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Integrated design of a semi-submersible floating vertical axis wind turbine (VAWT) with active blade pitch control

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Abstract. A semi-submersible Tri-Floater has been designed to support a 6 MW vertical axis wind turbine (VAWT) with active blade pitch control. Due to the low centre of gravity and large allowable floater tilt angle, a relatively small floater can be used to support a VAWT. Coupled simulations including hydrodynamics, mooring system, aerodynamics and control system have been performed to analyse the strongly coupled dynamics of floater and wind turbine. Software tools have been developed or upgraded to enable these simulations. Based on typical extreme operational and survival design load cases, it is illustrated that the active blade pitch control system can be successfully used to minimize the governing loads on the floater. Whereas for a VAWT with fixed blades, the parked survival conditions are typically design driving for the floating support structure, this is not the case if blade pitch control is applied. It is concluded that, compared to a horizontal axis wind turbine (HAWT) with the same rated power, a 20 percent lighter floater can be used as support structure for the VAWT with active blade pitch control.

Keywords: floating wind turbine; semi-submersible; vertical axis wind turbine (VAWT); active blade pitch control; coupled aero-hydro-servo-elastic simulations

1. Introduction

With the offshore wind industry moving towards larger turbines and deeper waters, the potential for floating vertical axis wind turbines (VAWT) is increasing. First of all, the VAWT can probably be scaled to larger turbine sizes more easily than the horizontal axis wind turbine (HAWT) [1]. Secondly, the VAWT is very well suited for application on a floating support structure. Compared to a HAWT, the generator and thus also the overall centre of gravity of a VAWT is located lower. Furthermore, a VAWT allows for larger floater tilt angles than a HAWT. Consequently, a smaller and more cost-effective floater can be used to support a VAWT.

During the last years, several studies on floating VAWT have been published. Vita et al [2] proposed a Darrieus rotor with a long vertical rotating shaft transitioning into a spar buoy, with the generator submerged at the keel of the floater. This concept was further developed and tested within the DeepWind project, as presented by Berthelsen et al [3] and Paulsen et al [4, 5]. Cahay et al [6] presented a semi-submersible floating VAWT design, comprising a 3-bladed rotor with twisted blades developed by Nenuphar. They concluded that the VAWT is very well fitted for floating offshore applications, especially due to the low centre of gravity. Blonk [7] studied the economic feasibility of both a straight bladed VAWT supported by a GustoMSC Tri-Floater semi-submersible and a guyed VAWT with curved blades on a floating buoy. Borg et al [8, 9] performed a long term global performance analysis for a semi-submersible VAWT and published a comparison between the dynamics of floating HAWT and VAWT. Galinos et al [10] investigated the design load cases for VAWT and compared these to HAWT. Based on the latter two studies, the main differences can be expected from the yaw moment induced by the rotor torque, the oscillating behaviour of the thrust force and, for fixed pitch VAWT, the increasing thrust and torque at wind speeds above rated wind velocity and a larger rotor drag when parked. All this previous work has been done for VAWT with fixed blades.

Vertical axis wind turbines with fixed blades, as built until now, are subject to high wind loads during parked survival conditions. As a consequence, the design of the floater for such a VAWT would be governed by the parked survival condition rather than the operational conditions. By introducing blade pitch control, this issue can be solved. In addition, blade pitch control improves the aerodynamic efficiency of the rotor and can be used to lower the loads during power production. With the objective to verify and quantify the assumed benefits of the VAWT with active blade pitch control for floating offshore applications, the S4VAWT project was initiated. Within this project, the design of a semi-submersible floating support structure based on GustoMSC's Tri-Floater technology, has been customized to support a 6 MW VAWT with pitched blades based on EOLFI's SpinFloat technology. An artist impression of the resulting design is presented in figure 1.

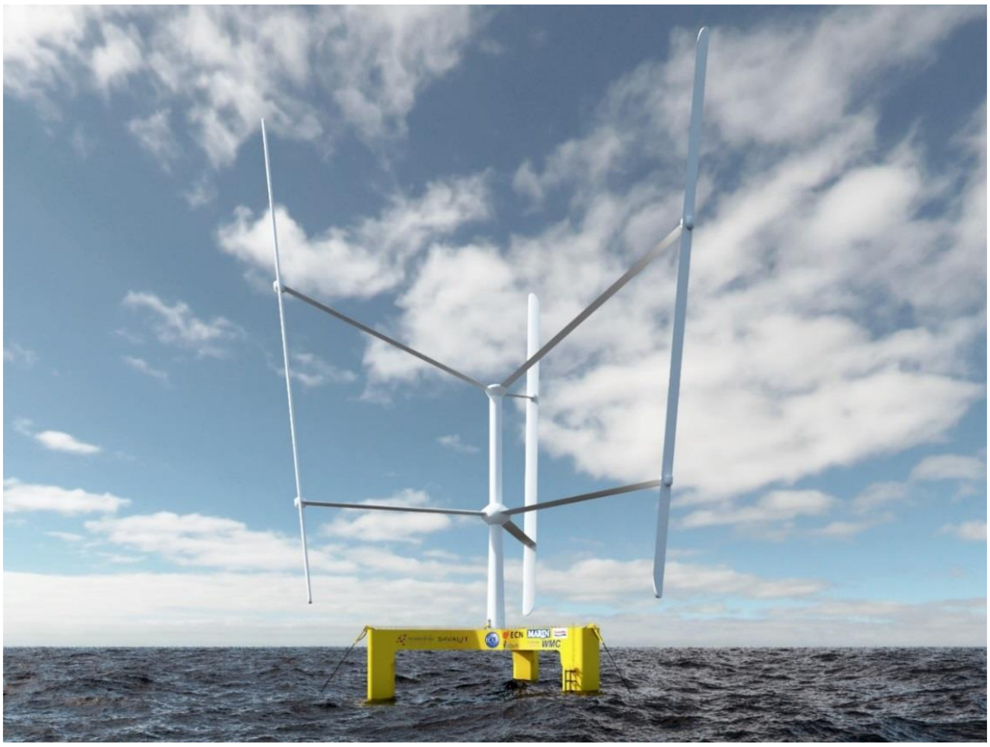

Figure 1. Artist impression of the semi-submersible floating vertical axis wind turbine (VAWT)

In this paper, a global overview of the S4VAWT project and its main finding are presented. First, the research objectives and approach are provided, followed by the basis of design. Sections 4 and 5 discuss the design of the wind turbine and the floater respectively. The coupled analysis of the floating VAWT is described in section 6, after which the results and recommendations for further work are discussed in section 7. Finally, section 8 summarizes the main conclusions of the paper.

2. Research objectives and approach

In the S4VAWT research project, ECN, EOLFI, Delft University of Technology, GustoMSC, MARIN and WMC have been cooperating with the following research objectives and approach.

2.1. Objectives

Aiming to verify and quantify the claimed advantages of the VAWT for floating wind turbine applications, the main objective of the S4VAWT project has been to design a competitive semi-submersible support structure for a large scale VAWT with active blade pitch control. In order to reach a safe, reliable and cost-effective floating support structure and mooring system, the performance in combined wind and waves had to be verified by state-of-the-art numerical simulations. Coupled design and simulation tools had to be developed and the governing load cases for the floating VAWT were to be identified.

2.2. Approach

An aerodynamic model has been developed for the vertical axis rotor using a method sufficiently fast for design calculations and the existing program Phatas in the FOCUS6 wind turbine design package of WMC has been modified to allow for vertically orientated blades. The Phatas code had been coupled to the hydrodynamic software packages Ansys AQWA and aNySIM before and this coupling has now been updated to deal with VAWT. The developed coupled tools have been used to optimize and verify the GustoMSC Tri-Floater and its mooring system for supporting a VAWT. During several design iterations, the floater dimensions have been optimized in order to achieve the most cost-effective design. A dedicated family of airfoils has been designed by Delft University of Technology, combining high aerodynamic and structural performance. ECN control system technology for floating wind turbines has been further developed for use on floating VAWT. Initial design loops have been performed using uncoupled and simplified analyses, followed by final integrated design loops with fully coupled simulations. Preparing already for future work, MARIN has defined requirements and a proposed setup for wave basin model testing of the floating VAWT.

3. Basis of design

This section provides the basis of design for the floating VAWT. The site conditions are presented, followed by the applied rules and regulations and turbine tilt design criteria.

3.1. Site conditions

The structure has been designed for operation in the French part of the Mediterranean Sea at a site with approximately 100 m water depth. Typical metocean data for this region has been used. Typical extreme operational and 50-year survival conditions for the site are presented in table 1. For these cases, a JONSWAP wave spectrum with a peak enhancement factor γ of 3.3 has been assumed. A wind shear profile based on a power law has been applied, with an exponent of 0.08.

Table 1. Extreme operational and 50-year survival current, wind and wave conditions

	extreme operational rated	extreme operational cut-out	50-year survival parked
Surface current velocity [m/s]	0.7	0.7	1.6
Significant wave height [m]	4.0	5.4	6.5
Associated wave peak period range [s]	7 – 11	8 – 12	9 – 13
10-min wind velocity at 100 m above SWL [m/s]	11	25	39
Associated turbulence intensity [%]	10	8	11

3.2. Rules and regulations
The floating VAWT has been designed according the standards for floating wind turbine structures of DNV GL [11], with a design life of 20 years. In line with UK regulations, a requirement for a minimum airgap of 23 m between SWL and the rotor blades has been applied for the non-inclined floater.

3.3. Turbine tilt
The floater has been designed such that the maximum static tilt angle of the VAWT during power production does not exceed 10 degrees. The VAWT has been designed to cope with this inclination. This static tilt design value is about twice as large as the typical values allowable for floating HAWT, which is one of the advantages of the VAWT. The semi-submersible floater has been designed to keep dynamic tilt angles and accelerations at the electrical generator as low as possible.

4. Vertical axis wind turbine (VAWT) design
The vertical axis wind turbine is a variation on the SpinFloat concept developed by EOLFI, with dedicated airfoils and control system developed within the S4VAWT project. The electrical generator and drive train are accommodated in the central tower.

4.1. Rotor
The three-bladed 6 MW VAWT rotor as shown in figure 1 has been designed with a projected area of 17700 m^2. This relatively low power density will secure high capacity factors in moderate wind climates. For sites with higher mean wind velocities, the turbine could be modified to a higher power rating. The rotor main dimensions and the mass properties of the VAWT are presented in tables 2 and 3 respectively.

Table 2. Rotor main dimensions

Dimension	Size [m]
Blade span	140
Blade chord	5
Rotor diameter at lower end	115
Rotor diameter at upper end	139

Table 3. VAWT mass properties

Item	Mass [t]
Rotor	130
Nacelle	240
Tower	180
Total: wind turbine	*550*

The rotor has been optimized for lowest aero-structural cost. A parametrized model has been created, including the main geometric variables. The goal was to find a trade-off between structural resistance, aerodynamic performance, material cost and rotor thrust, and to find it through a structural modelling with enough accuracy to be confident with the final weight estimate. Since most of the aerodynamic shapes are manufactured with composites, a dedicated calculation tool had to be used. There have been previous attempts to implement such an optimization, such as presented by Roscher [12], however this was not suited to the Spinfloat architecture. The present modelling uses a chaining between preComp [13], a pre-processor developed by NREL that provides span-variant structural properties for composite blades; code_aster, a finite element solver developed by EDF, used as a beam modelling tool; and Dakota, an optimization and uncertainty quantification framework developed by Sandia National Laboratories.

4.2. Airfoil family
The airfoil family for the rotor has been designed based upon the work of Ferreira and Geurts [14]. A multi-objective genetic algorithm has been used to maximize both the aerodynamic and structural properties of the airfoils. An initial airfoil population has been chosen which exhibits a wide range of airfoil qualities such as thickness or camber. Each of these airfoils has then been evaluated based upon two criteria: the aerodynamic performance, in this case the slope of the CL - α curve divided by the average drag of the airfoil during operation; and the structural performance, here, the area moment of

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inertia of the airfoil assuming a thin wall structure. The aerodynamic performance has been calculated in both clean and soiled conditions, a weighted average has then been applied to the airfoils that penalizes large differences in performance between clean and soiled conditions. This in effect penalizes airfoils which are highly sensitive to roughness.

The dual-objective optimisation generated a Pareto front of airfoils, trading aerodynamic and structural performance. This Pareto front set of airfoils then went through a series of calculations to determine overall turbine performance and loading. The airfoil shape which proved to provide the most consistent level of performance both aerodynamically and structurally has been incorporated into the VAWT design and has been used to determine rotor loads in the coupled simulations. The resulting airfoil has a 24 % relative thickness and a 1% camber toward the exterior of the rotor and is shown in figure 2.

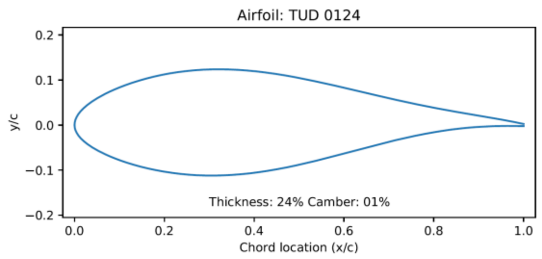

Figure 2. Shape of the selected airfoil

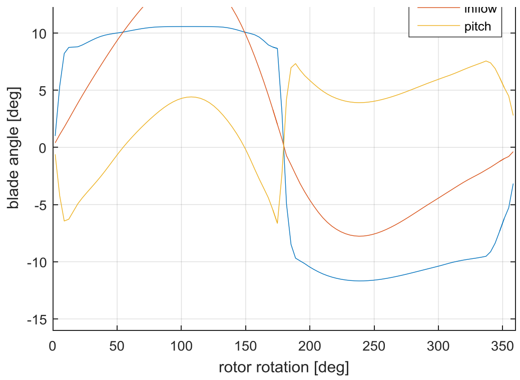

Figure 3. Blade pitch trajectory

4.3. Control system

Elaborating on the work presented in [15, 16], a dedicated VAWT blade pitch control algorithm has been developed, that 1) maximizes power production below rated wind speed and 2) regulates the generator speed and power to nominal above rated wind speed. For the first objective of maximum power production, a blade pitch trajectory (blade pitch angle depending on rotor rotation, see figure 3) has been derived that maximizes the aerodynamic torque along the revolution. The generator torque controller is used to obtain variable speed, optimum power operation. For the second objective (regulation), a blade pitch angle offset is applied in a feedback loop working on the measured generator speed. Generator torque is kept constant at its nominal value.

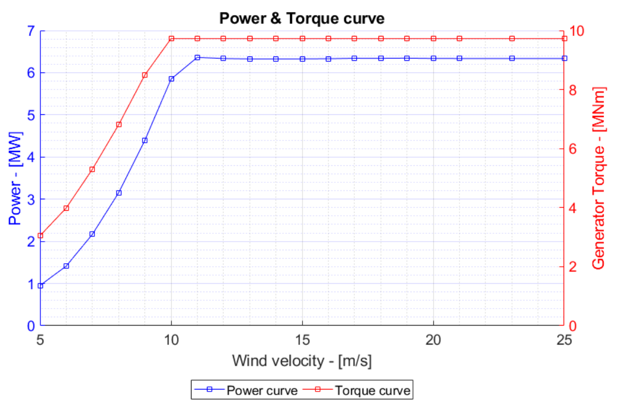

Figure 4. Generator power and torque curves

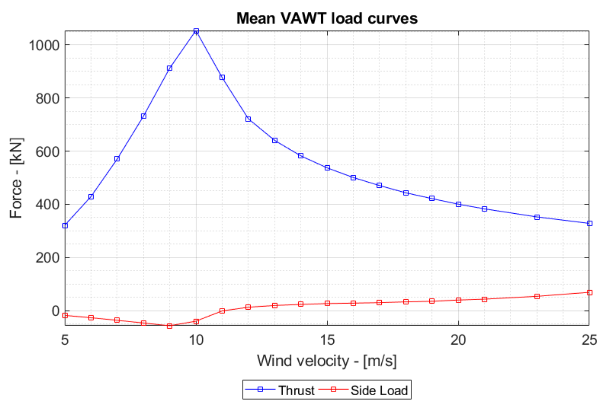

Figure 5. Thrust and side load curves

With this approach, the control strategy becomes similar to that of the conventional pitch to vane HAWT control. As a result, the operational curves of power and thrust (figure 4 and 5) are also similar, with decreasing thrust for increasing wind speed above rated. This is a clear benefit over stall regulation, where thrust does generally not decrease with wind speed. Another benefit of this approach is that stall is largely avoided, and the dynamic loads are also reduced.

As shown in [16], a similar instability as found for floating HAWT (see e.g. [17, 18]) is also present for floating VAWT with active blade pitch control regulation. This instability occurs when the lightly damped floater Eigenmodes are present within the pitch control bandwidth. Therefore, the blade pitch control system has been tuned for application on the floater, aiming to minimize motions and loads, while maintaining operational performance (generator speed and power regulation).

In addition to this normal production control algorithm, an active blade pitch control strategy has been developed to reduce the loads during survival conditions. When the wind turbine is parked or idling in storm with the blades locked in vane position, high sideways loads still occur due to the wind direction variations. To mitigate these loads, which would be design driving for the support structure, the blade pitch angles are actively adjusted with a feedback loop on measured blade loads.

5. Floating support structure design

The floating support structure (figure 1) is a three-column semi-submersible of the GustoMSC Tri-Floater type which is kept in position by a catenary chain mooring system.

5.1. Tri-Floater semi-submersible

The Tri-Floater semi-submersible comprises three columns, which are connected by a deck box structure above the water. The concept was first published in 2003 [19] and further improved and validated by model tests in 2013 [20, 21]. The structure is built out of flat steel panels, optimized for manufacturing using automated welding. The floater is sufficiently stable to assemble the wind turbine in a port, using an onshore crane. Tow-out and hook-up to the mooring system and electrical cables is done with low-cost vessels such as seagoing tugs. The floater dimensions have been minimized during several design loops, to take full advantage of the lower centre of gravity and larger allowable floater tilt angle. The main particulars and weights of the final design are presented in tables 4 and 5 respectively.

Table 4. Tri-Floater main particulars

Dimension	Size [m]
Radius to column centre	33
Overall length	68
Overall width	80
Depth (keel to main deck)	25
Operational draft	10
Transit draft	7

Table 5. Weight and loading condition

Item	Weight [t]
Floater lightship	1700
Wind turbine	550
Subtotal: transit displacement	*2250*
Water ballast	400
Static vertical mooring load	100
Total: operational displacement	*2750*

5.2. Mooring system

A conventional three-line catenary mooring system is used to moor the Tri-Floater to the seabed. Each mooring line comprises of 500 m chain of grade R4 with a diameter of 89 mm. The mooring lines are connected to the floater at main deck level at the outer edges of the columns, in order to minimize the wind overturning moment on the floater and to maximize the vertical distance between anchor and fairlead [22]. The mooring system is secured to the seabed using conventional drag anchors.

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6. Coupled analysis

Coupled simulations including hydrodynamics, mooring, aerodynamics and controls have been performed to analyse the strongly coupled dynamics of floater and wind turbine.

6.1. Simulation tools and methodology

Existing aerodynamic and wind turbine software packages, which had up to now only been used for HAWT, have been modified to allow for VAWT simulations. The overall structure and the components are discussed below.

6.1.1. Overall structure and coupling. The dynamic response of the floating VAWT is calculated in the time domain, by which all types of non-linearities – such as from control actions and mooring lines – can be included. Figure 6 shows the relation between the modules in the coupled software code. The time increment used for the floater motions is much larger than that for the wind turbine response, which is handled by two intermediate modules.

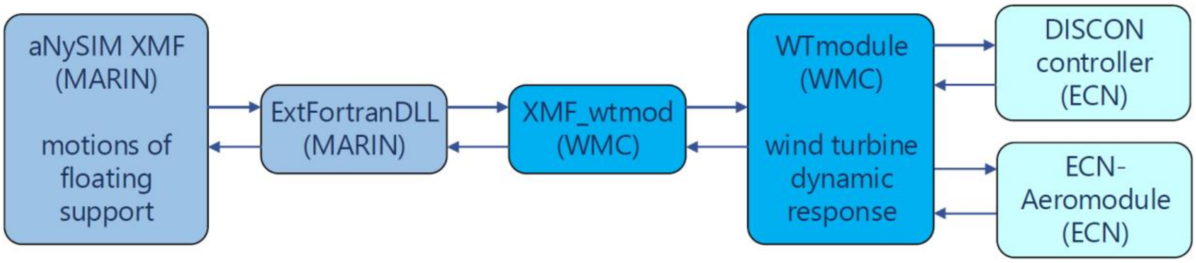

Figure 6. Coupled software for floating VAWT analysis

In the coupled application, the program aNySIM is calling the other codes that are provided as Dynamically Linked Libraries (DLL). In the call to WTmodule, the position and motion of the floating support is communicated. On return WTmodule provides the loads at the tower base together with a matrix with inertia properties to aNySIM. These loads and the inertia matrix are then used by aNySIM in solving the motions of the floating support. Also the gyroscopic moments are included as part of the solution by aNySIM.

6.1.2. Wind turbine simulation tool. WTmodule is the modular version of the program Phatas [23]. Both Phatas and WTmodule were initially developed for horizontal axis wind turbines and had to be modified to deal with the geometry of a VAWT rotor [24]. The standard rotor wake aerodynamics model of WTmodule is dedicated to a HAWT. For a VAWT however, the rotor wake is solved in ECN-Aeromodule using a vortex wake model, as described below. The wind field acting on the rotor is applied by files with the three-component wind on a 3D rectangular grid. The turbulence of the wind is generated with the program SWIFT following the Kaimal spectral model.

6.1.3. Lifting line free vortex wake method. Aerodynamic calculations have been performed by means of AWSM [25], a lifting-line free-vortex wake method implemented in ECN-Aeromodule [26]. In this approach the shape and strength of the blades' wake evolve in time, and are estimated based on the induced flowfield determined by AWSM iteratively. The loads along the blades account for the local induced velocities, and are calculated from user-prescribed 2D lift, drag and momentum coefficients as a function of the angle of attack.

6.1.4. Floater hydrodynamics and mooring system. The response of the Tri-Floater in waves and current has been simulated using aNySIM (v12.2.0), a software tool developed by MARIN. In this tool, the wave loads are determined based on potential flow theory. They include the linear wave excitation and the second-order low frequent excitations for all six degrees of freedom. The potential damping and the added mass are translated in time domain to a non-frequency-dependent added mass and a set of retardation functions. The viscous loads acting on the floater have been introduced by a quadratic damping matrix. The mooring lines have been modelled as a uniform catenary made of 50 lumped-masses. At each time step the equation of motion of the floater is solved taking non-linear platform response and interaction effects between the floater, the mooring lines and the wind turbine into account.

6.2. Simulation load cases

Typical operational and survival design load cases have been simulated using coupled software to assess the performance of the design in combined wind and waves. In this paper, results are only presented for the rated, cut-out and parked survival conditions provided in table 1, with wind, waves and current all acting in the positive surge direction. All simulations have a duration of 1 hour. The wind statistics for this 1-hour period have been derived from the 10-minute statistics.

Two different design philosophies for the survival condition are considered. The first considers a survival condition without any power available to operate a blade pitch control system. The rotor and the blades are therefore locked in a fixed position with respect to the mean wind velocity, considering a rotor yaw misalignment of 8° as prescribed by IEC [27]. The second philosophy assumes a back-up power supply to be on board. Controlling the blade pitch is therefore still feasible in the survival condition, in which case the controller switches to a regime where the blade pitch is controlled based on the instantaneous wind load on the blades.

6.3. Results

Table 6 presents the main results for the four selected load cases. The mean and maximum absolute values derived from a single 1-hour simulation are presented.

Table 6. Mean and maximum results of the coupled simulations

Design condition	extreme operational				50-year survival			
	rated		cut-out		blades locked		active control	
	mean	max	mean	max	mean	max	mean	max
Floater surge [m]	42.3	45.8	38.7	43.0	29.7	38.9	42.4	50.7
Floater sway [m]	-0.1	-1.0	0.3	-3.2	-10.3	-16.0	0.0	-2.7
Floater heave [m]	0.1	1.4	0.2	1.9	-0.3	-2.9	0.2	2.1
Floater roll [deg]	1.0	2.6	-0.3	-5.9	19.2	29.5	0.0	-3.4
Floater pitch [deg]	7.2	11.1	2.0	5.1	-3.2	-13.1	-0.1	4.8
Floater yaw [deg]	5.0	7.7	5.7	8.7	7.4	14.1	0.0	-5.6
Tilt (roll & pitch) [deg]	7.3	11.2	2.5	6.3	19.6	31.2	1.6	4.8
Hub acceleration[1)] [m/s^2]	1.2	2.3	0.5	1.5	3.3	5.9	0.5	1.5
Mooring tension (max) [kN]	1295	1745	1107	1745	2705	5192	1198	2211
Rotor thrust / drag[2)] [kN]	861	1356	315	786	440	1082	149	235
Generator power [MW]	6.2	7.5	6.3	7.6	0	0	0	0
Tower base moment [MNm]	102	156	46	118	249	523	18	68

[1)] Horizontal acceleration at the hub, including the gravity component.
[2)] The rotor does not generate thrust in survival conditions, but is subject to a drag load. This load includes the drag load on the rotor struts.

For the operational cases, the thrust on the rotor results in a mean surge offset and a mean pitch angle. As shown in figure 5, the rotor also experiences a small side load, which causes some floater roll. The combined floater tilt angle due to roll and pitch has a mean value of 7 degrees for the rated and 3 degrees for the cut-out condition, well below the design value of 10 degrees set in section 3.3. The extreme tilt angle including dynamics reaches maximum values around 11 degrees. The horizontal accelerations at the hub, including the gravity component due to tilt, reach values in the order of 2.3 m/s^2.

The difference between the responses of the two survival conditions is considerable, which is further illustrated by figure 7. For the survival condition in which the blades are locked, high lift loads on the blades are introduced due to both the 8 degrees yaw misalignment and turbulence in wind direction, resulting in high sway motions and (especially) roll motions. Not only would this survival condition be the governing design condition for the VAWT, floater and mooring, it would indeed require a (much) larger floater and heavier mooring system in order to arrive at acceptable tilt angles and mooring safety factors.

Controlling the blade pitch angles in survival conditions results in a much lower overall response, to such an extent that the survival condition is no longer governing the design of the floater and VAWT. Except for floater surge and heave (which is governed by wave loads), all responses are significantly lower compared to the fixed blade pitch survival condition. Whereas with the locked blades, the maximum floater tilt and yaw angles reach values of 31 and 14 degrees respectively, these are reduced to 5 and 6 degrees by utilizing the blade pitch control system. The mean roll and pitch angles are close to zero while mean and maximum mooring line tensions are reduced by more than 50 percent. It is therefore concluded that controlling the blade pitch angle during survival conditions is to be preferred over fixing the blades during survival conditions, even though this introduces the requirement of having a back-up power supply on board.

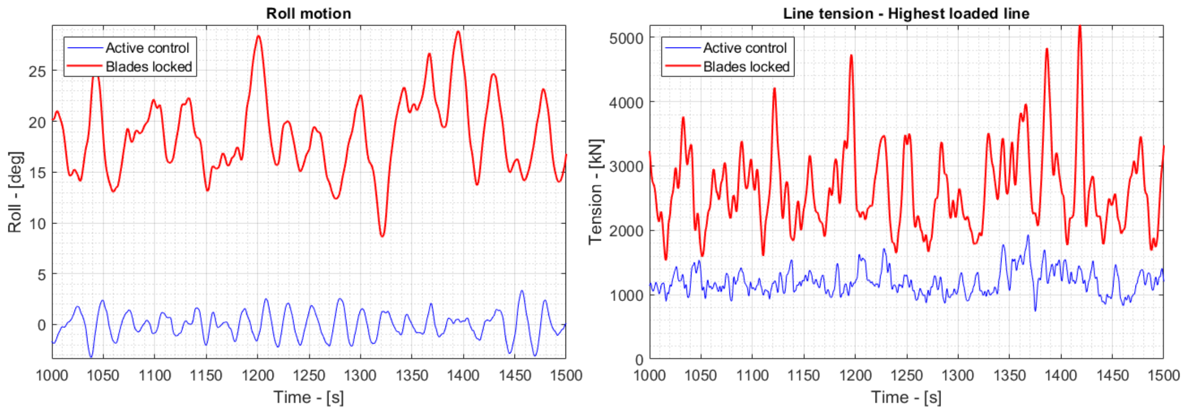

Figure 7. Time traces of roll and mooring line tension for the two control settings during survival

7. Discussion of results and further work

The main research results in terms of governing load cases and cost reduction potential are discussed below, followed by recommendations for future model testing.

7.1. Governing load cases

As highlighted by Galinos et al [10], the design of floating vertical axis wind turbines with fixed blades would typically be governed by high wind loads during parked survival conditions. The results presented in the previous section show that the introduction of active blade pitch control during these conditions effectively solves this issue. Critical floater design parameters such as maximum tilt angle, hub acceleration and tower base moment all reach their maximum values during power production at extreme operational conditions rather than during parked survival conditions. Only for floater surge offset and mooring line tension, the parked survival case is still governing, which is similar to what is often observed for floating HAWT.

The rotor torque during power production results in a 5 to 6 degrees mean yaw angle of the floater. Whereas this torque has been reported by Borg and Collu [9] to be severe for some floater types, this is not the case for the Tri-Floater and its mooring system design. This is probably due to the fairleads being located at sufficient distance from each other to achieve mooring stiffness in yaw. In addition, the floater columns generate hydrodynamic damping, keeping the yaw motions limited. An additional explanation can be found in the three-bladed active blade pitch setup, which almost completely eliminates the torque ripple and alleviates the load (and thus also reduces the cost) of the generator.

Applying active blade pitch control makes the design driving load cases of the floater for a VAWT more comparable to a HAWT. As discussed above, the rotor drag during survival is much lower than the thrust during power production at rated wind conditions. Also the negative slope of the thrust curve above rated occurs for the pitch controlled VAWT, which requires careful control system design in order to avoid floater-control instabilities. The thrust in the cut-out condition is greatly reduced compared to fixed blade pitch VAWT [15, 16], which makes the rated condition governing for the tilt angle and tower base moment. The largest roll and yaw motions are found during power production at cut-out wind velocity.

7.2. Cost reduction compared to floating HAWT

The main objective of the S4VAWT project was to verify and quantify the claimed advantages of the VAWT for floating wind turbine applications. In this study, this has been limited to the costs of manufacturing the floating support structure.

For the purpose of comparison, the required dimensions and weights of a Tri-Floater to support a 6 MW HAWT at the same site have been determined. From this comparison, it is concluded that the floater for the VAWT requires about 20 percent less steel, which implies that the manufacturing costs of the floater are also about 20 percent lower for the VAWT than for the HAWT. Further work is needed to assess all costs and calculate the cost of energy of the VAWT compared to the HAWT.

7.3. Wave basin model test set-up design

For future work it is recommended to perform wave basin model tests in order to verify the global motion response, mooring line tensions and airgap of the floater. Furthermore, wave basin model tests are valuable to validate the coupled simulation tools and identify unexpected hydrodynamic behaviour which may not be taken into account in the simulations.

Since the global motion response and mooring line tensions are highly dependent on both the wind and wave loads, it is important to model these simultaneously. The scaling of wind loads is complicated however, as wave testing requires Froude scaling which inevitably leads to very low Reynolds numbers on the airfoils. In 2014, a method for working around this scaling issue was presented by de Ridder et al [28] for a HAWT. A model scale turbine with performance scaled blades was constructed, meaning that the airfoil geometry was altered such that the model scale blades on low Reynolds number generate similar Froude scaled forces as the full scale blades on high Reynolds numbers. It has been investigated whether this approach is also feasible for the VAWT. However, it has been recognized that the individual blade pitch control would be most challenging to physically model, especially considering the high pitch speed. Also, it is expected that the gyroscopic moment of the VAWT is more relevant than for the HAWT, which gives strict weight restrictions on the hardware for the individual blade pitch control. Therefore it has been investigated to model the wind loads in an alternative way.

As described by Sauder et al [29], state of the art force controlled winches are capable of accurately delivering time varying forces on a moving platform. In such an approach, the wind loads are in real time calculated with aerodynamic software and applied to the physical scale model with force controlled winches. This is a hybrid approach, where the hydrodynamics are physically modelled with scaled waves and current, and the aerodynamic forces are numerically modelled in a dedicated tool. As the apparent wind at the turbine is a resultant of the incoming wind and the floater motions, the floater motions are input for the numerical aerodynamic model. The calculated wind loads are real-time allocated to a set of force controlled winches and applied to the physical scale model.

One requirement of this approach is that the calculation of the aerodynamic loads needs to be fast enough to keep pace with the model tests. As Froude scaling leads to a time scaling with the square root of the model scale, the calculation needs to be in the order of 6 to 8 times faster than real time (typical scale range is ~1:36 to ~1:64). It has been concluded that the lifting line free vortex wake method of section 6.1.3 cannot presently fulfil this requirement without exceeding a reasonable cost level for model tests. Therefore a lower fidelity model will need to be used.

8. Conclusions

The vertical axis wind turbine (VAWT) has specific features that make it highly suitable for offshore floating applications. Amongst these are the potential for scaling up, the low position of the centre of gravity and the large allowable tilt angle. However, VAWT with fixed blades typically have the disadvantage that the wind loads on the rotor become very large for the higher wind velocities, both during power production and parked survival conditions. The research described in this paper has shown that these design driving loads can be significantly reduced by introducing active blade pitch control for the VAWT.

A 6 MW VAWT with pitch control and its semi-submersible support structure have been designed for deployment in the French Mediterranean Sea. The airfoil and the control system have been optimized specifically for this floating application. The floater dimensions have been reduced to the minimum required to meet the design requirements, taking full advantage of the lower centre of gravity and larger allowable floater tilt angles. It is concluded that approximately 20 percent less steel material is needed for the floater, compared to a 6 MW HAWT for the same site, with potential for further optimization.

The final design has been verified by state-of-the-art simulations, using coupled software which has been developed specifically for this purpose. It is concluded that applying active blade pitch control makes the design driving load cases of the floater for a VAWT more comparable to a HAWT, with the rated condition being governing for the tilt angle and tower base moment, rather than the parked survival condition. Floater yaw due to rotor torque has turned out not to be an issue for the Tri-Floater, as its architecture provides sufficient mooring stiffness and hydrodynamic damping in yaw.

For future work, wave basin model tests could be performed to validate the coupled simulation tools and hydrodynamics. Given the challenges involved in modelling a VAWT with active blade pitch control at scale in the wave basin, it is recommended to represent the VAWT by force controlled winches and a real time numerical simulation model, rather than a physical model.

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