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Dynamic response and power production of a floating integrated wind, wave and tidal energy system

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ABSTRACT

This study deals with the hydro-aero-mooring coupled dynamic analysis of a new offshore floating renewable energy system, which integrates an offshore floating wind turbine (OFWT), a wave energy converter (WEC) and tidal turbines. The primary objective is to enhance the power production and reduce the platform motions through the combination of the three types of renewable energy systems. Simulation results show that the combined concept achieves a synergy between the floating wind turbine, the wave energy converter and the tidal turbines. Compared with a single floating wind turbine, the combined concept undertakes reduced surge and pitch motions. The overall power production increases by approximately 22%–45% depending on the environmental conditions. Moreover, the power production of the wind turbine is more stable due to the reduced platform motions and the combined concept is less sensitive to the transient effect induced by an emergency shutdown of the wind turbine.

1. Introduction

Due to the issues like environmental pollution, energy crisis and sustainable development, the exploitation of offshore energy is boosted by the global pursuit of renewable energy. Coastal areas provide the renewable energy sources in the form of wind, sea currents, and waves. Theories and technologies have been developed to exploit these types of offshore renewable energy resources.

Over the last decade, a large number of offshore floating wind turbine concepts have been developed. Statoil [1] proposed a SPAR-buoy floating wind turbine, namely the Hywind concept, which is the first full-scale floating wind turbine that has ever been built. Principle Power installed a full-scale 2 MW WindFloat prototype near the coast of Portugal [2]. In order to generate valid data for calibration and improvement of current analysis methodology as well as to assess the merits and demerits of different types of floating foundations, the OC4 DeepCwind consortium launched a model test campaign in MARIN. Measurements regarding the global motions, flexible tower dynamics and mooring system responses of a SPAR, a semi-submersible and a TLP foundation were presented and compared [3].

Compared to wind, wave energy is a renewable resource with a higher power density. Various types of WEC systems have been proposed, including the attenuator, the point absorber and the terminator, etc. Recent studies on WEC systems mainly focus on array effects and the control algorithms. Vicente et al. [4] studied the dynamics of arrays of point-absorber WECs with different mooring connections. Engstrom et al. [5] investigated the power variation in a large array of point-absorbing WECs, the smoothing effect due to the number of devices and their hydrodynamic interactions.

Sea current is increasingly being recognised as a solution to the sustainable generation of electrical power. The majority of tidal turbine designs are based on horizontal axis turbines, similar to those applied in the wind energy industry. Bahaj et al. [6] used blade element momentum (BEM) theory to predict the hydrodynamic performance of a horizontal axis tidal turbine in steady flow and compared the predicted results with experimental measurement. Zhang et al. [7] studied how the hydrodynamic performance of a tidal turbine was affected when installed on a floating platform. They revealed a positive correlation between the oscillation amplitude and the frequency of platform surge motion.

In a site where wind, waves and sea currents coexist, the combination of a floating wind turbine, a wave energy converter

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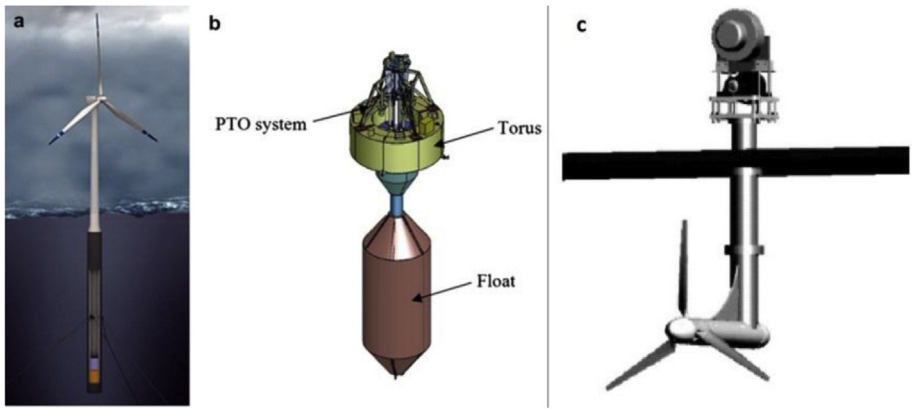

Fig. 1. (a) Hywind [1]; (b) Wavebob [9]; (c) Tidal turbine with application of the NACA 638xx series [6].

and a tidal turbine may be a prospective and economical solution to the full exploitation of offshore renewable energy. Some studies on the combined deployment of wind, wave and tidal energy have been conducted and reported by previous researchers. Aubault et al. [8] incorporated an oscillating-water-column type WEC into a semi-submersible floating wind turbine. In their work, the theory of such modelling was summarized and it was shown that the overall economic cost could be reduced by sharing the mooring and power infrastructure. Muliawan et al. [9] studied the dynamic response and the power performance of a combined SPAR-type floating wind turbine and coaxial floating wave energy converter in operational conditions. The analysis was performed in several operational conditions and the simulation results indicated that a synergy between wind and wave energy generation was achieved. Further experimental and numerical studies of the hybrid concept in survival mode were conducted by Wan et al. [10]. Several phenomena were observed in their model tests, such as wave slamming, Mathieu instability and vortex induced motions. Michailides et al. [11] incorporated a flap-type WEC to a semi-submersible floating wind turbine and investigated the effect of WECs on the response of the integrated system. Their study showed that the combined operation of the rotating flaps resulted in an increase of the produced power without affecting the critical response quantities of the semi-submersible platform significantly. Bachynski and Moan [12] studied the effects of 3 point absorber WECs on a TLP floating wind turbine in operational and 50-year extreme environmental conditions, in terms of power take-off, structural loads and platform motions. According to their research, reduced surge and pitch motions were observed in operational conditions while increased pitch motions and tendon tension variations were observed in extreme conditions.

In this study, an integrated floating renewable energy concept referred as 'Hywind-Wavebob-NACA 638xx Combination' (HWNC) is proposed by combing a SPAR-type floating wind turbine, a point absorber-type wave energy converter and tidal turbines. Aero-hydro-mooring coupled simulations are performed to investigate the performance of the HWNC, in terms of platform motions, power production and mooring line tension. No control scheme is applied in the modelling and the structural dynamics is neglected as well. The HWNC is compared with a single SPAR-type floating wind turbine in three operational conditions (below-rated, rated and over-rated) as well as emergency shutdown. It will examine whether the performance of the HWNC can be improved with the installation of the WEC and the tidal turbines.

2. Concept description

The combined concept proposed in this study is inspired by the SPAR-type floating wind turbine OC3 Hywind [13], the two-body floating WEC 'Wavebob' and the NACA 638xx aerofoil series. The sketch of each component is displayed in Fig. 1.

In the HWNC concept (see Fig. 2), the float component of the Wavebob is replaced by the SPAR platform and the torus is connected directly to the platform through mechanical facilities. The WEC is designed to move only in heave mode relative to the platform and no relative surge, sway, roll, pitch and yaw motions are allowed. Tidal turbines are installed to harvest energy from the sea current. The main dimensions of the HWNC concept are presented in Table 1 and the mass properties of each subsystem are listed in Table 2.

The HWNC is operated at sea site with a water depth of 320 m and moored by three slack catenary lines. The fairleads are connected to the platform at 70 m below the still water level. Fig. 4 displays the configuration of the mooring system. The three lines are oriented at 60°, 180°, and 300° about the vertical axis. The relevant properties of the mooring lines are listed in Table 3.

3. Modelling set-up

The simulation code, which is expanded to include

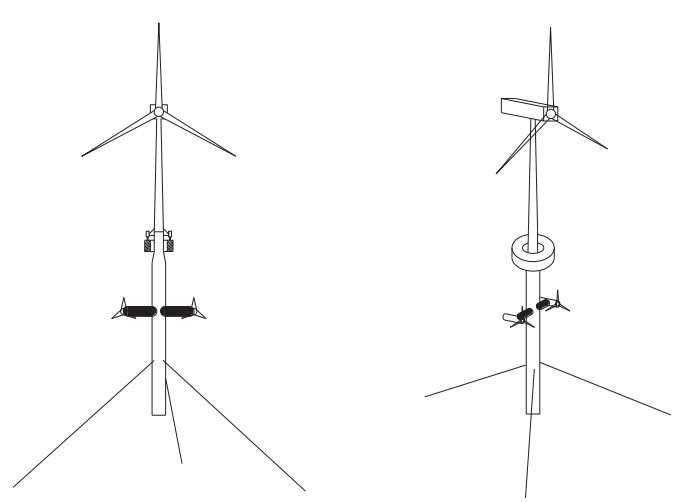

Fig. 2. HWNC concept.