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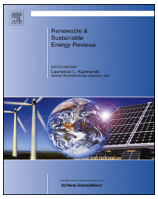

Review on electrical control strategies for wave energy converting systems[☆]

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ABSTRACT

Renewable energy techniques are now gaining more and more attention as the years pass by, not only because of the threat of climate change but also, e.g. due to serious pollution problems in some countries and because the renewable energy technologies have matured and can be depended upon an increasing degree. The energy from ocean waves bares tremendous potential as a source of renewable energy, and the related technologies have continually been improved during the last decades. In this paper, different types of wave energy converters are classified by their mechanical structure and how they absorb energy from ocean waves. The paper presents a review of strategies for electrical control of wave energy converters as well as energy storage techniques. Strategies of electrical control are used to achieve a higher energy absorption, and they are also of interest because of the large variety among different strategies. Furthermore, the control strategies strongly affect the complexity of both the mechanical and the electrical system, thus not only impacting energy absorption but also robustness, survivability, maintenance requirements and thus in the end the cost of electricity from ocean waves.

Contents

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1. Introduction

Oceans cover two thirds of the earth's surface and large amounts of energy is contained within its motion. This vast source of renewable energy has the potential of meeting an important part of the demand for non-polluting electricity for mankind.

Since the 1970s, following the oil crisis, research on renewable energy has gained increasing support and this has also affected the research on wave energy. So far, many types of wave energy converters (WECs) have been invented, developed and tested in small and large scale experiments.

When the electricity production from WECs depends on and varies synchronously with the wave movement then the amplitude and frequency of the converted electricity will naturally vary dramatically during each wave period. This electricity is incompatible with the electric grid since electricity supplied to the grid has to have a voltage that is of constant amplitude and frequency. Hence, some strategies of electrical control and storage as part of the energy conversion play a significant role in wave energy systems.

This paper is mainly concerned with electrical control strategies for wave energy conversion. In Section 2 a short introduction to wave energy absorption is presented. The purpose of this section is to help the uninitiated reader to understand what the control strategies are trying to achieve in terms of the interaction with, and absorption of energy from the wave. In order to facilitate relevant comparisons among control methods, the different types of wave energy converters are classified with respect to their mechanical structures in Section 3. In Section 4, electrical control strategies with devices as examples are discussed. Section 5 presents energy storage strategies that are used during the energy absorption.

This paper focuses on the control strategies and only provides a brief overview of existing wave energy technologies, for a more thorough review and classification of wave energy converters see [10]. It is necessary to mention that for various reasons, such as mechanical problems or lack of financial support, not all the control strategies have been experimentally verified as proposed and studied in their academic publications.

2. Energy absorption

Oceans transport huge amounts of energy, this energy is transported in form of polychromatic waves. An ocean wave is water particles moving in elliptical orbits, where the radius decreases with the water depth [1]. The power transport per unit width of wave front is given by the hydrodynamic pressure and the water particle velocity, according to

$$J = \int_{-z}^{0} p_i v_i \, dz \left[\frac{W}{m}\right] \tag{1}$$

The integral is calculated from bottom to still water level. An object or something else interacting with this incident wave will create a radiated and a diffracted wave that will change shape of the incident wave. To be able to take away energy from this incident wave this “object” has to interact in an advantage way to this wave. Being able to absorb energy from the waves, radiated and diffracted waves has to be created to interfere destructively with incident waves. A good wave absorber has to be a good wave maker [2]. Assume an arbitrary shaped area of the ocean surface (Fig. 1). The energy flux into this volume is denoted as E_i, and the energy flux out from the area is denoted E_o. According to energy balance the possible absorbable energy from the waves in the given volume is given by $E_i = E_o + E_{abs}$. Being able to absorb energy an outgoing wave has to be created by the absorber.

Assume an undisturbed incident wave has the water particle velocity, $v_i = (v_{i,x}, v_{i,y}, v_{i,z})$ and a hydrodynamical pressure p_o. The same for the diffracted/radiated wave from the wave absorber unit inside the volume, i.e. the outgoing wave from a wave absorber unit have water particle velocity,$v_o = (v_x, v_y, v_z)$, and a hydrodynamical pressure p_o. The total net flux of the energy in an arbitrary volume of the ocean during a time $2t$ is then given by

$$E_{abs} = \int_{-t}^{t} \oint_{S} \int_{-z}^{0} (p_i - p_o)(v_i - v_o) \cdot \hat{n} \, dz \, ds \, dt \tag{2}$$

Note that for an undisturbed wave the absorbed energy is zero, because the incoming energy to the volume is the same as the outgoing energy.

In order to maximize the energy absorption from the ocean wave, Eq. (2) has to be maximized. It can be seen in Eq. (2) that the interaction is not momentarily, to maximize outtake of energy the incident wave has to be known in advance.

Absorption is about to create a wave with right amplitude, frequency and phase angle to cancel out incident wave.

3. Classification of wave energy converters based on mechanical design

Several systems for the classification of WECs have been proposed through the years, ranging from detailed to rough, see [3,4]. For simplicity we have chosen a basic separation into three types: Oscillating Water Column devices (OWCs), overtopping devices, and attenuators (Fig. 2). OWCs and overtopping devices are both available for offshore and inshore installations. The attenuators are predominantly offshore devices.

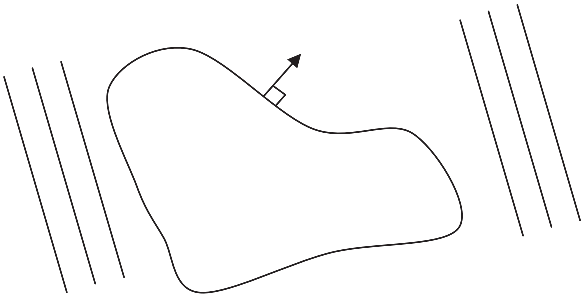

Fig. 1. An arbitrary area of the ocean surface.

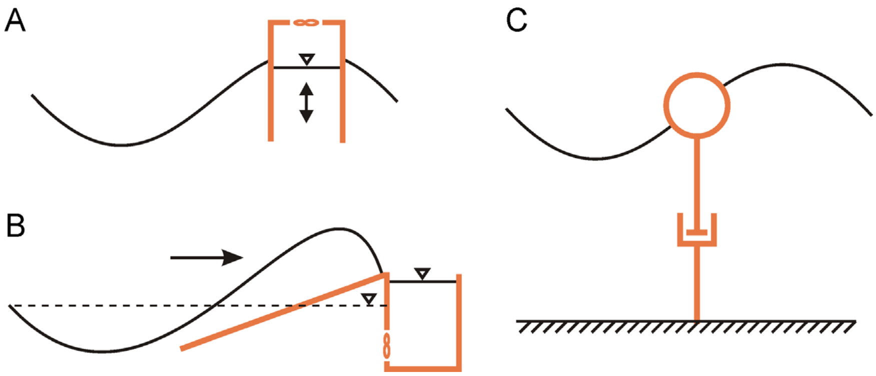

Fig. 2. Mechanical design on three types of WECs [5]: (A) Oscillating water column device; (B) Overtopping device; (C) Attenuator.

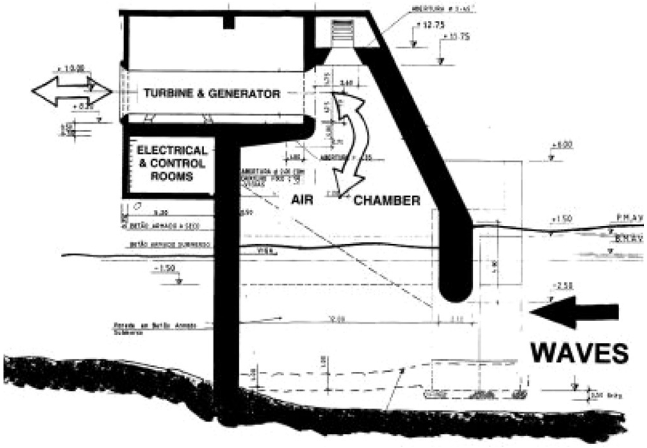

Fig. 3. The Pico Plant on Azores Island in Portugal [15].

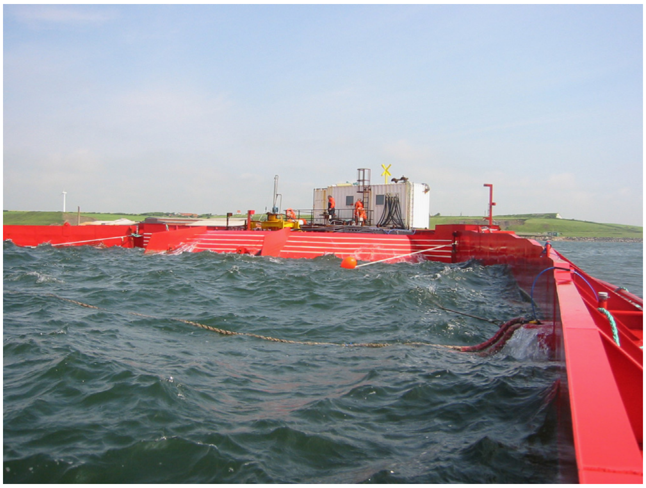

Fig. 4. The Wave Dragon deployed and tested in the sea [20].

3.1. Oscillating water column

The OWC (Figs. 2(A) and 3) device consists of a partially submerged chamber with a water column that rises and falls in response to the pressure from ocean waves [6]. Both the upwards and downwards movement of the column drive air through a turbine and the turbine drives a generator for electricity production [7].

The water level in the column rises when a wave crest is pushing against the WEC. This increases the pressure in the device and forces air go through the turbine. Conversely, the pressure is lowered during a wave trough, resulting in air being pulled back through the generator. Both of these two processes drive the air turbines [8], and the rotational speed of the turbines depends on the air pressure in the column and the control system to the turbines.

Whistling Buoy, a device used as a navigational buoy, is patented by J. M. Courtney of New York, and is the earliest OWC device recorded in 19th centuries [9].

Yoshio Masuda in Japan invented a navigation buoy situated in Osaka Bay in 1947. It initially utilized an air turbine to supply electricity [10]. An advanced version, called the Kaimei, was built in 1976 and was owned by the Ryokuseisha Company. The Kaimei had an output power of about 70–500 W [11]. During 1978–1980, Kaimei Floating Platforms with rated power up to 125 kW was built and tested [12].

During the 1980s and 1990s, technologies for wave energy conversion were developed with increasing support as a result of the oil crisis that broke out in 1973. Large amounts of OWC devices from Norway, India, Japan and England, etc. were proposed at that time, expressing their own unique designs and advantages.

Queen's University of Belfast developed a device with an installed capacity of 75 kW positioned on Islay in 1991 [13]. This was followed by the OWC LIMPET, which was installed in 2000 and rated at 500 kW. In 2010, the European Wave Energy Pilot Plant(Fig. 3), which is located on the Azores [14], was operated with a rated power of 400 kW. Its installation demonstrated the technical viability of wave energy in a small island grid.

3.2. Overtopping devices

Overtopping devices are partially submerged wave energy converter with reservoirs for capturing wave crests and water turbines to produce electricity [16]. The kinetic energy of the waves is converted to potential energy when incoming waves are led up a ramp and is collected in the reservoir (Fig. 2(B)). The water returns to the ocean from the reservoir through water turbines, thus utilizing the potential difference between the ocean and the reservoir to generate electricity.

A tapered channel wave power device, or Tapchan [17], utilizing this overtopping principle of operation, was installed on shore in the 1980s. The device was rated at 350 kW and located at Toftestallen, Norway [18]. Later on in 1998, a 1.1 MW Tapchan was started to be constructed on the Indonesian island of Java.

Wave Dragon installed a prototype in scale 1:4.5 (58 × 33 m, with a 28 m reflector and reservoir of 55 m^3) constructed in 2003 at Nissum Bredning in Denmark [19]. It had a rated power of 140 kW (7 turbines each with a rated power of is 20 kW). It became the first offshore overtopping device in the world (Fig. 4). Wave Dragon has started the development of 1.5 MW demonstrator offshore Hanstholm at the test center DanWEC, Denmark [20].

3.3. Attenuators

Attenuators are devices where the water physically pushes and induces motion in the WECs structure and energy is converted by dampening this motion [21]. Fig.2(C) represents the concept of attenuators. The devices are often constructions that float on and interact with the ocean waves without being physically fixed in place, e.g. the well-known Pelamis, but they can also be standing on the ocean floor or on land.

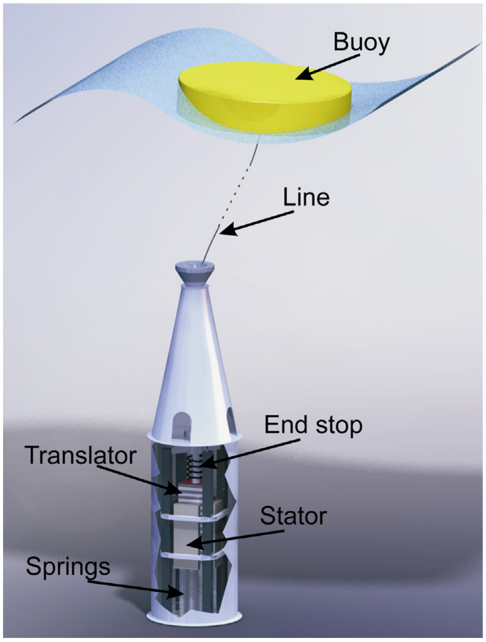

Fig. 5. The WEC developed in the Lysekil Project [25].

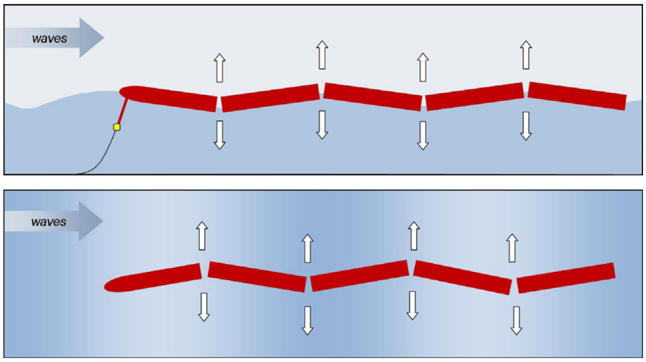

Fig. 6. The concept of the Pelamis with hydraulic conversion system [32].

The Archimedes Wave Swing, AWS, is a submerged device [22] point absorber with a linear generator. A prototype was deployed off the northern coast of Portugal in 2000 and tested during 2004. It had a maximum power 2 MW [23].

Another example of a point absorbing attenuator is the WEC utilized in the Lysekil Project and developed at Uppsala University. Today nine 10–40 kW prototypes have been installed outside Lysekil off the west coast of Sweden [24]. Its linear generator is settled on the ocean floor and is driven via a connection line from the top of the generator to a buoy floating on the ocean surface (Fig. 5).

In 2007, a prototype of a floating point absorber with a linear generator rated at 10 kW was developed by Oregon University and deployed off Newport in Oregon State in the US [26].

Wavebob is composed of two heaving buoys [27]: a torus of 14 m in diameter and a float linked to a submerged tank with a draught of 40 m. The Wavebob belongs to the heaving buoy point absorber type. In 2007, Wavebob ltd. deployed its first test device in Ireland and planned to install a more advanced version with desired power production capacity in the order of several hundred kW off the coast of Portugal in 2012 [28].

3.3.1. Point absorbers

Point absorbers are most commonly offshore devices that mainly utilize heave motion for energy absorption [29]. They are usually smaller size compared to other types of WECs. They can mathematically be regarded as a point-like object in the ocean due to their small size compared to the wave length of the wave from which they capture energy [30]. They are equally good at absorbing energy independent of the direction of the incoming waves. This type of wave energy converters are also categorized as oscillating body systems by Falcão.

Electrical controlling strategies devised for point absorbers vary depending on the mechanical design of the WEC. Hydraulic system and linear permanent magnet generator (LPMG) are, however, most common.

3.3.2. Hinged attenuators

Hinged attenuators are made up of several body parts linked horizontally by universal joints which allow flexing in two directions. Taking Pelamis [31] (Fig. 6) as the most known example, it floats semi-submerged on the surface of the water and faces the direction of waves. As waves pass down the length of the machine and the sections bend in the water, the movement is converted into electricity via hydraulic systems housed inside each joint of the machine tubes, and power is transmitted to shore using standard subsea cables and equipment.

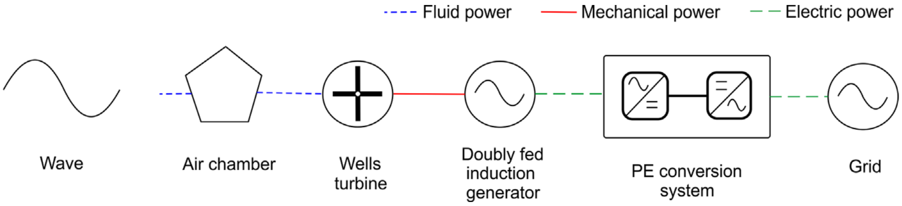

Fig. 7. Technology used in a Pico OWC device to produce electricity from wave [91].

4. Electrical control strategies for different types of WECs

4.1. Control strategies for OWCs

The performance of the OWCs lies in the combined efficiency of different stages (Fig. 7 [33] proposes three types of turbine set) in the conversion process [34], they are (i) wave to pneumatic conversion in the capture chamber, (ii) pneumatic to mechanical conversion in the turbine, (iii) mechanical to electrical conversion in the generator.

Due to challenges of the natural environment and device limitations, such as a mismatch between wave frequencies and the resonance frequency, variations in the air velocity, or variations in wave conditions, the efficiency of the overall system can be affected significantly [35]. For these reasons the combined efficiency has not been able to reach the theoretical values of efficiency of 70–80% in real operation. Additionally, the impact from flow oscillations onto the Wells turbine [36] also contributes to the low actual efficiency, with results that are far from the anticipated values.

In order to solve these problems, two control topologies are presented by Falcão [37]. These two topologies are utilized to solve the problems above to maximize the instantaneous power output of the wave energy converter: (i) the rotational speed control [38]; (ii) air-flow control strategy. They are designed to match the available wave level and the airflow control through the turbine, to prevent or reduce the aerodynamic blade losses at the turbine rotor blades.

4.1.1. A-Turbine rotational speed control

The goal of the rotational speed control is to regulate the output power of the generator according to the error signal caused by abrupt changes in the fluid dynamics through the Wells turbines. Several strategies on the rotational speed control are proposed.

A variable frequency control strategy[40] is used as one strategy for the rotational speed control, which is a feedback control loop based on the cubic relationship between the frequency of the rotor in the generator and the instantaneous power of generator.

Falcão points out that improvement of the turbine efficiency [41] depends strongly on the control strategy to the instantaneous rotational speed. Three methods are proposed on controlling the turbine rotational speed within a limited range of flow conditions around the optimal efficiency point, these are (i) constant torque control depending on the power estimation [42], (ii) speed control to a reference rotational speed, with linear derivative function between torque and rotational speed, and (iii) control within acceptable oscillation [43]. Numerical simulations and analyses have been performed wherein the conclusion is reached that the third method (iii), electric power output controlled in the Programmable Logic Controller (PLC) [44], seems to be the optimal control method in the OWC device.

Srinivasa [45] also made comparison among three speed-control topologies to Wells turbine by simulations, which are (i) uncontrolled scheme, (ii) *V/f* (Velocity/Frequency) [46] controlled scheme on the stator and (iii) *V/f* controlled scheme on the rotor. Conclusion is that controlled scheme on the stator is the optimal topology, as power fluctuations will bring serious harm to the power factor in the grid under uncontrolled condition, and rotor circuit will absorb power under the rotor controlled condition.

Table 1 gives a summary of the control strategies to control the rotational speed of the turbines.

Table 1
Summarized control strategies of rotational speed control for OWCs.

Control strategy	Different topologies	Conclusion
Rotational speed control	(a) Variable frequency control	It is a feedback control method for rotational speed control.
	(b) (i) Constant torque control (ii) Speed control (iii) Speed control within acceptable oscillation	Numerical simulations show that (iii) is the optimal strategy for speed control.
	(c) (i) Uncontrolled scheme (ii) *V/f* control on the stator (iii) *V/f* control on the rotor	Comparisons show controlled scheme on the stator is the optimal topology.

Table 2
Summarized control strategies of airflow control for OWCs.

Control strategy	Different topologies	Conclusion
Airflow control	(i) valves mounted in parallel with the turbine (ii) valves mounted in series with the turbine duct	(ii) is better topology compared with (i) by avoiding the undesirable stalling to enhance the output power.

4.1.1. B-Airflow control

As the efficiency of the Wells turbine depends strongly on the flow rate, flow oscillations will have a strong effect on the efficiency of OWC devices equipped with a Wells turbine. Thus, a method for controlling air valves in the chamber, in order to prevent excessive flow rate, has been proposed [47]. As Falcão describes in his article, two schemes of airflow control are compared and discussed: (i) valves mounted in parallel with the turbine; (ii) valves mounted in the turbine duct. According to the simulations, it is concluded that scheme (ii) is expected to achieve a better result [48,49].

In scheme (ii), error signals are induced by the difference between actual output power and reference output power. The reference power is set in accordance with the available pressure drop with the goal of maximizing the power output by avoiding the undesired stalling behavior. The control signal, attained by both the error signal and pressure regulation signal, drives the valve to adjust the pressure drop across the Wells turbine.

Furthermore, in practice, bypass valves with large capacity are required in order to limit the air flow through the turbine under extreme environmental conditions [50]. Table 2 gives a summary of the control strategies of the airflow control for OWC devices.

4.1.2. Typical OWC type wave energy converters

a. LIMPET. A turbine-generator system [51] is utilized and a torque control algorithm for the rotational speed control of the turbine is designed for the inverter drive connected to generators settled in LIMPET [52].

The system is composed of a simple switchboard feeding each generator system and connecting the plant to the grid via a 400/11 000 V transformer (Fig. 8). Each generator is controlled by the supervisory plant controller [53] that in turn controls an inverter drive connected to the machines.

Consisting of Insulated Gate Bipolar Transistor (IGBT) [54] based inverters and an anti-parallel Thyristor converter, the control system is used in LIMPET for adjusting the speed of the rotor is to optimize the relationship between its rotational speed and the velocity of the fluid flow. Three control strategies for rotational speed control are posited: (i) constant speed control; (ii) constant power control; (iii) constant torque control [55]. These three strategies are all implemented in the electric power interface in order to adjust the mean rotational speed to achieve the optimum speed by the generator's torque demand.

b. The Pico plant. The Pico plant was equipped with a horizontal axis Wells turbine with fixed pitch blades with a rotational speed is in the range of 750–1500 rpm [56]. An asynchronous generator rated at 400 kW of the wound rotor induction type was adopted. The by-pass valve for air flow relief was designed and installed on the top of the air chamber so excessive energy can dissipate to the atmosphere when stormy weather might otherwise cause damage to the turbine-generator system.

The control and monitoring is achieved in a programmable logic controller (PLC), with the use of an interface that allows visualization of the main relevant parameters such as temperature, vibrations, the lubrication system of the turbine bearings, and the position of the valves, the power electronics and other electrical components.

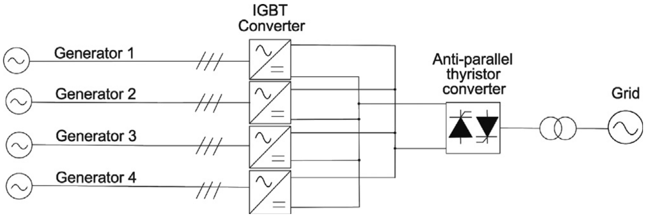

Fig. 8. The electrical system of LIMPET [55].

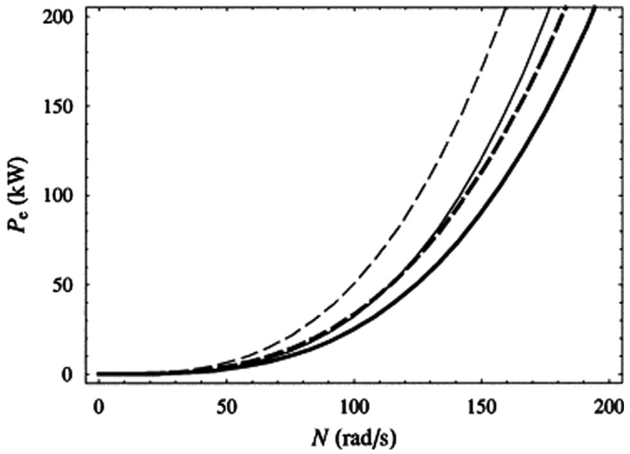

Fig. 9. Comparison of rotational speed control methods (with and without relief valve control) [61].

Because of the complexity and the high cost of implementation, and because the environment is not suitable for installation, direct torque measurement at the turbine shaft was never installed [57]. As a result, the lack of instantaneous torque measurements has led to a lack of the possibility to apply control strategies to the generator.

Nevertheless, theoretical research has been pursued in spite of this [58,59]. Based on stochastic modeling [60], Falcão pointed out that the so-called cube-law utilized into a control algorithm of the relationship between the electromagnetic torque and the rotational speed, may be the optimal control strategy for the Pico Plant. Furthermore, different rotational speed control methods (with and without relief valve control) were compared and the results (Fig. 9), thick and thin lines represent the cube-law method without and with controlled valve respectively, while dashed lines represent a simplified method. The result [61] showed that proper control of the relief valves might lead to an increase of 37%.

4.2. Control strategies for overtopping device

Tapchan is a typical demonstration of overtopping device in early years, however, the project stopped due to mechanical damage [62]. So far there is not any control information given out. In this section, the well-known Wave Dragon is used as the example to illustrate the electrical control to the WECs of overtopping devices. Fig. 10 gives an illustration on the conversion stages from fluid power processed to electric power of one Wave Dragon.

The Wave dragon, is a slack moored [63] floating device consisting of two reflector arms and a central hull with a storage reservoir. The reflector arms focus the waves onto the doubly curved ramp on the front of the hull, where the waves run up and fill the reservoir. The water in the reservoir, which is situated above the mean sea level [64], is released back into the sea through a set of specially designed low head water turbines.

Direct power control, utilizing Direct Power and Torque Space Vector Modulation (DPTC-SVM) [66], is applied for the control of the converters. Direct Torque Control with Space Vector Modulation (DTC-SVM) is used on the Generator Side Converter to control the variable speed [67], while Direct Power Control with Space Vector Modulation (DPC-SVM) is used on Grid Side Converter with Pulse Width Modulation.

In order to decrease the actual DC-link voltage fluctuation during transients, the power is fed into the DC-link using a control device named Active Power Feed-Forward (APF). Fig. 11 represents the control system used in Wave Dragon. This approach shows high performance in stabilizing the speed of the generator, and it has shown to operate safely even during transient conditions.

A frequency power converter [68] is proposed and the current controller of AC/DC/AC converters is designed and simulated in dq0 frame, Fig. 12 shows the results of generated power and generator rotational speed, which are regulated to values with the maximum efficiency of turbine. Table 3 gives a summary of the control strategies designed on the converters of Wave Dragon.

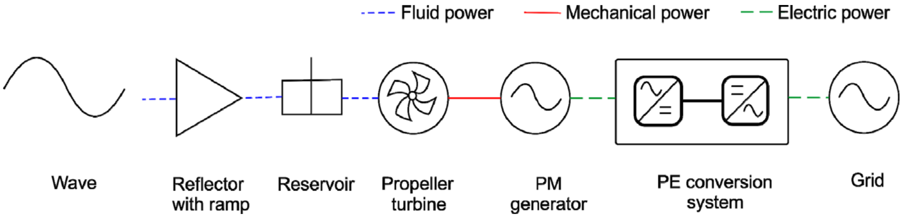

Fig. 10. Technology used in Wave Dragon to produce electricity from waves [91].

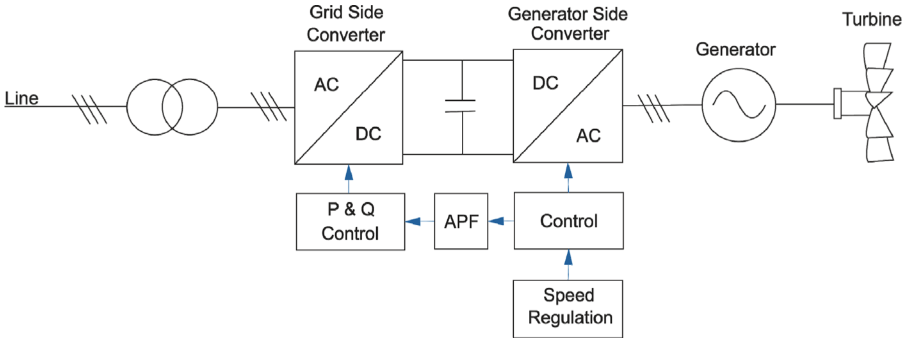

Fig. 11. DPTC-SVM with APF for Active and Reactive Power Control (P&Q Control) [65].

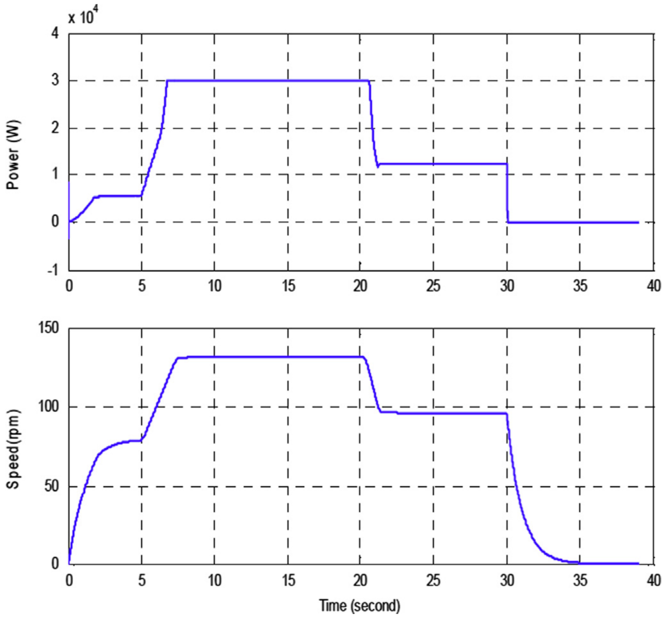

Fig. 12. Output power from generator and generator speed with current control algorithm [67].

Table 3
Summarized control strategies of the examples for Overtopping system.

WECs	Control strategies on the converters	Conclusion
Wave Dragon	DTC-SVM on the generator side converter APF on the DC/DC control DPC-SVM on the grid side converter	The combined control is possible to achieve maximum efficiency of the turbine.

4.3. *Control strategies for attenuators*

4.3.1. *A-Hydraulic system*

Hydraulic systems are typically efficient energy conversion systems consisting of two energy conversion steps. The first step is that mechanical energy from waves is absorbed by a floating body and converted to hydraulic energy through a compression unit [69], which functions synchronously with the motion of floating body. Second, the generator or motor produces electrical energy in relation to the pressure difference resulting from the compression unit. A basic hydraulic system is explained in Fig. 13. Components of a basic compression unit include a hydraulic cylinder, two pressure accumulators and a valve-control system (Fig. 17). The hydraulic cylinder is used to transfer the motion of the floating body into that of direct-linked double-acting piston in the cylinder. Two chambers are connected respectively to a high pressure accumulator and to a low pressure accumulator, and the cylinder motion leads to a varied pressure difference that results in a torque on the generator/motor. Since unstable power output and energy loss is due to the existence of irregular waves, the valve-control technique is used to significantly smooth the power as well as for achieving energy storage for better efficiency.

In the following section, two examples of WECs for hydraulic system are illustrated with the control technologies, which are summarized in Table 4.

4.3.1. *B-Typical WECs for hydraulic system*

a. Wavebob. In the hydraulic circuit of the Wavebob, two separate elevated pressure levels are set next to the biased low pressure (LP) level: the variable pressure (VP) and the high pressure (HP). They are established for de-coupling of power output and input. The HP level is used to maintain the displacement control through HP motor, in order to maintain the working pressure for the hydraulic motor and to compensate the variations. The VP level is used to provide a defined damping force through the pumping module by defining the backpressure [70].

A Hydraulic Parallel Circuit (HPC) is preferred to maintain constant pressure and speed conditions within the limits set by the accumulator capacity. The AC generator is driven by two variable displacement motors—A HP motor and VP motor placed in parallel on a common shaft. While the VP motor displacement ramps up and down with the wave-dependent input flow, the HP motor is used to maintain a constant generator speed.

According to the structure of a HPC, latching control [71] is used as a method to control the damping force. The latching control strategy is achieved by two different control methods: VP motor control and HP motor control. Control of the VP motor is to control the damping force and pressure linearly proportional to the velocity of buoy system [72], while control of the HP motor is to maintain the accumulator pressure by adjusting the flow rate of the HP motor. Fig. 14 shows a schematic block of the function of the hydraulic system in Wavebob [73]. And in Fig. 15, the one on the top is the absorbed mechanical power by Wavebob, while the bottom one represents the output electrical power from a Power Take Off (PTO) system with non-linear damping control. The test results conclude that Wavebob succeeds to gain smooth output power under irregular wave conditions with the damping control.

In [69], a general hydraulic model is built theoretically attached with a point absorber WEC. It could also be fitted to the Wavebob, in spite of having been conceived for SEAREV. In the model, an extra accumulator is designed for energy storage [74]. Controlled valves with a PID controller are installed in each accumulator [75]. Fig. 16 represents the output electrical power with different accumulators control method. When two accumulators are both working, the electrical power is enhanced by up to 50% in

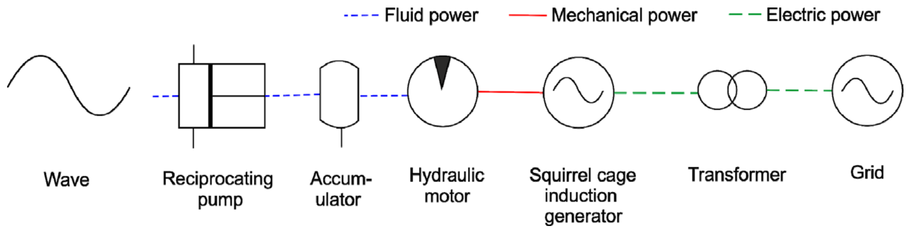

Fig. 13. Technology used in a hydraulic system to produce electricity from wave [91].

Table 4
Summarized control strategies of the examples for hydraulic system.

WECs	Control strategy	Description
Wavebob	Latching control	Control the damping force of the buoy system
Pelamis	Frequency tuning	Control the rotational speed and thus compressing motion in the cylinders

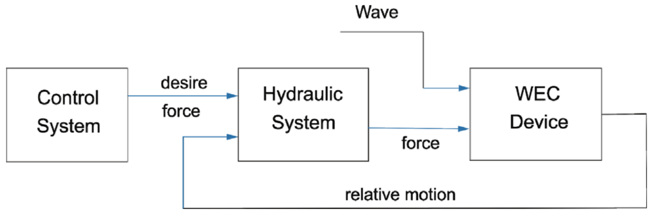

Fig. 14. Schematical block diagram of the control to WEC of the Wavebob [73].

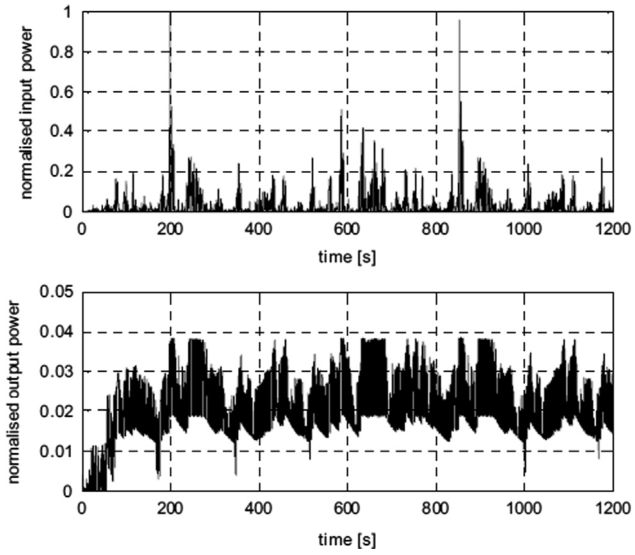

Fig. 15. The absorbed power and the output electrical power from Wavebob [73].

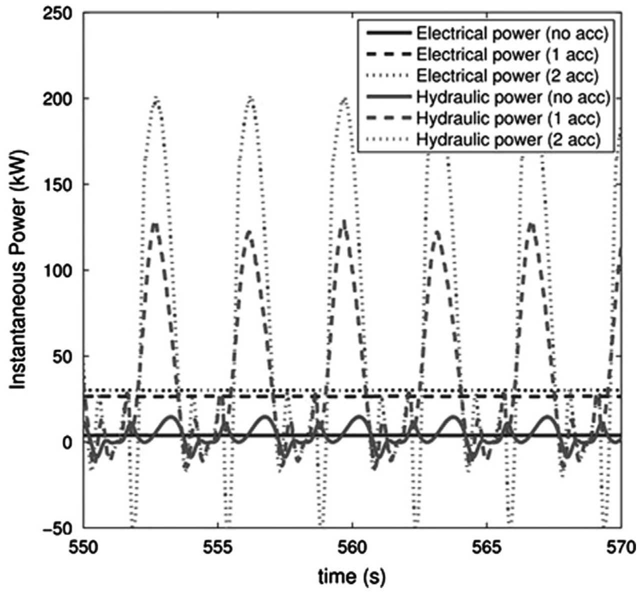

Fig. 16. Output electrical power from the hydraulic system with extra accumulator control [69].

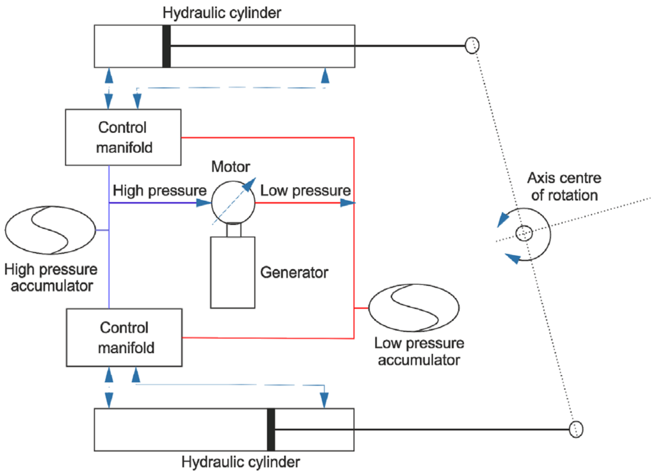

Fig. 17. Simplified schematic system of the Pelamis [78].

comparison with power with no accumulator control. In spite of the increase of the electrical power, this control strategy actually decreases the efficiency of the PTO.

b. Pelamis. The Pelamis is a hinged wave energy converter consisting of cylinders connected by the joints aiming at pumping high pressure oil through hydraulic motors to drive electrical generators to realize electrical conversion [76]. The structure is stretched out along the direction of the moving waves [77], its snake-like motion is caused by the forces from waves and produces an angular relative motion between the cylinders which in turn leads to the pressurization and de-pressurization of the hydraulic system.

The hydraulic system is composed of two transmission parts. One is the primary transmission, in which energy from wave motion is converted into the hydraulic energy stored in the accumulators [78]. The secondary transmission is the conversion of the stored energy into electricity in the generators by use of hydraulic motors (Fig. 17).

The efficiency of Pelamis can be enhanced [79] by the frequency tuning, which is achieved by the control to the bias angle, leading to the control of rotational speed and thus compressing motion in the cylinders. The frequency tuning [80] mainly depends on the high-pressure fluid inside the hydraulic system. Therefore, electronically controlled valves are installed to control the flow of fluid and consequently affecting and controlling the angular relative cylinder motion of the Pelamis. Fig. 18 gives a simulated plot of absorbed and generated power from full-scale Pelamis operating under regular sea condition. The generated power shows that the smoothening effect from the secondary transmission is achieved comparing with the instantaneous power absorbed in the primary transmission. Additionally, Pelamis Wave Power Ltd. goes further with the theoretical research on maximum wave energy absorption by volume constraints, more details in [81].

4.3.2. *A-Direct drive system*

Direct drive system is a type of wave energy converter that generally has a more simple mechanical structure compared to that of hydraulic systems. It is employed in order to absorb the available wave energy more efficiently. The direct drive system with a linear generator [82] consists of a magnetic translator which is driven to reciprocate synchronously with the motion of a directly coupled buoy/floating body [83]. A simplified structure of direct drive conversion system is shown in Fig. 19. The result is directly induced three phase AC power without intermediate energy converting steps.

Directly driven systems have the advantage of not requiring an intermediate mechanical interface and thus avoiding the losses that take place in these devices (turbines and hydraulic motors) in other PTO systems. On the other hand, linear electrical generators for wave energy applications are in need of power electronics in order to convert the generated electricity to a form that is suitable for the electric grid.

Table 5 gives a summary of the control strategies used in the examples in the following section.

4.3.2. *B-Typical WECs for direct drive system*

a. The Lysekil Project. The linear generator developed in the Lysekil Project [84] is settled on the sea floor, via the connection line from the top of generator hinged to a buoy floating on the ocean surface [85], as illustrated in Fig. 5. So far, three different control strategies have been experimentally tested in the project. They are the passive diode rectification, DC control [86] and resonance circuit [87]. Future work will continue with the testing of marine substation [88]. During 2011 and 2012, a novel passive rectifier circuit was tested. The circuit can be seen in Fig. 20 and is a combination of a diode rectifier and resonance circuit with capacitors. The purpose with the circuit is to achieve a higher damping, e.g. power absorption, and at the same time maintain a high voltage output from the generator.

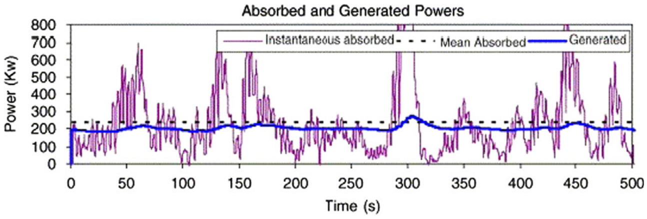

Fig. 18. Absorbed and generated power from hydraulic system with active control strategy during continuous wave periods [78].

The generator is connected to the rectified circuit [89] and in the experiments the translator's reciprocating motion was achieved with the help of a crane. The result from the experiment is presented in Fig. 21. The result [90] shows that the voltage across the capacitor C2, is increasing when the translator speed is decreasing to an operating frequency which is closed to the resonance frequency [91].

b. Archimedes Wave Swing. The AWS consists of a submerged floater [92] that oscillates with the frequency of the ocean waves passing the device overhead. It is standing on a foundation fixed to the sea floor. Its reciprocating motion is driven by the varying pressure from the waves that act on an internal gas spring, causing a synchronous motion relative to the waves [93]. Since the wave energy is converted via the directly driven LPMG to produce electrical energy, strategies on converter control is of significance for extracting maximum energy from the waves.

Consisting of two voltage source converters (VSCs) and one capacitor, a full scale back-to-back converter is used for the converter system in AWS, with target of higher energy yielding and the converted power fluctuation smoothening [94].

Table 5
Summarized control strategies of the examples for point absorbers.

WECs	Control strategy	Description
The Lysekil Project	Resonant circuit	To achieve electric resonance with the generator's winding
AWS	Feedback linearization control	To cancel the non-linear dynamics of the generator in order to achieve closed-loop linear control
	Reactive control	Control the output impedance to be equaled to the complex conjugate of the intrinsic impedance of generator
	Phase and amplitude control	Control the floater's vertical velocity in phase with wave excitation force, and the amplitude is also regulated
	Latching control	Control the water damper to prevent the floater from moving
	Stiffness and damping control	Current control in the dq0 frame to control the active and reactive power respective stiffness and damping factor
The Oregon University L10	Vector control of PADA system	Control the generated current's phase to be 90° ahead of the flux inside the generator

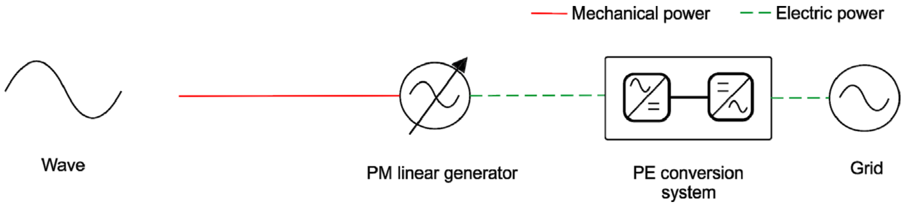

Fig. 19. Technology used in a direct drive system to produce electricity from wave [91].

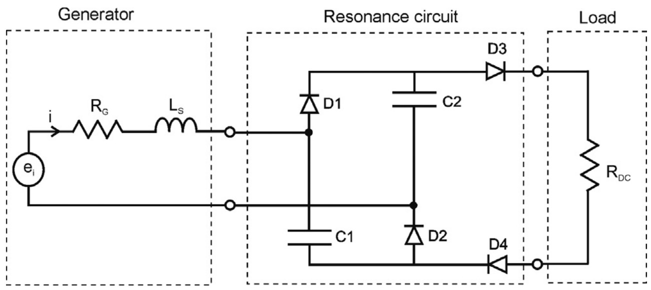

Fig. 20. Installed electrical system in the measuring station [85].

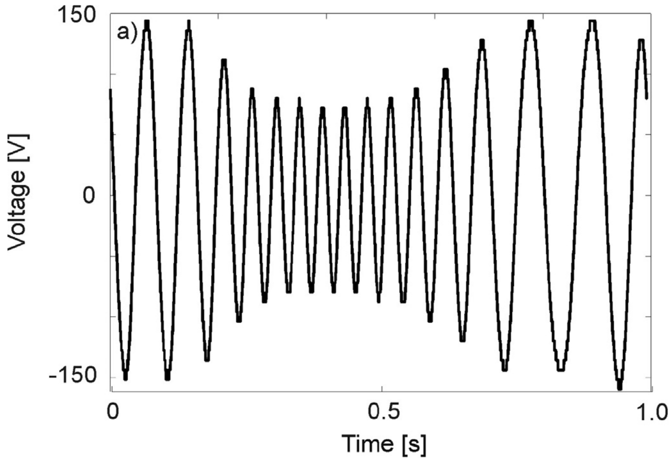

Fig. 21. Measured voltage across capacitor, C2, result from [85].

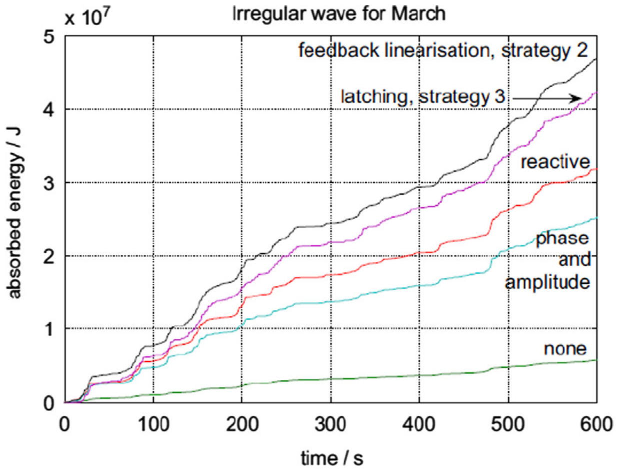

Fig. 22. Results of the energy absorption in March with comparison among different control strategies [102].

The generator side converter for AC/DC conversion is the one of the VSCs connected to the stator of LPMG, while the grid side converter for DC/AC conversion is also the VSC linked to the grid on land [95]. As variable frequencies and magnitudes of power induced in the generator will cause dramatically fluctuations in the transmission, it is necessary to insert the storage unit—capacitor to smooth the ripples and guarantee the constant output of power to the grid.

Electrical control strategies to generator side converter of AWS with anticipation for energy absorption have been proposed. Feedback linearization control [96] was employed in the prototype of AWS. Its aim is to provide a control action that cancels the non-linear system dynamics [97] of the plant.

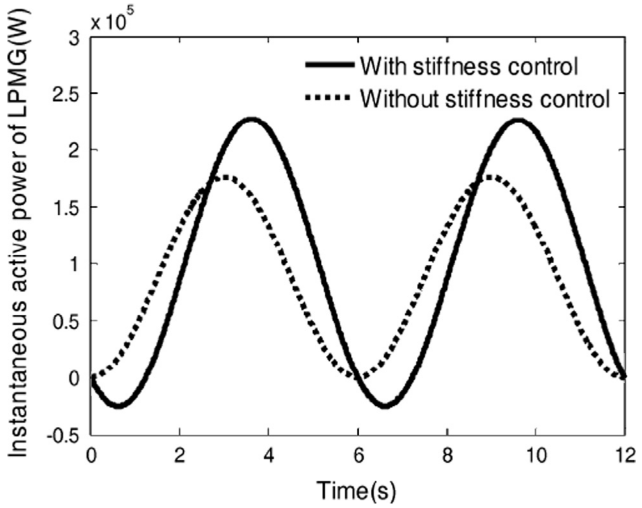

Fig. 23. Instantaneous active power from LPMG with stiffness control and without stiffness control [39].

In spite of employing it into the realistic environment, obvious increase of the energy absorption is obtained by the feedback linearization strategies. Furthermore, several control strategies including phase control and amplitude control [98], reactive control, and latching control [99–101] are proposed and relevant models are simulated comparatively. Fig. 22 shows the simulation result from database from different strategies and comparison with energy absorption without control is done [102]. From the result the feedback linearization is found to be the best control strategy, then following the latching control, the reactive control, the phase and amplitude control.

Furthermore, a method of a dq0 model was proposed for dynamics and stability analysis of the stiffness and for the damping control on the generator instead of abc model that was used to control the prototype. Results (Fig. 23) from simulation show the proposed controllers are able to yield higher output voltage [103], and higher reactive power with an increase of 14.3%, and a higher sensation is as well achieved in tracking control reference value, even under situation of small disturbance.

c. L10 of Oregon State University. The L10 consists of a deep-draught spar, restricting the device body to heaving motion. The motion of the linear generator is controlled by a stiff voltage applied to the terminals produced in an active control module.

The Power Analysis and Data Acquisition (PADA) system [104] for the electrical control to the generator is designed to fit in the WEC with rated power 30 kW [105], including functions of vector control [106], active and passive rectification [107,108], maximum power point tracking, and power control[109].

PADA system has two main power electronic components [110]: three-phase active rectified circuit and an output buck converter. The three-phase rectifier is connected to the generator and provides a path for the power flow into a common DC link. The output buck converter connected to the backside of the DC link provides control of the power flow to a fixed resistive load. The schematic system is described in Fig. 24, PWM controllers and phase controllers are comprised to control the IGBT Switch board on both side of the converter, aiming at regulating the energy absorption to maximum and to smoothen the power flow to the grid. All data from the voltage and current sensor to the DC link are sent through the remote monitoring.

Test results with active rectifier with PADA system show that the DC link voltage is achieved to maintain the desired DC link

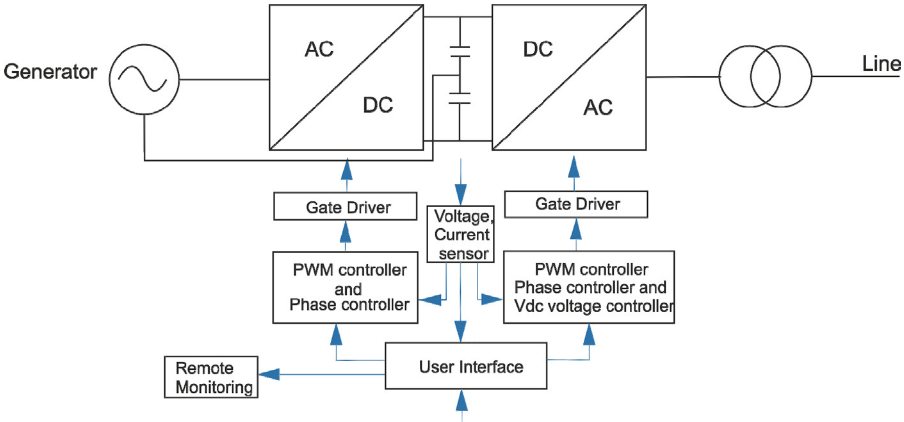

Fig. 24. Schematic conversion system of the so-called L10 of Oregon University.

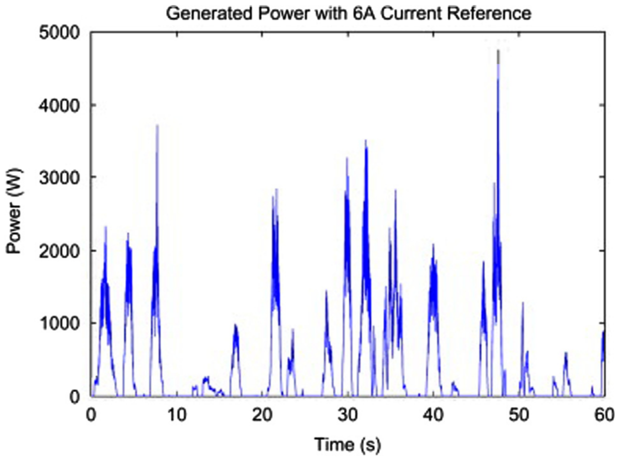

Fig. 25. Generated power with current reference during 1 h session [104].

voltage maximum of 600 V [111]. Fig. 25 presents the result of generated power with active control during one hour session, showing that PADA system is promising to improve the power factor of the generator over that of a passive rectifier.

5. Energy storage techniques for wave energy converters

The output of energy from WECs varies dramatically due to the intermittent nature of the wave motion, both on the second scale and on the scale of hours and days. The resulting fluctuations of the harnessed energy affect the quality of the electricity supplied the grid, and increase the costs of the transmission. Because of this physical fact of the energy source, energy storage or buffer systems are often deemed as particular necessary for smoothening the variations and delivering high quality electrical power, and in order to provide stable electricity to grid. Short time scale variations of the input power from the WECs to the grid can be handled by utilizing energy storage systems as the examples described below.

5.1. Oscillating water column devices

In the case of the demonstration wave energy plant in India [112], a high-speed flywheel type storage device was introduced along with an inverter to the three phase load for short duration energy storage. With the help of PID controller, the output load was switched to maintain the frequency and the voltage of AC supply within small variation, making it possible to gain balance between the input power from generator and output power to the load by adjusting the load value. Another solution is to place Superconducting Magnetic Energy Storage (SMES) across the DC link after the three-phase rectification with power electronic controller.

5.2. Hydraulic systems

In the Pelamis' conversion system, short-term energy storage is provided by high pressure accumulators that help to deliver a smooth power flow to drive grid-connected electric generators [113]. Storage takes effect whenever there is a fluid exchange between the pressurizing chamber and the high pressure accumulators. The main problems contributed to the energy loss are related to mechanics, including the compressibility, bearing and seal friction of the hydraulic cylinders, and flow losses through valves and pipes.

5.3. Direct drive systems

Battery Energy Storage (BES) is proposed to be integrated into the electrical converters of the AWS device in order to regulate the power quality and smooth the output power via a DC/DC converter [114]. In the case of a wave energy plant with multiple branches of WEC connection, BES is a possible solution to balance the power and phase difference between the instantaneous output powers from each individual WEC to the power grid. Within acceptable system disturbance, experiments have shown that BES is able to smooth the active power of WEC with improvement of power quality.

6. Conclusions

As an indispensable stage in the energy conversion process, electrical control strategies are taking a more and more important role and concern in how to harvest energy efficiently from ocean waves. The intermittent nature of ocean waves is a challenge that needs to be met in order to secure a good quality and reliability of power supply.

This paper has categorized the WECs into three groups with regard to the mechanism of the wave energy conversion. Different control topologies of the conversion system utilized in typical examples of WECs are explained. In Table 6, these three categories are listed, and different WECs with related control systems are presented and classified. Control strategies are also listed according to the different WECs discussed in the paper.

Table 6
Three categories of WECs.

Type		Device	Testing location	Rated power	Conversion system	Control strategies	Ref.
Oscillating water column		LIMPET	Islay, Scotland	500 kW	Turbine-generator	(a) Speed control (b) Power control (c) Torque control	[55]
		Pico plant	Azores, Portugal	100 kW 700 kW	Turbine-generator	(a) Speed control (b) Airflow control	[60] [61]
Overtopping		Wave Dragon	Portugal	1.5 MW	Turbine-generator	(a) DPTC-SVM (b) DTC-SVM	[66] [67]
			Nissum Bredning, Denmark	7 MW 11 MW		(c) APF	[68]
Attenuator	Hydraulic system	Wavebob	Ireland	500 kW	Hydraulic system	Hydraulic parallel circuit	[70] [72]
		Pelamis	Orkney, Scotland	750 kW	Hydraulic system	Frequency tuning	[73] [79] [80]
	Direct drive system	Lysekil Project	Lysekil, Sweden	10 kW	Linear generator	Passive rectification DC control Resonant circuit	[86] [87] [88] [89]
		AWS	Portugal	2 MW	Linear generator	(a) Feedback linearization control (b) Stiffness control	[96] [98] [102] [39] [94]
		Oregon L10	Oregon, USA	10 kW	Linear Generator	PADA system	[104] [110] [111]

One conclusion is that the control strategies are very dependent on the mechanical structure of the WECs. For example, OWCs are mainly focused on rotational speed control of the turbine and airflow control of the valve, while Point Absorbers are more concerned with the electrical control of the WECs. Although different control strategies are of course comparable when applied to a specific WEC device, it is not easy to make parallel comparisons between different WECs even within the same basic category, thus making it difficult to reach a conclusion on which overall control strategy, if any, that is optimal for wave energy extraction. Fundamental understanding of wave energy absorption, see Section 2, tells us what we are trying to achieve with the electrical control, but the necessary mechanical and electrical engineering choices taken in the design of a WEC strongly affects and constrains the possible control strategies. Taking the Wave Bob and the Lysekil Project as an example – in spite of both WEC technologies being based on linear drive point absorbers, the different power take-offs and choice of electrical system affects the possibilities of applying, e.g. a reactive control strategy. Conversely, for some control strategies on overtopping devices and OWCs, i.e. the controls of the turbine and the generator, there are similarities due to the form and purpose of the electrical conversion stage.

As indicated by this paper, although many studies have been performed on active control, the wave energy community would benefit a lot from more comparative studies and experimental verification of theory. Today the published knowledge of electrical control varies a good deal between the three general concepts and between the specific WEC technologies. Some technologies benefit from long periods of operation, e.g. some OWCs, where different control strategies have been developed and tested over time, while other technologies still await the experiences from experiments in the sea. The authors suggest that the control methods in Table 6 be used as a starting point for future comparative studies. Furthermore, it is of course valuable to study practical experiments of various control strategies carried out in the wave energy test sites, and to compare the experimental results with that from simulation modeling. Moreover, it is expected that much experience and knowledge on control strategies and related energy absorption is unpublished and owned by commercial wave energy developers. Although this information would be much appreciated by the scientific community that it is a lot to ask from industry to disseminate some of their intellectual property.

Although not much research has been presented on energy storage for wave energy as of yet, this often important and integrated part of the energy conversion strategies has been considered briefly in the paper. In wave energy, short time energy storage is often needed for smoothening of the output power and for improving the power quality and the dynamic response. Because of the nature of oceans waves, with large power variations on the second scale, the authors see energy storage as a natural and important future research topic for wave energy.

In general, due to the necessity of large-scale offshore installations and experiments, wave energy research and development is expensive. However, the physical nature of the resource, e.g. the large potential as a source of renewable energy for the world's societies, the relatively high density of energy, and its availability and predictability, stands as clear motivations to the substantial ongoing activity worldwide. Strategies for active control, often in combination with energy storage, have the potential to dramatically affect the absorbed energy and hence the economy of the devices. The complexity of the electrical control strategies and related technologies affect the risk of experiments in terms of survivability and cost, which is something that needs to be taken into consideration by the wave energy developers.

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