WindWEC: Combining Wind and Wave Energy Inspired by Hywind and Wavestar

Madjid Karimirad*
MARINTEK
Norwegian Marine Technology Research Institute
Trondheim, Norway
Madjid.Karimirad@marintek.sintef.no

Kourosh Koushan
MARINTEK
Norwegian Marine Technology Research Institute
Trondheim, Norway

***Abstract*—This article studies the feasibility of combining a spar-type offshore wind turbine (inspired by Hywind) and a wave energy converter (inspired by Wavestar) by performing numerical simulations in operational conditions. The dynamic responses and power production of wind turbine and wave energy device are investigated for different power-take-off systems. Coupled/integrated aero-hydro-servo-elastic time domain dynamic simulations considering multi-bodies are applied in this paper. The results show that by choosing proper power-take-off system, it is possible to minimize the effect of wave energy convertor on the floating wind turbine and hence maintaining the power performance of the wind turbine while getting more power through wave energy device.**

Keywords—Wave energy converter; Offshore wind; Floating wind turbine; Wavestar; Hywind; Hybrid marine platform

I. INTRODUCTION

This article studies an innovative hybrid marine platforms by combing wave- and wind energy devices, inspired by Hywind and Wavestar, to use the possible synergy effects and reduce the cost of electrical energy from offshore units while increasing the quality of the delivered power to the grid. More offshore wind farms are being constructed and hence the possibility of integrating other marine renewables such as wave energy converters (WECs) and ocean current turbines with offshore wind is increased. Integration of wave energy converter and offshore wind turbine may have several advantages including better utilization of the ocean space and decreasing the associated costs, e.g. installation/maintenance costs relative to separate installations. In addition, there are possibilities to share substructures and infrastructures between the offshore wind and marine energy devices.

Integration of wave and wind energy has two clear aspects [3]: (1) Combining the power production of wave-energy devices and wind turbines in a farm. For example, independent bottom-fixed wind turbines and WECs in an offshore energy farm. (2) Combining the wave- and wind-energy devices in one unit so-called hybrid platform. For example, bottom-fixed hybrid wind-WECs or floating hybrid wind-wave-energy converters. The latter is the focus of this paper.

The first combination is so-called "segregated" and the second one is so-called "hybrid". The core of this paper is the hybrid platform, its feasibility for a proposed concept and advantages achieved by such combination by integrating the wind- and wave-power devices presenting a hybrid concept called "WindWEC".

Although both WECs and offshore wind turbines are subjected to similar challenges (such as harsh marine environmental conditions), the maturity of them is different. Wave energy devices came earlier to offshore industry than offshore wind turbines. Offshore wind technology had a very good development both for bottom-fixed and floating concepts in the past decade. Several concepts have been introduced for floating wind turbines and few of them are constructed and commissioned, among those, Hywind is a successful example, see Fig. 1. Furthermore, better progress has been seen for marine energy devices and several concepts are tested in ocean, among those, Wavestar is a successful example, see Fig. 1. By the integration of wave to wind, there is a better chance for wave energy to reduce cost by taking advantage of the fact that the offshore wind energy industry is more mature.

Fig. 1. Hywind [1] and Wavestart [2], courtesy of Statoil and Wavestar

In an advanced combined concept, the wave energy device acts like a damper that takes out the coming incident wave energy with minimum effects on the wind turbine performance while WEC produces electricity in addition to the wind turbine. There are several other advantages when combining wave- and wind-energy devices including sharing the electrical subsea cables, survey and monitoring costs as well as sharing the supporting structures, foundation, mooring and anchoring systems.

In this paper, a floating wind turbine based on a spar substructure and a wave energy converter inspired by Wavestar are combined. The dynamic responses of the hybrid system is

---

*The corresponding author.

investigated applying coupled/integrated aero-hydro-servo-elastic time domain simulations considering multi-bodies. Different power-take-off (PTO) systems are considered for the present combination and the most reasonable one is selected. The results show that the WEC has a negligible effect on the motion responses and functionality of the floating wind turbine (FWT) while it produces extra electricity. In addition, it is seen that the integration of wind and wave energy devices can result in better quality of produced power as the frequency range of the fluctuation in mean power produced by wind turbine differs from those produced by wave energy conversion.

II. WINDWEC: A HYBRID WIND-WAVE ENERGY SYSTEM

As it is mentioned earlier, in this paper, a floating wind turbine based on a spar substructure and a wave energy converter using oscillating buoy are combined, see Fig. 2.

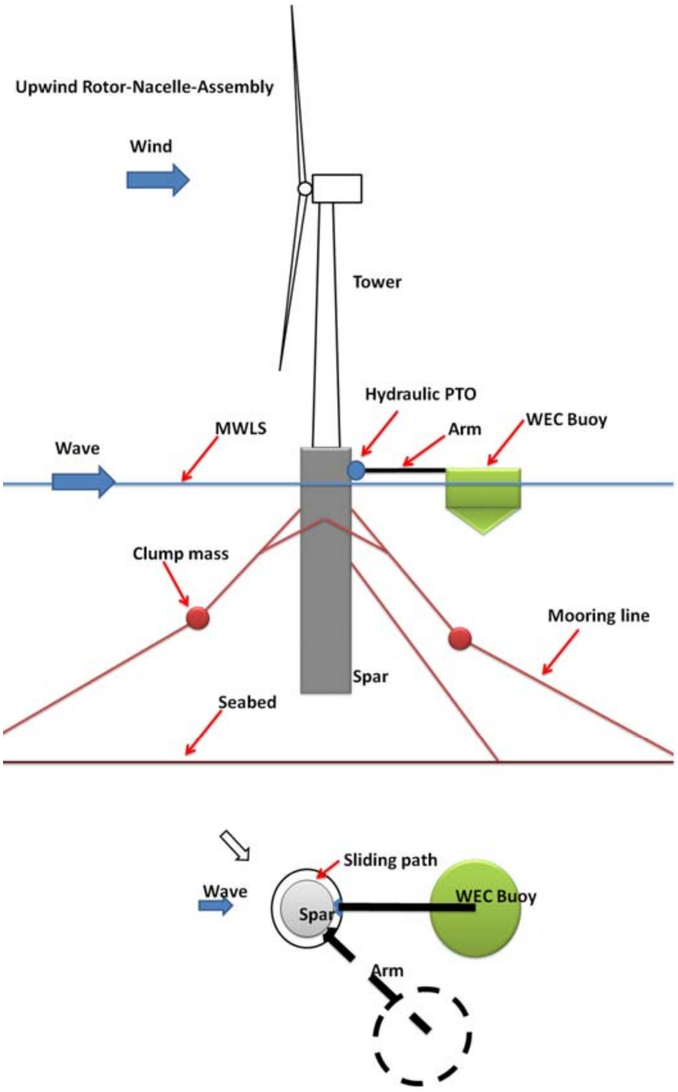

Fig. 2. WindWEC, a hybrid wind-wave energy system, combining spar-type floating wind turbine and a wave energy concept based on oscillating buoy

The relative motion of the spar and buoy results in mechanical power that is taken by a hydraulic system. The WEC buoy is attached to the spar wind turbine using an arm. This arm is a structural member carrying out the loads and connects the FWT and WEC. In real world, the arm is a frame structure capable of handling all the mechanical/structural loads and transfer the bending moments and shear forces to the spar platform. Design of the arm is out of the scope of this paper. One end of the arm is attached to the WEC buoy and the other end is attached to a hydraulic power-take-off (PTO) system.

The WEC buoy motions in heave-pitch are useful motions, resulting in relative rotation between spar and buoy. The relative rotation of the arm respect to the spar platform pumps the oil. The oil flow pumping in the cylinder-piston-mechanism is presented as damping. The oil pumped rotates the hydraulic motors and produces electrical power. As it is clear in Fig. 2, the WEC bouy of the WindWEC turns against the wave front. This is a passive way of adjustment, "weather vaning", without consuming energy.

A catenary moored spar-type wind turbine inspired by the Hywind concept is considered in this article. The schematic layout of the offshore wind turbine is shown in Fig. 2. The NREL 5MW wind turbine is selected for the present study [4]. Properties of the spar-type wind turbine are listed in Table I. Properties of the mooring system components are listed in Table II. The natural frequencies of the floating wind turbine (FWT) are listed in Table III; for more information, refer to [5].

TABLE I. PROPERTIES OF THE OFFSHORE WIND TURBINE*

Turbine	NREL 5-MW
Water depth (m)	320
Draft (m)	120
Displacement (m^3)	8016
Centre of buoyancy (m)	-62
Diameter at MWL (m)	6.5
Diameter at bottom (m)	9.4
Mass (kg)	8216 E+3
Centre of gravity** (m)	-78.5
Mass moment of inertia, I_{XX} ($kg.m^2$)	69.84 E+9
Mass moment of inertia, I_{ZZ} ($kg.m^2$)	16.78 E+7
Fairlead elevation (m)	-70

* The coordinate system in which the data are calculated is at MWLS and it passes the center of the spar. The Z-axis is upward and the X-axis is from left to right, see Fig. 2.

** Center of gravity of the floating wind turbine including rotor, nacelle, tower and spar (steel weight and ballast).

TABLE II. PROPERTIES OF THE MOORING SYSTEM COMPONENTS

Property	Delta line	Upper line	Lower line	Clump mass
Length (m)	50	250	600	2
Diameter (m)	0.09	0.09	0.09	1.67
Mass/length (kg/m)	42.5	42.5	42.5	17,253
Axial stiffness (kN)	384,243	384,243	384,243	384,243

TABLE III. NATURAL FREQUENCIES OF THE FLOATING WIND TURBINE.

Motion	Natural frequency (rad/sec)
Surge/sway	0.05
Pitch/roll	0.22
Heave	0.20
Yaw	0.84

The distance of the spar and WEC buoy is 20 m, center to center. The WEC buoy characteristics are listed in the Table IV. The total displacement of the WEC buoy is just 2.2% of the total displacement of the FWT. However, it will be shown that the added power production is more than 6%.

TABLE IV. PROPERTIES OF THE WEC BUOY*

Diameter (m)	10
Draft (m), total draft at center	3
Conic length (m)	1
Centre of buoyancy (m)	-1.17
Centre of gravity (m)	-1.5
Mass (kg)	180 E+3
Mass moment of inertia, I_{XX} (kg.m2)	1.690 E+6
Mass moment of inertia, I_{ZZ} (kg.m2)	3.018 E+6

* The coordinate system in which the data are calculated is at MWLS and it passes the center of the WEC buoy. The Z-axis is upward and the X-axis is from left to right, see Fig. 2.

III. NUMERICAL MODELING

This section briefly explains the state of the art numerical tools of MARINTEK for coupled/integrated simulations of offshore energy structures considering aero-hydro-servo-elastic formulations. The main code is SIMA (Advanced Analyses of Marine Operations and Floating Systems) suited for complicated coupled simulations. RIFLEX [6] is a nonlinear time domain program with a Finite Element (FE) formulation that can handle unlimited displacement and rotations. It also has the capability of performing a coupled analysis, where one or more rigid-body floating structures are integrated with a dynamic model of the mooring and riser systems and arbitrary coupling forces in the time domain. In the coupled analysis, SIMO [7], another computer program system developed by MARINTEK, is used to calculate the hydrodynamic loads. State-of-the-art models for low-frequency, wave-frequency, and high-frequency excitation can be employed for modeling the hydrodynamic loads on floating structures. The RIFLEX computer program is extended to include aerodynamic forces on elastic structural members using blade element momentum theory (BEM) with a number of correction factors applied including, Glauert correction, Prandtl factor, Dynamic wake, Dynamic stall, Skewed inflow and Tower shadow (influence). The extension comprises the aerodynamic loads and the control system implementation for blade pitch and electrical torque for power extraction. Taken together with the already coupled SIMO code, this extension to RIFLEX yields the coupled code SIMO-RIFLEX: a time-domain simulation for fixed and floating offshore energy structures [3].

The numerical analyses are carried out in time domain where the platforms motions (both spar and WEC buoy), turbine (tower, rotor and nacelle) and mooring line responses are solved simultaneously. The spar and WEC buoy platforms are modelled as rigid body where the hydrodynamic loads and motion responses are calculated using SIMO and the turbine as well as mooring line responses are calculated using the non-linear finite element tool RIFLEX. The numerical analysis is done using the simulation workbench SIMA, see Fig. 3 and Fig. 4. MultiSurf [8] is used to generate mesh needed for hydrodynamic analysis, see for example [5]. As an example, Fig. 3 shows the mesh generated by MultiSurf for WEC buoy.

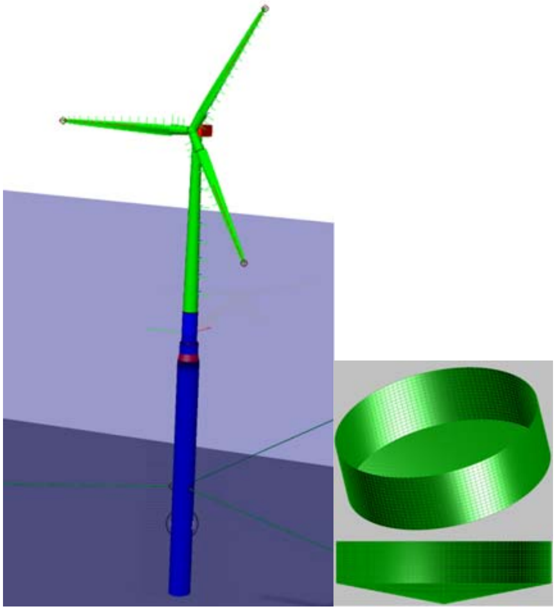

Fig. 3. A model of spar-type offshore wind turbine in SIMA (left) and example of generated mesh in MultiSurf for boundary element method (BEM) analysis i.e. in WAMIT for WEC buoy (right).

Linear radiation-diffraction analysis of the spar hull and WEC buoy has been carried out using a potential theory based panel model in WAMIT [9] to obtain frequency-dependent added mass and damping coefficients, frequency and direction dependent linear wave excitation coefficients and second order wave drift coefficients. The frequency dependent added mass and damping coefficients have been transformed into retardation functions for time domain simulations. Newman's approximation is applied to obtain the slow-drift excitation from the mean wave drift forces computed by WAMIT, thus only the diagonal terms of the quadratic transfer functions are needed. The wave drift load transfer functions for surge, sway and yaw were computed based on the conservation of momentum principle, whereas the wave drift load transfer functions in heave, roll and pitch were obtained from the pressure integration method. Wave drift damping has not been included in the numerical model.

Viscous effects are accounted for by slender element approach using Morison's equation. The viscous effects, such as viscous damping and drift forces, are accounted for using the drag term in Morison's equation. A total relative velocity approach is used when invoking the drag term in Morison's equation. The mooring system is modelled as bar elements, i.e. only the axial stiffness is considered, while torsional and bending stiffness are neglected.

The hydrodynamic interaction between spar and WEC buoy is neglected in the present work. This means that the diffraction/radiation problem is solved separately for each body. This should be reasonable assumption for investigating the feasibility of combining the wind and wave energy devices. More detailed analysis considering hydrodynamic interaction of two platforms is needed for further development of this hybrid concept.

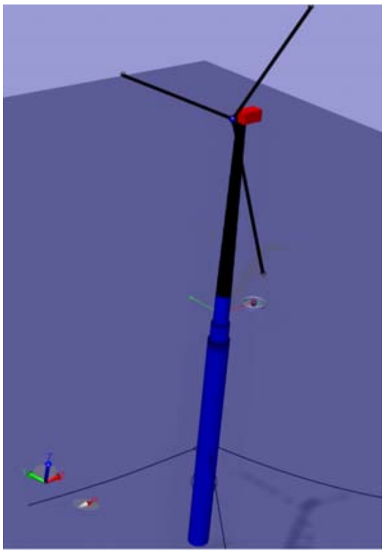

Fig. 4. Graphical representation of WindWEC (combined wind and wave energy devices) in SIMA

IV. RESULTS AND DISCUSSION

The effect of different power take off (PTO) systems on the response and functionality of the WindWEC concept has been investigated. Table V shows the properties of the power take off systems investigated in this article. For all PTOs, there is a hinge around local Y axis (Rot Y) meaning that there is no stiffness against relative rotation of arm and spar. Hence, the power is taken by damping. Different values of damping coefficient has been selected for PTOs covering a wide range.

TABLE V. PROPERTIES OF THE PTOS

ID	Stiffness (Nm/deg)			Damping (Nms/deg)*
	Rot X	Rot Y	Rot Z	Rot Y
PTO1	1.0 E+13	0	1.0 E+13	5.0 E+4
PTO2	1.0 E+13	0	1.0 E+13	6.0 E+05
PTO3	1.0 E+13	0	1.0 E+13	7.0 E+06
PTO4	1.0 E+13	0	1.0 E+13	1.3 E+07
PTO5	1.0 E+13	0	1.0 E+13	2.0 E+07

* All PTOs have zero damping in Rot X and Rot Z.

The wind speed of 11.4 m/sec, significant wave height of 5 m and peak period of 12 sec are selected for investigating the performance of WindWEC. The wind speed corresponds to rated wind speed that results in maximum aerodynamic loads for the wind turbine. The selected load case can be a reasonable selection to study the normal operational conditions of the hybrid concept.

In Fig. 5 and Fig. 6, the heave motion of spar wind turbine and WEC buoy for different PTOs selected for the wave energy convertor is shown. It is clear that the high values of PTOs damping increase the spar heave motion. The idea is limiting the motions of the FWT as far as it is possible. Fig. 7 and Fig. 8 shows the spectra of pitch motion response for FWT and WEC, respectively. It is found that the PTOs value does not significantly affect pitch motion of spar wind turbine. However, the PTO system damping value may have a significant effect on the WEC pitch motion. In Fig. 9, time series of the power produced by spar wind turbine for different PTOs selected for WEC buoy are shown. It is clear that the PTO system damping does not significantly influence the power production of the turbine. Fig. 10 shows the time series of power produced by WEC for different PTOs selected for WEC buoy.

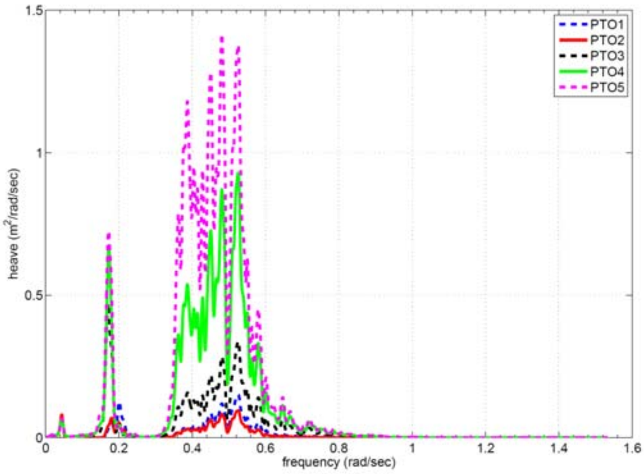

Fig. 5. Spectra of heave motion of spar wind turbine for different PTOs selected for WEC buoy

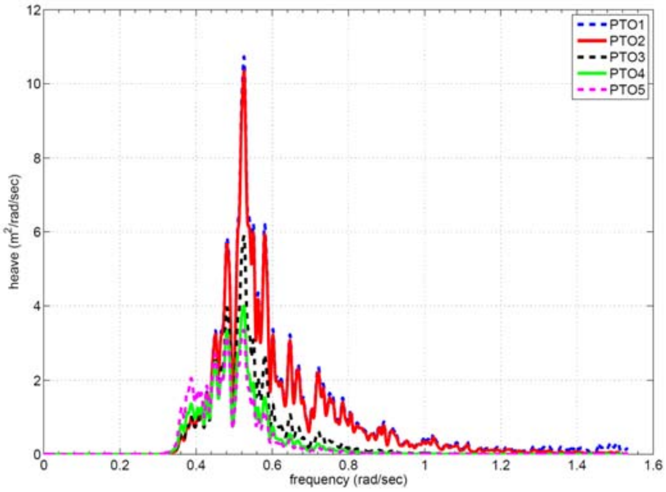

Fig. 6. Spectra of heave motion of WEC for different PTOs selected for WEC buoy

Spectra of the power produced by spar wind turbine for different PTOs selected for WEC buoy is shown in Fig. 11. Dynamic of produced power is influenced by spar motions at wave frequency. Fig. 12 shows Spectra of power produced by WEC for different PTOs selected for WEC buoy. Small damping value of PTO system (i.e. PTO1 and PTO2) is not sufficient for power production. By comparing Fig. 11 and Fig. 12, it is also seen that the dynamics of the produced power by the WEC does not occur at wave frequency region. So, combining the produced power by FWT and WEC can result in more smooth total electrical produced power.

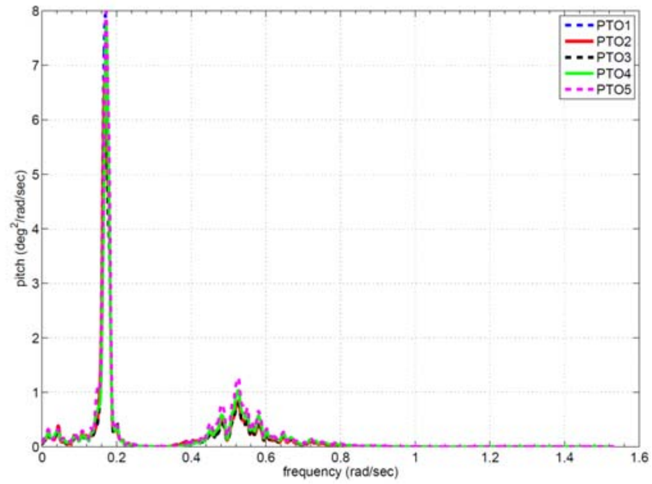

Fig. 7. Spectra of pitch motion of spar wind turbine for different PTOs selected for WEC buoy

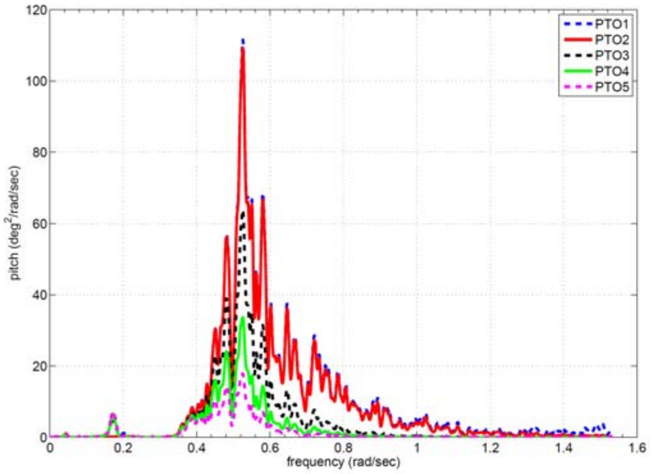

Fig. 8. Spectra of pitch motion of WEC for different PTOs selected for WEC buoy

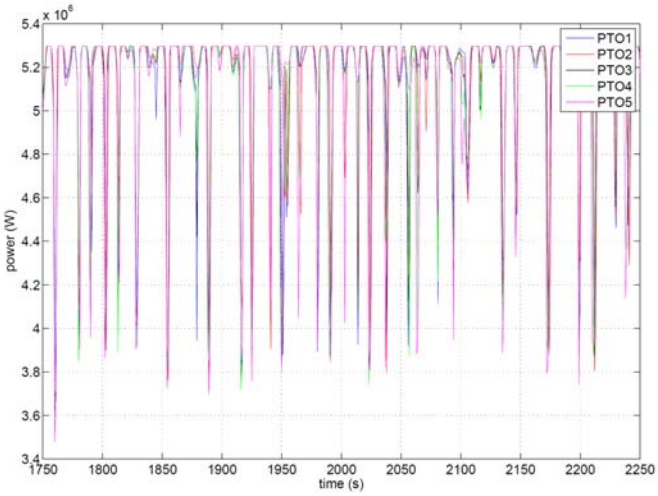

Fig. 9. Time series of power produced by spar wind turbine for different PTOs selected for WEC buoy

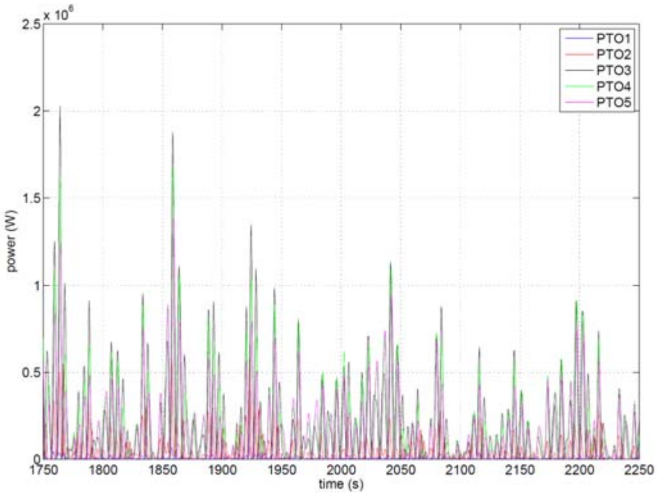

Fig. 10. Time series of power produced by WEC for different PTOs selected for WEC buoy

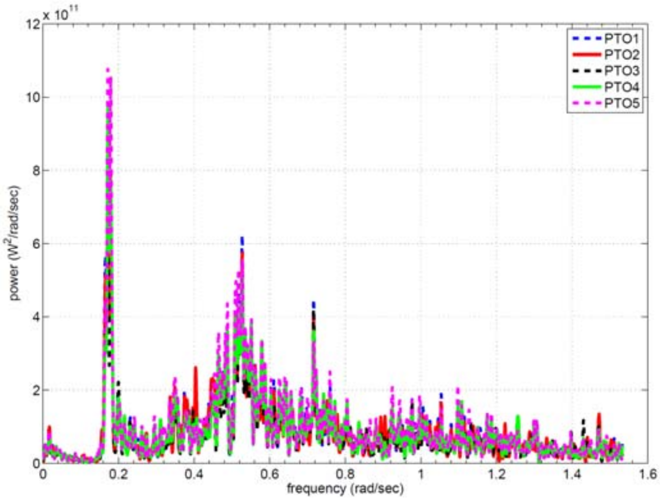

Fig. 11. Spectra of power produced by spar wind turbine for different PTOs selected for WEC buoy

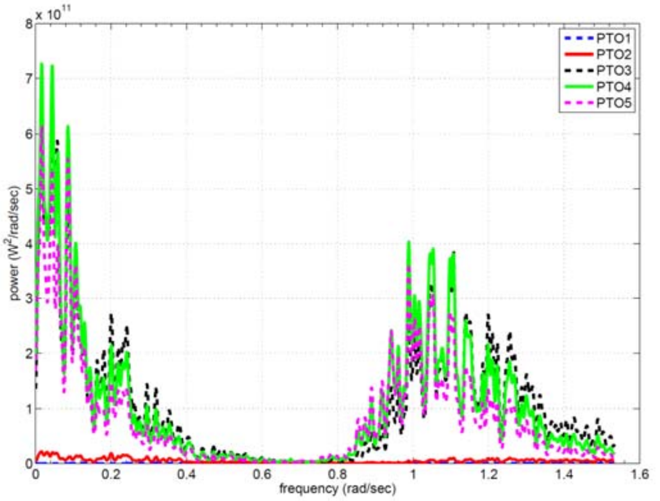

Fig. 12. Spectra of power produced by WEC for different PTOs selected for WEC buoy

In Fig. 13 and Fig. 14, the statistics of the produced power by spar wind turbine and wave energy converter are shown. As it mentioned before the characteristics of the power produced by wind turbine are not changed for different PTO system values. Fig. 14 shows that the maximum mean power produced by the WEC buoy is occurred for PTO3. The mean power produced by the WEC buoy is almost 6% of the mean power produced by spar wind turbine.

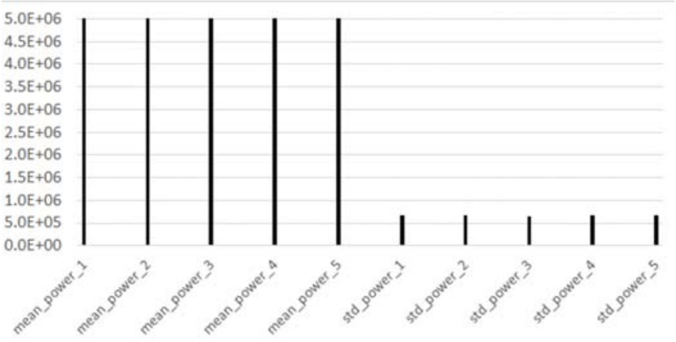

Fig. 13. Statistics of power produced (Watt) by spar wind turbine for different PTOs selected for WEC buoy

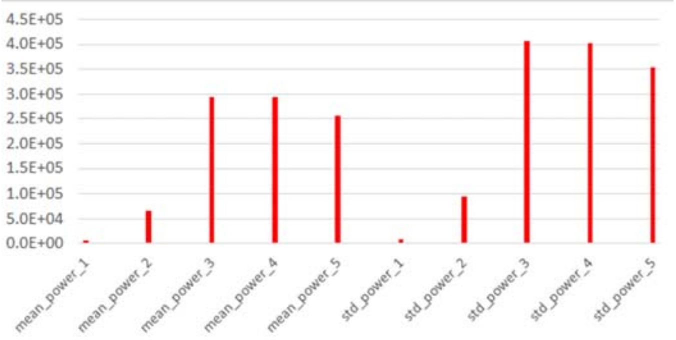

Fig. 14. Statistics of power produced (Watt) by WEC for different PTOs selected for WEC buoy

V. CONCLUSIONS

The feasibility of combining a spar-type offshore wind turbine inspired by Hywind and a wave energy converter inspired by Wavestar is studied in this article by performing numerical simulations in a selected operational condition at rated wind speed. Coupled/integrated aero-hydro-servo-elastic time domain dynamic simulations considering multi-bodies are applied. Different power take off (PTO) systems have been considered and the dynamic responses and power production of the wind turbine and wave energy device are investigated, correspondingly. The hydrodynamic interaction between spar and WEC buoy is neglected in the present work. This means that the diffraction/radiation problem is solved separately for each body. This should be reasonable assumption for investigating the feasibility of combining the wind and wave energy devices. More detailed analysis considering hydrodynamic interaction of two platforms is needed for further development of this hybrid concept. The results show that by choosing proper power-take-off system, it is possible to minimize the effect of wave energy convertor on the floating wind turbine and hence maintaining the power performance of the wind turbine while getting more power through wave energy device. The total displacement of the WEC buoy is just 2.2% of the total displacement of the 5MW spar type offshore FWT. However, it has been shown that the added power production is more than 6%.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Community's Seventh Framework Programme for DTOcean Project, Grant agreement number: 608597. The DTOcean (The Optimal Design Tools for Ocean Energy Arrays) project is aimed at accelerating the industrial development of ocean energy power generation knowledge, and providing design tools for deploying the first generation of wave and tidal energy converter arrays.

REFERENCES

[1] Statoil, "Hywind—The world's first full-scale floating wind turbine", http://www.statoil.com/

[2] Wave star energy, http://wavestarenergy.com

[3] M. Karimirad, "Offshore Energy Structures", Springer International Publishing, Switzerland, 2014

[4] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development", Tech. Rep. NREL/TP-500-38060, National Renewable Energy Laboratory, USA, February 2009

[5] M. Karimirad, "Modeling aspects of a floating wind turbine for coupled wave-wind-induced dynamic analyses", Renewable Energy 53 (2013) 299-305, 2013

[6] MARINTEK, "RIFLEX User's Manual", MARINTEK, Trondheim, Norway, 2015

[7] MARINTEK, "SIMO User's Manual", MARINTEK, Trondheim, Norway, 2015

[8] AeroHydro, "MultiSurf 8.0 Reference: Advanced Modeling", Maine 04679 U.S.A., 2012

[9] WAMIT, "User Manual". MA, USA: WAMIT, Inc. 2013