gain $K_{fsd|fa}$ for foreaft platform support damping is:

$$K_{fsd|fa}(V_w) = g_{fsd|fa}(V_w) \cdot \left[\begin{array}{cccccc} 0 & 0 & 0 & 0 & 1 & d_{cog|tt} \end{array} \right] \tag{6}$$

with $d_{cog|tt}$ the distance from the system centre of gravity to the tower top. The gain $g_{fsd|fa}$ is scheduled with average wind speed, using the thrust sensitivity to blade pitch angle variations. The complete state feedback law is:

$$\delta\theta_b = K_{fsd|fa}(V_w) \cdot q_{fsd|fa} \tag{7}$$

with the estimated states $q_{fsd|fa} = \left[\begin{array}{ccc} \hat{\ddot{q}}_f(i) & \hat{\dot{q}}_f(i) & \hat{q}_f(i) \end{array} \right]^T$ and $i = [1,5]$ for surge and pitch.

The floater damping loop is highpass filtered with sufficiently low cutoff frequency to eliminate static offset. Robustness of the controller has been assessed by introducing uncertainty in the model used for control design. This shows a (small) decrease in performance, but sufficient damping remains for proper operation of the system.

3.2. reduction of the loads due to wave excitation

Two methods come to mind for reducing the loads on a floating wind turbine system with the conventional system:

 (i) ignoring the apparent wind from floating support motion due to wave excitation
(ii) actively counteracting the wave induced loads by using the wind turbine rotor as a force actuator

A simple test showed the second approach is not feasible for the large loads due to waves (on the Tri-Floater); using the rotor as a force actuator needs excessive pitch actuation and therefor strongly reduces the power performance. However, this approach might be feasible for sites with less severe wave conditions (i.e. floating wind turbine in shielded see or lake) or with other floating support concepts.
The remainder of this section discusses the first approach in more detail.

The wave excitation of the floater will cause wind speed fluctuations. This in turn leads to rotor speed fluctuations, but with certain delay (depending on the system, i.e. rotor inertia, aerodynamic sensitivity $\frac{dT_a}{dV_w}$, filtering). The pitch control algorithm reacts on this delayed rotor speed variation to compensate. However, the delay (phase shift) decreases the effectiveness of the control loop. A direct pitch compensation based on estimated wind speed due to wave excitation will be more effective due to less delay in the loop.

Wind due to wave excitation can be derived from the measured acceleration and the estimated floater motion:

$$V_{w|wave} = \int (\ddot{x}_{tt}) dt - \dot{\hat{x}}_{tt} \qquad (8)$$

The measured wind due to floater wave motion $V_{w|wave}$ can be directly compensated with a scheduled 'pseudo' feedforward. It is labelled 'pseudo', because the signal is not a pure measured disturbance but partly (i.e. the estimated wind speed $\dot{\hat{x}}_{tt}$) based on measured outputs. The wind speed dependent gain $g_{wv}(V_w)$ that minimises thrust fluctuations is:

$$g_{wv}(V_w) = \frac{d\theta_b}{dF_a} \cdot \frac{dF_a}{dV_w} \qquad (9)$$

First analysis of this method revealed unwanted interaction with the speed regulation loop (above rated), because the thrust and torque sensitivities to wind speed variations are not equal; the pitch control feedback tries to compensate the rotor speed fluctuations due to the pitch feedforward control. A small modification of the strategy, minimising torque fluctuations due to wave excitation above rated, solves this issue. While it is somewhat less effective in reducing thrust fluctuations, this does work well with the pitch control feedback loop, as both feedforward and feedback now have compatible objectives (i.e. reducing torque and rotor speed fluctuations). The resulting scheduled gain is:

$$g_{wv}(V_w) = \begin{cases} \frac{d\theta_b}{dF_a} \cdot \frac{dF_a}{dV_w} & \text{for } V_w < V_{w|rated} \\ \frac{d\theta_b}{dT_a} \cdot \frac{dT_a}{dV_w} & \text{for } V_w > V_{w|rated} \end{cases} \qquad (10)$$

While pure feedforward control does not influence loop stability, this 'pseudo' feedforward method slightly improves stability of the controlled system.

4. Evaluation

The focus of the evaluation is on the modifications specific for the floating wind turbine controller. For comparison, also results for the OC3 type approach with lowered bandwidth (see §2.2) and the nonfloating controller are shown. The controllers listed all use collective pitch and only conventional measurements. The following labels are used thoughout this section:

- o **FPfloat** fixed pitch
- b **OC3float** OC3 type floating controller with low bandwidth
- m **ECNland** ECN CDT controller without modifications
- r **ECNfloat** ECN CDT controller including floating support damping and wave induced load reduction

For the Tri-Floater system, a comprised set of load cases with various combinations of constant and stochastic wind and waves has been analysed with AQWA+PHATAS. Emphasis is on the above rated wind speed ($14m/s$), where the conventionally controlled floating wind turbine is unstable. All turbulent cases are with wind shear (exponential type, $\alpha_{shr} = 0.14$). The turbulent wind time series are generated with SWIFT ([26]), using a Kaimal spectrum and turbulence intensity as specified in [4] for the 'K13 deep water site'. To be able to use this site specific data, the reference turbulence intensity for SWIFT (class S) is obtained for each wind speed by fitting the measured turbulence intensity at the site on the IEC61400-1 ed.3 ([9]) norm. The irregular waves are generated from JONSWAP spectra with peak enhancement factor $\gamma_p = 1$.

The stair case in figure 5 shows the controller response to steps in the wind speed. The 'ECNfloat' controller clearly stabilises the system and also improves damping of the floating support modes, which leads to lower fatigue loads. Control effort is much smaller compared to the land based controller, mainly due to increased stability (no limit cycling). Looking at the results in the frequency domain (figure 6) clearly shows the influence of the different controllers on the floating support motion. The damping of the pitch motion is largest for the 'ECNfloat' controller, resulting in lower standard deviation as shown in table 4.

Table 1. Floating support motion standard deviation for stochastic case at $V_w = 14m/s$

load — ctrl [m]/[deg]	ECNfixed	OC3float	ECNland	ECNfloat
surge	0	2.809	2.293	2.293
heave	0	0.261	0.250	0.253
pitch	0	1.687	3.085	1.129

Observed fatigue load reduction compared to the land controller for the stochastic case above rated is about 38% for the tower base bending moment and about 12% for the blade root bending moment.

For the OC3Hywind system, evaluation using aNySIM+PHATAS of the above mentioned cases shows even a little larger reductions in floater motions and turbine loads with the dedicated 'ECNfloat' controller, most likely due to smaller hydrodynamic damping.
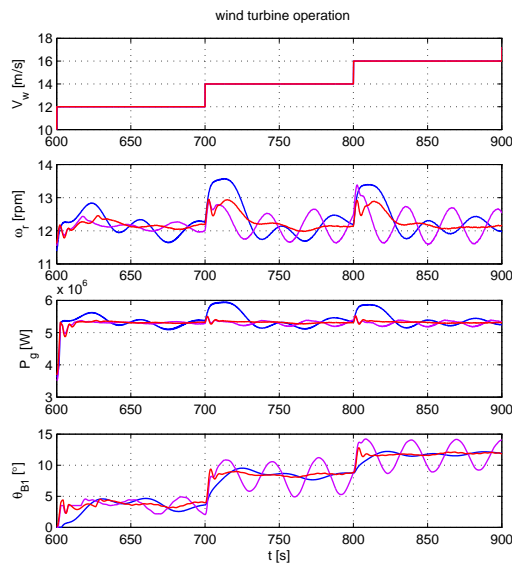
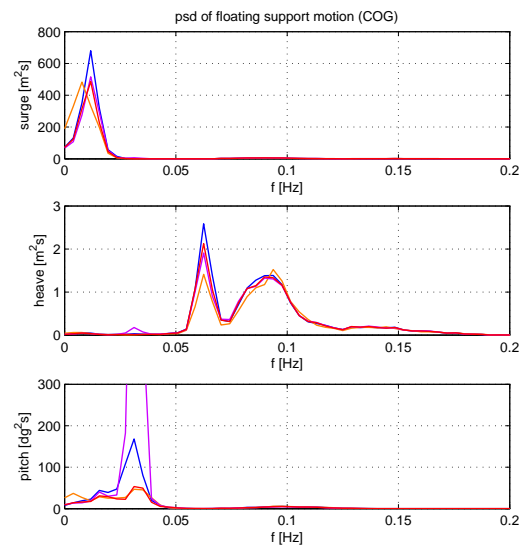**Figure 5.** Wind turbine operation for stair case

Figure 6. Power spectral density of floating support motion for stochastic case at $V_w = 14m/s$

5. Discussion

The main conclusion that can be drawn from this study is that not only the floating support has influence on the wind turbine (control), but also vice versa. Using the wind turbine controller, the motions of the floating support can be influenced to improve the damping of the system.

The developed algorithm for floating support damping stabilises the controlled floating wind turbine, while minimizing the impact on the performance of the regulating pitch control loop. Rotor speed variations due to normal turbulence stay within the desired band, while power fluctuation are minimal. Reponse to gusts is acceptable, not exceeding the rated speed by more than 20%. The improved damping leads to substantially lower fatigue loads. Reduction of the loads due to wave excitation is possible, however limited. The case study also shows that the developed controller strategy can be used with different floater concepts, such as the Tri-Floater semi-submersible and the OC3Hywind spar.

The presented results are based on a limited load set and thus give a first impression of the performance of the proposed approach. Next step is to evaluate the control strategy for a complete load set. Other foreseen future work is to combine this approach to floating wind turbine control with load reduction strategies like IPC.

Acknowledgments

References

[1] S. Butterfield, W. Musial, J. Jonkman, and P. Sclavounos. Engineering challanges for floating offshore wind turbines. Conference Paper NREL/CP-500-38776, NREL, Golden, Colorado, USA, 2005. Presented at the Offshore Wind Conference in Copenhagen, Denmark.

[2] R. de Bruijn. Aqwa-Phatas coupling software verification and benchmarking report. Technical Report P11522-8530-A, GustoMSC, Schiedam, The Netherlands, 2011.

[3] ECN. Dowec project webpage. http://www.ecn.nl/nl/units/wind/projecten/dowec/, 2003. Last accessed on 20121214.

[4] T. Fischer, W. de Vries, and B. Schmidt. UpWind design basis (WP4: offshore foundations and support structures). Technical report, USTUTT, Stuttgart, Germany, 2010.

[5] B. Fisher. Reducing rotor speed variations of floating wind turbines by compensation of non-minimum phase zeros. In *Proceedings of the European Wind Energy Conference in Copenhagen, Denmark*, 2012.

[6] S. Gueydon. Model description for the verification of aNyPHATAS. Technical Report 24796.150, Marin, Wageningen, The Netherlands, 2011.

[7] A.R. Henderson and J.H. Vugts. Prospects for floating offshore wind energy. Conference paper, TUD, Delft, The Netherlands, 2001. Presented at the European Wind Energy Conference in Copenhagen, Denmark.

[8] F. Huijs, J. Mikx, F. Savenije, and EJ. de Ridder. Integrated design of floater, mooring and control system for a semi-submersible floating wind turbine. Technical report, 2013.

[9] IEC. Iec 61400-1 ed. 3: Wind turbines - part 1: Design requirements for wind turbines. Technical report, IEC, 2005.

[10] J. Jonkman. Influence of control on the pitch damping of a floating wind turbine. In *Proceedings of the ASME Wind Energy Symposium in Reno, Nevada, USA*, 2008.

[11] J. Jonkman. Definition of the floating system for Phase IV of OC3. Technical Report NREL/TP-500-47535, NREL, Golden, Colorado, USA, 2010.

[12] J. Jonkman. Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV results regarding floating wind turbine modelling. Conference Paper NREL/TP-500-47534, NREL, Golden, Colorado, USA, 2010. Presented at the European Wind Energy Conference in Warsaw, Poland.

[13] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-MW Reference Wind Turbine for offshore system development. Technical Report NREL/TP-500-38060, NREL, Golden, Colorado, USA, 2009.

[14] S.K. Kanev, F.J. Savenije, D.A.J. Wouters, and W.P. Engels. FLOW project CDTup; Final report. Technical Report ECN-X--12-086, ECN, Petten, The Netherlands, 2012.

[15] S.K. Kanev, T.G. van Engelen, W.P. Engels, X. Wei, J. Dong, and M. Verhaegen. SUStainable CONtrol: A new approach to operate wind turbines; final confidential report. Technical Report ECN-X--12-065, ECN, Petten, The Netherlands, 2012.

[16] T.J. Larsen and T.D. Hanson. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. In *Proceedings of the Science of making torque from wind conference*, 2007.

[17] E. Lindeberg. Optimal control of floating offshore wind turbines. Technical report, NTNU, Trondheim, Norway, 2009.

[18] C. Lindenburg. PHATAS release 'JAN-2012b' user's manual. Technical Report ECN-I--05-005 r11, ECN, Petten, The Netherlands, 2012.

[19] H. Namik and K. Stol. Control methods for reducing platform pitching motion of floating wind turbines. In *Proceedings of the European Offshore Wind conference in Stockholm, Sweden*, 2009.

[20] H. Namik and K. Stol. Individual blade pitch control of floating offshore wind turbines. *Wind energy*, 13:74–85, 2010.

[21] Principle Power. Windfloat webpage. http://www.principlepowerinc.com/ products/windfloat.html, 2012. Last accessed on 20121214.

[22] Statoil. Hywind webpage. http://www.statoil.com/en/TechnologyInnovation/ NewEnergy/RenewablePowerProduction/Offshore/ Hywind/Pages/HywindPuttingWindPowerToTheTest.aspx, 2012. Last accessed on 20121214.

[23] E.L. van der Hooft and T.G. van Engelen. Estimated wind speed feed forward control for wind turbine operation optimisation. Conference Paper ECN-RX--04-126, ECN, Petten, The Netherlands, 2004. Presented at the European Wind Energy Conference in London, UK.

[24] E.L. van der Hooft, T.G. van Engelen, P. Schaak, and E.J. Wiggelinkhuizen. Design tool for wind turbine control algorithms. Conference Paper ECN-RX--04-128, ECN, Petten, The Netherlands, 2004. Presented at the European Wind Energy Conference in London, UK.

[25] G. van der Veen, I. Couchman, and R. Bowyer. Control of floating wind turbines. Presentation, DUT, Delft,

The Netherlands, 2011. Presented at the American Control Conference in Montreal, Canada.

[26] D. Winkelaar. SWIFT program for three-dimensional wind simulation. Technical Report ECN-R--92-013, ECN, Petten, The Netherlands, 1992.

[27] D.A.J. Wouters and T.G. van Engelen. Modern wind turbine controller design. Conference Paper ECN-M-- 08-060, ECN, Petten, The Netherlands, 2008. Presented at the Global Wind Power conference in Beijing, China.