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Review of control strategies for wave energy conversion systems and their validation: the wave-to-wire approach

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ABSTRACT

Ocean waves are a promising source of renewable energy. In this paper, we briefly introduce the characteristics of ocean wave energy and summarize the principles of harvesting ocean energy by wave energy converters. We also review the prototypes or commercial devices deployed in real sea between 2005 and July 2016.

In addition, we present the concept of a wave-to-wire model as a framework to systematically review and compare control strategies for wave energy conversion systems, with a focus on the numerical and experimental validation.

1. Introduction

Renewable energy sources, e.g. wind and sunlight, exist over wide geographical areas, and can be used to provide electrical power (on-grid or off-grid), cool water, heat water, and enable transportation. Compared to traditional energy sources, they produce less waste products such as chemical pollution and carbon dioxide, which means the negative influence on the environment is minimal. Due to the urgency to act against climate change caused by the growing carbon dioxide in the atmosphere, renewable energy is gaining attention all over the world. For instance in the European Union, the Renewable Energy Directive establishes an overall policy for the production and promotion of energy from renewable sources. It requires the European Union to meet at least 20% of its total energy needs with renewables by 2020. As shown in Fig. 1, all EU countries have a target of at least 10% of the gross consumption of energy coming from renewable sources by 2020. In the Nordic Countries, Sweden has a high target of 49%. Besides that, Norway has a target of 67.5% by 2020.

Among all the renewable sources, ocean wave energy is a promising one. It has a high power density and a huge potential. Its worldwide potential is estimated to be 2 TW [1], and has the ability to make a significant contribution to supply the world's energy demand. The use of ocean energy through wave energy converters (WECs) has been numerically and physically validated over the past decades. The results indicate that ocean wave power can be captured efficiently by the WECs and used for desalination [2] or converted into electricity (usually the latter). Now, the use of wave power is drawing more attention all over the world. The Department of Energy in United States for example, has initiated a new program, the Water Power Program, to develop and deploy a portfolio of innovative technologies for clean, domestic power generation [3]. Another example is the Blue Growth Program, funded under Horizon 2020 in the EU, which also supports, among others, several schemes to encourage harvesting ocean energy [4].

Over the past decades, many WEC concepts have been proposed or validated by numerical or physical experiments [6]. These experiments show the feasibility of WECs and investigate the influence of system parameters and control methods on performance enhancement. However, the majority of these experiments focus on different sub-systems separately, e.g., they focus on the fluid-structure interactions between ocean waves and absorbers, on control methods to maximize the power captured from ocean waves, or on linear generator technologies suitable for wave energy conversion. To investigate the system dynamics, optimize the performance and improve the overall efficiency at the same time, there is a need to take into account all the components, from ocean waves to the electrical network. This process of converting ocean wave power into electricity, is referred to as "wave to wire" (W2W).

The W2W model consists of the input and output of a wave energy conversion system, where the latter is the electrical power injected into grid or supplied to electrical machines. This model takes into account the interactions between the hydrodynamic part, the mechanical part, the electrical part, and the power electronics. It also makes it possible

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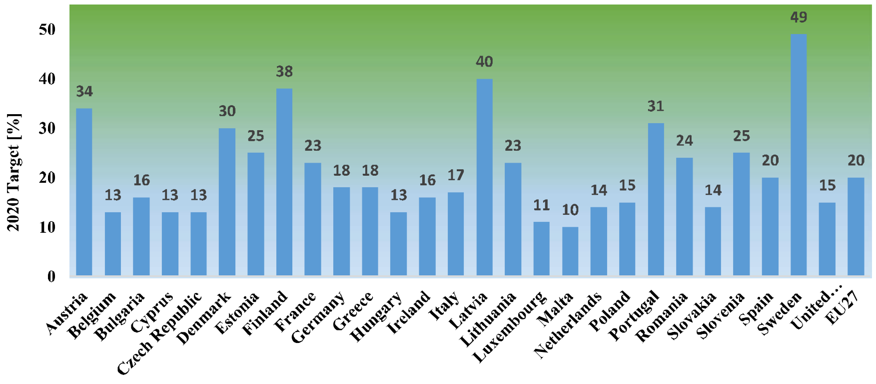

Fig. 1. 2020 renewable energy target for European Union members. Data are from "DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC" [5].

to study the coupling issues of the entire system. Another advantage is that, advanced control strategies can be embedded in the W2W model, to improve the system performance, to meet the grid code, or to meet the internal operating requirements of the subsystems.

Some work on the W2W model has been reviewed in [7,8], and introduced in [9,10]. In [7], the W2W model is divided into four stages, i.e., the absorption stage, the generation stage, the transmission stage, and the conditioning stage. The components related to these four stages and their dynamics and constraints, including grid constraints, are identified. The objective is to examine the current literature and the available models to see if a complete W2W model, suitable for advanced control, is available or can be assembled. In [8], the authors provide an overview of many aspects that feed into the W2W model and also give a summary of some tools for calculating hydrodynamic parameters. A new numerical tool is developed to calculate the power output from a specified WEC under specified ocean wave conditions, to assess and optimize the performance of a WEC design and to provide knowledge of the WEC behaviour under specific wave conditions. In [9], some issues on the hydrodynamic system, the power take-off (PTO) system, the mooring system, and the system reliability are investigated separately, and some works on the W2W model are also briefly introduced, including economic optimization and a brief overview of numerical and experimental tools. In [10], the author states that the WEC breakdown of a wave-activated-body type has six main subsystems. He studies a set of issues on three of them, i.e., the hydrodynamic subsystem, the PTO subsystem, and the reaction subsystem, and presents some available numerical and physical modelling techniques. An optimization methodology based on a modification of the control strategy is indicated to minimize the cost of energy. Refs. [8,9], and [10] were published in 2014 by a research group in Denmark, and some works are overlapping. As these four references show, various WECs using different operation principles and consisting of different primary capture systems, PTO systems, and power electronics are under development, so a W2W tool has to be very flexible, or composed of blocks with a focus on system parts such as the PTO design, or array interaction effects.

Unlike these works, our main focus is to provide a state of the art of control strategy suitable for wave energy conversion, especially for implementation in the W2W model. In addition, we investigate the numerical and experimental validations, while mathematical models of components like generators, voltage controllers and current controllers are left aside. It should be noted that the control of the hydrodynamic part is also reviewed, which is ignored in some articles.

The structure of this paper is as follows: ocean wave energy is introduced in Section 2. The ways to capture wave energy by WECs are summarized in Section 3, mainly according to the working principle of the primary and secondary conversion system. Then we review the representative WECs deployed in real sea between 2005 and July 2016. Section 4 describes the W2W model, including a review on this. In Section 5, control strategies suitable for W2W are summarized, with a focus on their numerical and experimental validations. Additional issues are discussed in Section 6, and Section 7 presents concluding remarks.

2. Ocean wave energy

Ocean waves can be generated by different mechanisms, e.g., earthquakes or planetary forces, but the majority of them are driven by wind blowing over an area of a fluid surface, referred to as wind waves. Their velocity depends on the wavelength and the depth of the ocean, which is expressed through the dispersion relation:

$$v = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(2\pi\frac{h}{\lambda}\right)}, \tag{1}$$

where λ is the wavelength, g is the acceleration of gravity, and h is the water depth.

As shown in Fig. 2, the diameter of a water particle motion circle decreases with water depth. Calculation results indicate that about 95% of the energy in the waves is available between the surface and a depth equal to a quarter of the wavelength for deep water [11]. The total energy of unity width below one wave length of ocean surface is expressed as:

$$E = \frac{1}{\lambda}\int_0^\lambda\int_0^1\frac{1}{2}g\rho\eta^2dxdy + \frac{1}{\lambda}\int_0^\lambda\int_0^1\int_{-\infty}^0\frac{1}{2}(v_x^2 + v_y^2 + v_z^2)dxdydz, \tag{2}$$

where ρ is the ocean water density, η is the wave elevation, and v_x, v_y, v_z are the velocity in the x, y, z direction, respectively. The first term on the right side in the equation is the potential energy, and the second term is the kinetic energy.

However, the ocean surface waves driven by wind are usually irregular. They have a certain amount of randomness: subsequent waves vary in height and period. One way to describe the irregular wave

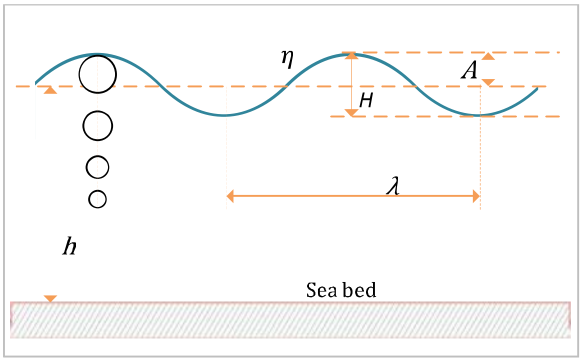

Fig. 2. A regular wave with finite depth [12]. The particle orbits are indicated for the deep-water case.

at a given position is using the Fourier series expansion with random phases.

Even though the waves have characteristics of randomness, they are still more predictable than wind. Some spectra are able to match the wave elevations in certain cases. For a fully developed sea, where a constant wind has blown for a sufficiently long time over a sufficiently long fetch of the ocean, the Pierson–Moskowitz spectrum can match the measured wave data well [13]. In situations where the fetch is limited, the JONSWAP spectrum is usually applied. This spectrum was developed by the Joint North Sea Wave Project (JONSWAP) for the limited fetch North Sea. It is more narrow-banded than the Pierson–Moskowitz spectrum, and used extensively by the offshore industry. The Bretschneider spectrum was presented at the 15th International Towing Tank Conference in 1978, and is for average sea conditions when a more specific appropriate form of the wave spectrum is well defined. It is expressed as:

$$S(w) = \frac{5}{16} H_s^2 \frac{w_0^2}{w^5} e^{-\frac{5}{4}(w_0/w)^4}, \tag{3}$$

where w is the angular frequency in radians per second, w_0 is the modal frequency of any given wave, and H_s is the significant wave height.

Then, the energy per unit area of sea surface amounting to an average in the irregular case is expressed as:

$$E = 2\rho g \int_0^\infty S(f) df, \tag{4}$$

where f is the frequency in hertz. The statistics of wave mean power density in the world are shown in Fig. 3.

3. Ocean wave energy converter

Wave energy converters are used to capture the energy from ocean waves, and convert it into electricity (conversion to electricity is the most common use so far, other types of use are not discussed in this paper). The research was initiated in the 1970s, and relevant technologies have been developed in many countries, including the United Kingdom, Ireland, Sweden, Norway, France, Germany, Denmark, Italy, Portugal, Spain, Belgium, Greece, the Netherlands, Iran, the United States of America, Canada, Mexico, China, Japan, South Korea, Singapore, India, Sri Lanka, Indonesia, Malaysia, Russia, Australia, and New Zealand. Some of these works have been introduced or reviewed in [11,15–37].

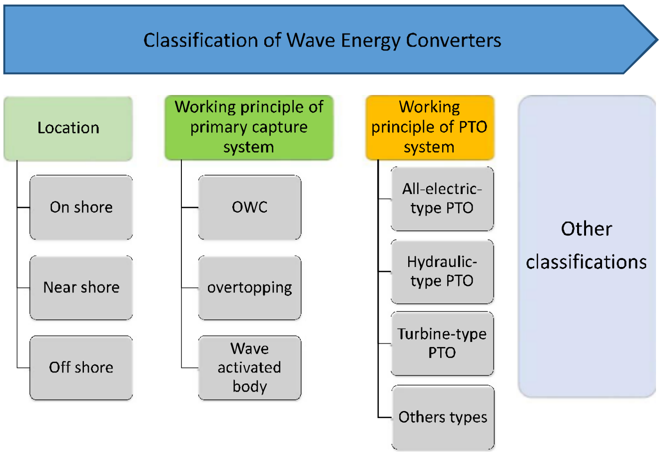

Fig. 4. Classification of WECs according to different criteria.

3.1. Classification of WECs

As shown in the references listed above, there are various ways to classify WECs. Two popular classifications are based on the working principle of the primary capture system and the secondary conversion system (the PTO system), as shown in Fig. 4 [13,15,33].

3.1.1. Classification by the primary capture system

When classified through the working principle of the primary capture system, WECs can be categorized into the oscillating-water-column (OWC) type, the overtopping type, and the wave-activated-body (WAB) type [38].

The OWC WEC consists essentially of a floating or bottom-fixed structure, where the upper part forms an air chamber and the immersed part is open to the action of ocean waves [39]. The air in the chamber is compressed by the motion of ocean waves to drive an air turbine [40]. LIMPET, OE buoy, and Mighty Whale are examples of this type WECs [41–43].

For the overtopping WEC, water from the incoming waves will overtop the structure, and is then stored in the reservoir. The overtopped water is used to drive turbines. The Wave dragon is a well-

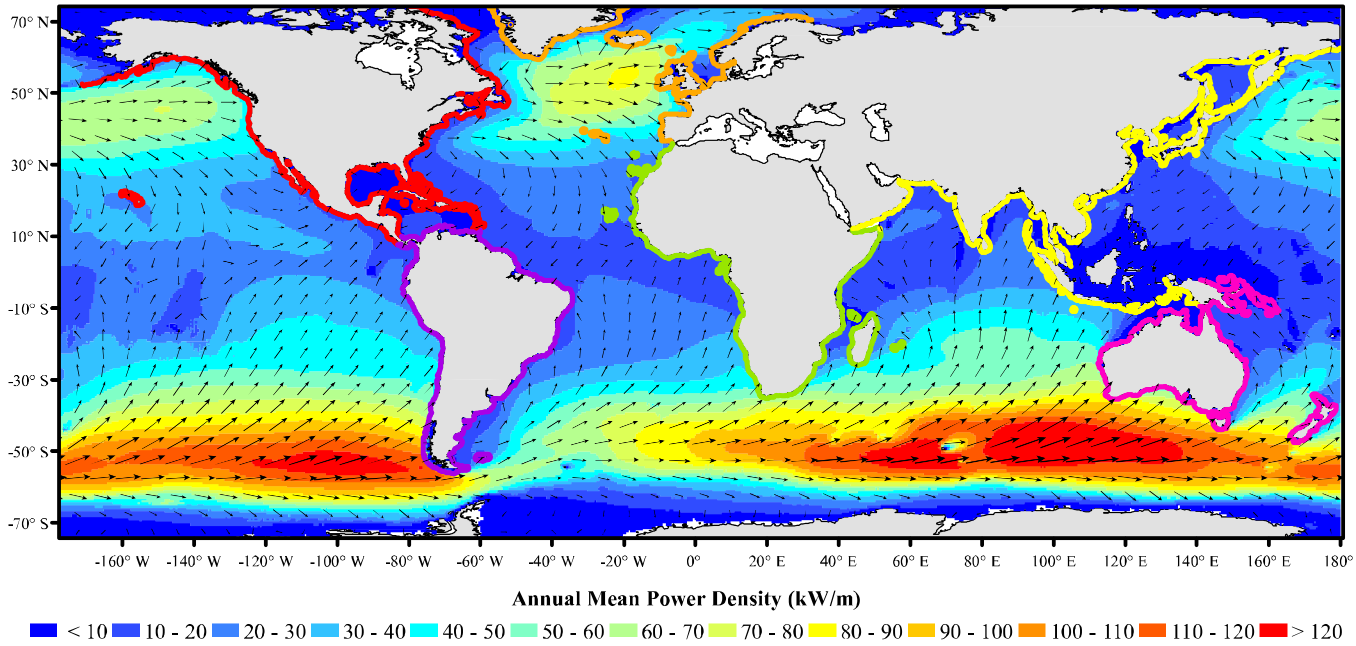

Fig. 3. Annual mean wave power density (marked by colour) and annual mean best direction (marked by arrows) [14].

Fig. 5. Lateral section of a three-levels SSG device with a Multi-stage Turbine [45].

known overtopping WEC. It has two wave reflectors focusing the incoming waves towards a ramp. The ocean waves are elevated to a reservoir above sea level where the water is released through a number of turbines and thus transformed into electricity [44]. Another example of overtopping WECs is the SSG WEC (shown in Fig. 5), where the overtopping water is captured in different basins above the mean sea level [45].

The WAB WECs can be classified into point absorbers, attenuators and terminators, according to the absorber size and its relation with the direction of the incident wave. An absorber that is substantially smaller than the wavelength is called a point absorber. The Budal latching-controlled-type WEC, the Archimedes Wave Swing, and the Uppsala University WEC fall into this category [46–51]. If the dominant wave propagation direction is perpendicular to the structure extension of the WEC, the WEC is called a terminator, e.g. the Wave Roller and the Oyster [52,53]. Attenuators are similar to terminators, and are usually long structures, but their structural extension is parallel to the wave propagation direction. The Pelamis is an attenuator-type WEC [54].

3.1.2. *Classification by the PTO system*

The power take-off is an important part of a WEC. For a WEC meant for electricity production, a PTO consisting of a generator is used to convert the captured wave energy into electricity. According to the methods used to drive generators, there are three main groups: hydraulic-PTO WECs, turbine-PTO WECs, and all-electric-PTO WECs [17].

The hydraulic PTO is robust and able to provide a large force at low speed, which coincides with the characteristics of ocean waves. Another advantage is that most of the components used in hydraulic circuits are commmercially available. Therefore, hydraulic PTOs are widely used for WECs, including the Pelamis and the Edinburgh Duck [55]. Their working principle is: ocean waves drive the hydraulic ram to increase the pressure of a working medium (usually hydraulic oil) to drive the motor, resulting in the motion of the generator, which produces electricity. Fig. 6 shows a hydraulic PTO system of a WEC using double-acting hydraulic cylinders.

Turbines are also widely used for WECs, and they are driven by water or compressed air. The most commonly used air turbines for wave energy conversion are Wells turbines and impulse turbines with or without fixed or variable guide vanes. A detailed introduction and comparison of them is made in [57], and it indicates that impulse type turbines are more suitable for irregular waves than Wells turbines. Different methods can be adopted to drive the turbine in a WEC. In the OWC WEC, the air in the chamber is compressed to drive the air turbine, while the turbine in the overtopping WEC is driven by the overtopped water. Generators are connected to those turbines to produce electricity.

Another type of PTO system is the all-electric PTO. In this case, generators should adapt to the slow motion of ocean waves, and are generally directly connected to the absorber. One technology is the direct-driven permanent magnet generator, avoiding many complexities of the conversion process thereby improving the efficiency. The generator can be the linear type or the rotating type, i.e. a linear permanent magnet generator (LPMG) or a rotating permanent magnet generator (RPMG). The relative motion between the absorber and the stator of the generator activates the translator or rotor, resulting in the generation of electricity. The Uppsala University WEC and the AWS WEC, use a LPMG [58–60]. The Lifesaver WEC uses a RPMG [61].

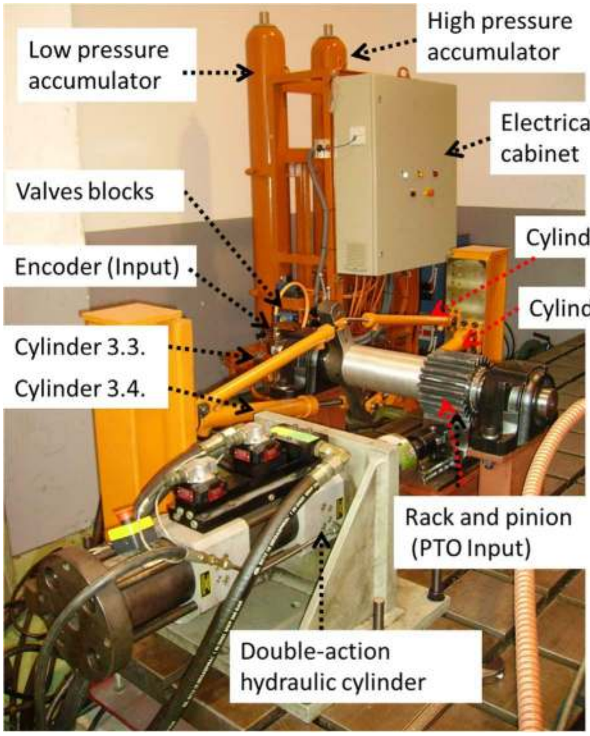

Fig. 6. Hydraulic PTO of a WEC, source is from [56].

There are some WECs that do not fall into these three categories. They use different mechanisms, such as using piezoelectric materials to convert ocean kinetic energy into electrical energy [62]. These WECs are not discussed here as they are still extremely rare.

3.1.3. *Other classifications*

WECs can also be classified by their deployment location, resulting in three types namely, onshore, offshore or nearshore. Onshore WECs can be fixed to a cliff, a dam or the land without a mooring system, resulting in easy installation and maintenance. The shoreline must be carefully selected , and requires construction on the shore of the sea, which increases the environmental issues [18,32]. Nearshore WECs are deployed hundreds or thousands of meters from the shore, and most are in shallow water. Offshore WECs are deployed in deep water, and have more opportunities to access high power waves. However, both offshore and nearshore WECs need a mooring system or other structures with a similar function, as well as a long length of sea cable to transmit the power to land [63].

Other criteria, e.g., floating or submerged, working in one degree or multiple degrees, can also be used to classify WECs, but are not discussed here as they are rarely used.

3.2. *Review of WECs deployed during 2005–2016*

Many WECs have been researched by numerical simulations or experiments in the last years. The progress of this research has been reviewed in [15,33,64–66], and [67]. The related theory is reviewed or introduced in [1,13,18,20,25,33,68–71], and [72].

Clément et al. [15], review the progress of wave energy conversion in Europe during ten years (until 2001), with a focus on the activities and initiatives at the national and European Union level. They present the most important wave energy developments and outline the technical status in wave energy conversion.

Falcão [33], reviews the development of wave energy utilization between the 1970s and 2009, and addresses the characterization of the wave energy source and the theoretical background of the hydrodynamics and the control.

In [64], the authors assess the current status and the future perspective of ocean energy development in Europe, focusing on the policy and the main barriers (technology development, finance and markets, environmental and administrative issues, and grid availability) of ocean energy, as well as the trends in tidal and wave energy. They identify and list developers in wave energy. A similar list is available at the website of European Marine Energy Centre [73].

In [65], the authors assess the experience of developers, regulators, and stakeholders in relation to obtaining consent for wave energy deployments in Europe, and address issues related to the planning and consenting processes, the administrative procedures, the consultation with stakeholders and the environmental impact assessment. This work is funded by Intelligent Energy Europe, and reflects the experience of those who have been actively involved in the planning of and consenting to wave energy projects in wave energy test centres and other project sites across the European Union.

In [74], the authors review the progress in wave energy conversion in China until 2007, and introduce the wave energy sources and national policy at that time. The majority of the WECs are developed and deployed by the Guangzhou Institute of Energy Conversion at the Chinese Academy of Sciences, and the details are reviewed in [75].

More recently, the OWC WECs were reviewed in [66], with a focus on the technologies and the air turbines. Three control strategies, i.e., the reactive phase control, the latching phase control, and the rotational speed control of the turbine, are discussed.

These papers give the status of the conversion technology at certain periods. There is a need to update this information. In this section, we focus on the WECs deployed in real sea with full-scale or large-scale testing from 2005 to July 2016, as shown in Table 1. Results show that more WECs have been deployed in recent years compared to earlier periods, and they are usually deployed at national-level test sites that are built for WEC tests.

4. Wave-to-wire model

4.1. Overview

The wave-to-wire concept is discussed in several references, and refers to a conversion from ocean waves into electricity by a single WEC or arrays of WECs. The word “wave” refers to the input of a WEC, the ocean waves, and the “wire” is related to the output, the electrical network.

The input and output of a WEC system have some well-known characteristics or requirements. One is that the input of a WEC is irregular, due to the nature of ocean waves. Another one is that the electricity produced by a generator must meet some requirements to supply electrical machines or to be injected into grid. For example, some electrical machines need to produce power with a fixed frequency if directly connected to the grid without power electronics (e.g. the grid connected induction generator), so they cannot optimize the power extraction from the waves. To overcome these challenges, a good wave energy conversion system should meet the following three requirements:

(1) Strong ability to capture energy from ocean waves;
(2) Good efficiency in converting the captured mechanical power into electric power.
(3) Ability to convert unstable electric power into stable electric power to meet grid codes or supply electrical load.

Table 1
Some WECs deployed in real sea during 2005–July 2016. Note that some deployments last more than one calendar year (such as the Wave Star), and some WECs are successively deployed in a farm in different years (such as the Lysekil WEC project). Only the time range of the deployment year is listed for these two situations, and more details can be found in the corresponding references.

WEC Name		Deployment Year	Deployment Place/ Country	Refs.
PowerBuoy		2005–2008	New Jersey/U.S.A.	[76]
		2008	Santoña/Spain	[77]
		2009–2011	Hawaii/U.S.A.	[77]
Oceanlinx	Mk1	2005	Port Kempla/ Australia	[78]
	Mk2	2007–2008		
	Mk3	2010		
Wave Star		2005–2006	Nissum Bredning/ Denmark	[79]
		2010	Hanstholm/ Denmark	
Lysekil WEC		2006–2016	Lysekil/Sweden	
OE Buoy		2007–2008	Galway Bay/Ireland	[42],
		2011		[66]
Mutriku Wave Energy Plant		2006–2011	Basque country/ Spain	[80]
Wavebob		2007	Galway/Ireland	
Pelamis		2008	Portuguese northern coast/Portugal	[33], [54],
		2010	Orkney/U.K.	[65]
		2012		
OCEANTEC		2008	Guipúzcoa /Spain	[81]
WaveRoller		2008	Peniche/Portugal	[33],
		2014		[82]
Oyster		2009	Orkney/U.K.	[83], [84],
		2011–2013		[85],
Duck		2009	WanShan/China	[75],
		2011		[86]
		2013		
PowerBuoy		2011	Invergordon/U.K.	[87]
Wello Oy		2011	Orkney/U.K.	[88]
Penguin WEC		2015	Plocan/Spain	
Fred. Olsen	BOLT33	2007	Risør/Noway	[89]
	BOLT22	2008		
	BOLT1	2009		
	LIFESAVER	2012	Cornwall/U.K.	
		2016	Hawaii/U.S.A.	
Azura		2012	Oregon/U.S.A.	[90]
		2015	Hawaii/U.S.A.	
Sharp Eagle		2012	WanShan/China	[86]
		2015		
M3 wave project		2014	Oregon/U.S.A.	
Oscilla Power		2014	New Hampshire/U. S.A.	
RivGen Power		2014	Alska/U.S.A.	
AWS-III		2014	Orkney/U.K.	[91]
Havkraft WEC		2014	Sogn og Fjordane/ Norway	[92]
CETO		2014–2016	Garden island/ Australia	[93]
Oceanus 2		2014	Cornwall/U.K.	[94]
		2016		[95]
Volta WEC		2015	Cornwall/U.K.	[96]
KRISO OWC		2012–2014	Yongsoo/South Korea	[97]
Seabased AB WEC		2015	Ada Foah/Ghana	[98]
		2015	Sotenäs/Sweden	
WaveEL		2016	Runde/Norway	[99]

The first requirement is related to the primary capture system, and the second to the PTO system, while the third is specifically related to the power electronic converters for grid connection. These are all covered by the W2W model. The primary capture system and PTO system, including their classification and function, have been introduced in the previous section. In Section 4.2, the power electronic converters will be introduced.

4.2. Power electronic converter

Power electronic converters are not studied widely in the early work of the wave energy community, nor in mathematical models or physical experiments. At that time, the majority of the WECs were connected directly to stand-alone electrical resistors or mechanical weights, which do not have strict requirements on the waveforms of electric voltage and current. Now, with the development of the technology and the trend towards commercialization, power electronic converters are more widely applied to WECs. With the emergent need of grid connection, WECs need the power electronic converters to provide a good interface with the grid [100] and comply with power quality requirements.

The working status of power electronics is determined by the switches. There are three classes of switches, according to their characteristics, namely, uncontrolled switches, semi-controlled switches and fully controlled switches. The uncontrolled switch (e.g. a diode) has no control terminal, and its switch states are decided by the external current or voltage of the electric circuit to which the switch is connected. Controlled switches (e.g. IGBTs) can be turned on or turned off by the control signal from a control terminal according to the specific algorithms. In switching technologies, different power electronic converters can be used to control the power conversion from an AC source to a DC source, DC to AC, DC to DC, and AC to AC, in the power range from watts to gigawatts and in a frequency range from hertz to hundreds of kilohertz. A list of power converters is presented in Table 2.

For the majority of WECs, the electric currents produced by generators are in three-phase with variable frequencies. In order to supply some electrical machines (load) with the generated power or inject it into electric grids, some electric power conversion is needed. For example, in the case of supplying an electrical machine which requires DC, the AC/DC rectifier is used, and sometimes DC/DC conversion is also needed to step-up or step-down the electric voltage. In the case of grid connection, the unstable AC source needs to be converted to a stable AC format to meet the grid codes. This AC/AC conversion has been widely studied in other renewable source converters, e.g., wind energy converters, and a popular solution is to use an AC/DC rectifier followed by a DC/AC inverter with a common DC capacitor.

Generally, the main functions of power electronic converters for a WEC system are:

(1) Achieve electric power conversion between different types, e.g., conversion of the electrical source between AC and DC;
(2) Increase the power captured from ocean waves;
(3) Control the electric power quality of the output waveform, and make it suitable for commercial use.

4.3. Review of research on wave-to-wire model

In this section, we will provide a detailed review of the existing work on the W2W model, including the related mathematical work, simulations, and experiments. The wave energy conversion is divided into the primary capture system, the PTO system, and the grid-side system (power electronic converters). The results of this recompilation have been systematically presented in Table 3. It shows a review and classification of the wave conditions and the types of the primary capture system, the types and the use of power electronic converters for the PTO system, and the grid connection condition and the use of power electronic converters for the grid side. All the control strategies used in the primary system, the PTO system, and the grid side are also investigated.

Table 2
Some power electronics converters.

Power conversion	Common Names
DC/AC	Inverter
DC/DC	Switching regulator; Boost; Buck; Chopper
AC/DC	Rectifier
AC/DC/AC	Back-to-Back Converter
AC/AC	Cycloconverters; Matrix converter

5. Review of control strategies and their validation

Many parameters influence the power generation of WECs, and their optimization can be conducted during the design stage or during real sea operation. The optimization performed during the real sea operation requires dynamic control, while the design optimization is relatively static. The advanced dynamic control strategies can be achieved by controllers in real time using mechanical mechanisms or electrical mechanisms. Controllers can be operated at different time scales or frequencies, e.g., in milliseconds, seconds, minutes, hours, days or larger time scales, and their performance highly depends on accurate measurements and predictions of incident ocean waves, and accurate measurement of system parameters.

Generally, these dynamic control strategies are implemented in different parts of the power chains of a W2W model. In this section, the reviewed work is divided into the hydrodynamic control, the PTO control, and the grid side control. We will focus on the corresponding numerical simulations and physical experiments.

5.1. Hydrodynamic control

It is well-known that the geometric shape and size of the primary capture system can influence the hydrodynamic performance and the power production of WECs [119,120]. One example is the Edinburgh Duck, which rotates around an axis parallel to the incident waves, and has a high primary capture efficiency due to its particular hydrodynamic shape [121,122]. Another example is shown in Fig. 7, where the radiation and the absorption of a point-type absorber and an attenuator-type absorber are compared. The radiated waves due to the motion of absorbers are clearly different. In Fig. 7(a), the point absorber creates a circular radiation pattern of waves radiating energy equally in all directions from the absorber at the centre. Fig. 7(b) shows waves incident from the left interacting with the radiated waves under optimal response conditions to maximize absorption. A lot of the radiated waves create a complex pattern of interfering wave fronts and can have a detrimental effect on the maximum absorption. The attenuator-type absorber has less radiation losses, as shown in Fig. 7(c). The radiated waves interfere with the incident wave and provide cancellation of the incident wave down-wave from the absorber [87].

Hydrodynamic optimizations based on the optimization of the geometric shape and efficiency maximization generally take place in the design and manufacturing stage. Another method of optimization is to dynamically control the hydrodynamics during the real-time operation of WECs in ocean waves, which allows for optimal tuning from wave to wave.

It is known that the mechanical structure of primary capture system interacts with ocean waves, and the resulting force due to wave motion is a driving force to the WEC system. The wave-activated body for example, has a wave excitation force that is an integral of the water pressure over the wetted surface of the absorber. This opens the possibility to control the excitation force by tuning related parameters. In other words, tuning the wetted surface area or changing the pressure in the given sea states will lead to a change of the excitation force and thus influence the system performance. As indicated in [123] the surface of an absorber is controlled when the sea states changes.

Another example is explained in [124], where a mechanical controller is designed to tune the buoy-shaft tilting angle according

Table 3
Review of the W2W work. Note: I.W. means irregular wave, R.W. means regular wave, BTBC means back-to-back converter, PEC means power electronic converters, S. means simulation, LT means lab test, E. means experiment.

Refs.	Primary capture system			PTO system			Grid/Load Side				Validation
	Type	Input	Cntrol strategy	Type	Control strategy	PEC	Grid connection	Control strategy	Control Aim	PEC	
[101]	OWC	I.W.	Valve control	Turbine-generator	Speed control	Yes, BTBC	Yes, A 400 V isolated grid.	PLC with control algorithm	N/A	Yes, BTBC	S. + LT
[102]	OWC	I.W.	No	Turbine-PMSG	Speed control	Yes, BTBC	Yes, A 400 V grid	PLC with control algorithm	Power quality	Yes, BTBC	S.+ LT
[103]	OWC	I.W.	No	Turbine-generator	Speed control	Yes, BTBC	Yes.	Voltage oriented control	power quality + power smooth	Yes, BTBC	S. + LT
[104]	WAB	R.W.+ I.W.	No	Hydraulic motor -generator	Valves control /Speed control /torque control	No	No	No	No	No	S.
[105]	WAB	I.W.	No	LPMG	Three current control strategies	Yes	No, math. model	No	No	No mathematical model	S.
[106]	WAB	I.W.	No	LPMG	MPPT	Yes, BTBC	Yes	Low-voltage ride-through control	Yes, control reactive power.	Yes, BTBC	S.
[107], [108]	Overtopping	Not mentioned	No	Turbine-generator	Speed Control	Yes, IGBT AC/DC converter	Yes, an infinite grid with line voltage of 690 V.	DC link voltage control	Power factor	PWM Voltage source inverter	S.
[109]	WAB	R.W.	No	LPMG	Reactive control	Yes, BTBC	Yes, an infinite bus	Yes,	Maintain active power and terminal voltage constant	Yes, BTBC	S.
[110]	OWC	I.W.	No	Turbine -generator	No	No	No	No	No	No	S.
[111]	WAB	I.W.	No	LPMG	Reactive control.	Yes, BTBC	Yes.	DC link voltage control	Not mentioned	Yes, BTBC	S.
[112]	WAB	R.W. + I.W.	No	LPMG	Reactive control.	Yes, BTBC	Yes	Dc link voltage control	Control frequency	Yes, BTBC	S.
[113]	WAB	I.W.	No	Hydraulic motor + generator	PID control.	No	Yes	No	No	No	S.
[114]	WAB	I.W.	No	LPMG	Passive control + reactive control.	Yes, BTBC	Yes, a strong grid	Yes,	Power factor	Yes, BTBC	S.
[115]	WAB	R.W. + I.W.	No	Turbine + generator	N/A. Select intial conditions to meet grid codes.	No	a strong grid	No	N/A	No	S.
[116]	OWC	I.W.	No	Turbine + generator	Speed control	No	No	No	No	No	S. + E.
[117]	WAB	R.W.+ I.W.	No	LPMG	Reactive control	Yes, BTBC		DC link voltage control	Maintain DC link voltage, output active power constant	Yes, BTBC	S.
[118]	WAB	I.W.	No	PMSG	Reactive control	Yes, inverter	No	DC link voltage control	Maintain the DC link voltage constant	Yes, rectifier	S.

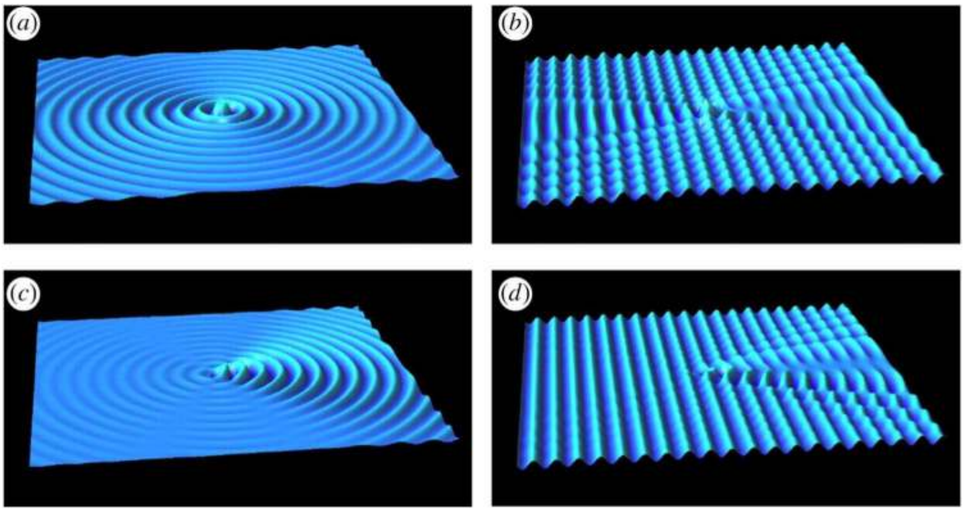

Fig. 7. (a) Far-field radiation of a heaving point absorber, (b) absorption patterns for a heaving point absorber, (c) far-field radiation of an attenuator-type absorber, (d) absorption patterns for an attenuator-type absorber. [6].

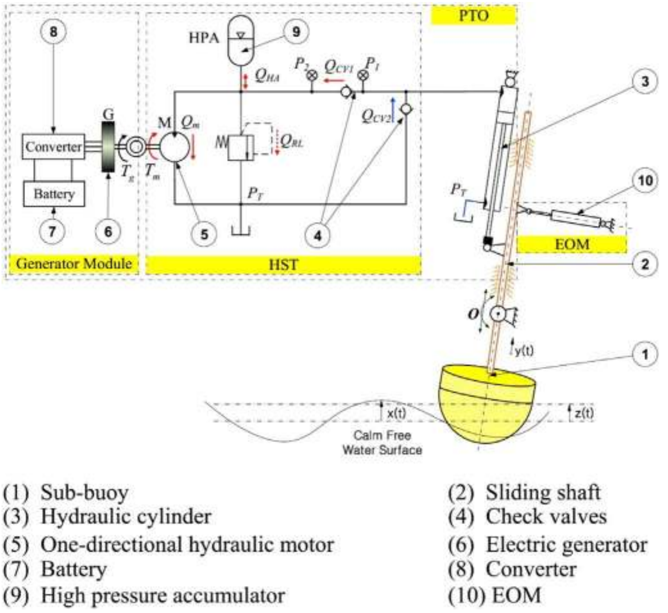

Fig. 8. Configuration of a sliding-buoy wave energy converter [124].

to wave conditions in such a way that the device can absorb most of the energy from the waves. The proposed WEC is shown in Fig. 8. The supervisor controller detects the incident wave conditions and provides the reference titling angles, then the secondary controller automatically regulates the slope angle to the desired value from the supervisor controller to maximize the power extraction. Results indicate that the optimal angle can be reached within 2 s and the overall efficiency of the system can be improved by 5%.

Another approach to optimize and control the hydrodynamics is to tune the inertia of the system. In [125], it is shown that the performance of the device is changed by rearranging the ballast distribution, and the performance of the device can be optimized for a certain sea state by choosing an appropriate value for the centre of mass of the ballast. In [126], a fully submerged mass is added to the WEC to properly shift the device's heave natural frequency to gain resonance with the most energetic waves and maximize the energy absorption. In [127], the inertia of the floating absorber is changed by regulating the position of a sliding mass. In [128], the power capture of a cylindrical bottom-hinged point absorber is improved by modifying the inertia through filling water into some compartment of the device. In [129], a variable liquid column oscillator is used as the absorber of a WEC, and the oscillation of the WEC is tuned to match with the incident waves to extract energy from ocean waves more efficiently through adjusting the volume of the air chamber of the absorber. The method of controlling the absorber inertia with supplementary mass is physically validated, and the results of the hydrodynamic performance and the energy absorption of a point absorber are compared with those from numerical calculations [130].

The hydrodynamics can also be controlled by tuning the WEC draft, the position, or by controlling the motion, when the sea states change. For example, during one sea trial of a solo Duck WEC in China, the floating device was fully submerged to protect the system from damage from extremely high power storm waves. This is achieved by controlling the gas volume in the chamber, resulting in a change of buoyance force. This principle is also used to control the floating status of Wave Dragon [131]. In [132], the wave energy conversion performance of a vertical-cylinder buoy using reactive control strategy in a floating situation and a submerged situation is investigated, which indicates the influence of absorber position.

Hydrodynamic forces can be influenced by the motion of the absorber. As described in Cummins' Equation, the radiation force is a convolution of the velocity and an impulse radiation kernel. It should be noted that, the impulse radiation kernel is a memory function, and will not vary with the velocity. Therefore, it is possible to control the fluid-structure interaction by motion control. In [133], a magnetic brake is used to lock and unlock the absorber using real time latching control in regular and random waves. This control on the absorber motion contributes to the improvement of the power production.

WECs in arrays or a farm can also influence each other by their motion through the hydrodynamic coupling, especially when they are spaced closely [134]. In [51], the motion of all WECs is coordinated by using the information of the hydrodynamic interaction under optimal PTO damping to maximize the mean power production of a farm. This improvement is significant for closely spaced buoys [135]. The improvement of coordinating the WECs'motion has been validated by experiments [136]. The analyses of wave interaction with complicated structures requires the use of numerical techniques, such as the panel method (also known as the boundary element model, the boundary integral equation method and the diffraction/radiation problem).

For an OWC WEC, the compressed air crossing the turbine rotor is the input to the PTO system, and its pressure can be controlled through a by-pass valve or a throttle valve in series or in parallel with the turbine, which can modify the air flow through the turbine. A numerical simulation of this is described in [39].

5.2. PTO control

5.2.1. PTO control strategies

Control on the PTO system affects the performance and the efficiency of the primary capture system and the electrical equipment. Many strategies have been investigated to improve the energy conversion efficiency, which is a key indicator for evaluating the performance of a WEC. These control strategies can be conducted on different components of a PTO system, such as the generator or the power electronic converter on the generator side. Here, we focus on the control issue related to the PTO force. Some control strategies on the PTO force are indicated in [101,137–145], and also reviewed in [18,138,146].

Generally speaking, these control strategies on the PTO force fall into two categories, namely, the reactive control and the resistive control [48,147–149]. The reactive control requires delivering some power back into the device in order to keep the velocity and the excitation force in phase. The resistive control (also referred to as the passive control) only handles the PTO damping force, and does not involve reactive power flow. Some strategies in the references, i.e., complex conjugate control [150] and the phase and amplitude control, can be categorized under the broader classification of the reactive control since the machinery has to handle a reactive power flow. Some strategies, e.g., latching control [151] and clutching control [152] belong to the so-called bang-bang control type of resistive control. A comparison of some control strategies is made in [49,125,141,148].

To further explain the tuning principles of reactive control and resistive control, we take the widely used heave motion as an example. The mathematical model of the heave force of a WEC PTO is generally described as a function of the velocity, the displacement, the damping coefficient, and the spring coefficient, written as follows,

$$F_{PTO} = K_{PTO}X(t) + C_{PTO}\dot{X}(t), \tag{5}$$

where F_{PTO} is the PTO force, X is the displacement, K_{PTO} is the spring coefficient of the PTO system, and C_{PTO} is the damping coefficient of the PTO system. By controlling the PTO spring coefficient and the damping coefficient, the PTO force is tuned, resulting in a modification of the phase and amplitude of the WEC's motion, as well as a variation of the power extraction from the waves. This process is referred to as reactive control. For the resistive control, only the PTO damping coefficient is tuned linearly or nonlinearly. Tuning principles for other modes are similar.

It should be noted that, most of these control strategies in each mode yield an expression for the optimal velocity and may therefore be seen as a velocity tracking problem. Other issues also impose the necessity of investigating the optimal speed tracking of the PTO component. One is that some mechanical components must be operated within the proper speed range to avoid excessively high mechanical losses or premature failure. An example of this is shown in Fig. 9, where the Wells turbine has a higher mechanical efficiency at a certain range of the speed ratio. Another issue is that there are some limits on the motion (speed, displacement or stroke), the force, and the power of the physical devices, which may require a limited speed range. To actually improve the WEC performance in terms of power generation, it is necessary to take into account the main constraints acting on the real-world WECs and affecting the system efficiency [155].

5.2.2. Numerical and experimental validation

Once the reference signals are provided by advanced control strategies, the tracking can be achieved physically by mechanical or electrical mechanisms [157]. Those physical components can provide pneumatic, hydraulic or electrical damping. The control logic is normally included in the definition or the design of the PTO system. The practical implementation of these advanced control strategies, and the evaluation of their true capability in physical models, are key issues of the PTO system. This is due to the bad scalability of PTO systems, and infeasibility of implementing advanced control schemes in laboratory tests [10].

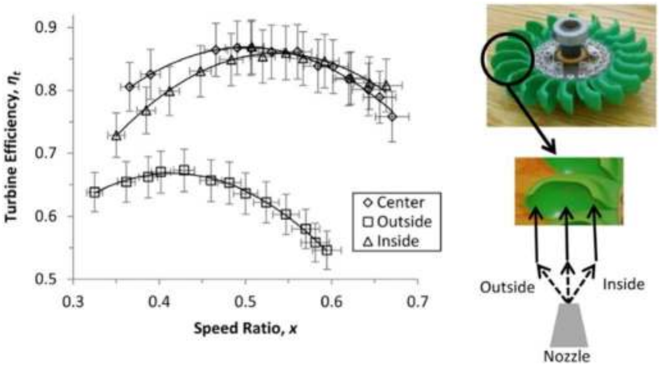

Fig. 9. Turbines efficiency versus speed ratio. Source is from [156].

The rest of Section 5.2.2 will focus on the practical implementation of these strategies in real time, and their validation by numerical and experimental methods. These works are introduced based on the classification of the PTO system.

5.2.2.1. All-electric PTO.

For the LPMG and RPMG, the PTO force, i.e., the electromagnetic force on the translator can be controlled by controlling the power or the current drawn from the coils to achieve the desired dynamic interaction between the primary capture system and the generator system to optimize the power extraction. The power electronic converter is a mature solution for generator-side control. One example is shown in Fig. 10, where the LPMG is connected to a back-to-back converter with a common DC link. The generator-side converter is used to control the phase currents from the generator to maximize the power extracted from the ocean waves. Using this scheme, advanced control strategies can be implemented.

Simulations indicate that the phase current of the generator can be controlled by the rectifier to lock it in phase with the induced electromotive force. Two control strategies, reactive control and passive control, for arrays of WECs are investigated in [158]. They provide the reference PTO force derived from the hydrodynamic study, which is finally achieved by the current control in the rectifier on the generator side. Results validate that using the reactive control produces more power than using the passive control. In [105], three current control strategies, hysteresis-band current control, space-vector PWM current control, and spatial hysteresis current source control, are introduced and compared. The results indicate that these three current controllers are able to provide an optimal resistance to improve the WEC efficiency and good current quality, with the space-vector PWM current control presenting the smallest ripple. In [106], using the back-to-back converter, a maximum power point tracking (MPPT) strategy based on speed control is proposed for the AWS WEC, which confirms the possibility of controlling an all-electric PTO force through power electronic converters.

One experimental validation is shown in [159]. Through experimental work with a LPMG test rig and a power electronic converter (back-to-back), the theoretical work on linear generator reaction force control through phase and amplitude control is verified. The generator force is controlled effectively by controlling the current by the generator-side rectifier. The controlled force aims to follow the reference force generated by the reactive control strategy. In such a way, the WEC characteristics are optimized to match the incident wave climate. This is particularly important for a WEC using the point absorber since it has a rather narrow capture bandwidth. In [154], a 35 kW test rig is used for a LPMG of a WEC, and a combined

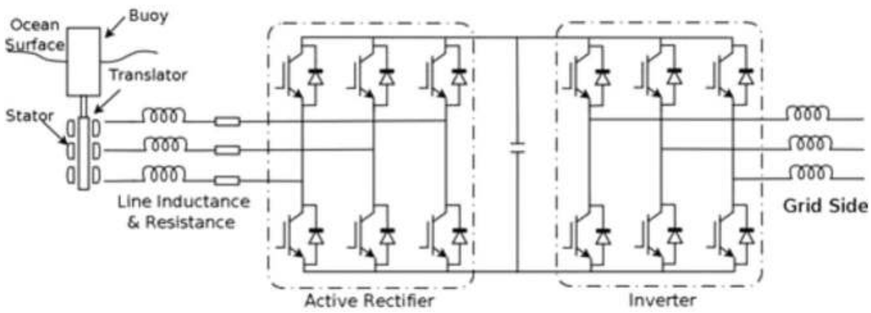

Fig. 10. A direct driven linear generator with the back-to-back converter. Source is from Ref. [111].

unidirectional boost DC-DC converter with IGBT-controlled chopper is adopted between the MOSFET-controlled rectifier and the IGBT-controlled inverter. The generator-side DC link voltage is controlled between 60 and 200 volts, while the grid-side DC link voltage is kept constant. In addition, a power smoothing control strategy is presented to control the chopper. Results indicate that this strategy can smoothen the power flow in the downstream power electronic stage and attenuate the impact on the grid.

5.2.2.2. Turbine PTO. Turbines can be operated at a fixed speed or a variable speed. The fixed speed turbines have strict requirements on the variation of the rotor speeds, and the generator can be connected directly to the grid. Variable speed turbines are designed to operate at a wide range of rotor speeds, and have less dynamic load on the electrical and mechanical systems. For both types of turbines, the speed control is important to guarantee the normal operation and improve the system efficiency, and has been studied widely.

For the PTOs consisting of turbines, advanced control strategies can be implemented by employing mechanical or electrical methods. One way is to control the electrical torque provided by the generator. In this case, power electronics and programmable logic controllers are required to control the electrical signals. The advantage of this method is the efficiency improvement of the turbine by matching the turbine speed to the incident sea states. Fig. 11 gives an example of the variable speed control on a doubly-fed induction generator (FDIG). Another method is to control the rotor blades, the vanes or the valves through tuning their angles or their status of open or close, as indicated in [160,161], resulting in a change of the water or air flow through the turbines. In some cases, the optimal phase can be achieved by latching control through fully closing or opening the valve. Both the mechanical and electrical methods are feasible in the practical implementation, but the electrical control has a faster response, and seems more reliable for speed control.

In [107], low-head hydro-turbines are controlled using the variable speed scheme through an IGBT AC/DC converter, and the turbines are switched on and off frequently by controlling a cylinder gate at the turbine inlet. In [66], the reactive control, the latching control and the turbine rational speed control for an OWC WEC are compared. The results indicate that the relatively modest efficiency of the turbine limits the gains from the active control and its application in OWCs. In [162], a Wells turbine with variable pitch-rotor blades is used for an OWC WEC, and the reactive control strategy is investigated to maximize the overall efficiency of the system, considering the PTO losses, by assuming a constant PTO efficiency in the mathematical model. The results indicate that the reactive control provides the maximum energy absorption, but not the maximum overall energy production.

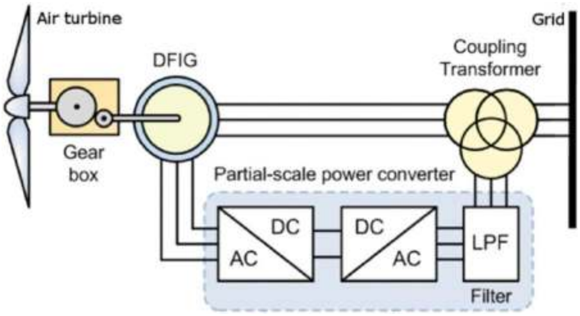

Fig. 11. Variable-speed topology with a doubly fed induction generator. Source is from [23].

Some practical implementations and experiments have been performed to validate these numerical schemes. In [163], results from the model test of a self-rectifying radial flow turbine of a WEC indicate that if the rotational speed is controlled properly, a biradial air turbine can achieve a peak efficiency exceeding 80%, and a time-averaged efficiency higher than 70% in bidirectional flows induced by random waves. In [103], three generator control strategies are investigated to achieve optimal speed for OWCs, and are validated by experiments in an electrical test rig. In [164], a latching control algorithm that does not require incident wave prediction is validated experimentally for an OWC. In [165], the overall efficiency of the WEC is improved by a control scheme consisting of a rotational speed control and an airflow control. The series throttle valves control the airflow through the turbine to avoid undesired stalling behaviour, while the rotational speed is controlled to increase the allowed slip of an induction generator coupled to the turbine. This regime makes it possible for the WEC to match the available wave energy at each time instant without entering into a stalling regime. In [166], variable speed operation of the turbine is achieved by varying the slip of a doubly fed induction generator, and the results are compared with those from the air flow control achieved by the valve control. A small-scale physical system is tested to prove the feasibility and the suitability of the proposed strategies.

5.2.2.3. Hydraulic PTO. For hydraulic-PTO systems, advanced control strategies can be achieved by controlling the generator or the hydraulic components. One example is shown in [167], where a PTO system using conventional electrical and hydraulic components is used for the Wavestar WEC. Its PTO force is controlled by tuning the generator torque and the motor displacement to track a reference force of the particular cylinder.

Hydraulic components, such as the hydraulic cylinders, the motor, the valves, and the accumulators can also be used to control the pressure of the hydraulic circuits or the PTO force provided by the hydraulic system. The accumulator can play the role of energy storage in a short time range and provide decoupling between the motor and the hydraulic ram. With these components, different hydraulic circuits can be used to implement the control strategies.

As indicated in [168], the pressure of an accumulator is controlled according to the incident sea states by a main solenoid valve or by regulating the working fluid flow passing the motor by controlling the swash plate angle of a hydraulic motor, resulting in a different power production by the generator and different PTO efficiencies. In [169], a rectifying valve is used to pump the liquid from the cylinder into the high pressure accumulator and suck the liquid from the low pressure accumulator into the opposite side of the cylinder. In [170], a cylinder with multiple chambers and connected to multiple on/off valves is used in the hydraulic system. By rapidly turning on/off different valves, different PTO forces are achievable. A wave power extraction algorithm based on the reactive control, is used for power extraction optimization, taking into account the efficiency of the PTO system. In [171], a generic hydraulic circuit consisting of a hydraulic transformer is presented, and speed control and reactive control strategies are used to improve the power extraction. As indicated in [46], phase control through latching can be implemented in a hydraulic PTO system consisting of a gas accumulator, by using a valve system to control the fluid flow.

Comparing results from three control strategies on the motor and the generator indicate that the motion control strategies affect the overall performance of the PTO system, and the best efficiency is achieved by keeping the motor displacement at maximum by controlling the generator speed [167]. The influence of the speed control strategy on a motor is addressed in [172], where the aim is to maintain the maximum flow of electrical power to the grid from a WEC using a doubly-fed induction generator. The influence of the speed control strategy on a hydraulic cylinder is addressed in [173].

Some physical experiments have been performed to validate these strategies. In [174], a 1/7 scale hydraulic PTO is tested for the Pelamis WEC. The results indicate that this PTO system is able to provide the signal demanded by a control strategy to the joint axis of the device at an arbitrary moment, and the reactive power capability is provided to enable impedance matching to maximize power capture. In [175], a heaving floating absorber is tested with monochrome waves at two subresonant frequencies. By applying the latching control strategy, an increase by a factor of 2.8 and 4.3 for a frequency of 0.75 Hz and 0.5 Hz, respectively, is achieved for the fraction of the captured hydraulic energy.

5.3. Grid/Load side control

Besides the application on the generator side, power electronic converters can also be used for the control on the grid or load side. They are essential for converting electric power generated by renewable and distributed energy into stable power that can be connected directly to the [153] grid. Power electronic converters at the grid/load side can also be used to decouple the generator from the grid or the electrical load regardless of the states of the incident wave, or to help the system to meet the grid codes. For example, in the case of using a back-to-back converter with a DC link, the grid-side controller can be used to independently control the real and the reactive power injected into the grid, while the generator-side controller is used to improve the power captured from ocean waves by using advanced control strategies. The DC capacitor decouples the grid side and the generator side.

These control actions are implemented in power electronic converters by controlling the switches to be turned on or off quickly, to follow the reference signal of the voltage, the current, or the electric power provided by advanced control strategies. The knowledge available on switching techniques is extensive, and it is a well-established technology. A review of such methods for WECs can be found in [100,145,176,177]. For other renewable sources it can be found in [178,179], which provide some reference values.

The load control is investigated by some researchers. The results indicate its influence on the generator performance, as well as on the system performance. In [180], experiments are conducted to validate the influence of the electrical load resistance on the peak active electric power and the generator speed. The influence of a nonlinear electrical load on a linear generator connected to a filter and rectifier are validated in [181]. The selection of electrical damping circuits with unidirectional and bidirectional power are reviewed in [182]. The electrical control strategies on different types of WECs are also reviewed in [183]. The influence of load control strategies is obvious.

6. Discussion

Control strategies and their validation for WECs by numerical or experimental methods are summarized in Section 5. These strategies apply control on the primary capture system or the PTO system, and most of them can be implemented in the W2W model. However, it should be noted that most of these mathematical models do not consider the losses in the real system, including the hydrodynamic losses, the mechanical losses, and the electrical losses. One example of the influence of electrical losses is introduced in [184], where the control efficiency, the electric efficiency and the total efficiency are compared to classical solutions through a simple loss model taking into account the electrical losses. Another example is introduced in [105], where the converter switching losses under different filter cut-off frequencies are compared. These results indicate that losses can significantly influence the system efficiency.

Another issue is that the majority of these investigations only focus on the application of control strategies to a single part or several parts of the whole conversion system. For example, the hydrodynamic control is only one part of the global optimization of the system efficiency. This control on a separate part, without considering the coupling with the power take-off part and the grid or load part, can lead to maximum energy absorption, but maybe not the maximum global efficiency of the entire conversion system. Since different parts of a wave energy conversion system have a close relationship with each other or can even be fully coupled, a wave-to-wire model must be built and a complex algorithm must be designed to balance the local control strategies to maximize the overall benefit. The cost function to evaluate this can be the overall efficiency, the mean power, the system stability, the power quality, etc.

Other issues can also be considered in the W2W model, but are not discussed here. These issues can be the cost, the reliability, the power smoothing, and the physical constraints, such as the limitation on the stroke of a linear generator or a hydraulic cylinder, or the force or torque limitations of the PTO.

7. Conclusion

This review indicates that various wave energy converters can be designed to capture ocean wave energy and convert it into electric power. These converters can be classified into different types according to different criteria. The R & D of wave energy converters is speeding up around the world, and more devices are being tested in sea or deployed for a commercial trial. There has indeed been a significant advance in wave energy conversion technologies of late.

The energy conversion chain from ocean waves to electric power injected into the grid or supplied to an electrical load, referred to as wave to wire, consists of multiple components, e.g., the mechanical components, the electrical machines and the power electronic converters. The performance of the entire conversion system depends on physical characteristics, parameters and control strategies. These control strategies can be implemented in controllers integrated in the primary capture system, the power take-off system and the power electronic converters.

These three control loops can be partially or fully employed in a wave-to-wire conversion system to improve the system efficiency, the grid stability, etc, and can be arranged in parallel or in series. The first loop controls the hydrodynamics of the primary capture system, and the second control loop maintains the speed or the efficiency of the PTO. The third loop controls the power injected into grid or supplied to the load. It is found that back-to-back converters with a DC link and using Pulse Width Modulation are the most general type of converters for wave energy conversion.

To evaluate the contribution of separate control loops (local control loops) to the overall efficiency is difficult. But to maximize the overall benefit, a complex algorithm must be designed to consider all the variables and couplings, and balance the gains.

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