Review of oscillating water column converters

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***Abstract*—Ocean waves are a huge largely unexploited energy resource, and the potential for extracting energy from waves is great. Research in this area is driven by the need to meet renewable-energy targets, but it is relatively immature compared to other renewable-energy technologies. This review introduces some device types that represent the state of the art of oscillating water column technology, a kind of wave energy converter (WEC). Unlike other works in literature, typically limited to specific aspects of WECs, in this paper, a system-wide perspective will be pursued, from the sea waves to the grid connection.**

***Index Terms*—Control strategies, ducted air turbines, ocean energy, oscillating water column (OWC), wave energy converter (WEC).**

I. Introduction

In the last decade, the interest on renewable energy has grown rapidly, reaching, in some cases, a thriving market with excellent perspectives. At present, different types of technologies are under the spotlight, joining the more traditional ones, such as solar, wind, and geothermal. Among these, the exploitation of the huge resources of seas and oceans might be a valuable solution to satisfy the electricity demand as much as possible by renewables.

The technology development and the market growth of renewable energies, including the marine one, will contribute in realizing significant economic, environmental, and social objectives in the early decades of the 21st century. Then, many governments are adopting new energy generation strategies and guidelines toward an ecologically sustainable society [1]–[7].

Energy can be extracted from the sea by exploiting several physical phenomena: salinity, temperature gradient, tides, waves, and ocean currents [1]. Several devices and equipment have been developed to convert sea energy into electricity with different outcomes. Only some of them have shown results close to the theoretical predictions when tested in real operating conditions. Since neither computer simulation nor laboratory testing can effectively assess the converters' performance in any weather, the real condition trials are essential in evaluating the feasibility of wave energy converters (WECs) and their endurance in a hostile environment such as the sea [8]. Therefore, although many studies were carried out until now, research in this area is still a challenge [9], [10]. During the last 40 years, inventors and scientists have presented many ideas based on different mechanisms to convert wave energy into electricity. The scheme shown in Fig. 1 sums up the power take-off (PTO) mechanisms of WECs that can be found in literature. The energy conversion chain requires many blocks that belong to different areas of expertise, from mechanical and aeronautical engineering to electric and electronic, even in the simplest case of a direct drive, i.e., a WEC with linear generator PTO (for instance, see the authors' affiliations in [11]).

The gray-filled blocks fall in the electric engineers' expertise area. Technological problems, uncertainty of results, and high costs of installation and maintenance for the power plants are the main barriers to the deployment of these systems. In addition, there is a lack of convergence on the best method of extracting energy from the waves; thus, techniques and/or technologies implemented to optimize the powertrain are extremely diversified.

This paper is focused on oscillating water column (OWC) systems because it seems to be one of the most promising technologies among WECs to build power plants of different sizes and power ratings, with acceptable performance and low environmental impact [12]–[16]. Moreover, OWC systems exhibit a potential benefit in terms of reliability due to the moving mechanical parts that are not submerged into the seawater [17]. Although OWCs have been under development since the end of the 19th century, to build whistling buoys for navigation aid (Fig. 2), the idea to use this technique in order to produce electricity has been applied starting from 1947 to supply onboard autonomous lights of navigation buoys [19]. Tests to produce electricity with more powerful generators, which can be conveniently connected to the grid, have been started in 1970s, but the high costs of production and maintenance, together with lifetime problems, have limited their diffusion.

Unlike other reviews, mainly focused on particular aspects, as [20], where strategies for electrical control of WECs as well as energy storage techniques are the presented topics, or the more cited [17], [19], [21], without discussions about power electronics and/or controls, this paper deals with all of the components of an OWC.

This paper is organized as follows. Section II describes the operating principle of OWCs and some design aspects and provides an overview of primary PTO technologies. Sections III–V are dedicated to a survey of turbines, electrical generators, and power electronics, respectively. Sections VI shows some issues

Manuscript received April 10, 2015; revised July 7, 2015 and September 24, 2015; accepted September 28, 2015. Paper 2015-SECSC-0192.R2, presented at the 2014 IEEE Energy Conversion Congress and Exposition, Pittsburgh, PA, USA, September 20–24, and approved for publication in the IEEE Transactions on Industry Applications by the Sustainable Energy Conversion Systems Committee of the IEEE Industry Applications Society.

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Digital Object Identifier 10.1109/TIA.2015.2490629

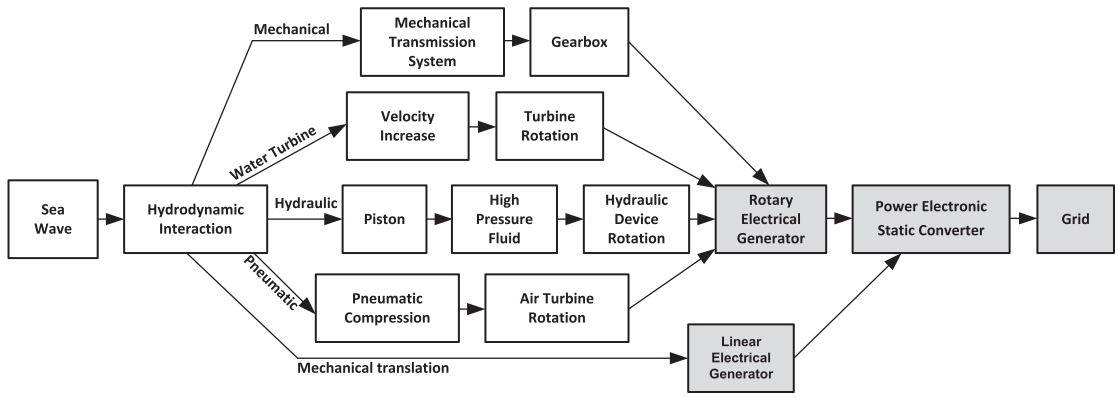

Fig. 1. Wave-to-wire power conversion alternatives.

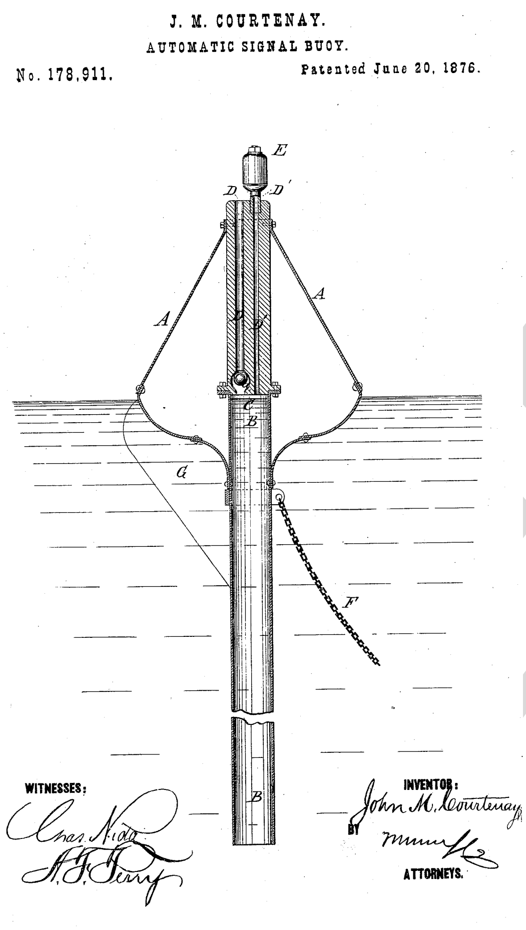

Fig. 2. Whistling buoy by OWC, patented by Courtenay in 1876 [18].

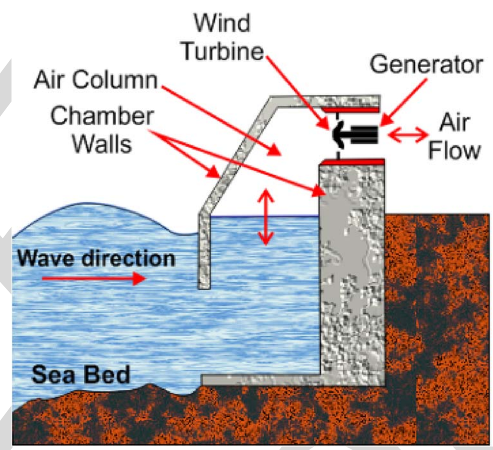

Fig. 3. Schematic vertical cross section of a single-chamber OWC.

of the control system used to improve as much as possible the efficiency of OWCs. In Section VII, a brief discussion is drawn. Finally, Section VIII presents the conclusion.

II. Wave Energy and OWC System Overview

The sea waves are mainly shaped by the wind (produced by the sun energy) blowing over the water surface. Only a little amount of the total solar irradiance on the surface of the Earth is transmitted to the seas to produce waves [8]. In oceanic areas, wind energy is transferred to waves and locally concentrated at power levels up to more than 60 kW/m of wave crest length, where relative high wave energy occurs [22]. There is no perfect regularity in sea waves. Their amplitude, energy, and direction vary randomly through the year, the seasons, or the day. While in some conditions they can change slowly from an absolute calm to 1 MW/km, in other places, they can reach 10 MW/km in a short time period (minutes). Variations shorter than a minute are also possible. In addition to this, the wave shapes are heavily affected by the characteristics of the coastlines [22].

Generally, WECs are categorized by location (shoreline, nearshore, and offshore) and type. Although the large variation in designs and concepts, depending on their shape, size, and direction of elongation with respect to the wave propagation direction, WECs can be classified into three main types: attenuators, point absorbers, and terminators.

Offshore WECs have more power at the input, but they must withstand more severe weather conditions, and both connection to the grid and maintenance are more expensive. An OWC is a partially submerged chamber where alternate pneumatic air compression and decompression take place in response to the incident wave. By means of pipes (and valves in some systems), the air can flow into a ducted wind turbine to drive an electric generator (Fig. 3). Then, the main parts of an OWC plant are one or more oscillating chambers with valves and ducts, air turbines, electric generators, and electronic power converters. Starting from this concept, many ideas have been developed.

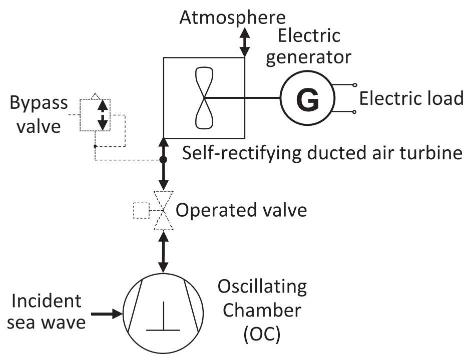

Fig. 4. Schematic of the hydropneumatic part of a single-chamber OWC. The dashed lines are depicted to represent the optional components.

OWCs can be installed either onshore, embedded in a cliff or a harbor wall, or in close proximity to the shore, standing on the seabed, or offshore in deep waters. They can be point absorbers as the Spar-buoy OWC [23], terminators as the LIMPET [24], and attenuators as the iVEC Floating Power Plant [15].

Starting from standard symbolism, the schematic of the hydropneumatic part of a single-chamber OWC can be drawn as in Fig. 4. Beyond the oscillating chamber, which acts as a piston pump, and the self-rectifying air turbine, a controlled valve to regulate the airflow can be mounted in the duct between the chamber and the turbine. To avoid the freewheeling of the turbogenerator when the electrical load is disconnected (e.g., during extreme sea conditions), one or more bypass valves can be added at the top of the oscillating chamber or just before the inlet duct of the turbine.

A. Design Aspects

The OWC concept differs from other WECs for a number of technological features. The most relevant of these features is associated with the oscillating chamber, which works as a pneumatic converter to obtain high-speed airflow through the air turbine by the slow internal free surface water motion. Initial design featured a vertical uniform column; then, to improve the capture efficiency (i.e., the ratio of the pneumatic energy to the hydrodynamic wave input energy [25]), many solutions were tested to reduce the entrance turbulence and internal sloshing and to increase the water plane area for a given chamber cross-sectional area. Some examples of solutions are the inclined chamber in LIMPET [24], the parabolic-shaped collector of the Oceanlinx Mark 1 [26], and the backward bent duct of the backward bent duct buoy (BBDB) [27]. The increase of the water plane area allows the coupling of the primary water column resonance to the major period of the incoming wave [28], which has a random envelop. Most OWCs operate optimally at resonance, and a key point to obtain higher efficiencies is the chamber design. Typically, the chamber sizes and shapes are chosen to produce a column whose natural frequency of oscillation coincides with that of the most occurring wave at the location where the OWC will be installed [29]. The variability of sea state conditions can affect the OWC feasibility because the size and shape of the structure cannot be modified. Phase-locking mechanisms were developed to improve the performance when the devices are out of resonance [30], [31]. Dynamic tuning devices have been developed to maintain a resonant condition despite the variations in the wave spectra to the most occurring waves [32], but in this case, the OWC is used for a kinetic–kinetic conversion, instead of converting kinetic energy into electricity.

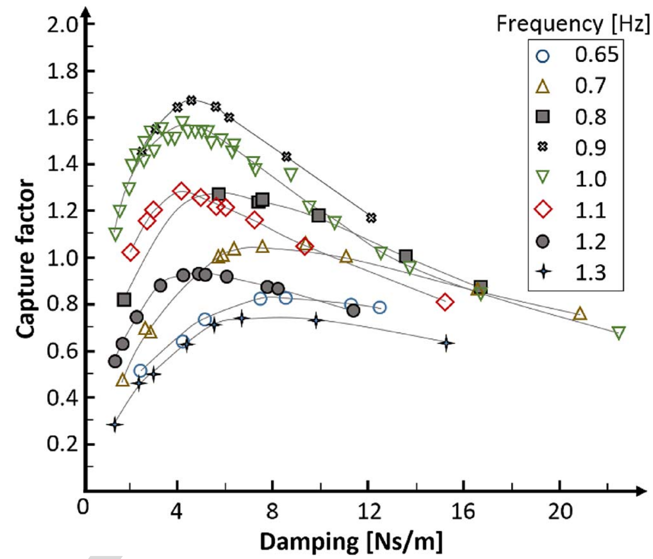

Fig. 5. OWCs' characteristics used in [33].

Another key point of the OWC design is the coupling between the chamber and the turbogenerator. The overall plant efficiency is the product of the efficiencies of each stage in the conversion chain of Fig. 1. As the turbine serves as a damping for the chamber, the overall plant efficiency is affected by the turbine and its state of rotation, which, in turn, depends on the electrical generator and its working state. As an example, in [33], the graph of Fig. 5 can be found, which reports the result of the tests done on a prototype based on the Indian Wave Energy plant with regular waves, for various values of damping. The graph shows the dependence of the capture efficiency on the turbine damping and the incident wave.

The operating state of the electrical generator can be influenced by a control applied to the power electronics used as interface to the grid, and this has been addressed by a number of works in the literature [20].

B. Power Plants

The literature review has been organized into two categories:

1) the more mature onshore and nearshore OWCs;
2) the floating OWCs, which are designed to operate at a wide variety of nearshore and offshore sites where higher wave energy is available.

As can be seen in the following, the second-generation systems are at the early R&D stage. The development of floating OWCs allows designing large-scale offshore devices, both in terms of physical size and power rating, which can be considered as the third-generation systems.

(a)

(b)

Fig. 6. Shoreline OWCs. (a) Pico OWC Plant [34]. (b) Demonstration plant at Toftestallen (photograph courtesy of Johannes Falnes).

1) Shoreline Power Plants: The most famous developed systems are based on a concrete caisson built on the coast, with the bottom side open to the sea in order to create an air chamber. In these OWCs, the air can be channeled through a bidirectional turbine. Depending on the size and the volume of the waves, such shoreline power plants may have power ratings from a few hundred kilowatts up to a few megawatts. Good examples of this technology are the following.

1) The Pico OWC [Fig. 6(a)], built as a pilot plant, to demonstrate the technical feasibility of wave energy. The project started in 1992, and its construction was ended in 1999. Nevertheless, several technical problems caused the interruption of the project until 2005, when the first test ran. Significant improvements have been obtained only after 2009. The main problem comes from the vibrations generated by the turbogenerator.
2) The LIMPET, the first commercial-scale grid-connected wave energy plant. It was commissioned in November 2000, off the Scottish Isle of Islay, and it is still operating today. Originally, LIMPET was equipped with a 500-kW Wells turbine, which was later downgraded to 250 kW.

Before Pico and LIMPET onshore OWCs, in 1985, a 500-kW demonstration plant was built at Toftestallen, Norway [Fig. 6(b)]. This plant operated for around three years before being partly destroyed by a severe winter storm, and it was subsequently decommissioned.

(a)

(b)

Fig. 7. Breakwaters with OWC. (a) Wavegen's Mutriku breakwater [4]. (b) REWEC prototype (photograph courtesy of wavenergy.it).

2) Breakwater Power Plants: In this kind of systems, the power plant is integrated into a newly build coastal structure, such as a harbor breakwater or a coastal protection. The main advantage of this approach is the significant reduction of the power plant cost.

The world's first built breakwater wave power plant was commissioned in 2011 on the Spanish Atlantic coast at Mutriku [Fig. 7(a)]. It consists of 16 single-chamber OWCs, each one with a Wells turbine, and the total nominal output power is around 300 kW (the power rate could be much higher in locations where waves are more powerful) [35]. It was built into the breakwater around a harbor, which was rebuilt by the local municipality. This enabled the use of existing infrastructure (mains connection, access roads, etc.), resulting in a cost savings. The Mutriku power plant has been operated successfully since its opening and is currently the only commercially operated power station by OWC in the world.

Another interesting breakwater OWC, named REWEC3 [Fig. 7(b)], is under development in Italy. The OWC structure has been integrated in new docks. It employs an additional vertical duct (U-OWC) that achieves an eigenperiod greater than that of a conventional OWC [36], [37].

3) Floating OWCs: Other examples of OWC devices include the Australian Oceanlinx (Fig. 8), the Irish floating OE buoy, the Japanese Mighty Whale, the Osprey, and the Portuguese Spar Buoy. These devices are not located on the shoreline but just in shallow water (less than 20 m deep), so they are classified as nearshore point absorber plants. These have the advantage of larger waves, but they are in a more challenging environment.

Fig. 8. Floating OWC: Oceanlinx MK1 full-scale prototype [34].

Fig. 9. Scaled prototype of a three-chamber segmented OWC for wave flume tests [40].

As an example, the first Osprey prototype, made of steel, was destroyed during a storm in 1995.

Except for Oceanlinx, which was successfully tested and which is now getting precommercial products, all of the other projects have been dismissed or suspended after a period of testing in the sea.

4) Multichamber OWCs: The last kind of technology considered here is that of OWCs based on the array of chambers. Under this category, three types of plants can be distinguished.

1) OWC array, many chambers, everyone with its own turbine generator, mounted in a single frame, as in the Orecon MRC, or the Oceanlinx MK3.
2) Segmented OWC, some chambers, each one with its own turbine, mounted in a single frame connected to a single electric generator [38], [39]. Fig. 9 shows a photograph of a scaled prototype of this kind of WEC.
3) Modular OWC, many chambers cooperate to produce a unidirectional airflow. Although *ad hoc* valves are required, this solution allows the use of conventional turbines instead of the self-rectifying ones adopted for the other OWC plants.

The first ideas of multichamber OWCs have been experimented from the late 1980s. Some examples are the following: 1) the Japanese breakwater at Sakata Port based on four caissons that produce airflows feeding two Wells turbines connected to the same electric generator [41]; 2) the 30-kW multi-OWC built in 1987 in the Kujukuri (Japan) harbor [42], which uses pressure storage vessels to supply conventional turbines without reversing the airflow; and 3) the Twin-OWC composed of two adjacent chambers producing unidirectional airflows through the same conventional air turbine [43].

Fig. 10. Leancon's scale 1:10 offshore test (photograph courtesy of Kurt Due Rasmussen).

An Italian OWC described by Martinelli *et al.* [13], the ShoreSWEC (South Africa) [44], [45], the Leancon, and the iVEC Floating Wave Power (FWP) plant (Australia) [46] can be cited as newer multi-OWCs.

The OWC in [13] and the FWP are based on a modular and scalable design, promoted to be assembled with a total power rate ranging from a few kilowatts to greater than 50 MW. The OWC in [13] and the ShoreSWEC performances have been simulated and/or tested only in wave flumes or tanks, while the FWP has been experimented also in a real environment in 2009. In spite of the initial encouraging results, no new developments in the FWP project are reported in literature. In addition, the Leancon's WEC [47] was tested in wave flume and tank. Leancon completed offshore tests using a 1 : 40 scaled prototype. In July 2015, Leancon had also launched offshore tests with a 1 : 10 scaled prototype (Fig. 10).

The multichamber OWCs mentioned in this paper can be considered as the second generation of this kind of WEC. Even if today it is not possible to foresee their commercially operating phase, they are hypothetically more promising than the previous chamber OWCs. The PTO schematics inferred by literature are drawn in Fig. 11. They can be useful is comparing the different solutions.

The segmented multi-OWC does not require nonreturn valves, and then, possible less head losses, together with the simpler structure, can be the advantages, with respect to the other solutions. A disadvantage arises from the use of self-rectifying turbines that usually are less efficient than the standard ones working with unidirectional airflows.

In order to compare the other three solutions, let us assume that the chamber arrays are equal, as well as the ducts, the valves, and the efficiencies of the turbines.

As it can be noted by the patent [45], in the ShoreSWEC, the pneumatic circuit is closed, and then, the mass balance requires that the total airflow of the chambers where the water column is moving up has to be equal to the total one of the chambers where the column is moving down. Thus, compared to the multi-OWC in [44] and the FWP, where the mass balance takes into account airflows getting to and from the atmosphere, there are matching losses between the high-pressure and low-pressure duct flows.

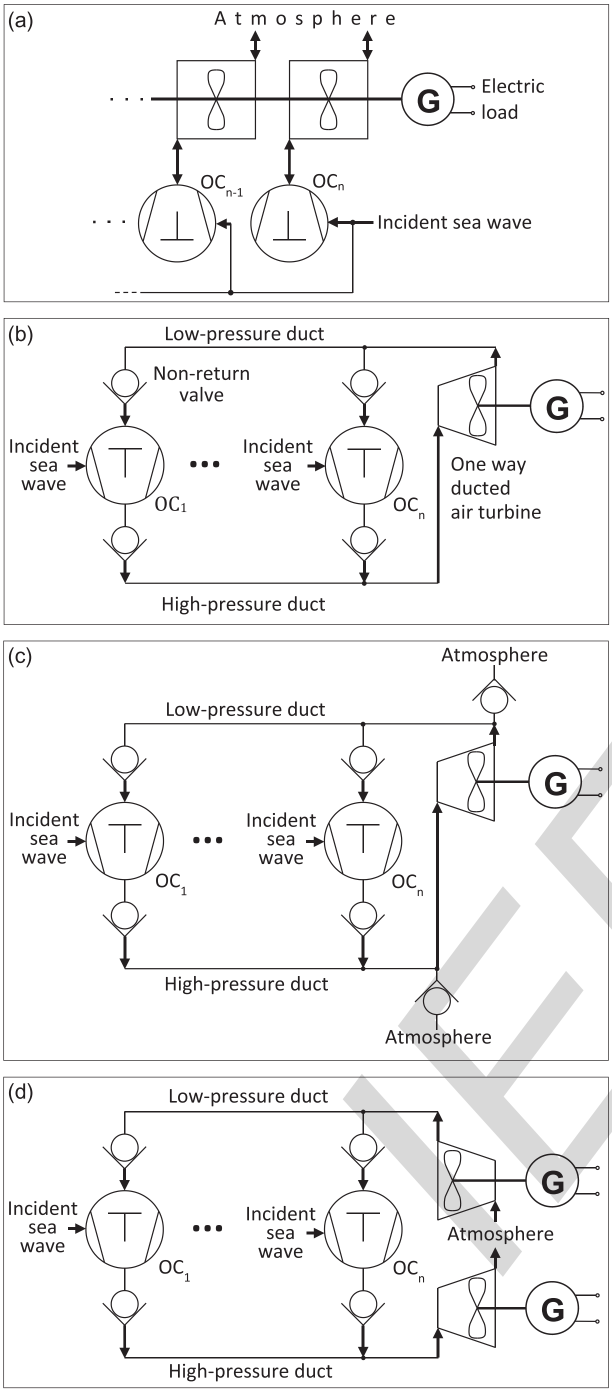

Fig. 11. Pneumatic circuits of multi-OWCs. (a) Segmented. (b) ShoreSWEC. (c) Multi-OWC in [13]. (d) FWP.

In comparison with the FWP, the multi-OWC in [13] has two valves more and then has more pressure drops. However, the absence of these balancing valves in the FWP is paid by doubling the turbogenerator. The design of both has to consider not only the chamber design to get resonance but also the overall length of the array, which have to match an integer number of wavelength of the most energetic incident waves.

The ShoreSWEC is an array of chambers mounted on the seabed to form a pair of submerged collectors coupled in a "V"-formation to a conventional unidirectional air turbine generator mounted above the water level, in a tower at the apex of the V. The oblique angle orientation to the incident waves enables its capture chambers to be activated sequentially, providing, by means of the collectors, smooth unidirectional airflow to the turbine [14].

The KNSWING is a multichamber attenuator OWC, whose first concept validation tests have been recently presented in [48] and [49]; it can be considered as a device of the third generation because it is suitable for large-scale offshore systems. The target installation site of the KNSWING is the Danish North Sea. The full-scale chamber measures are set to give a resonant period of 5.9 s. The total device length is 150 m. The PTO efficiency and rated power estimated for the chosen installation site are 65% and 2.9 MW, respectively.

III. Turbines

Single-chamber OWC plants should be equipped with the so-called self-rectifying turbines, which are able to keep the same rotation direction despite the alternating airflows. Among these turbines, the Wells is the most common, but many other different designs have been developed over the last 30 years to overcome some of its drawbacks when compared to conventional turbines, such as lower efficiency, poorer starting, stall, and higher noise level [50]. Some of the main proposed examples of suitable turbines for OWC devices are listed in Table I. Also, some open-field vertical axis wind turbines, such as the Savonius or the cross-flow turbine, which do not need reorientation when the flow comes from multiple directions, can be suitable for OWC systems and have been used for test purposes [38]. The hydrodynamic behavior of self-rectifying turbines has been already investigated in depth, and several reports compare their overall performances in steady-state and irregular wave conditions [51]. An extensive and detailed description of these turbines is beyond the objectives of this review.

Despite the large number of research projects addressing turbine design for use in OWC systems, the reported total wave-to-wire efficiencies are often low, compromising the economic feasibility of these energy plants. Thus, in literature, there are a lot of works on turbines to improve the efficiency with respect to Wells turbines, typically used for OWCs. Impulse turbines, however, are becoming more widespread and are designed to accommodate sudden spikes in pneumatic power at the input. The efficiency of impulse turbines can reach 75% [52].

Multichamber OWC, in which more caissons cooperate to generate a unidirectional airflow, should theoretically overcome this limit allowing the use of conventional air turbine, featuring a higher efficiency [53]. However, the devices that have been developed so far are at the prototype stage, and the actual improvement of the overall system efficiency with suitable turbines has not been demonstrated yet. Even though in multi-OWCs the airflow is unidirectional, its magnitudes can show a pulsed or fluctuating behavior. For this reason, the efficiency of conventional air turbines, such as the bulb axial or the Francis, is usually lower than the ones with steady flows [53]. Furthermore, the development of this ducted air turbines has been almost abandoned since the 1980s, while the evolution and the optimization of the self-rectifying ones are still in progress. Then, today, with fluctuating unidirectional flows,

TABLE I
TURBINES FOR OWCS

Type	Subtype	Device
Wells	monoplane rotor without guide vanes	Vizhinjam WEP (NIOT), OE Buoy (OceanEnergy)
	monoplane rotor with guide vanes	Mighty Wale (JAMSTEC)
	monoplane with self-pitch-controlled blades	Pico OWC Plant (Azores Pilot Plant)
	variable pitch blades	Pico OWC Plant (WavEC)
	contra-rotating rotors	LIMPET (Wavegen)
	biplane rotor without guide vanes	LIMPET (Wavegen)
Impulse turbines	with self-pitch-controlled guide	Vizhinjam WEP (NIOT)
	with fixed guide vanes	Vizhinjam WEP (NIOT), Backward Bent Duct Buoy
	with movable guide vanes	OE Buoy (OceanEnergy)
	McCormick counter rotating turbine	Kaimei (JAMSTEC)
Radial	with fixed guide vanes	--
	with active-pitch-controlled guide vanes	--
Denniss-Auld		MK1, MK2 (Oceanlinx)
HydroAir		MK3 (Oceanlinx), MRC (Orecon)
Twin Turbine		Vizhinjam WEP (NIOT)

it is not obvious to assume that the conventional turbine might be the best choice.

IV. GENERATORS

The task of an OWC is to produce airflow to be converted into electricity, as for wind generators. Therefore, the solutions adopted for open-field applications can be successfully applied to the OWCs as well, but it must be considered that the turbine and the converter will face quite harsh environmental conditions, mainly due to the presence of the saline water, vibrations, and, in floating devices, large mechanical stresses due to heavy motions during severe sea states. For this reason, although it is possible to adopt gearboxes, it is preferable to use direct-drive generators that imply the use of multipole machines.

Until the recent past, the attention of the OWC developers was mainly focused on the primary PTO mechanisms because, first, it is necessary to validate the concept of wave energy to pneumatic energy conversion and then to verify sea performance and reliability. Once the primary PTO technology has matured, from the point of view of system optimization, it is essential to begin a detailed development of the electrical PTO [54].

Compared to that of WECs, the technological evolution of turbogenerators for open-field wind energy converters is at a stage of relative maturity. Offshore wind farms, for example, operate at similar environmental conditions to those of fixed OWCs. The experience made for wind systems can be borrowed without excessive efforts in WECs. Unfortunately, for floating systems, the mechanical constraints are more stringent, and the choice of the possible generator is limited [55].

As reported in [54], there is a convergence to one or two electrical machine technologies in wind energy systems. This is due to technical and economical consideration. O'Sullivan and Lewis tried to seek whether a similar rationale can be identified in the case of floating WECs.

Since the beginning of the OWCs for electricity production experimentation, both brushed and brushless induction machines [56]–[60], as well as permanent magnet machines [61], have been used for such devices.

Since the airflow produced by the primary PTO shows large variations over time intervals of a few seconds or less, a high-dynamic speed control is necessary in order to optimize the power harvesting. A variable-speed generator-converter is required.

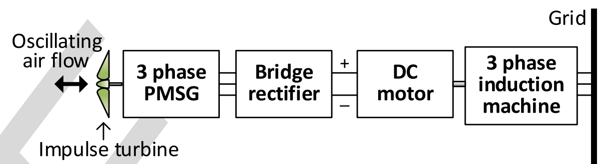

Fig. 12. Topology of the electrical PTO used in the Vizhinjam OWC plant [57].

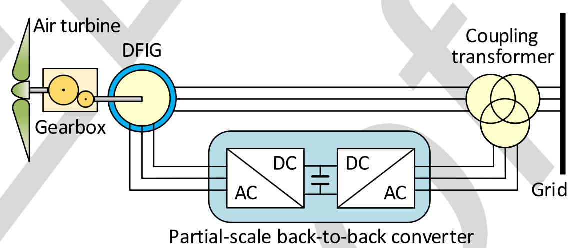

Fig. 13. Variable-speed topology with DFIG.

Over time, technological change is evident considering the first used topologies, as the one in Fig. 12 and the latest with doubly fed induction generators (DFIGs) [12] and PMSG [62] with a back-to-back converter.

The DFIG is an induction machine with the stator directly connected to the mains. The rotor terminals are available owing to a slip-ring connection. In this way, as the rotor currents can be controlled, it is possible to vary the speed of the rotating magnetic field, thus controlling the generator's speed.

The main advantage of this application (Fig. 13) is the high controllability of the generator with respect to the squirrel-cage generator directly connected to the grid. Moreover, the converter that feeds the rotor does not need to be sized for the rated power of the generator, limiting the cost of the converter, especially for high-power applications. Typically, the converter size is 30% of the stator rated power. A DIFIG allows variable speed and active/reactive controls within certain limits [63].

Considering the OWC applications, the main drawback of the DFIG is that the rotor terminals are available through brushes or slip rings that degrade over time. Although brushless DFIGs

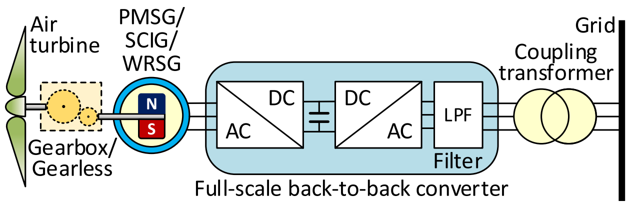

Fig. 14. Full converter topology.

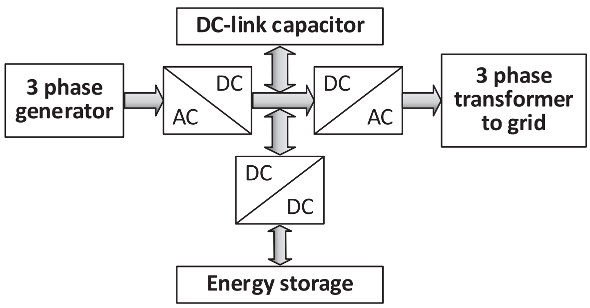

Fig. 15. Electrical energy flows in a WEC with energy storage.

are available, the control issue and the optimization of this kind of machine [64] have prevented its widespread application. Especially for offshore systems, the presence of the brushes and of the gearbox represents a reliability issue, and for this reason, the choice of a different generator/converter system may be preferable.

In the full-size converter topology (Fig. 14), the back-to-back converter has to be designed by considering the overall power of the generator. Despite the fact that this solution is commonly adopted for the permanent magnet generator (PMSG), it is possible to use a wound rotor synchronous generator and also a squirrel-cage induction generator.

The PMSG is one of the most adopted solutions for low-power systems due to its higher efficiency with respect to the induction generator [65]. In order to smooth the output power and improve the injection into the grid, an energy storage element could be added to this topology (Fig. 15). Viable technologies for this purpose are batteries, flywheels, capacitors, and superconducting magnetic energy storage [66].

For instance, in [67], supercapacitors (SCs) have been considered for an energy storage system exploiting the turbine inertia in a variable-speed control (variable power at the output of the generator). Reliability issues suggest the use of SCs in a floating OWC, as the BBDB developed by the OceanEnergy (oceanenergy.ie). Fig. 16 shows the scheme of the topology for the BBDB proposed in [68] to improve power quality.

V. Power Electronics

Regardless the OWC topology, the power electronics has to extract the energy from the turbogenerator and transfer it to the electric grid. Even if it is possible to employ an asynchronous generator directly connected to the grid without a power electronics front-end (fixed speed generator), this choice would lead to unacceptable performance of the OWC, and thus, the generator has to operate at variable speed.

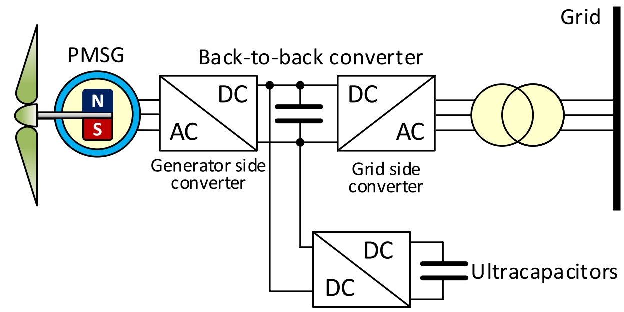

Fig. 16. Electrical PTO proposed in [68] for the BBDB OWC.

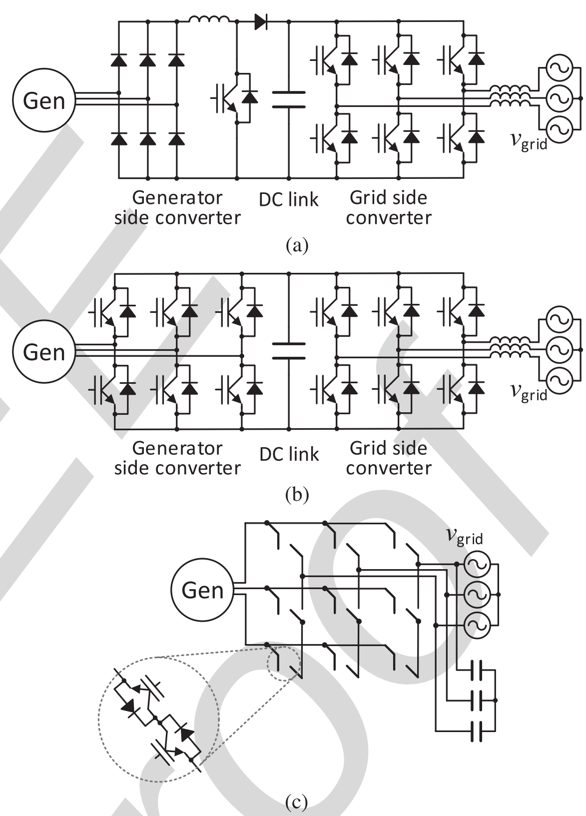

Fig. 17. AC/AC converter topologies. (a) Diode bridge rectifier followed by dc/ac converter. (b) Back-to-back. (c) Matrix converter.

The ac/ac conversion has been widely studied, once again before for wind energy power plants, and the most common solutions are the ac/dc converter [diode bridge rectifier Fig. 17(a) or active rectifier Fig. 17(b)], followed the by dc/ac converter and the matrix converter [Fig. 17(c)].

The diode bridge rectifier allows the decoupling of the two conversion stages, and standard topologies for the dc/dc converters can be employed to regulate the amplitude of the dc-link voltage. The main drawback of this solution is that the generators' currents are not directly controlled, depending on the machines' parameters; thus, the phase displacement between the currents and electromotive forces can decrease the overall system efficiency.

The active rectifier is a current-controlled voltage source converter that usually implements a field-oriented control of the machine, like an industrial drive. As in the previous solution,

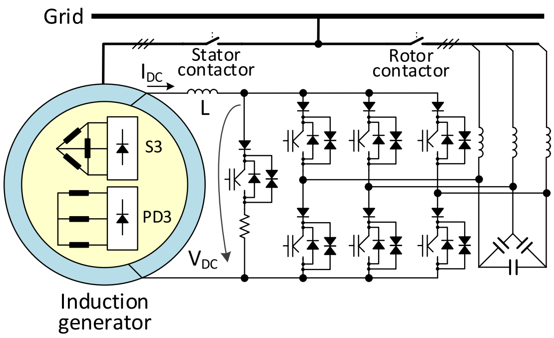

Fig. 18. Schematic of the electrical PTO of the PICO OWC. A filter reactor smooths the dc bus current supplied to the CSI and limits the CSI switching frequency currents that the rotor windings absorb. The ac capacitors are needed for the CSI commutation. Together with three inductors, they form a low-pass filter for the CSI output current [71].

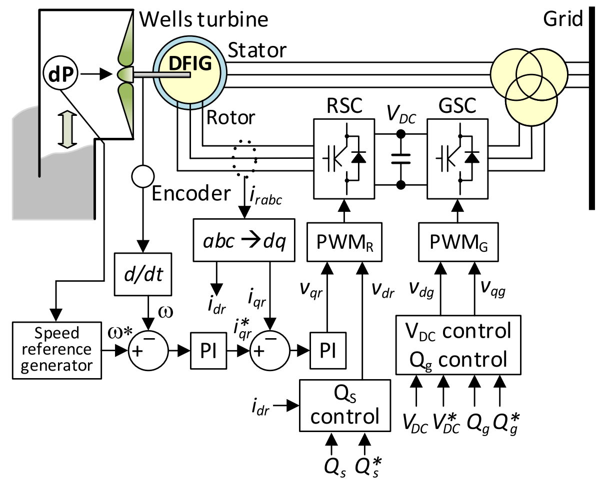

Fig. 19. Schematic of the electrical PTO of the Wavegen's Mutriku breakwater OWC [12].

the two conversion stages are decoupled, and well-known control strategies may be employed. Moreover, with the decreasing price of semiconductor devices and digital signal processors, recently, multilevel converters have become a feasible solution.

The matrix converter topology realizes a direct ac/ac conversion and does not feature a dc-link. The matrix converter control has been a topic of research in recent years. The more complex control system with respect to the topologies that imply an intermediate dc conversion and the absence of voltage boosting have limited its application, but in some cases (e.g., WEC), the absence of a dc-link made by electrolytic capacitors can represent an unmistakable advantage in terms of lifetime. On the contrary, the system cannot be used to supply reactive power, as requested for grid-connected converters by modern standards, when power is not extracted from the OWC. In addition, multilevel and fault-tolerant matrix converter drives have been investigated [69], [70].

As for the generators, a change of the state of the art over the last 20 years can be observed, as the technological evolution of power electronics and microprocessors enables us to perform increasingly complex functions.

The use of the bridge rectifier at the generator side is the simpler solution, which has been used between 1990s and 2000s [57], [59], [71]. As an example, in 1997, the use of a variable-speed electrical generator was one of the most important and innovative features of the PICO OWC plant. The major task of the project was the development of the nonconventional (at that time) power electronics and control equipment. The power electronic converter adopted for this system was a current source inverter (CSI), which has a variable dc voltage at its input and the grid voltage and frequency at its output. Fig. 18 shows the schematic of the power electronics made for the PICO OWC.

In the last five years, the back-to-back with synchronous rectifier has been increasingly adopted because it allows a more flexible control. As an example, for the Wavegen's Mutriku breakwater OWC, the electrical PTO shown in Fig. 19 has been used.

VI. Control Laws

The performance of the OWCs lies in the combined efficiency of the different stages of conversion in Fig. 1: 1) wave to pneumatic (capture chambers, valves, and ducts); 2) pneumatic to mechanical (turbine); 3) mechanical to electrical (generator); and 4) electrical to electrical (power electronics). Device limitations, such as a mismatch between wave frequencies and the resonance frequency, or airflow oscillations onto the turbine and challenges of the natural environment, such as variations in wave conditions, can affect significantly the efficiency of the overall system. Thus, in real operation, the overall efficiency has not been able to reach the theoretical values anticipated by designers. In order to solve some problems affecting the efficiency of the OWC, a control system has been introduced, applying different strategies and algorithms, with the aim of maximizing the instantaneous power output of the WEC [20].

Newer control systems of OWCs are composed of two subsystems, a wave converter control and an electrical converter control. The first one controls the rotational speed of the turbine and the airflow [72], and the second one controls the electrical variables as active and reactive powers, or the voltage of the back-to-back dc bus, to interface the generator to the grid.

A scheme of a system with control on primary and electrical PTOs can be found in [73] (Fig. 20), which presents the control applied to the Wavegen's Mutriku breakwater OWC.

Generally, a power electronics unit controls the turbogenerator of a WEC (e.g., the rotor-side converter RSC in Fig. 20), while, as grid interface, another power electronics unit (e.g., the grid-side converter GSC in Fig. 20) can be used. The choice of these units in terms of topology and rating is strongly dependent on the control laws to be applied [74]. The control strategies can increase the complexity of both the mechanical and electrical parts of an OWC. Consequently, the application of a strategy will not affect only the efficiency of the energy conversion but also other requirements such as robustness, survivability, maintenance, and, ultimately, cost of electricity produced by sea waves.

In the OWCs, the control has to meet a number of requirements, such as rotational speed allowable range, electric power quality, and acceptable fluctuations in the power supplied to the grid. Conversely, the turbine's rotational speed should match the sea conditions as much as possible to achieve an efficient sea wave conversion. Then, the approaches to maximize the power extraction from the waves and satisfy the grid connection rules

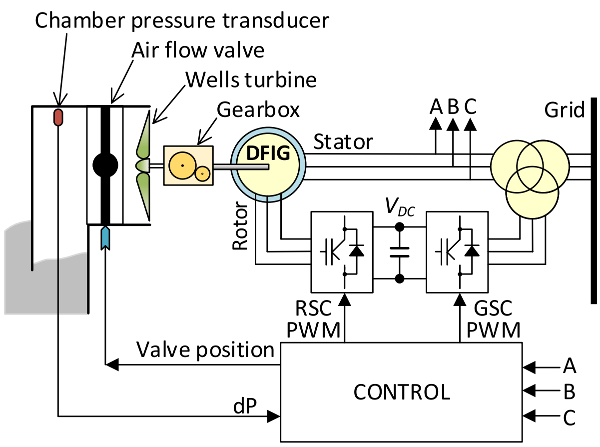

Fig. 20. System scheme of the Wavegen's Mutriku breakwater OWC [73].

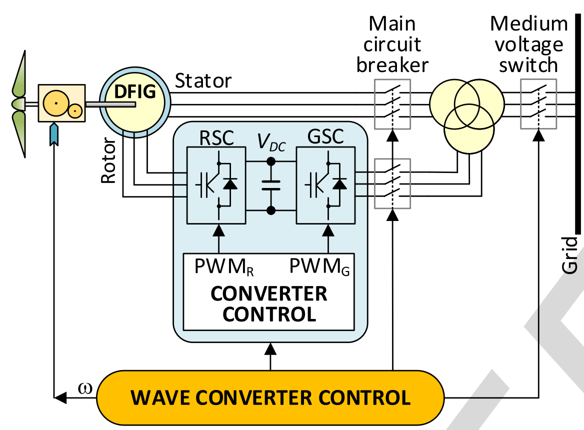

Fig. 21. Scheme of the control applied to DFIG proposed in [75].

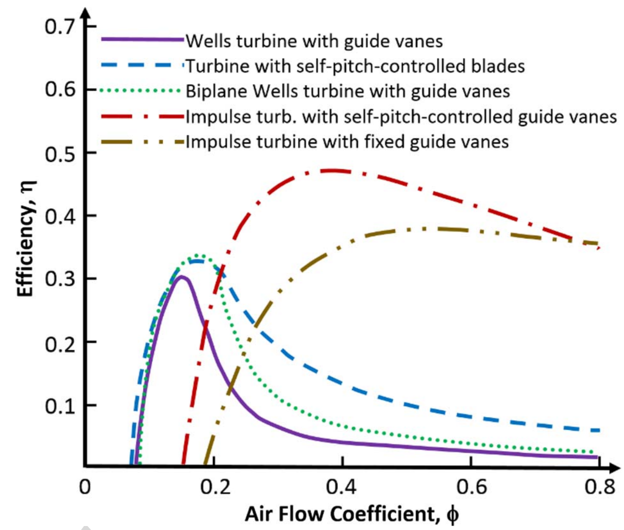

Fig. 22. Self-rectifying turbine efficiency [51].

can be different. Theoretically, as mentioned in Section IV, control strategies of wind power plants may be eligible also for OWC systems; however, not all of the state of art in this field has been applied to this technology yet. For instance, the predictive power control has been considered for an OWC application only recently [75]. The scheme of the proposed control is shown in Fig. 21.

Referring to the wind power system, classical techniques include power, speed, or torque control.

Depending on the inertia of the turbine, fixed or variable speed implementing a maximum power point tracking (MPPT) can be the most advantageous strategy. The MPPT for open-field wind systems has been the topic of several studies, and it can be pursued with different algorithms and techniques, such as perturbation and observation (P&O), or laws obtained by known mechanical performances of the turbine or neural network [76]. The scheme of the neural rotational speed control proposed in [76] is shown in Fig. 19, presented in Section V.

One of the most adopted solutions aims to track the maximum power locus depending on the rotational speed with a preprogrammed characteristic obtained from the turbine's model, like the torque reference-based MPPT method in [77]. The measurement or the evaluation of the air speed is mandatory for these methods. In literature, some works were successful in estimating the wind speed with a model of the turbine employing neural network [78] or the support-vector-regression theory [79].

In [80], an adaptive algorithm (P&O algorithm widely employed for photovoltaic converters) adjusts the duty cycle of a dc/dc converter to go toward the increasing power. The same approach was followed in [81]. In order to improve the tracking performance of the P&O method, a study of the power coefficient against a new MPPT indicator was performed in [82].

As explained before, in the case of monochamber OWC, the bidirectional wind flow implied the choice of a specific turbine technology, i.e., the Wells turbine. The Wells turbine is the most widespread solution for OWCs. However, it presents the serious issue of the stall phenomenon, which happens when the ratio between the wind velocity and the blade tip speed exceeds a specific threshold, and then, it is necessary to design the control to avoid it [83]. In order to prevent this condition, it must be ensured that the airflow coefficient is between specified limits, as shown in Fig. 22 (where the airflow coefficient ϕ is defined by the ratio between axial flow velocity VX and circumferential velocity UR), and then, several works in literature are focused on this topic.

For example, in [84], a throttle valve mounted in series with the turbine, in the duct connecting the chamber to the atmosphere, is used to control the flow through the turbine, in order to prevent or reduce the stalling losses and then to increase the amount of energy produced by the plant.

In [62], two approaches were pursued, comparing the potential benefits for low- or high-inertia turbine. In particular, if the pressure measurement inside the chamber is available, the optimum generator speed can be computed to keep the Wells turbine in the maximum efficiency region. This solution implies the presence of torque and speed loops for the generator, so there may be issues in the case of small inertia values. Without the pressure measurement, the locus of the points of maximum efficiency in the torque versus generator's speed curve can be computed offline. A lookup table linking the reference torque to the actual generator speed is used in order to make the system able to follow the maximum power point.

For multichamber OWC systems, the control issues are similar to the ones of the open-field wind energy conversion systems if the same unidirectional flow turbines are used [85]. Since these kinds of power plants are at early development stages, this research area is still to be explored.

Good summaries of the control strategies to control the rotational speed of the turbines and the airflow of single-chamber OWCs can be found in [20].

VII. Discussion

It may be noted that it is difficult to compare the performance achieved by the various experiments or operating plants because of different solutions and different boundary conditions. What is clear is that theoretical performances, in practice, are difficult to reach, although in recent years, the implementation of new and more complex control techniques is helping in reducing this difference. The development of simulation tools available to designers leads in the same direction. As a matter of fact, the ability to simulate increasingly accurate models allows faster improvements of all of the OWC's components.

The literature reading made for this work has also shown that, even if the number of published works is great, one can find more or less detailed information only about few relatively mature technologies (e.g., PICO, LIMPET, and Wavegen's Mutriku). Typically, private companies or inventors do not publish the results obtained by developments because they care to protect their patents or because results, probably considered not exiting, may misrepresent their products or ideas.

To achieve success in WEC's R&D project, it is essential to consider that a long-term development plan is needed, as well as the quite large team of experts and facilities. Consequently, great investments are unavoidable. The actions taken by governments to finance the R&D projects cannot be enough to remove the obstacles to the diffusion of the WECs. The ocean energy sector is creating a new industry, but there are not yet commercially available machines, although many projects are at an advanced stage of development. The risks for this development are large, and then, coordinated efforts and collaboration between nations to avoid repetitions and accelerate the progress are required. A good example of this kind of cooperation is the MArine Renewables Infrastructure Network for emerging Energy Technologies (MARINET), made by 29 European partners, including universities and national government research centers, industry research centers, government agencies, and industries. Among the objectives of MARINET, there is the dissemination of good practices, collected by highly experienced research groups for WEC development and the networking of a number of world-class research facilities, which can support the R&D of the ocean energy industry at all stages of development.

In addition, the dissemination of information related to the experimental results can contribute to obtaining a higher success rate of the solutions under development.

VIII. Conclusion

Some developed OWCs have been presented considering five issues: structures to convert sea waves to airflows, turbines, electric generators, power electronics, and electronic controls.

By the literature, it can be inferred that, despite decades of studies and tests to ensure features such as reliability, durability, and cost-effectiveness of these technologies, further research and development are required. Because of the hostile environment in which they must operate, the development of these systems, beyond large and advanced facilities, requires long-term projects, relying on teams composed of many people with different skills. In most cases, the need for large-size R&D budgets, rather than high costs of construction and maintenance, led to the project decommissioning. To date, the single-chamber OWCs are those in more advanced state of R&D, with the development of different structures with high survival, types of ducted self-rectifying turbines, and customized electronic controls. While the development of these three issues is typical of WECs, the power electronic topologies are borrowed from the solutions adopted for open-field wind energy converters.

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Review of Oscillating Water Column Converters

Nicola Delmonte, *Member, IEEE*, Davide Barater, *Member, IEEE*,
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***Abstract*—Ocean waves are a huge largely unexploited energy resource, and the potential for extracting energy from waves is great. Research in this area is driven by the need to meet renewable-energy targets, but it is relatively immature compared to other renewable-energy technologies. This review introduces some device types that represent the state of the art of oscillating water column technology, a kind of wave energy converter (WEC). Unlike other works in literature, typically limited to specific aspects of WECs, in this paper, a system-wide perspective will be pursued, from the sea waves to the grid connection.**

***Index Terms*—Control strategies, ducted air turbines, ocean energy, oscillating water column (OWC), wave energy converter (WEC).**

I. Introduction

In the last decade, the interest on renewable energy has grown rapidly, reaching, in some cases, a thriving market with excellent perspectives. At present, different types of technologies are under the spotlight, joining the more traditional ones, such as solar, wind, and geothermal. Among these, the exploitation of the huge resources of seas and oceans might be a valuable solution to satisfy the electricity demand as much as possible by renewables.

The technology development and the market growth of renewable energies, including the marine one, will contribute in realizing significant economic, environmental, and social objectives in the early decades of the 21st century. Then, many governments are adopting new energy generation strategies and guidelines toward an ecologically sustainable society [1]–[7].

Energy can be extracted from the sea by exploiting several physical phenomena: salinity, temperature gradient, tides, waves, and ocean currents [1]. Several devices and equipment have been developed to convert sea energy into electricity with different outcomes. Only some of them have shown results close to the theoretical predictions when tested in real operating conditions. Since neither computer simulation nor laboratory testing can effectively assess the converters' performance in any weather, the real condition trials are essential in evaluating the feasibility of wave energy converters (WECs) and their endurance in a hostile environment such as the sea [8]. Therefore, although many studies were carried out until now, research in this area is still a challenge [9], [10]. During the last 40 years, inventors and scientists have presented many ideas based on different mechanisms to convert wave energy into electricity. The scheme shown in Fig. 1 sums up the power take-off (PTO) mechanisms of WECs that can be found in literature. The energy conversion chain requires many blocks that belong to different areas of expertise, from mechanical and aeronautical engineering to electric and electronic, even in the simplest case of a direct drive, i.e., a WEC with linear generator PTO (for instance, see the authors' affiliations in [11]).

The gray-filled blocks fall in the electric engineers' expertise area. Technological problems, uncertainty of results, and high costs of installation and maintenance for the power plants are the main barriers to the deployment of these systems. In addition, there is a lack of convergence on the best method of extracting energy from the waves; thus, techniques and/or technologies implemented to optimize the powertrain are extremely diversified.

This paper is focused on oscillating water column (OWC) systems because it seems to be one of the most promising technologies among WECs to build power plants of different sizes and power ratings, with acceptable performance and low environmental impact [12]–[16]. Moreover, OWC systems exhibit a potential benefit in terms of reliability due to the moving mechanical parts that are not submerged into the seawater [17]. Although OWCs have been under development since the end of the 19th century, to build whistling buoys for navigation aid (Fig. 2), the idea to use this technique in order to produce electricity has been applied starting from 1947 to supply onboard autonomous lights of navigation buoys [19]. Tests to produce electricity with more powerful generators, which can be conveniently connected to the grid, have been started in 1970s, but the high costs of production and maintenance, together with lifetime problems, have limited their diffusion.

Unlike other reviews, mainly focused on particular aspects, as [20], where strategies for electrical control of WECs as well as energy storage techniques are the presented topics, or the more cited [17], [19], [21], without discussions about power electronics and/or controls, this paper deals with all of the components of an OWC.

This paper is organized as follows. Section II describes the operating principle of OWCs and some design aspects and provides an overview of primary PTO technologies. Sections III–V are dedicated to a survey of turbines, electrical generators, and power electronics, respectively. Sections VI shows some issues

Manuscript received April 10, 2015; revised July 7, 2015 and September 24, 2015; accepted September 28, 2015. Paper 2015-SECSC-0192.R2, presented at the 2014 IEEE Energy Conversion Congress and Exposition, Pittsburgh, PA, USA, September 20–24, and approved for publication in the IEEE Transactions on Industry Applications by the Sustainable Energy Conversion Systems Committee of the IEEE Industry Applications Society.

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Digital Object Identifier 10.1109/TIA.2015.2490629

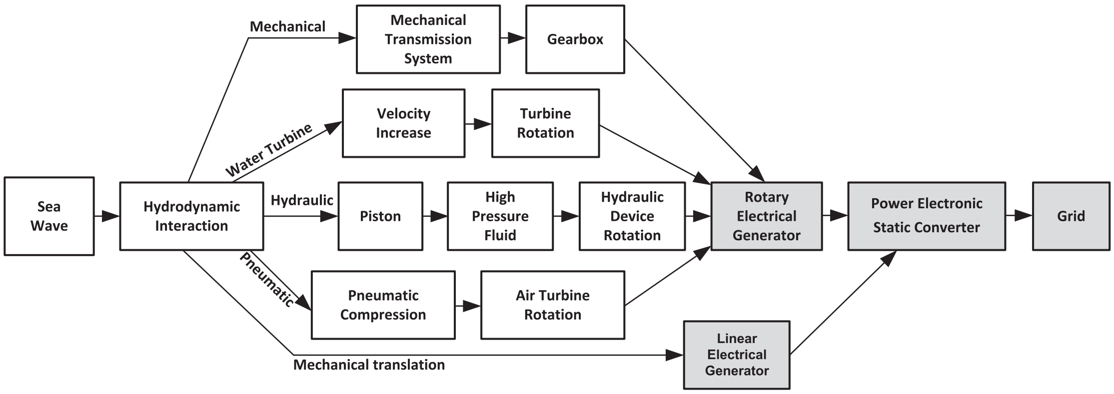

Fig. 1. Wave-to-wire power conversion alternatives.

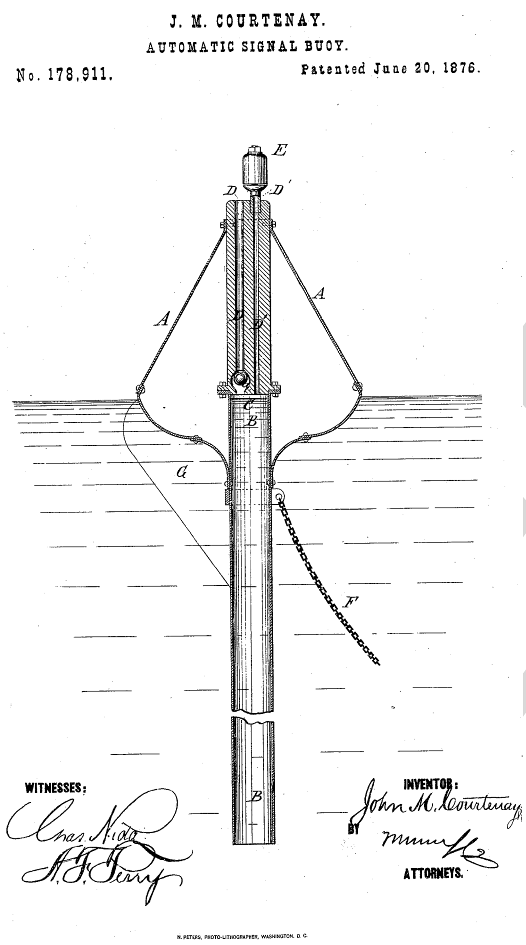

Fig. 2. Whistling buoy by OWC, patented by Courtenay in 1876 [18].

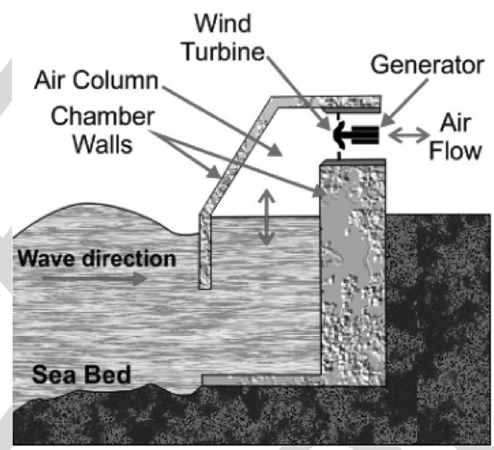

Fig. 3. Schematic vertical cross section of a single-chamber OWC.

of the control system used to improve as much as possible the efficiency of OWCs. In Section VII, a brief discussion is drawn. Finally, Section VIII presents the conclusion.

II. Wave Energy and OWC System Overview

The sea waves are mainly shaped by the wind (produced by the sun energy) blowing over the water surface. Only a little amount of the total solar irradiance on the surface of the Earth is transmitted to the seas to produce waves [8]. In oceanic areas, wind energy is transferred to waves and locally concentrated at power levels up to more than 60 kW/m of wave crest length, where relative high wave energy occurs [22]. There is no perfect regularity in sea waves. Their amplitude, energy, and direction vary randomly through the year, the seasons, or the day. While in some conditions they can change slowly from an absolute calm to 1 MW/km, in other places, they can reach 10 MW/km in a short time period (minutes). Variations shorter than a minute are also possible. In addition to this, the wave shapes are heavily affected by the characteristics of the coastlines [22].

Generally, WECs are categorized by location (shoreline, nearshore, and offshore) and type. Although the large variation in designs and concepts, depending on their shape, size, and direction of elongation with respect to the wave propagation direction, WECs can be classified into three main types: attenuators, point absorbers, and terminators.

Offshore WECs have more power at the input, but they must withstand more severe weather conditions, and both connection to the grid and maintenance are more expensive. An OWC is a partially submerged chamber where alternate pneumatic air compression and decompression take place in response to the incident wave. By means of pipes (and valves in some systems), the air can flow into a ducted wind turbine to drive an electric generator (Fig. 3). Then, the main parts of an OWC plant are one or more oscillating chambers with valves and ducts, air turbines, electric generators, and electronic power converters. Starting from this concept, many ideas have been developed.

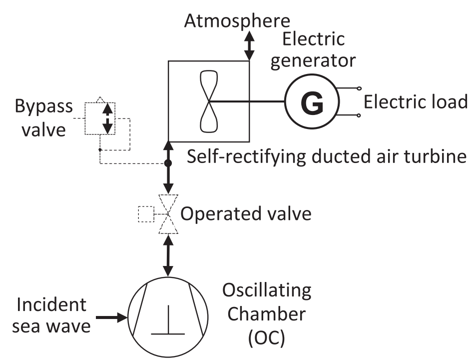

Fig. 4. Schematic of the hydropneumatic part of a single-chamber OWC. The dashed lines are depicted to represent the optional components.

OWCs can be installed either onshore, embedded in a cliff or a harbor wall, or in close proximity to the shore, standing on the seabed, or offshore in deep waters. They can be point absorbers as the Spar-buoy OWC [23], terminators as the LIMPET [24], and attenuators as the iVEC Floating Power Plant [15].

Starting from standard symbolism, the schematic of the hydropneumatic part of a single-chamber OWC can be drawn as in Fig. 4. Beyond the oscillating chamber, which acts as a piston pump, and the self-rectifying air turbine, a controlled valve to regulate the airflow can be mounted in the duct between the chamber and the turbine. To avoid the freewheeling of the turbogenerator when the electrical load is disconnected (e.g., during extreme sea conditions), one or more bypass valves can be added at the top of the oscillating chamber or just before the inlet duct of the turbine.

A. *Design Aspects*

The OWC concept differs from other WECs for a number of technological features. The most relevant of these features is associated with the oscillating chamber, which works as a pneumatic converter to obtain high-speed airflow through the air turbine by the slow internal free surface water motion. Initial design featured a vertical uniform column; then, to improve the capture efficiency (i.e., the ratio of the pneumatic energy to the hydrodynamic wave input energy [25]), many solutions were tested to reduce the entrance turbulence and internal sloshing and to increase the water plane area for a given chamber cross-sectional area. Some examples of solutions are the inclined chamber in LIMPET [24], the parabolic-shaped collector of the Oceanlinx Mark 1 [26], and the backward bent duct of the backward bent duct buoy (BBDB) [27]. The increase of the water plane area allows the coupling of the primary water column resonance to the major period of the incoming wave [28], which has a random envelop. Most OWCs operate optimally at resonance, and a key point to obtain higher efficiencies is the chamber design. Typically, the chamber sizes and shapes are chosen to produce a column whose natural frequency of oscillation coincides with that of the most occurring wave at the location where the OWC will be installed [29]. The variability of sea state conditions can affect the OWC feasibility because the size and shape of the structure cannot be modified. Phase-locking mechanisms were developed to improve the performance when the devices are out of resonance [30], [31]. Dynamic tuning devices have been developed to maintain a resonant condition despite the variations in the wave spectra to the most occurring waves [32], but in this case, the OWC is used for a kinetic–kinetic conversion, instead of converting kinetic energy into electricity.

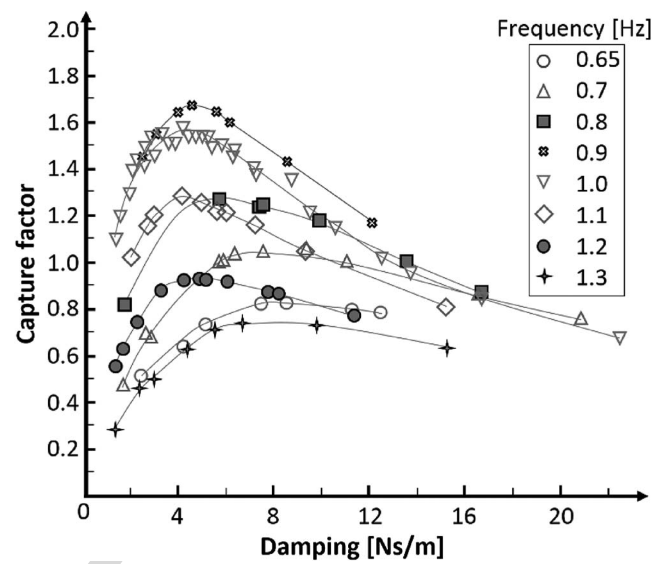

Fig. 5. OWCs' characteristics used in [33].

Another key point of the OWC design is the coupling between the chamber and the turbogenerator. The overall plant efficiency is the product of the efficiencies of each stage in the conversion chain of Fig. 1. As the turbine serves as a damping for the chamber, the overall plant efficiency is affected by the turbine and its state of rotation, which, in turn, depends on the electrical generator and its working state. As an example, in [33], the graph of Fig. 5 can be found, which reports the result of the tests done on a prototype based on the Indian Wave Energy plant with regular waves, for various values of damping. The graph shows the dependence of the capture efficiency on the turbine damping and the incident wave.

The operating state of the electrical generator can be influenced by a control applied to the power electronics used as interface to the grid, and this has been addressed by a number of works in the literature [20].

B. *Power Plants*

The literature review has been organized into two categories:

1) the more mature onshore and nearshore OWCs;
2) the floating OWCs, which are designed to operate at a wide variety of nearshore and offshore sites where higher wave energy is available.

As can be seen in the following, the second-generation systems are at the early R&D stage. The development of floating OWCs allows designing large-scale offshore devices, both in terms of physical size and power rating, which can be considered as the third-generation systems.

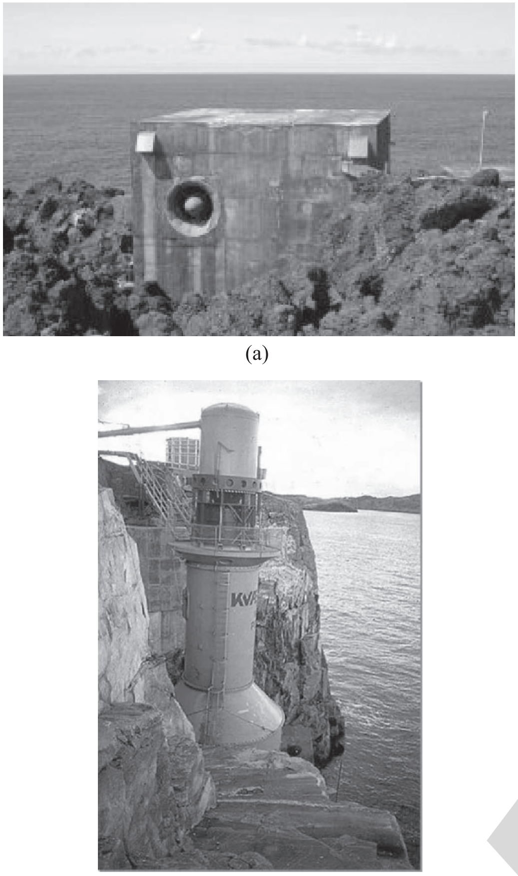

Fig. 6. Shoreline OWCs. (a) Pico OWC Plant [34]. (b) Demonstration plant at Toftestallen (photograph courtesy of Johannes Falnes).

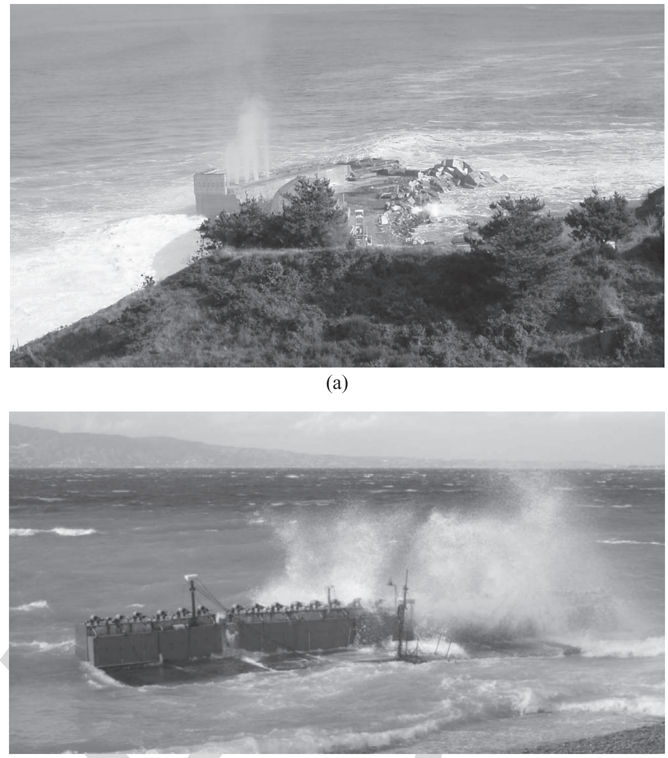

Fig. 7. Breakwaters with OWC. (a) Wavegen's Mutriku breakwater [4]. (b) REWEC prototype (photograph courtesy of wavenergy.it).

1) Shoreline Power Plants: The most famous developed systems are based on a concrete caisson built on the coast, with the bottom side open to the sea in order to create an air chamber. In these OWCs, the air can be channeled through a bidirectional turbine. Depending on the size and the volume of the waves, such shoreline power plants may have power ratings from a few hundred kilowatts up to a few megawatts. Good examples of this technology are the following.

1) The Pico OWC [Fig. 6(a)], built as a pilot plant, to demonstrate the technical feasibility of wave energy. The project started in 1992, and its construction was ended in 1999. Nevertheless, several technical problems caused the interruption of the project until 2005, when the first test ran. Significant improvements have been obtained only after 2009. The main problem comes from the vibrations generated by the turbogenerator.
2) The LIMPET, the first commercial-scale grid-connected wave energy plant. It was commissioned in November 2000, off the Scottish Isle of Islay, and it is still operating today. Originally, LIMPET was equipped with a 500-kW Wells turbine, which was later downgraded to 250 kW.

Before Pico and LIMPET onshore OWCs, in 1985, a 500-kW demonstration plant was built at Toftestallen, Norway [Fig. 6(b)]. This plant operated for around three years before being partly destroyed by a severe winter storm, and it was subsequently decommissioned.

2) Breakwater Power Plants: In this kind of systems, the power plant is integrated into a newly build coastal structure, such as a harbor breakwater or a coastal protection. The main advantage of this approach is the significant reduction of the power plant cost.

The world's first built breakwater wave power plant was commissioned in 2011 on the Spanish Atlantic coast at Mutriku [Fig. 7(a)]. It consists of 16 single-chamber OWCs, each one with a Wells turbine, and the total nominal output power is around 300 kW (the power rate could be much higher in locations where waves are more powerful) [35]. It was built into the breakwater around a harbor, which was rebuilt by the local municipality. This enabled the use of existing infrastructure (mains connection, access roads, etc.), resulting in a cost savings. The Mutriku power plant has been operated successfully since its opening and is currently the only commercially operated power station by OWC in the world.

Another interesting breakwater OWC, named REWEC3 [Fig. 7(b)], is under development in Italy. The OWC structure has been integrated in new docks. It employs an additional vertical duct (U-OWC) that achieves an eigenperiod greater than that of a conventional OWC [36], [37].

3) Floating OWCs: Other examples of OWC devices include the Australian Oceanlinx (Fig. 8), the Irish floating OE buoy, the Japanese Mighty Whale, the Osprey, and the Portuguese Spar Buoy. These devices are not located on the shoreline but just in shallow water (less than 20 m deep), so they are classified as nearshore point absorber plants. These have the advantage of larger waves, but they are in a more challenging environment.

Fig. 8. Floating OWC: Oceanlinx MK1 full-scale prototype [34].

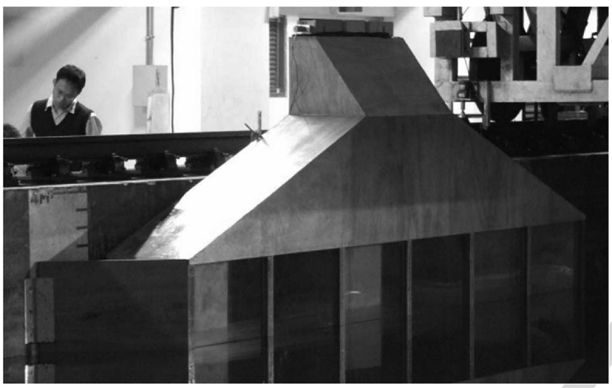

Fig. 9. Scaled prototype of a three-chamber segmented OWC for wave flume tests [40].

As an example, the first Osprey prototype, made of steel, was destroyed during a storm in 1995.

Except for Oceanlinx, which was successfully tested and which is now getting precommercial products, all of the other projects have been dismissed or suspended after a period of testing in the sea.

4) Multichamber OWCs: The last kind of technology considered here is that of OWCs based on the array of chambers. Under this category, three types of plants can be distinguished.

1) OWC array, many chambers, everyone with its own turbine generator, mounted in a single frame, as in the Orecon MRC, or the Oceanlinx MK3.
2) Segmented OWC, some chambers, each one with its own turbine, mounted in a single frame connected to a single electric generator [38], [39]. Fig. 9 shows a photograph of a scaled prototype of this kind of WEC.
3) Modular OWC, many chambers cooperate to produce a unidirectional airflow. Although *ad hoc* valves are required, this solution allows the use of conventional turbines instead of the self-rectifying ones adopted for the other OWC plants.

The first ideas of multichamber OWCs have been experimented from the late 1980s. Some examples are the following: 1) the Japanese breakwater at Sakata Port based on four caissons that produce airflows feeding two Wells turbines connected to the same electric generator [41]; 2) the 30-kW multi-OWC built in 1987 in the Kujukuri (Japan) harbor [42], which uses pressure storage vessels to supply conventional turbines without reversing the airflow; and 3) the Twin-OWC composed of two adjacent chambers producing unidirectional airflows through the same conventional air turbine [43].

Fig. 10. Leancon's scale 1:10 offshore test (photograph courtesy of Kurt Due Rasmussen).

An Italian OWC described by Martinelli *et al.* [13], the ShoreSWEC (South Africa) [44], [45], the Leancon, and the iVEC Floating Wave Power (FWP) plant (Australia) [46] can be cited as newer multi-OWCs.

The OWC in [13] and the FWP are based on a modular and scalable design, promoted to be assembled with a total power rate ranging from a few kilowatts to greater than 50 MW. The OWC in [13] and the ShoreSWEC performances have been simulated and/or tested only in wave flumes or tanks, while the FWP has been experimented also in a real environment in 2009. In spite of the initial encouraging results, no new developments in the FWP project are reported in literature. In addition, the Leancon's WEC [47] was tested in wave flume and tank. Leancon completed offshore tests using a 1 : 40 scaled prototype. In July 2015, Leancon had also launched offshore tests with a 1 : 10 scaled prototype (Fig. 10).

The multichamber OWCs mentioned in this paper can be considered as the second generation of this kind of WEC. Even if today it is not possible to foresee their commercially operating phase, they are hypothetically more promising than the previous chamber OWCs. The PTO schematics inferred by literature are drawn in Fig. 11. They can be useful is comparing the different solutions.

The segmented multi-OWC does not require nonreturn valves, and then, possible less head losses, together with the simpler structure, can be the advantages, with respect to the other solutions. A disadvantage arises from the use of self-rectifying turbines that usually are less efficient than the standard ones working with unidirectional airflows.

In order to compare the other three solutions, let us assume that the chamber arrays are equal, as well as the ducts, the valves, and the efficiencies of the turbines.

As it can be noted by the patent [45], in the ShoreSWEC, the pneumatic circuit is closed, and then, the mass balance requires that the total airflow of the chambers where the water column is moving up has to be equal to the total one of the chambers where the column is moving down. Thus, compared to the multi-OWC in [44] and the FWP, where the mass balance takes into account airflows getting to and from the atmosphere, there are matching losses between the high-pressure and low-pressure duct flows.

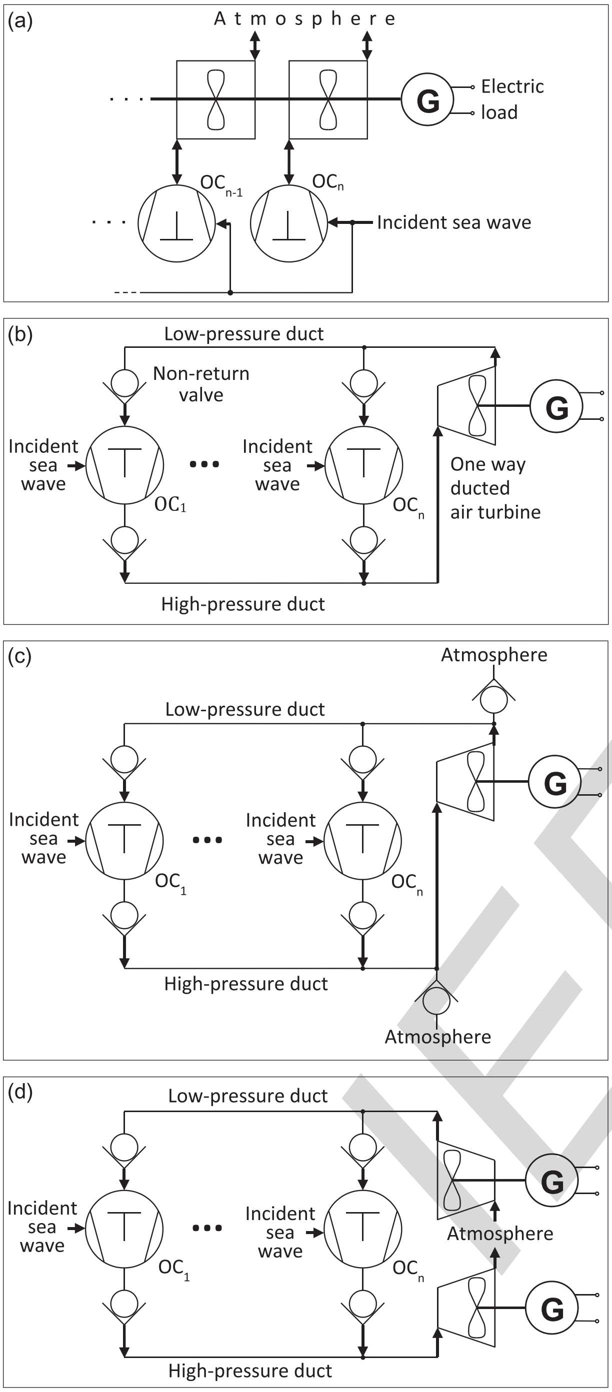

Fig. 11. Pneumatic circuits of multi-OWCs. (a) Segmented. (b) ShoreSWEC. (c) Multi-OWC in [13]. (d) FWP.

In comparison with the FWP, the multi-OWC in [13] has two valves more and then has more pressure drops. However, the absence of these balancing valves in the FWP is paid by doubling the turbogenerator. The design of both has to consider not only the chamber design to get resonance but also the overall length of the array, which have to match an integer number of wavelength of the most energetic incident waves.

The ShoreSWEC is an array of chambers mounted on the seabed to form a pair of submerged collectors coupled in a "V"-formation to a conventional unidirectional air turbine generator mounted above the water level, in a tower at the apex of the V. The oblique angle orientation to the incident waves enables its capture chambers to be activated sequentially, providing, by means of the collectors, smooth unidirectional airflow to the turbine [14].

The KNSWING is a multichamber attenuator OWC, whose first concept validation tests have been recently presented in [48] and [49]; it can be considered as a device of the third generation because it is suitable for large-scale offshore systems. The target installation site of the KNSWING is the Danish North Sea. The full-scale chamber measures are set to give a resonant period of 5.9 s. The total device length is 150 m. The PTO efficiency and rated power estimated for the chosen installation site are 65% and 2.9 MW, respectively.

III. Turbines

Single-chamber OWC plants should be equipped with the so-called self-rectifying turbines, which are able to keep the same rotation direction despite the alternating airflows. Among these turbines, the Wells is the most common, but many other different designs have been developed over the last 30 years to overcome some of its drawbacks when compared to conventional turbines, such as lower efficiency, poorer starting, stall, and higher noise level [50]. Some of the main proposed examples of suitable turbines for OWC devices are listed in Table I. Also, some open-field vertical axis wind turbines, such as the Savonius or the cross-flow turbine, which do not need reorientation when the flow comes from multiple directions, can be suitable for OWC systems and have been used for test purposes [38]. The hydrodynamic behavior of self-rectifying turbines has been already investigated in depth, and several reports compare their overall performances in steady-state and irregular wave conditions [51]. An extensive and detailed description of these turbines is beyond the objectives of this review.

Despite the large number of research projects addressing turbine design for use in OWC systems, the reported total wave-to-wire efficiencies are often low, compromising the economic feasibility of these energy plants. Thus, in literature, there are a lot of works on turbines to improve the efficiency with respect to Wells turbines, typically used for OWCs. Impulse turbines, however, are becoming more widespread and are designed to accommodate sudden spikes in pneumatic power at the input. The efficiency of impulse turbines can reach 75% [52].

Multichamber OWC, in which more caissons cooperate to generate a unidirectional airflow, should theoretically overcome this limit allowing the use of conventional air turbine, featuring a higher efficiency [53]. However, the devices that have been developed so far are at the prototype stage, and the actual improvement of the overall system efficiency with suitable turbines has not been demonstrated yet. Even though in multi-OWCs the airflow is unidirectional, its magnitudes can show a pulsed or fluctuating behavior. For this reason, the efficiency of conventional air turbines, such as the bulb axial or the Francis, is usually lower than the ones with steady flows [53]. Furthermore, the development of this ducted air turbines has been almost abandoned since the 1980s, while the evolution and the optimization of the self-rectifying ones are still in progress. Then, today, with fluctuating unidirectional flows,

TABLE I
TURBINES FOR OWCs

Type	Subtype	Device
Wells	monoplane rotor without guide vanes	Vizhinjam WEP (NIOT), OE Buoy (OceanEnergy)
	monoplane rotor with guide vanes	Mighty Wale (JAMSTEC)
	monoplane with self-pitch-controlled blades	Pico OWC Plant (Azores Pilot Plant)
	variable pitch blades	Pico OWC Plant (WavEC)
	contra-rotating rotors	LIMPET (Wavegen)
	biplane rotor without guide vanes	LIMPET (Wavegen)
Impulse turbines	with self-pitch-controlled guide	Vizhinjam WEP (NIOT)
	with fixed guide vanes	Vizhinjam WEP (NIOT), Backward Bent Duct Buoy
	with movable guide vanes	OE Buoy (OceanEnergy)
	McCormick counter rotating turbine	Kaimei (JAMSTEC)
Radial	with fixed guide vanes	--
	with active-pitch-controlled guide vanes	--
Denniss-Auld		MK1, MK2 (Oceanlinx)
HydroAir		MK3 (Oceanlinx), MRC (Orecon)
Twin Turbine		Vizhinjam WEP (NIOT)

it is not obvious to assume that the conventional turbine might be the best choice.

IV. GENERATORS

The task of an OWC is to produce airflow to be converted into electricity, as for wind generators. Therefore, the solutions adopted for open-field applications can be successfully applied to the OWCs as well, but it must be considered that the turbine and the converter will face quite harsh environmental conditions, mainly due to the presence of the saline water, vibrations, and, in floating devices, large mechanical stresses due to heavy motions during severe sea states. For this reason, although it is possible to adopt gearboxes, it is preferable to use direct-drive generators that imply the use of multipole machines.

Until the recent past, the attention of the OWC developers was mainly focused on the primary PTO mechanisms because, first, it is necessary to validate the concept of wave energy to pneumatic energy conversion and then to verify sea performance and reliability. Once the primary PTO technology has matured, from the point of view of system optimization, it is essential to begin a detailed development of the electrical PTO [54].

Compared to that of WECs, the technological evolution of turbogenerators for open-field wind energy converters is at a stage of relative maturity. Offshore wind farms, for example, operate at similar environmental conditions to those of fixed OWCs. The experience made for wind systems can be borrowed without excessive efforts in WECs. Unfortunately, for floating systems, the mechanical constraints are more stringent, and the choice of the possible generator is limited [55].

As reported in [54], there is a convergence to one or two electrical machine technologies in wind energy systems. This is due to technical and economical consideration. O'Sullivan and Lewis tried to seek whether a similar rationale can be identified in the case of floating WECs.

Since the beginning of the OWCs for electricity production experimentation, both brushed and brushless induction machines [56]–[60], as well as permanent magnet machines [61], have been used for such devices.

Since the airflow produced by the primary PTO shows large variations over time intervals of a few seconds or less, a high-dynamic speed control is necessary in order to optimize the power harvesting. A variable-speed generator-converter is required.

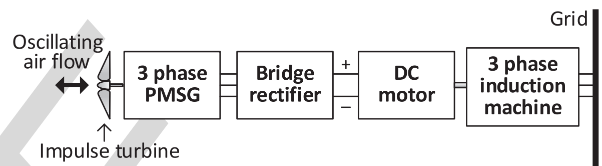

Fig. 12. Topology of the electrical PTO used in the Vizhinjam OWC plant [57].

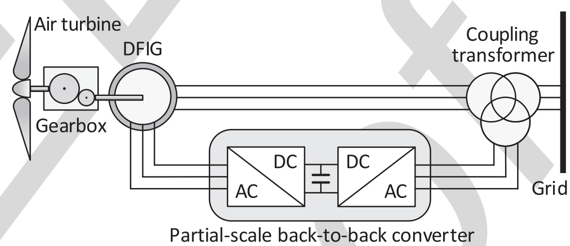

Fig. 13. Variable-speed topology with DFIG.

Over time, technological change is evident considering the first used topologies, as the one in Fig. 12 and the latest with doubly fed induction generators (DFIGs) [12] and PMSG [62] with a back-to-back converter.

The DFIG is an induction machine with the stator directly connected to the mains. The rotor terminals are available owing to a slip-ring connection. In this way, as the rotor currents can be controlled, it is possible to vary the speed of the rotating magnetic field, thus controlling the generator's speed.

The main advantage of this application (Fig. 13) is the high controllability of the generator with respect to the squirrel-cage generator directly connected to the grid. Moreover, the converter that feeds the rotor does not need to be sized for the rated power of the generator, limiting the cost of the converter, especially for high-power applications. Typically, the converter size is 30% of the stator rated power. A DIFIG allows variable speed and active/reactive controls within certain limits [63]. AQ3

Considering the OWC applications, the main drawback of the DFIG is that the rotor terminals are available through brushes or slip rings that degrade over time. Although brushless DFIGs

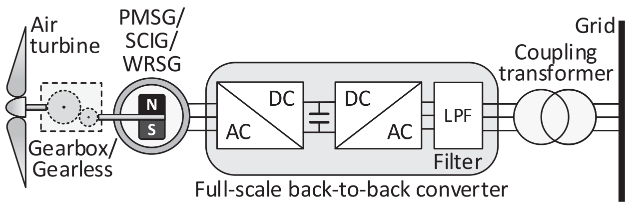

Fig. 14. Full converter topology.

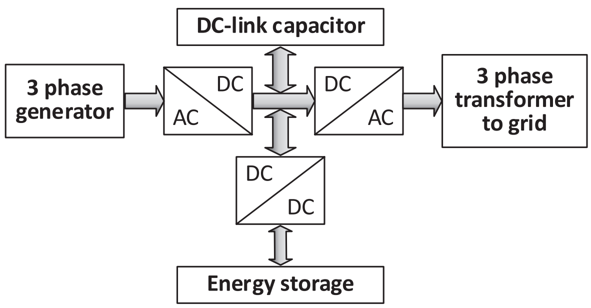

Fig. 15. Electrical energy flows in a WEC with energy storage.

are available, the control issue and the optimization of this kind of machine [64] have prevented its widespread application. Especially for offshore systems, the presence of the brushes and of the gearbox represents a reliability issue, and for this reason, the choice of a different generator/converter system may be preferable.

In the full-size converter topology (Fig. 14), the back-to-back converter has to be designed by considering the overall power of the generator. Despite the fact that this solution is commonly adopted for the permanent magnet generator (PMSG), it is possible to use a wound rotor synchronous generator and also a squirrel-cage induction generator.

The PMSG is one of the most adopted solutions for low-power systems due to its higher efficiency with respect to the induction generator [65]. In order to smooth the output power and improve the injection into the grid, an energy storage element could be added to this topology (Fig. 15). Viable technologies for this purpose are batteries, flywheels, capacitors, and superconducting magnetic energy storage [66].

For instance, in [67], supercapacitors (SCs) have been considered for an energy storage system exploiting the turbine inertia in a variable-speed control (variable power at the output of the generator). Reliability issues suggest the use of SCs in a floating OWC, as the BBDB developed by the OceanEnergy (oceanenergy.ie). Fig. 16 shows the scheme of the topology for the BBDB proposed in [68] to improve power quality.

V. Power Electronics

Regardless the OWC topology, the power electronics has to extract the energy from the turbogenerator and transfer it to the electric grid. Even if it is possible to employ an asynchronous generator directly connected to the grid without a power electronics front-end (fixed speed generator), this choice would lead to unacceptable performance of the OWC, and thus, the generator has to operate at variable speed.

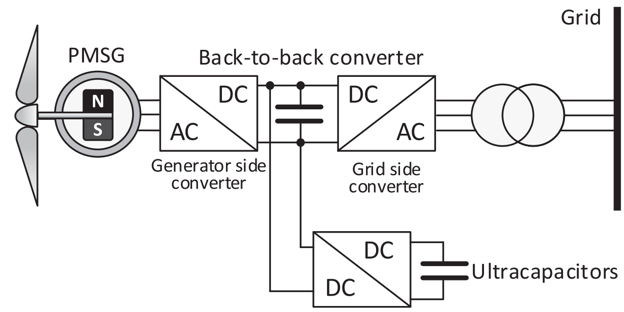

Fig. 16. Electrical PTO proposed in [68] for the BBDB OWC.

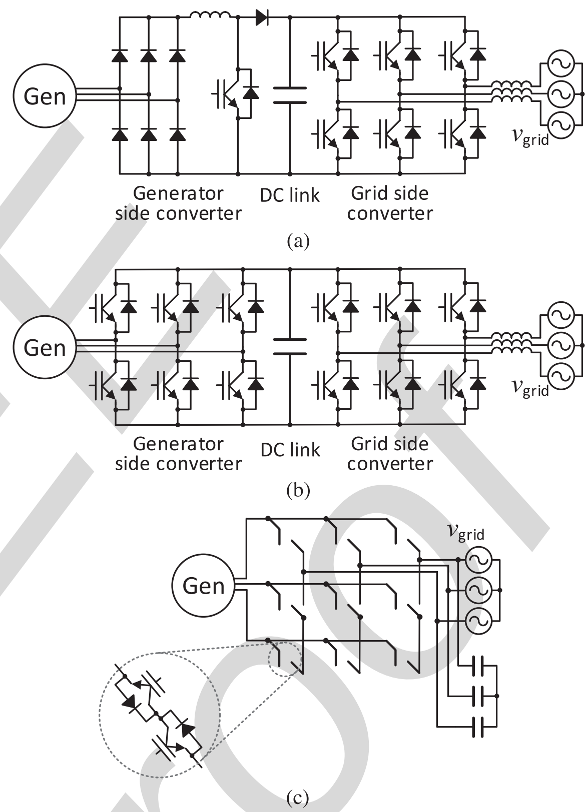

Fig. 17. AC/AC converter topologies. (a) Diode bridge rectifier followed by dc/ac converter. (b) Back-to-back. (c) Matrix converter.

The ac/ac conversion has been widely studied, once again before for wind energy power plants, and the most common solutions are the ac/dc converter [diode bridge rectifier Fig. 17(a) or active rectifier Fig. 17(b)], followed the by dc/ac converter and the matrix converter [Fig. 17(c)].

The diode bridge rectifier allows the decoupling of the two conversion stages, and standard topologies for the dc/dc converters can be employed to regulate the amplitude of the dc-link voltage. The main drawback of this solution is that the generators' currents are not directly controlled, depending on the machines' parameters; thus, the phase displacement between the currents and electromotive forces can decrease the overall system efficiency.

The active rectifier is a current-controlled voltage source converter that usually implements a field-oriented control of the machine, like an industrial drive. As in the previous solution,

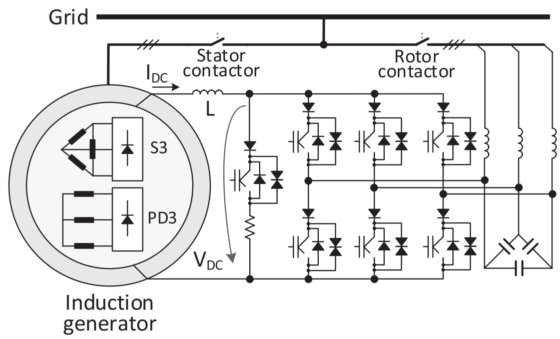

Fig. 18. Schematic of the electrical PTO of the PICO OWC. A filter reactor smooths the dc bus current supplied to the CSI and limits the CSI switching frequency currents that the rotor windings absorb. The ac capacitors are needed for the CSI commutation. Together with three inductors, they form a low-pass filter for the CSI output current [71].

the two conversion stages are decoupled, and well-known control strategies may be employed. Moreover, with the decreasing price of semiconductor devices and digital signal processors, recently, multilevel converters have become a feasible solution.

The matrix converter topology realizes a direct ac/ac conversion and does not feature a dc-link. The matrix converter control has been a topic of research in recent years. The more complex control system with respect to the topologies that imply an intermediate dc conversion and the absence of voltage boosting have limited its application, but in some cases (e.g., WEC), the absence of a dc-link made by electrolytic capacitors can represent an unmistakable advantage in terms of lifetime. On the contrary, the system cannot be used to supply reactive power, as requested for grid-connected converters by modern standards, when power is not extracted from the OWC. In addition, multilevel and fault-tolerant matrix converter drives have been investigated [69], [70].

As for the generators, a change of the state of the art over the last 20 years can be observed, as the technological evolution of power electronics and microprocessors enables us to perform increasingly complex functions.

The use of the bridge rectifier at the generator side is the simpler solution, which has been used between 1990s and 2000s [57], [59], [71]. As an example, in 1997, the use of a variable-speed electrical generator was one of the most important and innovative features of the PICO OWC plant. The major task of the project was the development of the nonconventional (at that time) power electronics and control equipment. The power electronic converter adopted for this system was a current source inverter (CSI), which has a variable dc voltage at its input and the grid voltage and frequency at its output. Fig. 18 shows the schematic of the power electronics made for the PICO OWC.

In the last five years, the back-to-back with synchronous rectifier has been increasingly adopted because it allows a more flexible control. As an example, for the Wavegen's Mutriku breakwater OWC, the electrical PTO shown in Fig. 19 has been used.

VI. Control Laws

The performance of the OWCs lies in the combined efficiency of the different stages of conversion in Fig. 1: 1) wave to pneumatic (capture chambers, valves, and ducts); 2) pneumatic

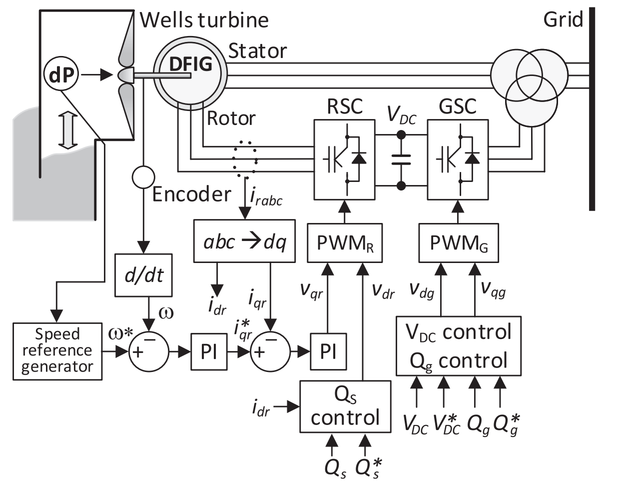

Fig. 19. Schematic of the electrical PTO of the Wavegen's Mutriku breakwater OWC [12].

to mechanical (turbine); 3) mechanical to electrical (generator); and 4) electrical to electrical (power electronics). Device limitations, such as a mismatch between wave frequencies and the resonance frequency, or airflow oscillations onto the turbine and challenges of the natural environment, such as variations in wave conditions, can affect significantly the efficiency of the overall system. Thus, in real operation, the overall efficiency has not been able to reach the theoretical values anticipated by designers. In order to solve some problems affecting the efficiency of the OWC, a control system has been introduced, applying different strategies and algorithms, with the aim of maximizing the instantaneous power output of the WEC [20].

Newer control systems of OWCs are composed of two subsystems, a wave converter control and an electrical converter control. The first one controls the rotational speed of the turbine and the airflow [72], and the second one controls the electrical variables as active and reactive powers, or the voltage of the back-to-back dc bus, to interface the generator to the grid.

A scheme of a system with control on primary and electrical PTOs can be found in [73] (Fig. 20), which presents the control applied to the Wavegen's Mutriku breakwater OWC.

Generally, a power electronics unit controls the turbogenerator of a WEC (e.g., the rotor-side converter RSC in Fig. 20), while, as grid interface, another power electronics unit (e.g., the grid-side converter GSC in Fig. 20) can be used. The choice of these units in terms of topology and rating is strongly dependent on the control laws to be applied [74]. The control strategies can increase the complexity of both the mechanical and electrical parts of an OWC. Consequently, the application of a strategy will not affect only the efficiency of the energy conversion but also other requirements such as robustness, survivability, maintenance, and, ultimately, cost of electricity produced by sea waves.

In the OWCs, the control has to meet a number of requirements, such as rotational speed allowable range, electric power quality, and acceptable fluctuations in the power supplied to the grid. Conversely, the turbine's rotational speed should match the sea conditions as much as possible to achieve an efficient sea wave conversion. Then, the approaches to maximize the power extraction from the waves and satisfy the grid connection rules

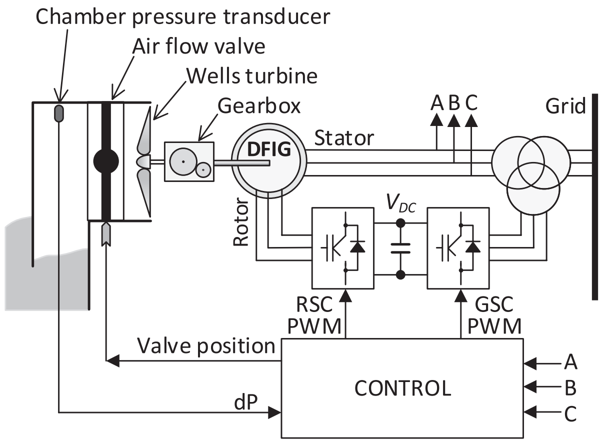

Fig. 20. System scheme of the Wavegen's Mutriku breakwater OWC [73].

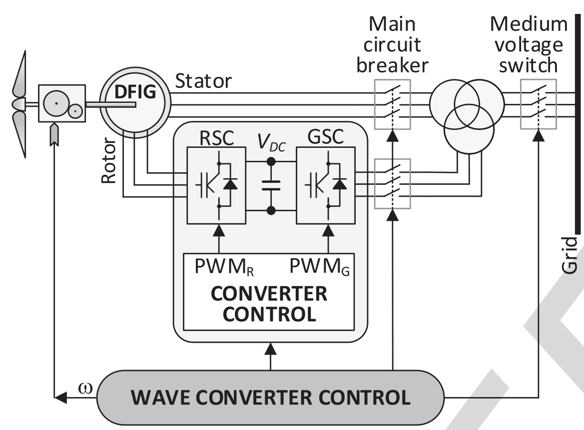

Fig. 21. Scheme of the control applied to DFIG proposed in [75].

can be different. Theoretically, as mentioned in Section IV, control strategies of wind power plants may be eligible also for OWC systems; however, not all of the state of art in this field has been applied to this technology yet. For instance, the predictive power control has been considered for an OWC application only recently [75]. The scheme of the proposed control is shown in Fig. 21.

Referring to the wind power system, classical techniques include power, speed, or torque control.

Depending on the inertia of the turbine, fixed or variable speed implementing a maximum power point tracking (MPPT) can be the most advantageous strategy. The MPPT for open-field wind systems has been the topic of several studies, and it can be pursued with different algorithms and techniques, such as perturbation and observation (P&O), or laws obtained by known mechanical performances of the turbine or neural network [76]. The scheme of the neural rotational speed control proposed in [76] is shown in Fig. 19, presented in Section V.

One of the most adopted solutions aims to track the maximum power locus depending on the rotational speed with a pre-programmed characteristic obtained from the turbine's model, like the torque reference-based MPPT method in [77]. The measurement or the evaluation of the air speed is mandatory for these methods. In literature, some works were successful in estimating the wind speed with a model of the turbine

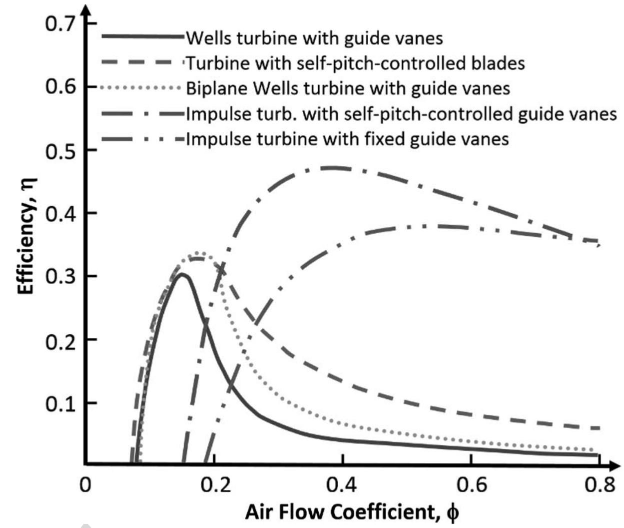

Fig. 22. Self-rectifying turbine efficiency [51].

employing neural network [78] or the support-vector-regression theory [79].

In [80], an adaptive algorithm (P&O algorithm widely employed for photovoltaic converters) adjusts the duty cycle of a dc/dc converter to go toward the increasing power. The same approach was followed in [81]. In order to improve the tracking performance of the P&O method, a study of the power coefficient against a new MPPT indicator was performed in [82].

As explained before, in the case of monochamber OWC, the bidirectional wind flow implied the choice of a specific turbine technology, i.e., the Wells turbine. The Wells turbine is the most widespread solution for OWCs. However, it presents the serious issue of the stall phenomenon, which happens when the ratio between the wind velocity and the blade tip speed exceeds a specific threshold, and then, it is necessary to design the control to avoid it [83]. In order to prevent this condition, it must be ensured that the airflow coefficient is between specified limits, as shown in Fig. 22 (where the airflow coefficient ϕ is defined by the ratio between axial flow velocity VX and circumferential velocity UR), and then, several works in literature are focused on this topic.

For example, in [84], a throttle valve mounted in series with the turbine, in the duct connecting the chamber to the atmosphere, is used to control the flow through the turbine, in order to prevent or reduce the stalling losses and then to increase the amount of energy produced by the plant.

In [62], two approaches were pursued, comparing the potential benefits for low- or high-inertia turbine. In particular, if the pressure measurement inside the chamber is available, the optimum generator speed can be computed to keep the Wells turbine in the maximum efficiency region. This solution implies the presence of torque and speed loops for the generator, so there may be issues in the case of small inertia values. Without the pressure measurement, the locus of the points of maximum efficiency in the torque versus generator's speed curve can be computed offline. A lookup table linking the reference torque to the actual generator speed is used in order to make the system able to follow the maximum power point.

For multichamber OWC systems, the control issues are similar to the ones of the open-field wind energy conversion systems if the same unidirectional flow turbines are used [85]. Since these kinds of power plants are at early development stages, this research area is still to be explored.

Good summaries of the control strategies to control the rotational speed of the turbines and the airflow of single-chamber OWCs can be found in [20].

VII. Discussion

It may be noted that it is difficult to compare the performance achieved by the various experiments or operating plants because of different solutions and different boundary conditions. What is clear is that theoretical performances, in practice, are difficult to reach, although in recent years, the implementation of new and more complex control techniques is helping in reducing this difference. The development of simulation tools available to designers leads in the same direction. As a matter of fact, the ability to simulate increasingly accurate models allows faster improvements of all of the OWC's components.

The literature reading made for this work has also shown that, even if the number of published works is great, one can find more or less detailed information only about few relatively mature technologies (e.g., PICO, LIMPET, and Wavegen's Mutriku). Typically, private companies or inventors do not publish the results obtained by developments because they care to protect their patents or because results, probably considered not exiting, may misrepresent their products or ideas.

To achieve success in WEC's R&D project, it is essential to consider that a long-term development plan is needed, as well as the quite large team of experts and facilities. Consequently, great investments are unavoidable. The actions taken by governments to finance the R&D projects cannot be enough to remove the obstacles to the diffusion of the WECs. The ocean energy sector is creating a new industry, but there are not yet commercially available machines, although many projects are at an advanced stage of development. The risks for this development are large, and then, coordinated efforts and collaboration between nations to avoid repetitions and accelerate the progress are required. A good example of this kind of cooperation is the MArine Renewables Infrastructure Network for emerging Energy Technologies (MARINET), made by 29 European partners, including universities and national government research centers, industry research centers, government agencies, and industries. Among the objectives of MARINET, there is the dissemination of good practices, collected by highly experienced research groups for WEC development and the networking of a number of world-class research facilities, which can support the R&D of the ocean energy industry at all stages of development.

In addition, the dissemination of information related to the experimental results can contribute to obtaining a higher success rate of the solutions under development.

VIII. Conclusion

Some developed OWCs have been presented considering five issues: structures to convert sea waves to airflows, turbines, electric generators, power electronics, and electronic controls.

By the literature, it can be inferred that, despite decades of studies and tests to ensure features such as reliability, durability, and cost-effectiveness of these technologies, further research and development are required. Because of the hostile environment in which they must operate, the development of these systems, beyond large and advanced facilities, requires long-term projects, relying on teams composed of many people with different skills. In most cases, the need for large-size R&D budgets, rather than high costs of construction and maintenance, led to the project decommissioning. To date, the single-chamber OWCs are those in more advanced state of R&D, with the development of different structures with high survival, types of ducted self-rectifying turbines, and customized electronic controls. While the development of these three issues is typical of WECs, the power electronic topologies are borrowed from the solutions adopted for open-field wind energy converters.

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