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Horizontal and Vertical axis wind turbines: impacts on the dynamics of a floating wind system

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ABSTRACT:

Floating Vertical Axis Wind Turbines (VAWTs) benefit from increased static stability, lower maintenance costs, and reduced aerodynamic wakes. However, to compete with Horizontal Axis Wind Turbines (HAWTs), further analysis is needed regarding the influence of foundations and wind turbine loads to provide a quantitative difference between the two technologies. This study compares the dynamics of floating offshore systems supporting HAWTs and VAWTs. The VAWT is simulated with a novel numerical model combining the Double Multiple Stream Tube method for aerodynamics and WEC-Sim for hydrodynamics, while the HAWT uses the tool MOST. The study aims to understand differences in productivity, loads, and displacements using the same floating foundation and mooring system under identical metocean conditions. Results show that VAWTs generate lower torque but higher wind loads on the turbine base. HAWTs exhibit reduced surge and pitch movements, providing greater stability and transmitting lower forces to the moorings compared to VAWTs.

1 INTRODUCTION

The use of Vertical Axis Wind Turbines (VAWTs) for offshore applications has garnered significant interest due to their potential, as evidenced by various projects such as NOVA, DeepWind, Inflow, and H2Ocean. When compared with Horizontal Axis Wind Turbines, a more widespread and established technology, VAWTs benefit from greater stability, thanks to the placement of the rotor-nacelle assembly (RNA) at the base of the turbine, as well as easier operations and maintenance (O&M) due to greater accessibility (Ghigo et al. 2024a). Additionally, the dynamics of the wake, which requires shorter distances to dissipate, allow for a reduction in aerodynamic losses and result in an increase in Annual Energy Production (AEP) for the same maritime area occupied by the wind farm.

However, few quantitative analyses to estimate these benefits and compare floating VAWTs and HAWTs are available in literature. Some studies have focused on comparing aerodynamic performances: in (Gumilar et al. 2019), the influence of blade design on the generated power was evaluated, while in (Ahmudiarto et al. 2019) a comparison was made considering the same swept area, using the number of blades and wind speed as input parameters. Both studies considered small wind turbines, less than 1 kW, for onshore applications.

The influence of aerodynamics on a floating VAWT has been investigated in (Leroy et al. 2018). Two numerical models were considered: the Double Multiple Stream Tube (DMST) and the Free Vortex Wake (FVW) theories, to evaluate the DeepWind VAWT supported by the OC3HyWind spar platform for different Design Load Cases. However, no comparison with a HAWT was made.

A full comparison between two floating wind turbines, the NOVA 5 MW (VAWT) and the NREL 5 MW (HAWT), was presented in (Borg & Collu 2015), considering two different foundations: a spar-buoy and a semi-submersible. The aerodynamic loads considered included static rotor loads, such as thrust and inclining moments along pitch. The aerodynamic forces on the VAWT were highly oscillatory compared to those on the HAWT, which were constant but lower in absolute value when averaged over the entire revolution of the turbine. Furthermore, the dynamic response was analyzed, considering only wind and no waves, using Fast for the HAWT and FloVAWT for the VAWT (Collu et al. 2013b; a). The dynamic responses showed similar trends for both floating offshore wind turbines (FOWTs), but with numerous peaks due to oscillatory forces, indicating more fatigue loading on the VAWT system.

A detailed comparison was performed in (Cheng et al. 2017), where the performance of a 5 MW three-bladed HAWT was compared with three 5 MW VAWTs with 2, 3, and 4 blades, each installed on a semi-submersible platform. The analysis was conducted to investigate extreme structural responses and fatigue damages under wind and wave conditions, using two codes based on SIMO and RIFLEX programs. Similar performance for the four cases was found in terms of power generated, maximum tower base bending moment, and fatigue damage. Significant tensions in the mooring lines were found for the 3 and 4-bladed floating VAWTs (approximately four times higher than that of the floating HAWTs).

This work aims to compare the dynamics of a floating offshore wind system supporting both a HAWT and a VAWT. The tool MOST, developed by Politecnico di Torino and compared with OpenFast, is used to simulate the HAWT. MOST's aerodynamics is based on Blade Element Momentum (BEM) look-up tables, while its hydrodynamics is modeled using WEC-Sim, a tool developed by NREL and SANDIA. To simulate the floating VAWT, MOST has been modified to include Double Multiple Stream Tube (DMST) look-up tables, with additional corrections.

The aim of this work is to understand the main differences in terms of productivity, loads, and displacements by considering the same floating foundation, similar nominal wind turbine power, and mooring system under identical wind and wave conditions. For each type, the response of the system to waves and wind is considered, evaluating the displacements along surge, heave, and pitch, as well as velocities, accelerations, and the main loads acting on the floater and the moorings.

2 NUMERICAL MODEL

MOST (Matlab for Offshore wind turbine Simulation Tools) is a numerical tool developed by Politecnico di Torino for simulating floating wind turbines (Cottura et al. 2021). It is built on Wec-Sim within a Matlab-Simscape environment, offering significant flexibility for analyzing complex devices such as hybrid wind and wave platforms (Cottura et al. 2022; Sirigu et al. 2022).

MOST enables the analysis of floating platforms in six degrees of freedom, power production, nacelle acceleration, and the loads affecting the tower and moorings (Cottura et al. 2022). The Simscape environment facilitates the inclusion of toolboxes for implementing control systems and additional features.

The structure of MOST is based on several blocks that includes:

- *Aerodynamics*: Aerodynamic forces and torque are calculated using the Blade Element Momentum (BEM) theory. These calculations are precomputed and stored in look-up tables, which use inputs such as wind speed, rotor speed, and blade pitch angle. Users can choose between a constant wind speed or a turbulent one, which incorporates wind speed variability using TurbSim, a code developed by NREL. Blade flexibility, rotor misalignment, and wake dynamics deflection are not considered.
- *Hydrodynamics*: The hydrodynamics of the floating structure are computed using WEC-Sim, which determines the dynamics of floating bodies in the time domain based on a frequency-domain boundary element method. Hydrodynamic properties such as linear hydrostatics, added mass, radiation damping, and wave excitation coefficients are evaluated using external software, specifically Nemoh in this study.
- *Moorings*: Two options are implemented. A quasi-static mooring lookup tables within the Simulink model to account for the nonlinear stiffness of the chains through catenary equation solutions, or Moordyn, a built-in module in WEC-Sim that considers the inertia and viscous friction of the chains.
- *Control system*: Two control strategies are implemented: the Baseline and ROSCO. The Baseline control is a conventional variable-speed, variable collective pitch controller consisting of a generator torque controller designed to maximize power extraction below nominal wind speed, and a blades collective pitch controller to regulate rotor and generator speed above nominal wind speed. The ROSCO controller, a Reference Open-Source Controller for fixed and floating offshore wind turbines, uses two methods of actuation (generator torque and collective blade pitch) and defines four main regions based on the strategies of actuation.

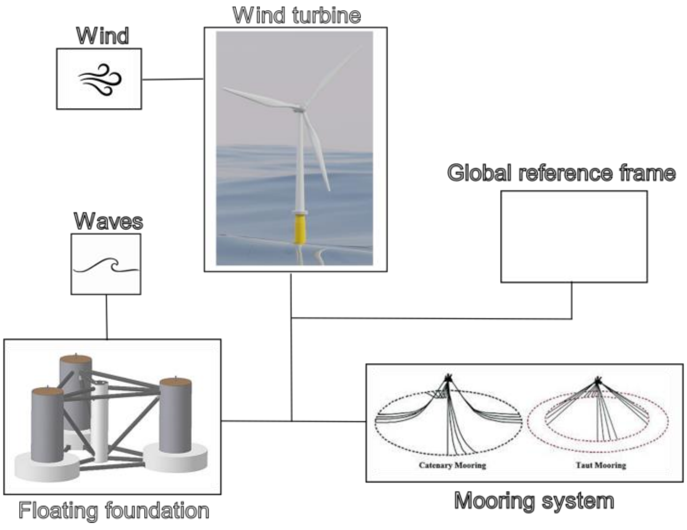

Figure 1 - The numerical model representation.

MOST has been compared with OpenFast, showing a good agreement in terms of accuracy and a reduced computational time (Cottura et al. 2021; Sirigu et al. 2022). Figure 1 shows a graphical representation of the model.

2.1 *VAWT implementation*

The Double Multiple Stream Tube (DMST) is an analytical approach used to evaluate the performance of Vertical Axis Wind Turbines (VAWTs). Based on Blade Element Momentum (BEM) theory, it extends the single stream tube concept by considering the rotor to be divided into multiple stream tubes. The VAWT is modeled as a drag disk that slows the wind speed in the upstream stream tubes and the wake velocity in the downstream stream tubes. By doing this, it effectively captures the dynamic interactions between the blades and the wind, which vary significantly over each rotation due to the relative motion between the blades and the airflow.
The methodology for pre-calculating the aerodynamic look-up tables has been detailed in (Ghigo et al. 2024c).

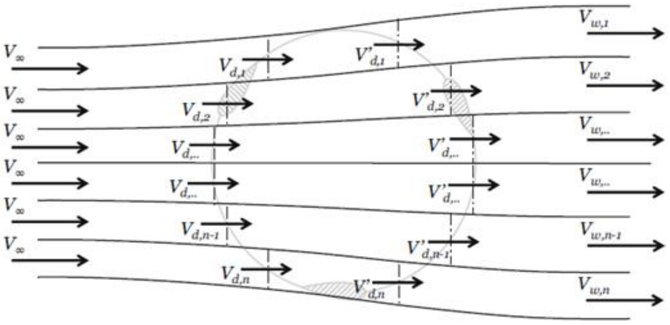

Figure 2 - Double Multiple Stream Tube model

Two corrections have been implemented: the Glauert correction and the dynamic stall. The first occurs when the induction factor assumes values higher than 0.4, to decrease the thrust force acting on the rotor. The dynamic stall occurs when there is a rapid change angle of attack change, affecting VAWT performances, especially at low TSRs. In this study, the Masse model is implemented.

3 THE CASE STUDY

The comparison between a floating HAWT and VAWT has been made considering two wind turbines with a similar nominal power, the NREL 5 MW and the 6 MW VAWT, both installed on a semi-submersible foundation, with a mooring system. In the following sections further details are provided.

3.1 *Wind turbines*

The NREL 5 MW is a conceptual reference turbine, designed to be representative of large multi-megawatt class wind turbines, mainly used for offshore wind research and development (Jonkman et al. 2009).

The VAWT used is a Darrieus H-rotor, developed starting from H2OCEAN (2012) and S4VAWT (2016) projects, with in-depth analysis concerning the influence of the chord size and the type of airfoil (Ghigo et al. 2024b).
Main data are reported in Table 1.

Table 1 - Wind turbines considered in the study.

Wind turbine	***NREL 5 MW***	***VAWT***
Nominal power	5 MW	6 MW
V_cut_in, V_rated, V_cut_off	3, 11.4, 25 m/s	3, 10, 25 m/s
Ω_min, Ω_rated	6.9, 12.1 rpm	2.1, 6.6 rpm
Wind turbine radius	63 m	63 m
Wind turbine height	90 m	140 m
Chord length	Var	5 m
Airfoil	Var	NACA 0024

3.2 *Floating Foundation*

The floating foundation considered is a semi-submersible platform, the VolturnUS (Allen et al. 2020). The platform has a triangular shape at whose vertices there are three columns plus a central column which supports the wind turbine. The columns are connected to each other via horizontal cross members forming a triangular base. The VolturnUS main data are reported in Table 2.

Table 2 - Floating foundation considered in the study.

Floating foundation	**VolturnUS**
Main column diameter	10 m
Offset column diameter	15 m
Draft	20 m
Column height	35 m
Mass including ballast	1.785E+7 kg
Roll, Pitch & Yaw moment of inertia	1.251E+10 kg · m^2 1.251E+10 kg · m^2 2.367E+10 kg · m^2

3.3 *Mooring System*

The mooring system adopted is made of three catenary lines spread symmetrically about the platform Z-axis, with a 120° angle between each line. The water depth considered is 200 m below the sea water level. All the information about the mooring layout is reported in (Allen et al. 2020). A graphical representation of the floating VAWT system, including the global reference frame, is reported in Figure 3.

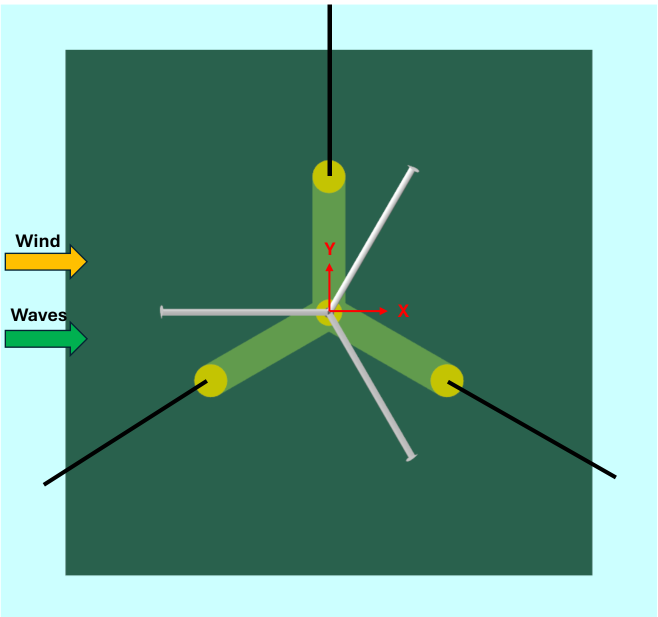

Figure 3 - Floating VAWT system coordinates.

3.4 *Design Load cases*

To compare the two different technologies and to evaluate the influence of metocean conditions, the following design load cases have been proposed, as reported in Table 3.

Table 3 - Design load cases considered in the study.

Design load case	***Wind***	***Waves***
DLC 1.1	5 m/s (Const)	-
DLC 1.2	11 m/s (Const)	-
DLC 1.3	18 m/s (Const)	-
DLC 2.1	5 m/s	Hs = 0.25 m, Tp = 6 s
DLC 3.1	8 m/s	Hs = 0.75 m, Tp = 8 s
DLC 4.1	11 m/s	Hs = 1.25 m, Tp = 9 s
DLC 5.1	15 m/s	Hs = 2.0 m, Tp = 10 s
DLC 6.1	24 m/s	Hs = 3.5 m, Tp = 12 s

4 COMPARISON

In this section, a comparison between the two technologies is presented. Firstly, aerodynamic performances are compared, followed by consideration of the complete system and comparison of platform displacements and tensions generated by the systems on the mooring system.

4.1 *Only aerodynamics*

In this section, the comparison between HAWT and VAWT technology has focused only on aerodynamics: specifically, the Design Load Cases considered are 1.1, 1.2, and 1.3. As a result, displacements have been neglected. Wind speed is considered constant over time, without anticipating the presence of possible turbulence. Figure 4 shows a comparison in terms of generated power.

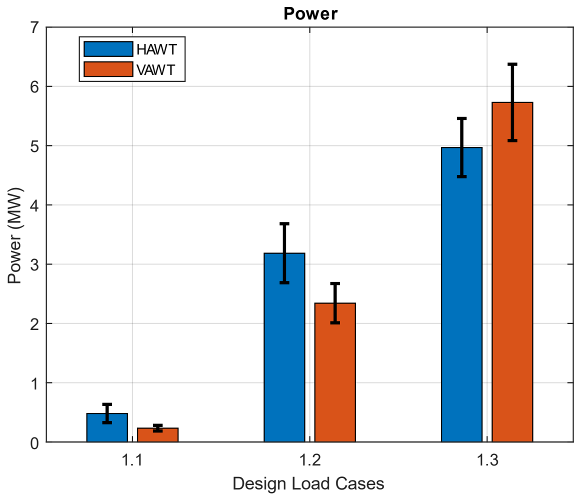

Figure 4 - Comparison of generated power

It's important to highlight that the size of the turbines is different (5 MW for the HAWT, 6 MW for the VAWT). This is due to the absence in the literature of a fully open-source VAWT turbine, for which all information such as masses and inertias is known to perform a complete simulation. Consequently, it was decided to consider a VAWT turbine with a different nominal power compared to the HAWT, but for which all the main quantities were known (Ghigo et al. 2024b).

At the same wind speed, the average power generated by the VAWT is generally lower because of its oscillatory behaviour, despite the nominal capacity is 6 MW, compared to the 5 MW of the HAWT. This also depends on how the power curves of the two turbines are defined.

In Figure 5, a comparison in terms of torque is shown. From the comparison, it clearly emerges that the torque generated by the HAWT is significantly higher than that generated by the VAWT. Furthermore, the generated torque increases until reaching nominal conditions, which are a wind speed of 11 m/s for the VAWT and 11.4 m/s for the HAWT.

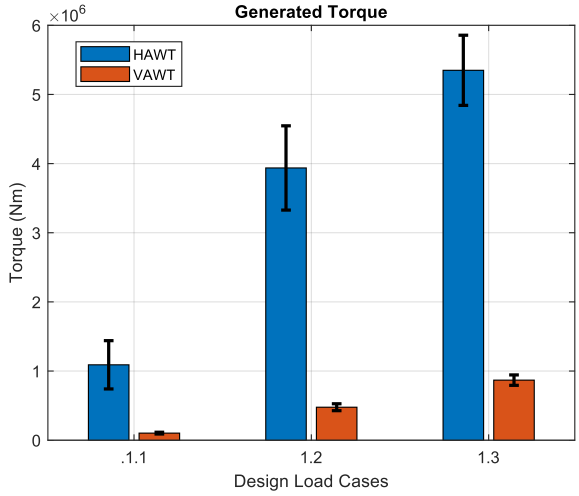

Figure 5 - Comparison of generated torque

4.1.1 *Wind loads acting on the base of the wind turbine*

In this subsection, the loads transmitted by the wind force to the base of the turbine tower are analysed. Since aeroelasticity of the turbine has not been implemented in the tool, the assumption made is that of a rigid body.

In Figure 6, the force applied to the base of the turbine and acting along the x direction (surge) is shown; in Figure 7, the force acting along the z direction (heave) is shown; and in Figure 8, the moment acting along the y direction (pitch) is shown.

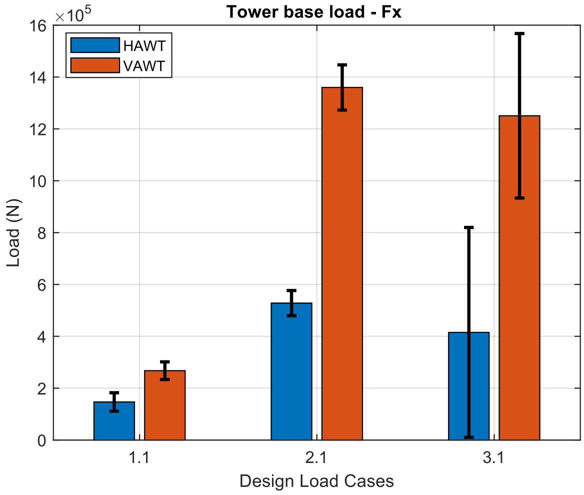

Figure 6 – Wind load acting on the tower base along the x direction

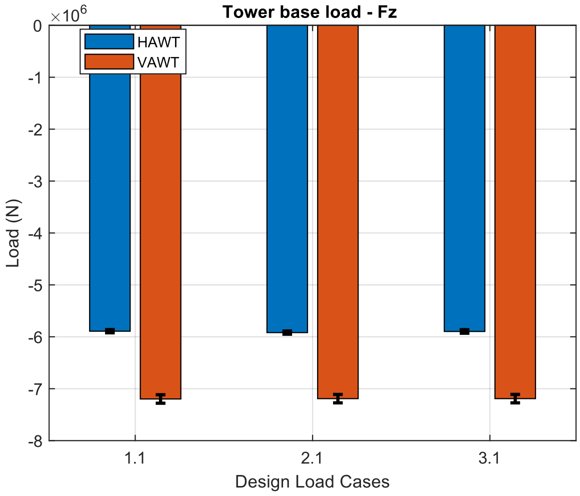

Figure 7 – Wind load acting on the tower base along the z direction

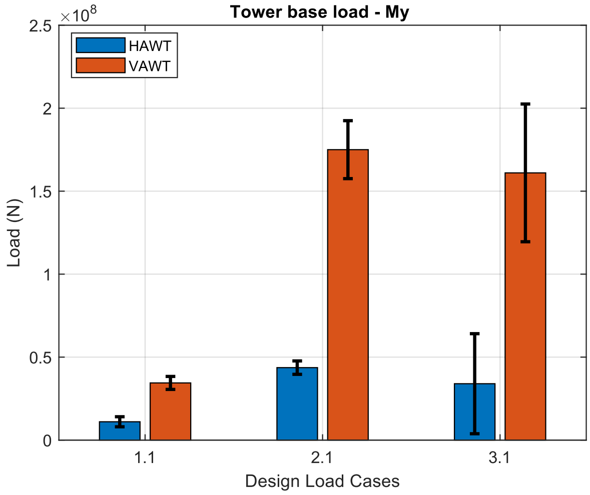

Figure 8 – Wind load acting on the tower base along the y direction

From the comparison between HAWT and VAWT regarding the loads generated by the wind and transmitted to the base of the turbine, it emerges that higher values are generated in the configuration with VAWT. This is partly justified by the different technical characteristics, especially the height of the VAWT hub (140 m), which is much higher than that of the HAWT (90 m).

4.2 *Aerodynamics and hydrodynamics*

In this section, the comparison between the two technologies concerns the complete systems, consisting of the turbine and the floating foundation. The Design Load Cases considered range from 2.1 to 6.1 and include both wind and wave actions. The wind profile is generated using TurbSim, considering the proposed average wind speed and a Kaimal turbulence model. The power law exponent considered is equal to 0.11, while the length of each simulation is 1200 s.

Regarding the wave generation, the wave spectra used in this work is the Jonswap.

In Table 4, the natural periods for the floating HAWT and VAWT are reported.

Table 4 - Natural periods for the floating HAWT and VAWT.

Mode	*Natural period (HAWT)*	*Natural period (VAWT)*
Heave	33.58 s	31.89 s
Roll	20.66 s	37.47 s
Pitch	20.66 s	37.47 s

4.2.1 Power and torque

The first parameters compared concern the aerodynamic characteristics of the two systems, namely power and torque. In this case, the wind does not have a constant speed, but a wind profile generated by Turbsim. Figure 9 shows the average power values, while Figure 10 shows the torque average values.

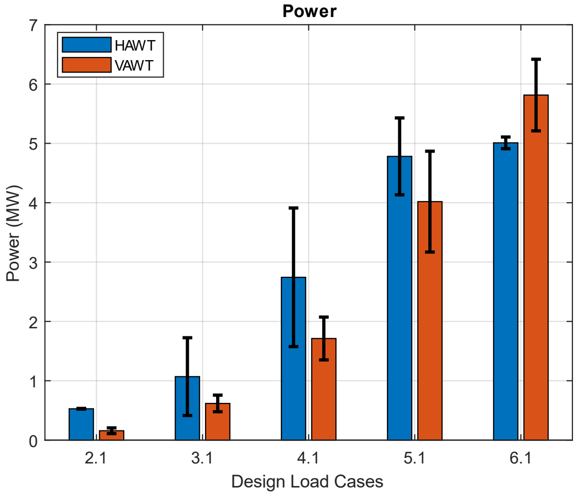

Figure 9 - Wind turbines power

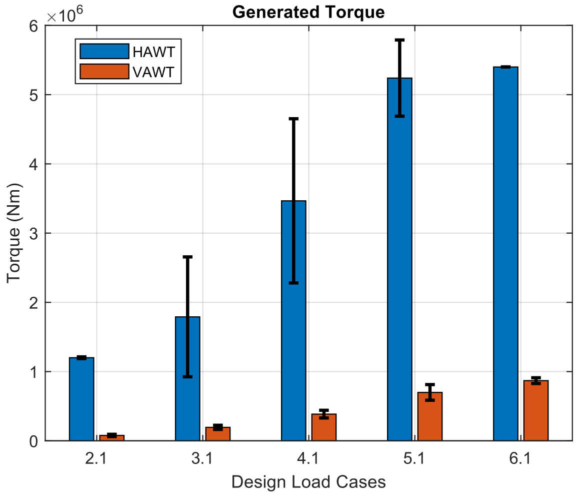

Figure 10 - Wind turbines torque

As already discussed in the previous section, although the nominal power of the VAWT is greater than that of the HAWT, with the same wind input speed, the HAWT's curve is superior. This aspect is the result of the power curves of the two devices, rather than their performance in different configurations. However, the higher standard deviation values of the VAWT, compared to those of the HAWT, are a direct consequence of the oscillatory behaviour of the generated power.

Regarding the average torque, which is reported here for completeness, the HAWT shows significantly higher average values compared to those of the VAWT. These differences are related to the different operating mechanisms of the two wind turbines.

4.2.2 Foundation displacements

In this section, the main platform displacements are analysed, including surge, sway, pitch and yaw.

The surge, reported in Figure 11, shows an increasing trend for both systems as the Design Load Case increases, with a peak for DLC 5.1. The average values of the HAWT are much lower compared to those of the VAWT: this is partly due to the mooring system considered, which is not optimized for both systems and in particular for the VAWT.

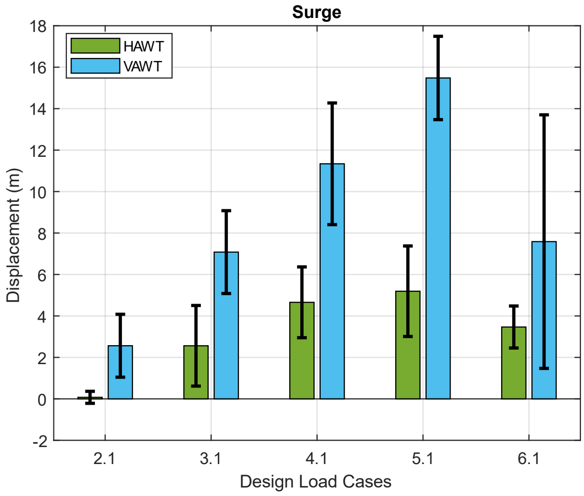

Figure 11 - Surge displacement

The sway, shown in Figure 12, is barely noticeable for the HAWT, with average values close to zero, while it is more significant for the VAWT, as it affects the dynamics of the system. The rotation of the VAWT's rotor is not fully countered by the action of the moorings, which are not designed for the system, and thus results in a displacement related to the direction of rotation of the turbine, represented in the chart by a slightly negative average value, but different from zero.

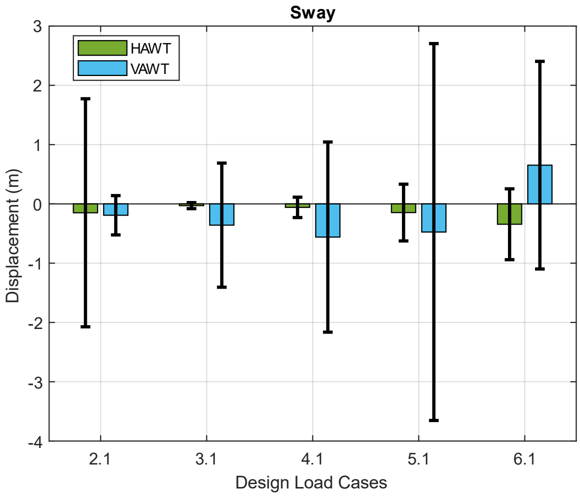

Figure 12 - Sway displacement

Regarding the pitch, shown in Figure 13, both systems display similar trends: as the considered DLC increases, there is an increase in the average pitch inclination values, until reaching nominal conditions.

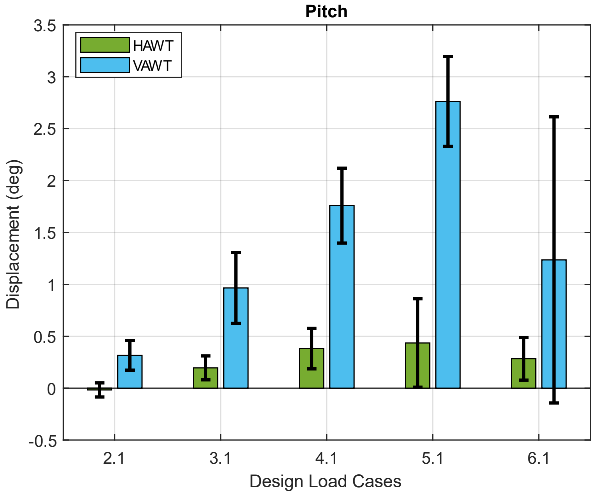

Figure 13 - Pitch displacement

Subsequently, the blade pitch control mechanism contributes to reducing the action of the thrust force and decreasing the pitch oscillation. Moreover, from the figure, it is evident that the HAWT exhibits lower average pitch values compared to the VAWT.

However, unlike HAWTs, which must strongly limit pitch oscillation to reduce the oscillation values at the nacelle, VAWTs do not have restrictive constraints, since the Rotor Nacelle Assembly (RNA) is located near the floating foundation. Finally, the last degree of freedom analyzed concerns the yaw. As reported in Figure 14, this degree of freedom significantly affects only the dynamics of the VAWT, as a result of the aerodynamic forces acting on the system, which are not compensated by the platform inertia or the mooring system.

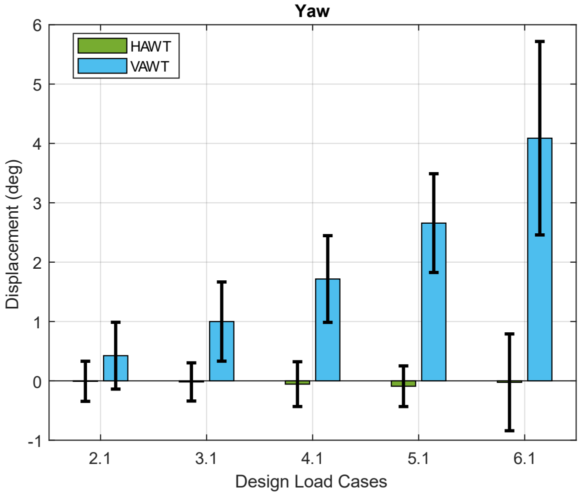

Figure 14 - Yaw displacement

4.2.3 *Mooring tensions*

Regarding the forces generated by the mooring system, the trends of the tension Tx, acting along the wind & wave direction, and Ty, perpendicular to Tx, are shown in Figures 15 and 16.

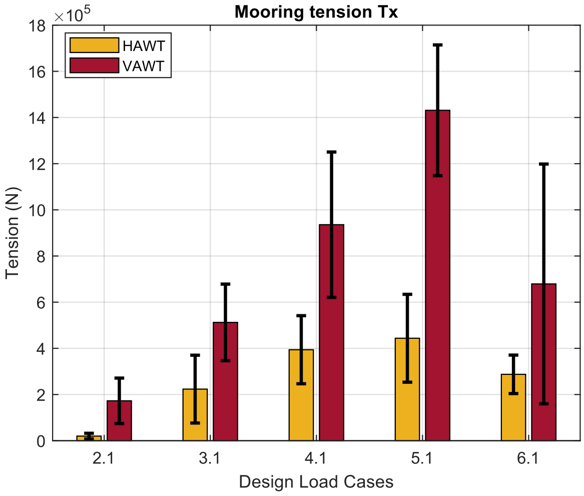

Figure 15 - Mooring tension Tx

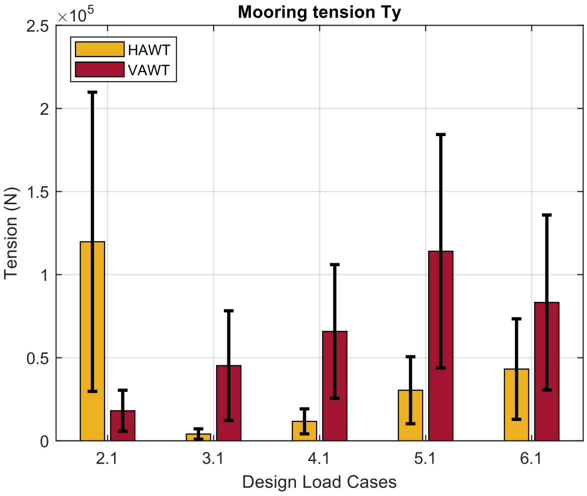

Figure 16 - Mooring tension Ty

The tensions generated by the VAWT are considerably greater than those of the HAWT, both along the x component and the y component. In particular, the fact that the VAWT is subject to rotation around the center of the platform causes the Ty tensions to be significantly higher than those sustained by the HAWT.

It clearly emerges that the mooring system for the VAWT needs to be specifically designed, also taking into account new configurations like the taut and semi-taut mooring layouts.

5 CONCLUSIONS

The aim of this work is to understand the main differences in terms of productivity, loads, and displacements between a floating VAWT and HAWT under the same conditions. The comparison involves two turbines, the NREL 5 MW (HAWT), and a Darrieus H-rotor (VAWT) with a nominal power of 6 MW. The floating foundation considered is a semi-submersible platform, the VolturnUS, provided with a specific mooring system layout for a 200 m water depth site. Regarding the metocean conditions, the action of the waves, reproduced with a Jonswap spectrum, and the wind, modelled both with constant wind speed and including a turbulent profile via TurbSim, were considered.

The comparison primarily addresses the system's performance in terms of productivity, loads generated by the wind, displacements, and mooring forces. Several Design Load Cases (DLCs) have been proposed, corresponding to the most typical operational conditions for offshore wind turbines.

Concerning the turbines' performance, it is evident that the VAWT generates lower torque due to its different operating mechanism. However, the differences in dimensions and nacelle height are responsible for higher loads at the tower base of the VAWT. Subsequently, the main displacements along surge, sway, pitch, and yaw are evaluated. Among the most evident results is the oscillatory nature of the VAWT, clearly visible in the higher standard deviation values measured for each DLC compared to the HAWT. Overall, the HAWT exhibits lower displacements, especially along surge and sway, and lower pitch and yaw angles, ensuring better dynamic stability for the proposed DLCs. The lower stability of the system and the greater displacements have consequences on the forces transmitted from the foundation to the moorings, with the order of magnitude of the tension generated by the VAWT being higher compared to the HAWT, also presenting larger standard deviations.

While the analysis shows that the VAWT's performance appears to be inferior to the HAWT, it is important to emphasize that both the floating foundation and the mooring system were designed to support a HAWT. Consequently, accurate design and optimization of the foundation to support a VAWT, as well as a mooring system suitable for compensating the loads transmitted by the VAWT, would allow for an increase in the dynamic stability of the VAWT system and better performance.

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