Offshore Wind, Wave and Integrated Energy Conversion Systems: A Review and Future

Qiang Gao[1], Nesimi Ertugrul[1], Boyin Ding[2], Michael Negnevitsky[3]
[1]School of Electrical and Electronic Engineering, The University of Adelaide, Adelaide, Australia
[2]School of Mechanical Engineering, The University of Adelaide, Adelaide, Australia
[3]School of Engineering, The University of Tasmania, Hobart, Australia
qiang.gao@adelaide.edu.au, nesimi.ertugrul@adelaide.edu.au, boyin.ding@adelaide.edu.au, michael.negnevitsky@utas.edu.au

***Abstract*—The offshore wind and wave are two promising renewable resources to address the concerns about the repaid growing energy demand across the world and the reduction of dependency on fossil fuels. Although these two resources have experienced significant development in the past decades, few research studies have been identified discussing the electrical systems as a part of various power transfer topologies. There is a lack of study which effectively considers potential configurations of highly intermittent wind and wave energy source and their impacts on the entire system operation, system efficiency, reliability and grid connection. This paper aims to fulfil this gap and to provide a comprehensive review on the electrical systems that can be utilised in both wind and wave energy conversion systems. The types of generators and control systems with power electronics used in the offshore wind turbines are presented and compared. The operation principles within the wave energy converters are discussed and classified. The selection of generators in the wave power take-off systems are discussed. A comprehensive guideline for the development of future integrated systems is provided in this paper primarily to reduce the cost of offshore systems, increase energy yield and improve reliability, predictability and dispatchability.**

Keywords— wind energy, wave energy, wave energy power take-off systems, integrated wind and wave systems.

I. INTRODUCTION

Wind turbine systems already offer low-cost energy as highly matured technologies which consist of turbine blades, generators and converters. Among the various renewable energy technologies, on-shore wind resources have already been utilised effectively, approaching various limits in terms of availability of suitable lands, maximum power ratings and capacity factors. The offshore wind systems, although still in early-stage development, present significant potential to expend the wind resources to much greater penetration levels. As illustrated in Table I, the major advantages of the offshore wind turbines are the potential to build larger turbine systems at locations with higher wind energy density in form of smaller footprint wind farms.

As the interests in offshore wind farms grow, another form of ocean/marine based renewable energy, wave energy has also received significant attentions. The wave energy converter is defined as a system converting the wave energy into more useful forms of energy such as electricity. The efficiency of wave conversion system is highly depended on the suitability of various power take-off (PTO) systems in specific wave site. Moreover, majority of energy contained in a wave is located between the water surface and the top of one fourth of the wavelength. The marine area with water depth more than 40m at medium-high latitudes is identified as the best wave condition for harnessing wave energy, approaching the power densities up to 70 kW/m [1]. Note that there are more than 16,000 km of coastline globally (about 2% of the world coastline) with a power density exceeding 30kW/m. This indicates a wave energy potential of 2000-4000TWh/year which is approximately equal to the total wind energy potential globally.

However, the main barriers of developing offshore wind and wave energy systems are primarily their high construction and operation/maintenance (O&M) costs. There have been few attempts to reduce these costs by integration of floating offshore wind turbines and wave energy converter systems [2-4]. Different possibilities have been considered to combine wave and wind array configurations: co-located wave and offshore wind converters, hybrid energy converters and combination of both. Increased energy yield and reduction on the O&M costs (in particular in the electrical system) are the primary driving forces in a number of combined studies in the literature on wave and offshore wind energy arrays [5].

Since wave energy is more predictable than wind energy [6], and due to the lagging nature of the wave energy, the inclusion of battery storage system is likely to reduce combined power capacity (resulting in a smooth and continuous power output and smaller converter) and intermittency related balancing cost in the power grid. Moreover, hybrid systems offer shared common grid infrastructure, shared substructure foundation system and other shared operational costs. Furthermore, reduced environmental impacts and the shadow effects (reducing the mean wave height) are the other benefits.

Therefore, this paper aims to understand the state of art in offshore wind and wave energy technologies. The existing conversion systems for wind and wave energy are discussed in detail in the consecutive sections. The paper concludes with a potential integrated solution to improve the desirable characteristics from two highly intermittent renewable energy resources which can also offer low capital cost and reliable energy.

II. OFFSHORE WIND ENERGY CONVERSION SYSTEMS

Although offshore wind farms are at their early-stage development, they present greater potential for higher energy output due to vast and consistent offshore wind resources. They also address issues on limited land space for constructing wind farms on shore and have higher capacity factors. The principal components of offshore wind energy conversion systems are briefly discussed in the following sections to provide the basis of the hybrid system.

A. Hardware Structures

There are many similarities between onshore and offshore wind turbine components, such as nacelle, rotor hub, pitch drive, blades, main shaft, mechanical brake, yaw drive, gearbox and generator. However, the tower foundation has distinct features in offshore applications. Three main floating structures suitable in the deep-water area are illustrated in Fig.1: spar type, tensioned-leg platform and semi-submersible.

TABLE I COMPARISON OF ONSHORE AND OFFSHORE WIND ENERGY

Types	Advantages	Disadvantages
Offshore	• Larger wind turbines per unit installed; • Elimination of visual impact and noise; • Greater and more stable marine wind source; • Easy to transport large systems components by sea.	• High cost of construction including marine foundations, undersea cables and substations; • Restricted access due to weather conditions; • Limited access for O&M.
Onshore	• Mature technology; • Lower installation and O&M cost.	• Road restriction for transporting large wind turbines. • Territory constrains.

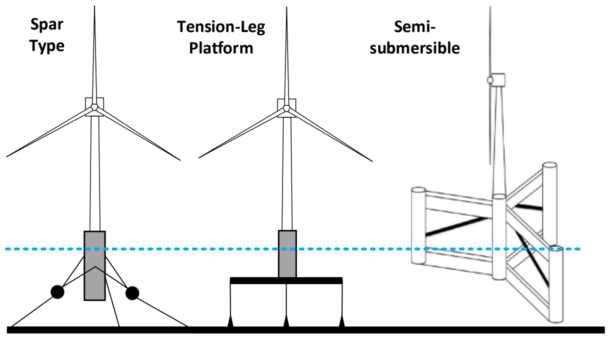


Fig. 1 Three main floating substructures.

B. *Types of Generators Used in Wind Energy*

Fig.2 illustrates the major generator types and suitable drive techniques used in wind energy applications, which can be divided into two groups: induction generators and synchronous generators.

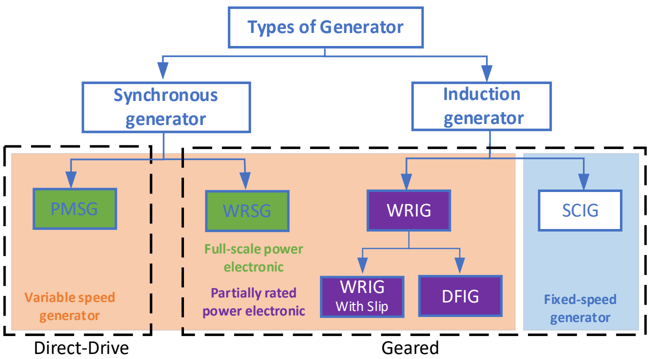


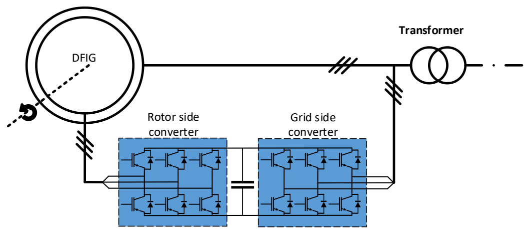
Fig. 2 Types of generators used in wind turbines: Permanent Magnet Synchronous Generator (PMSG), Wounded Rotor Synchronous Generator (WRSG), Wounded Rotor Induction Generator (WRIG), Double Fed Induction Generator (DFIG) and Squirrel Cage Induction Generator (SCIG).

DFIGs, WRSGs and PMSGs are commonly used in large scale wind turbines. However, due to harsh marine environments, access restrictions and maintenance difficulties, direct drive (no-gearbox) PMSGs are currently the prime generator types preferred in offshore as well as in onshore wind turbines. In addition, due to the absence of rotor windings, PMSGs offer much greater efficiency. Although the requirement of fully rated power electronics converters may be seen as a major disadvantage compared to the converters of DFIGs, their variable speed and four quadrant operation are highly desirable features. Furthermore, it is envisaged that large power PMSGs are likely to accommodate high temperature superconducting generators (HTSG) in the near feature offering lighter, smaller and more efficient power conversion characteristic [7-9].

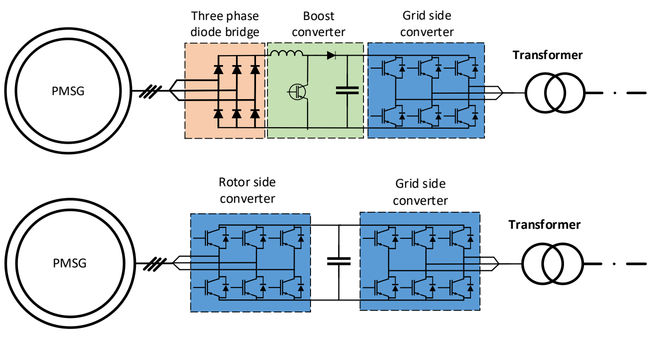
C. *Converters Used in Wind Energy*

Power electronics converters are an integral part of the wind energy conversion which do not only perform voltage/current regulations but also offer accurate power flow control as well as protection [10] when required. The integrated wind generator and turbine control system has the ability to perform voltage control, reactive power support functions and maximum power tracking during the changes in wind and loading conditions. The utilisation of power electronics converters with high switching frequencies are desirable to increase power density (gravitational and volumetric) of the converters that are working in harsh environmental conditions. Therefore, wide bandgap devices are likely to replace the silicon based power switches in the future converters [11], which will not only offer high reliability (due to higher operating temperature and higher dv/dt and di/dt) but higher efficiency.

The converter ratings in large scale wind generators primarily depend on the type of generators used. Three well-known and adapted converters are illustrated in Fig.3.



(a)



(b)

Fig. 3 Types of converter used wind generators: a) Partially-rated power electronic converter arrangement in DFIGs, b) Fully-rated converters used in brushless PMSGs.

In DFIGs, two back-to-back converters are used to connect the rotor circuit to the grid via slip rings as it is shown in Fig.3a. The generator provides about ±30% of rotor speed variation to capture the varying turbine speed. This scheme offers capability of real and reactive power control, eliminating the need for reactive power compensation. The rotor side converter is typically to control the active and reactive power output of the induction machine, while the grid side converter is employed to maintain the DC link voltage constant and provide limited reactive power support to the grid. Furthermore, a power electronics circuit known as Crowbar [12] for rotor circuit of DFIG is developed to protect the rotor side converter, since when there severe voltage sage occurs on the grid side leads to large current in the stator and then transfer it to the rotor and consequently, damage the rotor side converter. Note that a transformer is usually accommodated to match the voltage rating of the grid at common connection point.

Power electronics converters used in PMSGs system are designed to handle the full voltage and current ratings of the generator and control the full power and in four quadrants to be fed to the grid [13]. As it is illustrated in Fig.3b, a back-to-back voltage source converter provides the speed flexibility in wind turbines for optimal operation of capturing the wind energy while controlling the active and reactive power for the grid via grid side converter. The benefits of brushless PMSGs were listed in the previous section. Noting that the utilisation of fully-rated converters presents few drawbacks: high-cost converters, higher voltage stress on the switches and higher converter loses. However, these drawbacks are about to be eliminated with the technological developments in switch technologies (using wide bandgap devices) and converter topologies (such as using resonant converters).

Note that converters in offshore wind turbines (which can accommodate in a dedicated substation) are connected to the main grid using underwater cables (AC or DC).

III. Wave Conversion Systems

The common components of the wave energy conversion systems are illustrated in Fig. 4. The power take-off system (PTO) can involve hydraulic, pneumatic and mechanical/electrical power transmitter and controller. The type of generator attached to a PTO primarily depends on the wave characteristics, the operation principles and specifications. The remaining components (power electronics and transmission cables) depend on the proximity of the nearest substation.

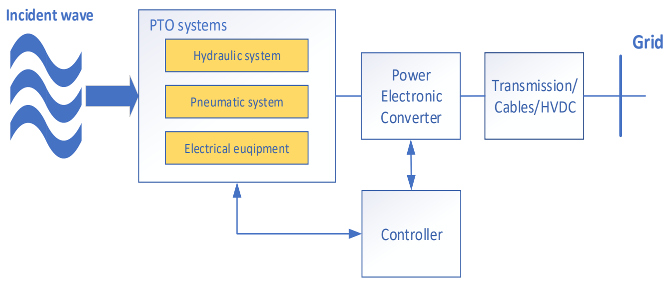


Fig. 4 The components of a wave energy conversion system.

Unlike the wind energy conversion system discussed in the previous section, the technology used in wave energy conversion systems have a wide range of options, which is subject to the operating principles of PTO systems used, and the location of the system (shoreline, nearshore and offshore). More than one hundred wave energy conversion system designs are reported in [14]) which displayed various stages of the developments from prototypes to commercialization (as in Japan, UK and China).

A. Operating Principles of Wave Energy Converters

The waves essentially contain three motions: a horizontal front/back motion (the surge), a horizontal side to side motion (the sway) and a vertical up/down motion (the heave). It was identified that all of the wave energy available in a wave is located between the water surface and the top ¼ of the wavelength, which can be extracted by various technologies (such as roll, pitch or yaw rotation). Therefore, operating principle of a wave energy converter defines the method or mechanism that how the movement energy involved in the incident wave field can be obtained by a wave converter by interacting together (hydrodynamics).

Based on the working principle of wave observation [15], there are three primary types of wave energy converters: Oscillating Water Column (OWC), Oscillating Bodies (OB) and Overtopping (OT) as shown in Fig. 5.

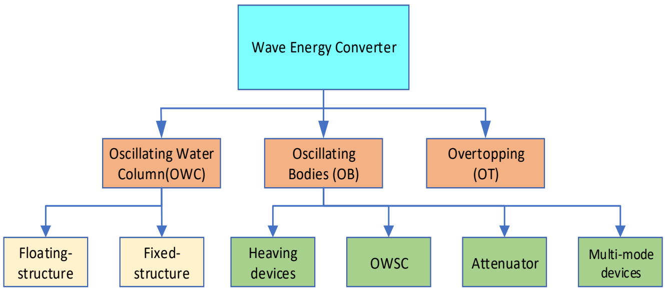


Fig. 5 Three main operating principles of wave converters

The OWC converter utilizes the change of wave-induced water level inside a chamber to compress or decompress the trapped air which drives the air turbine by the different air forces between inside and outside of chamber. A rotatory generator is usually used for power generation which is driven by the air turbine.

The OB wave energy converter is preferred in offshore applications. It utilises the energy contained in oscillating bodies, either floating or fully submerged. Therefore, it can exploit more powerful wave in the deep-water regime with typical depth of 40m. Based on the oscillating modes, it can be identified under four different categories: heaving devices, oscillating wave surge converters, attenuator and multi-mode converters.

The OT converter converts wave energy by capturing the water closed to the wave crest and introduce it to over-spill into a reservoir. Due to the different average free-surface level between the surrounding sea and the reservoir, the water is returned to the ocean by flowing through a number of turbines. The conventional low-head hydraulic turbines are commonly used.

B. PTO Systems used in Wave Energy Converters

The PTO system can be used to convert the wave energy into electrical energy, which can have different types as illustrated in Fig. 6: hydraulic system, pneumatic system, hydro and direct-drive electrical linear generator. It was reported in [16] that 42% of recent wave energy converters use a hydraulic PTO, 30% of wave energy converters use a direct drive PTO (such as a linear generator), 11% of that use hydro turbines and 11% for pneumatic system with 5.6% unspecified.

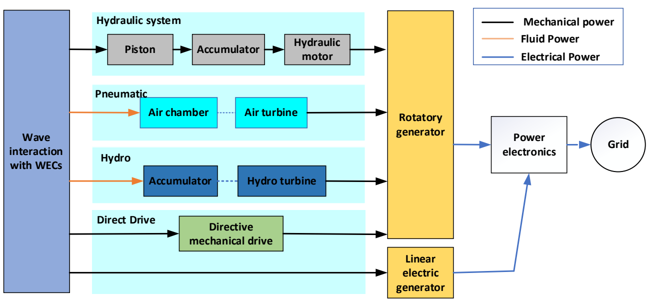


Fig. 6 Different PTO systems utilized in wave energy converters.

The Hydraulic PTO is a system designed to transmit the high-pressure hydraulic oils between pistons, motors and accumulators for driving an electrical generator. It is suitable to convert energy from a very large force or moments associated in slowly oscillating bodies in wave converters. The system includes a hydraulic cylinder or rams which can convert the mechanical energy from motion of oscillating body into the hydraulic energy. Then the hydraulic circuit transmits the hydraulic energy to other system components, such as a gas accumulator which has the capacity to storage the energy over a few wave periods for smoothing the output energy absorbed from irregular waves, and a fast hydraulic motor to drive a conventional electrical generator

The Pneumatic PTO utilizes the movement of trapped air caused by wave action to drive a conventional air turbine. The time-average of an air turbine used in OWC device is lower than conventional hydro turbine, gas turbines and wind turbines, resulting from the reciprocated flow through the turbine which is random and high variable time scales ranging from seconds to the seasonal variations. There are three air turbines utilized in OWC systems: Well, Denniss-Auld and Impulse turbines.

The Hydro PTO systems are widely used in overtopping waver converters, which are classified as impulse and reaction turbines.

The direct-drive PTO directly connects the prime mover via mechanical linkages (belts, pulleys, gearboxes and clutch mechanisms). A 1/100 scale and a 1/10 scale prototype have been tested [17]. Its simplicity and robust structure makes its maintenance much easier and cheaper, but it has low efficiency in maximum power output since the energy can be extracted for half of a wave period [18].

C. *Generators Used in Wave Energy Converters*

Two generator types are used in wave energy converters: rotatory and linear generators. As in the wind generators, the PMSGs are also preferred in wave energy due to their high power density and high efficiency at low speed.

Due to the absence the mechanical interface (which reduces the conversion efficiency and increases complexity) linear generators (see Table II, adapted from [19]) with direct-drive is preferred in PTO systems that offer linear or reciprocal motion. The linear generators in such systems are directly coupled to a vertical cylinder (which is commonly used a heaving oscillating device). However, their simplicity in few intermediated conversion steps can make the regulation challenging. Moreover, more strict support structures are required in linear generators to overcome the attraction force and maintain a suitable air gap width.

D. *Power Converters Used in Wave Energy Converters*

Due to the synergy between the wind turbine and wave turbine generators, similar power electronic converters are used in both systems. Although the final PTO system and wave energy pattern defines the generator ratings, the power electronics converter may require specific attention to withstand potential large transients. Availability of battery storage system and the integration of wind energy also define the converter type and ratings.

IV. INTEGRATED CONVERSION SYSTEMS

Since the offshore wind and the wave energy systems share the same environment and platforms, they face various administrative and technological limitations. As it was mentioned previously the capital cost of a typical offshore wind power system is 2 to 3 times higher than the onshore systems (3300-5000 US$/kW in offshore versus 1700-2450 US$/kW in onshore systems) [20]. Although the cost share of the wind turbine has decreased, the cost share of grid connection, construction and other capital cost has increased significantly.

Table II COMPARISON OF LINEAR GENERATORS

Types	Advantages	Disadvantages
Longitudinal Flux PM Generator	• Simple/robust stator. • Low synchronous reactance.	• Limitation on geometry design. • Low power rating per air gap area.
Transverse Flux PM Generator	• No limitation on geometry design between cross-section of yoke and armature conductor. • High power per air gap area.	• High synchronous reactance. • Complex stator • High armature current produced. • Phase compensation or PE equipment are required;
Variable reluctance PM Gen.	• Short pole pitch with large magnets fluxes.	• High synchronous reactance.
Tubular air cored PM generator	• No normal forces in air gap.	• Low power/air gap area.

A. *Synergies and Challenges*

A number of synergies makes the offshore wind and wave integrated system highly desirable. These include enhanced energy yield, better predictability, smoothed power output, shared common facilities (including platforms and substations) and operation/maintenance, shadow effects and environmental benefits. Note that power output per unit area increases, and the dynamic motions also improve and consequently increasing the power output [21]. The integrated system also minimizes the power interruptions and fluctuations [22] due to lagging nature of the wave energy reference to the wind [23]. The shadow effects [6] created by converter arrays can be used to obtain a milder wave climate inside the park via suitable design. Furthermore, the integration results in reduction in environmental impacts [24, 25] including noise, visual impact and maritime transport. However, full-scale integration of wind and wave energy is still in its infant state.

B. *Classification of Integrated Systems*

The integrated systems can be classified based on the technology used (stand-alone, hybrid or co-located), or on the water depth (shallow, transition or deep water) or their distance from the shoreline (shoreline, nearshore or offshore). An alternative classification is also reported in [2] that is based on the degree of connectivity between three types of converters (co-located system, hybrid system and island system). However, the primary criteria about the selection of a system integration in a specific site are feasibility, ease of construction and the cost of electricity produced [21].

1) *Co-located System*

It is relatively the simplest option as independent foundations are used for wind and wave energy but sharing the same site, energy storage facilities, operation and maintenance equipment and grid connection. Note that there are two groups within the co-located systems, covering independent arrays and combined arrays as illustrated in Fig. 7.

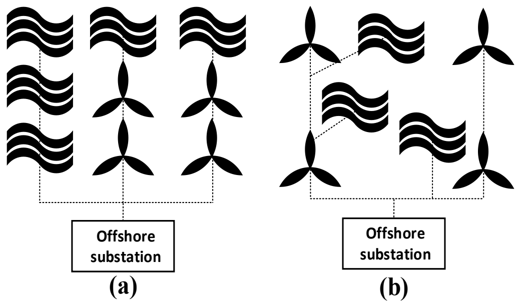


Fig. 7 Schematic of co-located combined systems with the peripherally distributed arrays (a) and the non-uniformly distributed arrays (b).

It is also possible to classify the integration of wind turbines and wave energy conversion based on the initially development technology and technology readiness level [26]. Compared to the co-located systems, the hybrid system presents a further step of cost reduction in construction and operation/maintenance because of sharing more common infrastructure.

2) Hybrid System

If a smaller level of wave energy system (less than 20% of the power output) is combined with the existing wind energy systems [26], there are few design options as illustrated in Fig.8.

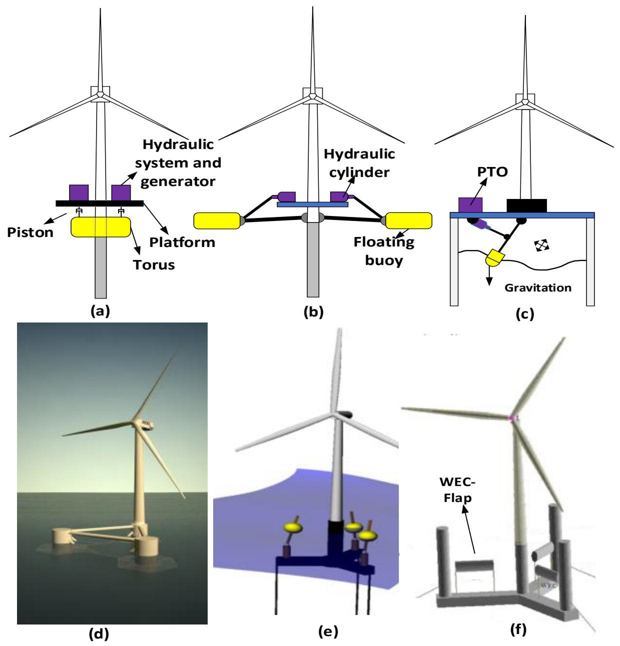


Fig. 8 Hybrid System, wind turbine concept with added wave energy: a) Spar-Torus combination [27], b) Wave treader [28], c) Wave energy gravitational absorber [29], d) Wind wave float [14], e) Tension Leg Platform with 3-point absorber [30], f) Semi-submersible flap [31].

Alternatively, a smaller level of wind energy can be added to the existing wave energy systems, which can be classified under four different categories as shown in Fig. 9.

C. Future Integrated Systems

Due to the increasing trend to utilise offshore wind and wave energy there are significant benefits for integrated solutions. It is likely that the future systems may accommodate different permanent magnet generator technologies due to their inherent benefits (high power density and high efficiency). Although full-rated power converters can be used in such integrated systems, their combined ratings can be reasonably low due to the lagging nature of wave energy, the PTO system used and on-site battery storage.

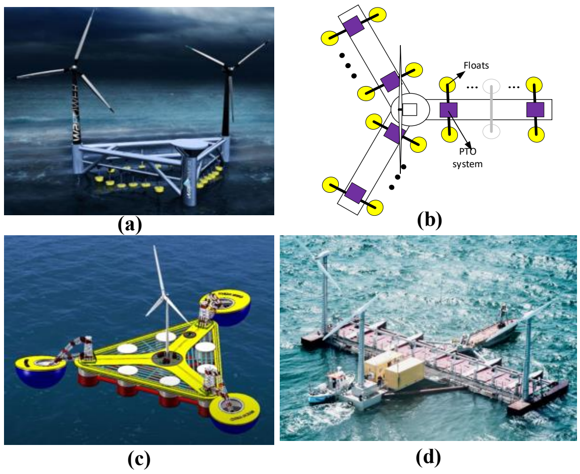


Fig. 9 Hybrid System, wave system with added wind energy: a) W2Power [32], b) Wave star hybrid [33], c) W2P [34] and d) Poseidon Floating Power [35].

Fig.10 illustrates a feasible solution of hybrid conversion system with a wind turbine and a wave energy system with DC link energy storage. Note that such topology can reduce intermittency, transmission cost (and associated losses) and size of the offshore substation. In addition, the complexity of control is reduced and redundancy is offered in an energy farm application. Note also that as the cost of power electronic systems reduce and new switching devices become available (wide bandgap devices), high voltage dc transmission becomes highly feasible even at short distances.

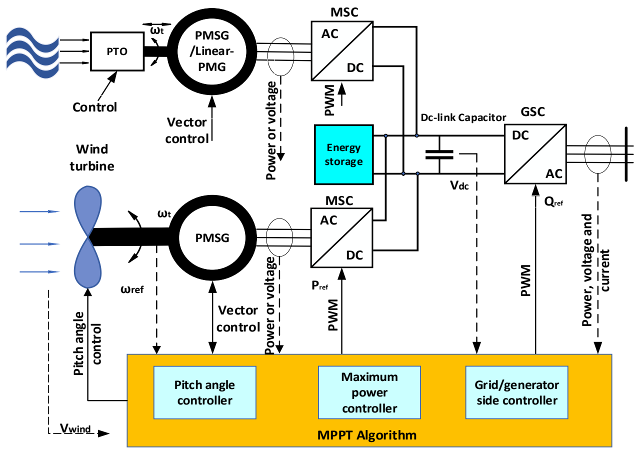


Fig. 10 A possible integration principle of wind and wave energy, DC coupled with a battery storage and transmitted with a DC-DC link

V. Conclusion

This paper has highlighted the growing need in offshore wind and wave energy. The distinct features and the similarities of the energy conversion systems of both technologies are provided to demonstrate their potential towards the integration. Since the wind energy systems are highly mature, a specific attention is given to the wave energy systems which can be utilised to develop the most suitable power take-off technology to increase power transfer while reducing the complexity of the system and to reduce the development and operation cost.

The existing hybrid systems are discussed in detail, and it is concluded that combing wind and wave energy utilization presents an inevitable trend for future offshore renewable energy development. It is also concluded that the integrated systems can offer not only a greater power generation but also reduce intermittency and much greater dispatchable and predictable power.

The future work in this research will develop new knowledge in the electrical system design for offshore wind and wave integrated system, with a focus on the overall conversion topologies. The integrated system model will be verified by using real offshore wind and wave energy data as well as lab-scale experiment.

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