A review of wave energy converter technology

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The manuscript was received on 26 March 2009 and was accepted after revision for publication on 16 June 2009.

DOI: 10.1243/09576509JPE782

Abstract: Ocean waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves is considerable. Research in this area is driven by the need to meet renewable energy targets, but is relatively immature compared to other renewable energy technologies. This review introduces the general status of wave energy and evaluates the device types that represent current wave energy converter (WEC) technology, particularly focusing on work being undertaken within the United Kingdom. The possible power take-off systems are identified, followed by a consideration of some of the control strategies to enhance the efficiency of point absorber-type WECs. There is a lack of convergence on the best method of extracting energy from the waves and, although previous innovation has generally focused on the concept and design of the primary interface, questions arise concerning how best to optimize the powertrain. This article concludes with some suggestions of future developments.

Keywords: wave energy converter, power-take-off, wave power

1 INTRODUCTION

Despite being discussed in patents since the late 18th century [**1**], modern research into harnessing energy from waves was stimulated by the emerging oil crisis of the 1970s (for example, see reference [**2**]). With global attention now being drawn to climate change and the rising level of CO_2, the focus on generating electricity from renewable sources is once again an important area of research.

It is estimated that the potential worldwide wave power resource is 2 TW [**3**], with the UK's realistic potential being 7–10 GW [**4**]. To put these figures into perspective, the UK's total grid capacity is 80 GW, with peak demand stabilized at around 65 GW (George Ulewande, nPower, 2008, personal communication). As such, up to 15 per cent of current UK electricity demand could be met by wave energy; when combined with tidal stream generation, up to 20 per cent of the UK demand could be met [**5**].

There are several reviews of wave energy converter (WEC) concepts (for example, see references [**2**], [**3**], [**6**], and [**7**]). These show that many wave energy devices are being investigated, but many are at the R&D stage, with only a small range of devices having been tested at large scale, deployed in the oceans. The LIMPET shoreline oscillating water column (OWC), installed at Islay, Scotland, in 2000 represents one system that is currently producing power for the National Grid [**8**]. In September 2008, another commercial wave power system started operating in Northern Portugal. It makes use of the Pelamis power generating device built by Pelamis Wave (formerly OPD) in Scotland (see section 2.4.1 for more information).

1.1 Benefits

Using waves as a source of renewable energy offers significant advantages over other methods of energy generation including the following:

1. Sea waves offer the highest energy density among renewable energy sources [**6**]. Waves are generated by winds, which in turn are generated by solar energy. Solar energy intensity of typically 0.1–0.3 kW/m^2 horizontal surface is converted to an average power flow intensity of 2–3 kW/m^2 of a vertical plane perpendicular to the direction of wave propagation just below the water surface [**9**].
2. Limited negative environmental impact in use. Thorpe [**3**] details the potential impact and presents an estimation of the life cycle emissions of a typical nearshore device. In general, offshore devices have the lowest potential impact.

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3. Natural seasonal variability of wave energy, which follows the electricity demand in temperate climates [**6**].
4. Waves can travel large distances with little energy loss. Storms on the western side of the Atlantic Ocean will travel to the western coast of Europe, supported by prevailing westerly winds.
5. It is reported that wave power devices can generate power up to 90 per cent of the time, compared to ~20–30 per cent for wind and solar power devices [**10**, **11**].

1.2 Challenges

To realize the benefits listed above, there are a number of technical challenges that need to be overcome to increase the performance and hence the commercial competitiveness of wave power devices in the global energy market.

A significant challenge is the conversion of the slow (~0.1 Hz), random, and high-force oscillatory motion into useful motion to drive a generator with output quality acceptable to the utility network. As waves vary in height and period, their respective power levels vary accordingly. While gross average power levels can be predicted in advance, this variable input has to be converted into smooth electrical output and hence usually necessitates some type of energy storage system, or other means of compensation such as an array of devices.

Additionally, in offshore locations, wave direction is highly variable, and so wave devices have to align themselves accordingly on compliant moorings, or be symmetrical, in order to capture the energy of the wave. The directions of waves near the shore can be largely determined in advance owing to the natural phenomena of refraction and reflection.

The challenge of efficiently capturing this irregular motion also has an impact on the design of the device. To operate efficiently, the device and corresponding systems have to be rated for the most common wave power levels. Around the British Isles and the western coasts of Europe, the most common offshore waves are around 30–70 kW/m [**12**]. However, the device also has to withstand extreme wave conditions that occur very rarely, but could have power levels in excess of 2000 kW/m. Not only does this pose difficult structural engineering challenges, but it also presents one of the economic challenges as the normal output of the device (and hence the revenue) are produced by the most commonly occurring waves, yet the capital cost of the device construction is driven by a need to withstand the high power level of the extreme, yet infrequent, waves [**13**]. There are also design challenges in order to mitigate the highly corrosive environment of devices operating at the water surface [**6**].

Lastly, the research focus is diverse. To date, the focus of the wave energy developers and a considerable amount of the published academic work has been primarily on sea performance and survival, as well as the design and concept of the primary wave interface. However, the methods of using the motion of the primary interface to produce electricity are diverse. More detailed evaluation of the complete system is necessary if optimized, robust yet efficient systems are to be developed

2 WAVE ENERGY CONVERTERS

There is a large number of concepts for wave energy conversion; over 1000 wave energy conversion techniques have been patented in Japan, North America, and Europe [**6**]. Despite this large variation in design, WECs are generally categorized by location and type.

2.1 Location

Shoreline devices have the advantage of being close to the utility network, are easy to maintain, and as waves are attenuated as they travel through shallow water they have a reduced likelihood of being damaged in extreme conditions. This leads to one of the disadvantages of shore mounted devices, as shallow water leads to lower wave power (this can be partially compensated by natural energy concentrated locations [**6**]). Tidal range can also be an issue. In addition, by nature of their location, there are generally site-specific requirements including shoreline geometry and geology, and preservation of coastal scenery, so devices cannot be designed for mass manufacturing.

Nearshore devices are defined as devices that are in relatively shallow water (there is a lack of consensus of what defines 'shallow' water, but it has been suggested that this could be a depth of less than one-quarter wavelength [**4**]). Devices in this location are often attached to the seabed, which gives a suitable stationary base against which an oscillating body can work. Like shoreline devices, a disadvantage is that shallow water leads to waves with reduced power, limiting the harvesting potential.

Offshore devices are generally in deep water although again there is little agreement about what constitutes 'deep' water. 'Tens of metres' is one definition [**5**], with 'greater than 40 m' [**4**], and 'a depth exceeding one-third of the wavelength' [**9**] being others. The advantage of siting a WEC in deep water is that it can harvest greater amounts of energy because of the higher energy content in deep water waves [**4**]. However, offshore devices are more difficult to construct and maintain, and because of the greater wave height and energy content in the waves, need to be designed to survive the more extreme conditions adding cost to construction. Despite this, it is argued that with more powerful waves, floating devices in deep water offer greater structural economy [**14**].

It is useful to note that wave energy occurs in the movements of water near the surface of the sea [**5**]. Up to 95 per cent of the energy in a wave is located between the water surface and one-quarter of a wavelength below it [**4**].

2.2 Type

Despite the large variation in designs and concepts, WECs can be classified into three predominant types.

2.2.1 Attenuator (A)

Attenuators lie parallel to the predominant wave direction and 'ride' the waves. An example of an attenuator WEC is the Pelamis, developed by Ocean Power Delivery Ltd (now known as Pelamis Wave Power [**15**]). Figure 1 shows an artist's impression of a Pelamis wave farm. See section 2.4.1 for more details about this particular WEC.

2.2.2 Point absorber (B)

A point absorber is a device that possesses small dimensions relative to the incident wavelength. They can be floating structure that heave up and down on the surface of the water or submerged below the surface relying on pressure differential. Because of their small size, wave direction is not important for these devices. There are numerous examples of point absorbers, one of which is Ocean Power Technology's Powerbuoy [**16**]. Figure 2 shows an artist's impression of a wave farm using Powerbuoys.

2.2.3 Terminator (C)

Terminator devices have their principal axis parallel to the wave front (perpendicular to the predominant wave direction) and physically intercept waves. One example of a terminator-type WEC is the Salter's Duck, developed at the Unviersity of Edinburgh, as shown in Fig. 3 (for more details, see section 2.4.2).

Fig. 1 Attenuator device: Pelamis wave farm [**17**]

Fig. 2 Point absorber device: OPT Powerbuoy [**18**]

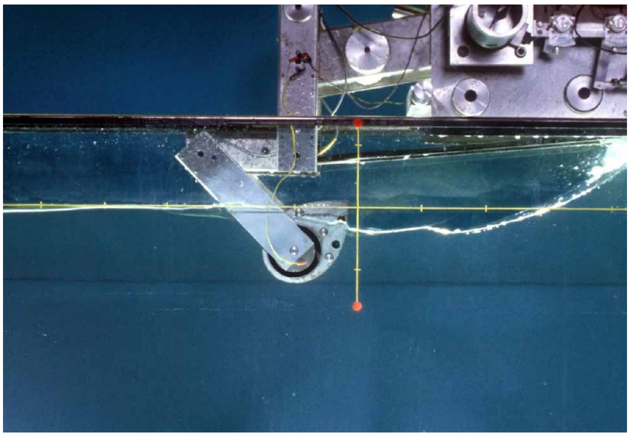


Fig. 3 Terminator device: Salter's Duck [**19**]

2.3 Modes of operation

Within the categories identified above, there is a further level of classification of devices, determined by their mode of operation. Some significant examples are given below.

2.3.1 Submerged pressure differential

The submerged pressure differential device is a submerged point absorber that uses the pressure difference above the device between wave crests and troughs. It comprises two main parts: a sea bed fixed air-filled cylindrical chamber with a moveable upper cylinder. As a crest passes over the device, the water pressure above the device compresses the air within the cylinder, moving the upper cylinder down. As a trough passes over, the water pressure on the device reduces and the upper cylinder rises. An advantage of this device is that since it is fully submerged, it is not exposed to the dangerous slamming forces experienced by floating devices [**20**], and reduces the visual impact of the device. Maintenance of the device is a possible issue however. Owing to part of the device being attached to the sea bed, these devices are typically located nearshore. An example of this device is the Archimedes Wave Swing, an artist's impression of which is shown in Fig. 4.

Fig. 4 Submerged pressure differential: the Archimedes Wave Swing [**21**]

2.3.2 *Oscillating wave surge converter*

An oscillating wave surge converter is generally comprised of a hinged deflector, positioned perpendicular to the wave direction (a terminator), that moves back and forth exploiting the horizontal particle velocity of the wave. An example is the Aquamarine Power Oyster [**22**], a nearshore device, where the top of the deflector is above the water surface and is hinged from the sea bed. A prototype of this device has been constructed. Figure 5 illustrates the device.

2.3.3 *Oscillating water column*

An OWC consists of a chamber with an opening to the sea below the waterline. As waves approach the device, water is forced into the chamber, applying pressure on the air within the chamber. This air escapes to atmosphere through a turbine. As the water retreats, air is then drawn in through the turbine. A low-pressure Wells turbine is often used in this application as it rotates in the same direction irrespective of the flow direction, removing the need to rectify the airflow. It has been suggested that one of the advantages of the OWC concept is its simplicity and robustness [**4**].

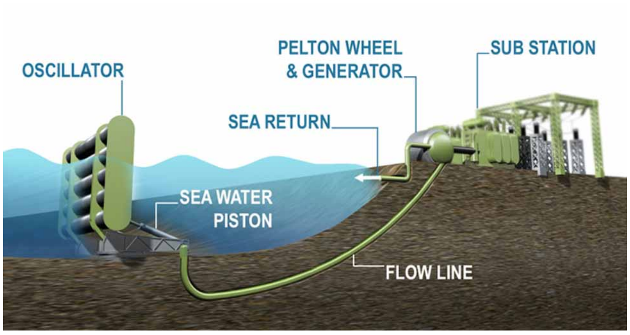


Fig. 5 Oscillating wave surge converter: Aquamarine Power Oyster [**23**]

There are examples of OWCs as point absorbers, as well as being built into the shoreline, where it acts as a terminator. An example of a shoreline mounted device is the Wavegen Limpet. The device is installed on the island of Islay, Western Scotland, and produces power for the national grid. Figure 6 shows the design of the Limpet. The OWC concept has also been proposed by Oceanlinx, an Australian wave energy developer, in a nearshore tethered device [**24**].

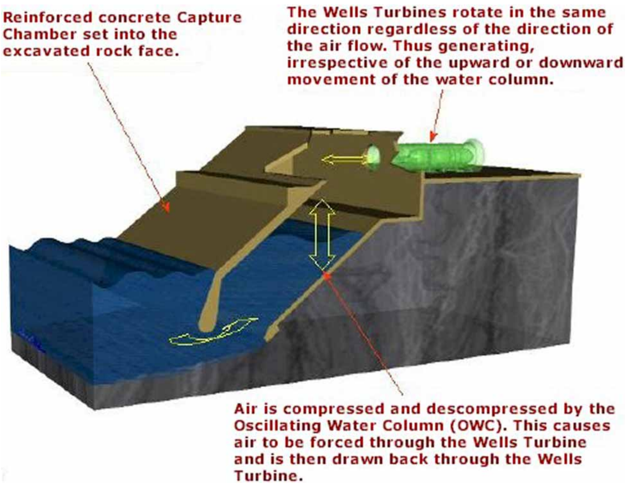
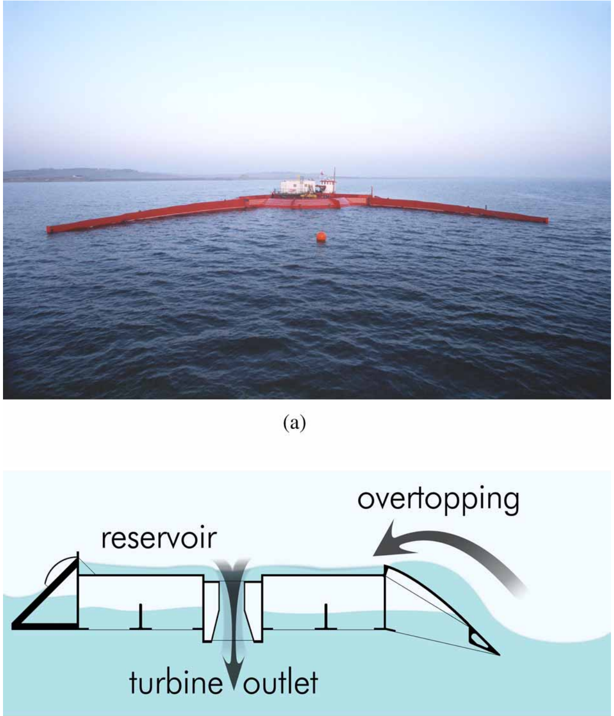


Fig. 6 OWC: the Limpet [**25**]


(a)

(b)

Fig. 7 Overtopping WEC: the Wave Dragon [**26**, **27**]

2.3.4 *Overtopping device*

An overtopping device captures sea water of incident waves in a reservoir above the sea level, then releases the water back to sea through turbines. An example of such a device is the Wave Dragon, which is shown in Fig. 7. This device uses a pair of large curved reflectors to gather waves into the central receiving part, where they flow up a ramp and over the top into a raised reservoir, from which the water is allowed to return to the sea via a number of low-head turbines.

2.4 UK-based research and development

2.4.1 *Commercial operations*

There are many companies currently developing wave power devices. UK-based companies are listed in Table 1. A more exhaustive list of companies worldwide can be found at the European Marine Energy Centre (EMEC) website [**28**].

The Pelamis device deserves more details as it is the offshore device closest to commercial operation (the Wavegen Limpet, while it also operates commercially, is a shoreline mounted OWC). The Pelamis is a floating device comprised of cylindrical hollow steel segments (diameter of 3.5 m) connected to each other by two degree-of-freedom hinged joints. Each hinged joint is similar to a universal joint, with the central unit of each joint containing the complete power conversion system. The wave-induced motion of these joints is resisted by four hydraulic cylinders that accommodate both horizontal and vertical motion. These cylinders act as pumps, which drive fluid through a hydraulic motor, which in turn drives an electrical generator. Accumulators are used in the circuit to decouple the primary circuit (the pumps) with the secondary circuit (the motor), and aid in regulating the flow of fluid to produce a more constant generation. The hydraulic power take off (PTO) system uses only commercially available components.

Each Pelamis is 120 m long, and contains three power modules, each rated at 250 kW. It is designed to operate in water depths of ∼50 m. The shape and loose mooring of Pelamis lets it orient itself to the predominant wave direction, and its length is such that it automatically 'detunes' from the longer-wavelength high-power waves, enhancing its survivability in storms [**29**]. A wave farm using Pelamis technology was recently installed in Aguçadora Wave Park, about 3 miles from Portugal's northern coast, near Pòvoa do Vorzina. This followed full-scale prototype testing at the EMEC facility in Orkney [**30**]. The wave farm initially uses three Pelamis P-750 machines developing a total power of 2.25 MW.

2.4.2 *University-based research*

Working in parallel and sometimes collaboratively with the wave energy developer companies listed in Table 1, are universities and other research institutes. The primary ones identified in this study are listed below.

1. The University of Edinburgh: The Wave Power Group at the University of Edinburgh [**31**], founded in 1974, is very active in WEC development. Stephen Salter, one of the early pioneers in wave energy research, was based at Edinburgh, and thus much work was focused on the Salter's nodding 'duck' device. The Duck concept is reported to be theoretically one of the most efficient devices, and the primary interface is able to absorb 100 per cent of the energy contained in a wave [**20**]. The efforts to efficiently convert motion from this device to electricity have motivated research into efficient hydraulic drives [**32**, **33**]. The University of Edinburgh is also involved in the EquiMar project (see below).
2. Lancaster University: There is a wide range of wave energy projects in which the Lancaster University Renewable Energy Group (LUREG) is involved. They were involved in Supergen 1 and

Table 1 UK-based wave energy developers

Company	Website	Device type
Aquamarine Power	www.aquamarinepower.com	C
AWS Ocean Energy	www.awsocean.com	B
Checkmate Seaenergy (Anaconda)	www.checkmateuk.com/seaenergy	A
C-Wave	www.cwavepower.com	A/C
Embley Energy (Sperboy)	www.sperboy.com	B
Green Ocean Energy Ltd	www.greenoceanenergy.com	A
Neptune Renewable Energy Ltd	www.neptunerenewableenergy.com	C
Ocean Navitas	www.oceannavitas.com	B
Ocean Power Technology	www.oceanpowertechnology.com	B
Offshore Wave Energy Ltd	www.owel.co.uk	C
ORECon	www.orecon.com	B
Pelamis	www.pelamiswave.com	A
Trident Energy	www.tridentenergy.co.uk	B
Wave Dragon	www.wavedragon.net	C
Wavegen	www.wavegen.com	C

now Supergen 2 (see below), along with the Carbon Trust's Marine Energy Accelerator Programme and NaREC's development test rig (see below for more information on NaREC). They work in a wide range of fields within wave energy, looking at new device designs, numerical modelling and control, PTO development (with a focus on electrical linear generation), and device evaluation.

3. PRIMaRE (Universities of Plymouth and Exeter): The Peninsular Research Institute for Marine Renewable Energy is a collaboration between the universties of Exeter and Plymouth to research marine renewable energy [**34**]. This recently established group undertakes inter-disciplinary research and is directly linked to the SWERDA-funded Wave Hub project [**35**] (see below for more details). The University of Exeter is also involved in the EquiMar project (see below).

2.4.3 Wave energy projects and organizations

The list below includes some of the wave energy projects currently being undertaken, with links to UK institutions and companies. The following have technical content, but there are a number of other wave energy organizations and projects that focus on promotion, economics, marketing, and other aspects to speed up the introduction of marine energy (for example Waveplam [**36**] and WavEC [**37**]).

1. EMEC: The European Marine Energy Centre was set up in 2003 with funding partly from the Carbon Trust and aims to stimulate and accelerate the development of marine power devices, initially through the operation of a testing centre in Orkney [**30**]. Similar to the planned Wave Hub project, the facilities at EMEC are test berths, with electrical connections enabling wave energy device developers to test full-scale prototypes.
2. EquiMar: The Equimar Project (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of performance, cost, and environmental impact) is an FP7-funded (European Commission) collaborative research and development project that involved a consortium of 23 partners and will run for 3 years from 15 April 2008. The aim of the EquiMar project is to 'deliver a suite of protocols for the equitable evaluation of marine energy converters. These protocols will harmonize testing and evaluation procedures across the wide variety of devices'. These protocols will be used to establish a base for future marine energy standards. More details about this project can be found in reference [**38**].
3. Marine Energy Accelerator: The Carbon Trust's current Marine Energy Accelerator is an initiative to reduce the costs associated with marine energy technologies, bringing forward the time when marine energy devices can contribute to emissions reduction [**39**]. It follows on from the Marine Energy Challenge project [**5**], which supported development and understanding of wave and tidal stream energy technologies.
4. SuperGen (Sustainable Power Generation and Supply): Engineering and Physical Sciences Research Council supported research (in partnership with Biotechnology and Biological Sciences Research Council, Economic and Social Research Council, Natural Environment Research Council, and the Carbon Trust) in sustainable power generation and supply, enabling the UK to meet environmental emissions targets. The Marine Energy Research Consoritum, led by Edinburgh University, and including LUREG (Lancaster), Heriot-Watt, Robert Gordon University, Strathclyde and Queen's University Belfast, aims to increase the knowledge and understanding of extraction of energy from the sea. Funding is £2.6 million over 4 years. More information about the SuperGen Marine, currently in its second phase, can be found in reference [**40**].
5. Wave Hub: The aim of the Wave Hub project is to construct a wave farm demonstration/evaluation site off the northern coast of Cornwall [**36**]. The budget of the project is £28 million, with £21.5 million coming from the South West of England Regional Development Agency. The project will lay a high-voltage cable 10 miles out to sea and connect it to the National Grid. Companies will be able to test their WECs in a leased and consented area of sea. It is reported that the installation of Wave Hub is planned for Spring 2010.

More details on other wave energy projects and operations world wide can be found in references [**3**], [**6**], [**7**], [**9**] to [**11**], and [**41**].

3 POWER TAKE OFF METHODS

The method of energy capture varies from device to device, but with the exception of linear electrical generation, discussed later, the general method of producing electrical power is through conventional high-speed rotary electrical generators [**42**]. One of the major challenges of WECs is concerned with how to drive these generators. Heaving- and nodding-type devices are not directly compatible with conventional rotary electrical machines, and a transmission system is required to interface the WEC with the electrical generator [**20**].

In this section, different types of rotary generators are briefly presented, followed by an overview of different energy transfer methods. This starts with turbine transfer, moving on to hydraulic conversion methods, and then discussing direct electrical linear generators,

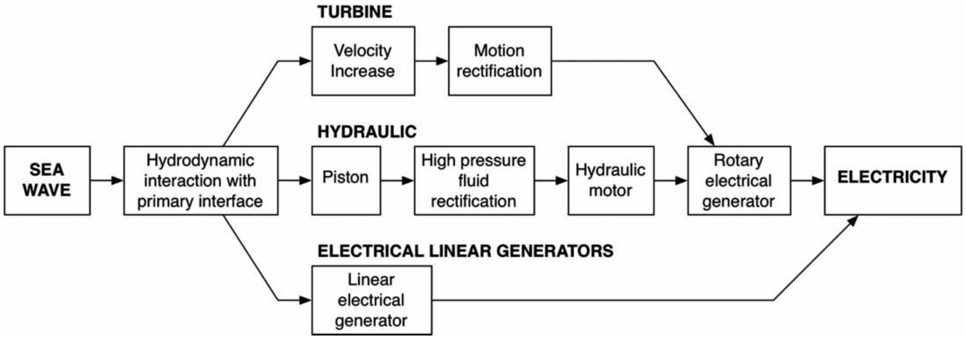


Fig. 8 Alternative PTO mechanisms

which could be considered as a competing technology. These different PTO mechanisms are shown in Fig. 8.

3.1 Rotary generator types

Traditional power stations use on-line synchronous generators (SGs), and are operated at a virtually constant speed, matching the frequency of the grid connection. Depending on the conversion system, generators used for wave energy may have to cope with variable speed. Four generator types are identified: doubly fed induction generators (DFIG), squirrel cage induction generators, permanent magnet SGs, and field would SGs.

O'Sullivan and Lewis [**43**] discuss these generator options in terms of suitability for an OWC application, by examining the advantages and disadvantages in terms of environmental, electrical, and cost factors, and by using a time-domain MATLAB model. The generators in OWC devices typically operate at variable speed. There are similarities in this application with the mature technologies currently used in wind turbines. The favoured generators used in wind turbines (DFIG driven via a gear box, and direct drive low-speed SG with dedicated power electronics) are possible candidates for use in OWC WECs. O'Sullivan and Lewis's study concludes that the latter, the SG, are the preferred option due to its better energy yield, weight, and controllability, despite the requirement for a full frequency converter between the generator and the grid. The significant disadvantage of the DFIG is its maintenance requirement; DFIGs are not brushless machines – a significant issue in offshore WECs.

Linear electrical generators are discussed in greater detail in section 3.4.

3.2 Turbine transfer

'Turbine transfer' is the term used here to represent the method employed in devices where the flow of fluid (either sea water or air) drives a turbine, which is directly coupled to a generator. The types of devices using direct transfer include OWCs and overtopping devices.

As discussed above, the requirements for generators in OWCs, such as variable speed input, are similar to those of a wind turbine, and thus have been well researched (for example, see references [**44**] to [**46**]).

The significant advantage of using sea water turbines is that leakage of fluid causes no environmental problems. The disadvantage is that sea water is a complex fluid with various unpredictable constituents. In addition, in nearshore devices, abrasive particles could damage seals and valves. Cavitation could also be a problem, unless the turbine is in deep water to maintain positive pressure. In low-pressure situations, experienced in overtopping devices, propeller-type turbines are often used, such as the Kaplan design.

Using air as the working fluid has the advantage of increasing the slow velocities of waves to high air flow rate. The most popular air turbine design is the Wells turbine, because of its ability to rotate in the same direction, irrespective of airflow direction. Inherent disadvantages include low efficiency (around 60–65 per cent [**47**, **48**]), poor starting, high noise, and high axial thrust when compared to traditional turbines [**49**]. Pitch control of the turbine blades can increase efficiency [**50**].

3.3 Hydraulics

Another method of converting the low-speed oscillating motion of the primary WEC interface is to employ a hydraulic system. Waves apply large forces at slow speeds and hydraulic systems are well suited to absorbing energy in these situations [**51**]. The use of hydraulics operating at a pressure of 400 bar is a distinct advantage of some types of WEC where size and weight are an issue [**42**], and the force created by these pressures are considerably greater than those from the best electrical machines.

Figure 9 is a circuit diagram for a basic hydraulic PTO system for a WEC. The rod of the hydraulic cylinder is forced up and down by a floating buoy, which forces fluid through check valves, rectifying the flow, to a hydraulic motor. In this case, the generator could be a constant speed device, and the hydraulic motor has variable capacity, to drive the generator at close

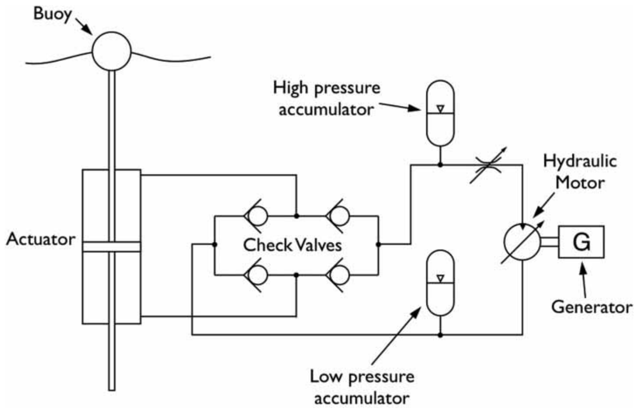


Fig. 9 Typical hydraulic circuit for WEC

to constant speed despite a variable flowrate. The control of the motor capacity could be based on measured or predicted sea states around the WEC, or fluid flow measurements within the system. Additionally, a throttling valve could also be used to control the flow to the motor. Accumulators are included in the circuit to provide energy storage and to maintain constant flow to the hydraulic motor. In addition, the low-pressure accumulator provides a small boost pressure to reduce the risk of cavitation on the low-pressure side.

If the incident waves are close to sinusoidal, then the flow from one port of the actuator is represented in Fig. 10(a). Rectification through the check valves results in the flow represented in Fig. 10(b). The accumulator would then smooth this, with the variable capacity motor driving the generator.

The hydraulic circuit employed in the Pelamis WEC (see section 2.4.1 for further details) essentially follows the design shown in Fig. 9. The accumulators provide a decoupling between the hydraulic cylinders and the motors, providing enough energy storage to supply the pumps with a relatively constant energy supply. Active valves are employed to rectify the flow, and are also used to vary the reaction torque. In reference [**51**], it is noted that losses in the primary transmission can be kept below 20 per cent over a wide range of operating conditions.

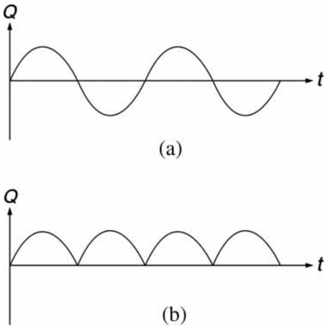


Fig. 10 Flow-time representations for hydraulic WEC

There are a number of challenges associated with hydraulic conversion systems in WECs. These include the following.

3.3.1 *Fluid containment*

Containment of hydraulic fluid is of great importance, as is ingress of sea water. The UK Department of Trade and Industry (DTI) Wave Energy Programme sponsored a report to review the current status of wave energy technologies [**52**]. This report highlighted fluid containment as an issue for performance and environmental reasons, with a recommendation to investigate the development of hydraulic systems based on water or other environmentally acceptable fluid. The Carbon Trust Guidelines on design and operation of WECs [**53**] indicate pressure containment as the primary consideration for the hydraulic system. There are a number of alternative biodegradable fluids, but each comes with various benefits and disadvantages. In addition, the compatibility of the fluids with the components and seals must be ensured. Using sea water as the working fluid may be the most environmentally friendly method, but there are limitations in terms of leakage, sealing, temperature, pressure, speed, size, cycling, deposition of solids, biological growth, lubrication, and corrosion.

The Pelamis WEC uses hydraulic fluid that is biodegradable in the marine environment (biodegradable transformer fluid). In addition, there is reported to be two levels of egress/ingress protection in the form of flexible rubber bellows that would have to fail to allow water to ingress to a point where fluid could escape to the outside environment [**51**].

3.3.2 *Sealing*

The issue of sealing is linked to fluid containment. In addition, however, standard dynamic seals are designed to operate at velocities lower than a typical WEC [**42**]. The temperature rise caused by shear loss and friction at the moving interface is a serious contributor to seal wear; the life of the seal is inversely related to the speed, distance, and length of its application, which in turn has an impact on maintenance requirements. It is argued that the lack of 'land-based demand' for high-velocity seals, rather than any technical difficulty, is the reason for the high-speed issues with seals [**50**].

3.3.3 *Efficiency*

The efficiency of the PTO system is vital to the ability to harness the energy of the device. Traditional hydrostatic transmissions tend to use coupled variable displacement pumps and motors, which have an ideal operating point and a peak efficiency of around 80 per cent. Away from this ideal operating point, efficiency drops away; the part-load losses (including coulomb and viscous friction, leakage, and compressibility) are significant. Although the hydraulic system may have a high rating, it is reasonable that the device will spend most of the time operating at a fraction of this rating, and therefore the system must have the highest part-load efficiencies [**54**]. The DTI report [**52**] also highlights the efficiency issue of hydraulics, recommending that work should focus on the development of dedicated hydraulic motors with low part-load losses and high torque pumps. In addition, the check valves used to rectify the flow, and the throttling valve to control the flow, have pressure drops associated with their orifices, leading to a loss in power and reduced efficiency.

Driven by the need for very high-efficiency high-pressure bi-directional oil hydraulic transmissions that could implement the advanced control algorithms required to obtain the most energy out of waves, a novel digital displacement pump–motor concept was developed [**32**, **50**, **55**]. The basic structure of the pump–motor is similar to a conventional radial piston pump–motor, but includes electromagnetically operated poppet valves for each cylinder, allowing the device to go from full output to zero output in one revolution. Part-load efficiency is also greatly increased due to the complete deactivation of cylinders. A prototype digital displacement transmission is currently being developed for a wind turbine application, obviating the need for heavy gearboxes or full-power electronics and frequency converters for low-speed electrical generators [**56**]. A similar device is currently being developed for marine energy applications [**57**, **58**].

3.3.4 Maintenance

Carrying out maintenance in the marine environment is expensive, time-consuming, and poses many risks. In a hydraulic conversion system, there are likely to be several stages between the primary interface and the electrical generator, each comprising moving parts, and thus may require maintenance. It is important that the required maintenance is minimized, preferably only requiring inspection annually or less [**52**]. In addition, metal surfaces and components must be protected from corrosion and erosion. Ceramic coatings (such as Ceramax, manufactured by Bosch Rexroth) offer a promising method of protecting the components in direct contact with sea water.

One method that could be employed to minimize maintenance costs (and potentially reduce the possibility of leakage from hydraulic devices) would be to position the hydraulic PTO system at the shore. This has received limited interest due to the long, costly, and inefficient pipework required to transport the fluid from the offshore or nearshore device to shore, and the associated significant power loss.

3.3.5 End-stop

The end-stop issue is not exclusive to devices employing a hydraulic PTO system; it applies to all moving body converters with rigid connections to PTOs. The problem arises from the oscillating interface exceeding its design travel. With a hydraulic transfer system, the oscillating interface could be connected to linear hydraulic rams used to pump fluid to the motor. The high forces and corresponding energy experienced in extreme conditions cannot be suddenly absorbed by hitting the end of cylinder stroke, damaging the system. Mitigating this by employing high-stroke actuators is compromised by their mass and expense, and their stroke capability will not be exploited most of the time. Buckling of extended stroke actuators may also be an issue, particularly if side loads are present at maximum extension.

Methods to mitigate end-stop issues with hydraulic actuators include specific designs that mechanically limit the stroke (Pelamis uses this technique), or are based on rotation, in which case a radial piston pump can be employed (the SEAREV [**59**] uses this method). A winch mechanism could also be employed to drive a rotary pump, and Salter has also examined a rotary machine for use with the duck WEC [**50**].

There are other designs such as the inter project service heaving buoy [**21**] (such as AquaBuOY [**60**]) that does not suffer from the end-stop issue. The inter project service concept consists of a long tube, open at both ends attached to a floating buoy. Within the tube is a piston. As the buoy heaves, the water within the tube forces the piston to move relative to the buoy. As the tube is open at both ends, the concept does not suffer from the 'end-stop' issue.

3.3.6 Energy storage

Some form of energy storage is usually incorporated in a PTO system, as the fluctuations in absorbed wave power will result in very variable electrical power output, which is unsuitable for the grid [**61**]. Accumulators can function as short-term energy storage as part of the hydraulic system. By storing energy, accumulators would help the system deal with the high level of variance, reducing the capital cost and power losses of all subsequent powertrain elements [**50**]. The Pelamis hydraulic PTO system uses accumulators to provide a 'smooth' flow to the hydraulic motors, and are used to separate the primary transmission (hydraulic cylinders and their controls) from the secondary transmission (hydraulic motors and electric generators). It is argued that this separation allows for efficient absorption over a large range of incident power; up to 80 per cent is reported [**51**].

3.4 Electrical linear generation

During early wave power research, the possibility of using electrical linear generators was investigated. The conclusions at this stage were that these machines would be too heavy, inefficient, and expensive. New magnetic materials and the reduced costs of frequency converting electronics mean that this technology may now be possible. It is argued that the increased complexity of hydraulic or turbine systems introduce reliability and maintenance issues, which are important to minimize in offshore environments [**20**, **62**].

A linear SG offers the possibility of directly converting mechanical energy into electrical energy. The electrical direct drive PTO alternative, as shown previously in Fig. 8, is much simpler than hydraulic systems, with no intermediate steps between the primary interface and the electrical machine.

Conventional electrical machines are designed to be driven with high-speed rotary motion. The airgap speed between the rotor and stator in these machines can be high (upwards of 60 m/s) allowing for easy conversion into a rapid change in flux. Linear oscillatory motion from a WEC, however, is expected to have a peak of around 2 m/s [**43**]. Developments for the wind power industry have focused on direct drive generators (to replace unreliable and heavy gearboxes). These direct drive generators have an airgap speed of 5–6 m/s. The development of linear electrical generators requires continuing research into slow-speed electrical machines.

The basic concept of a linear generator is to have a translator (what would be the rotor in a rotary machine) on which magnets are mounted with alternating polarity directly coupled to a heaving buoy, with the stator containing windings, mounted in a relatively stationary structure (connected to a drag plate, a large inertia, or fixed to the sea bed). As the heaving buoy oscillates, an electric current will be induced in the stator. The schematic of this device is shown in Fig. 11.

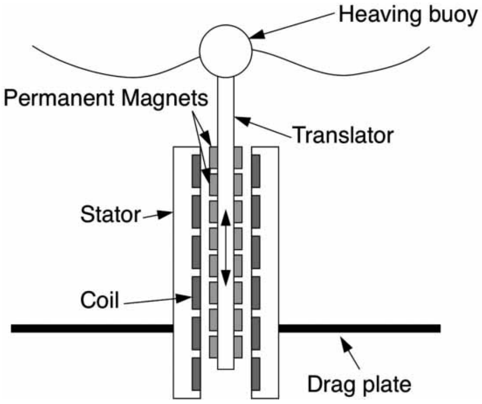


Fig. 11 A schematic of a linear electrical generator based on a permanent magnet generator

3.4.1 *Linear generator types*

The need for very low maintenance machines implies the use of brushless generators. Baker and Mueller rule out induction machines (induction machines have been used in wind turbines, because of their ability to cope with varying speeds), which require a large minimum pole pitch to achieve sufficient flux density and so are too large, and reluctance machines, owing to their very small airgaps, which are difficult to maintain. The focus lies in permanent magnet machines [**20**]. The development of high-energy density permanent magnets such as Neodymium–Iron–Boron (Nd–Fe–B), which can produce high magnetomotive force for a relatively small magnet height, has significantly improved the power density of permanent magnet machines.

Part of the SuperGen project, mentioned in section 2.4.3, covers PTO and conditioning, and confirms that induction machines are not suitable because of the low-speed motion of WECs. Permanent magnet generators exhibit high part load efficiencies and, while they have been demonstrated at sea to a limited extent, designs are not yet fully optimized [**40**].

There are three main topologies of linear electrical generators:

(a) longitudinal flux permanent magnet generators;
(b) variable reluctance permanent magnet generators (with transverse flux permanent magnet generators as a subset of these);
(c) tubular air-cored permanent magnet generators.

The design of electrical generators for direct drive WECs was examined by Mueller [**42**], by comparing the longitudinal flux permanent magnet machine with the transverse flux permanent magnet machine. He identified that the transverse flux machine as having the best potential, owing to the design having higher power density and efficiency, compared to the longitudinal design. Despite the high shear stress offered by transverse flux machines (up to 200 kN/m^2 [**63**]), their topology requires structural support and they suffer from low power factor requiring reactive power compensation [**64**].

Baker *et al.* [**65**] discuss the permanent magnet vernier hybrid machine (a type of variable reluctance permanent magnet generator) and the air-cored machine, both of which attempt to solve some of the issues with the transverse flux machine. Although the vernier hybrid machine offered a high shear stress, it suffered from a low power factor, requiring a high rating power electronic converter, and bearing issues owing to large magnetic attraction forces. The tubular air-cored machine, being developed at the University of Durham, has no attraction forces (and thus a less complex support structure) and low inductance, which results in a high power factor (thus necessitating a lower rated power electronic converter), but suffers from having significantly less shear stress. These two topologies are also discussed in reference [**66**].

Leijon *et al.* [**67**] have conducted multiphysics simulations of a three-phase linear permanent magnet generator (using the Archimedes Wave Swing as the target device), with the results confirming its potential. This work was followed by an experimental setup that successfully verified the simulations [**13**]. The work also briefly discussed the interconnection scheme when dealing with an array of devices. Polinder *et al.* [**68**] also discuss the linear permanent magnet generator designed for use with the Archimedes Wave Swing. The authors highlighted that such a machine was chosen because of its high force density, reasonable efficiency at low speeds, the availability of cheaper magnets with high power density, and the lack of electrical contact to the translator. Reasonable correlation between calculated results from simulations and measured results from experimental testing indicates that the generator is appropriate [**69**].

3.4.2 Signal processing

One issue of linear electrical generators is converting the signal to one appropriate for grid connection. If the motion of the WEC is sinusoidal, the induced EMF varies in amplitude and frequency during a wave cycle. As the translator reciprocates, the speed is continuously changing, resulting in a varying frequency of the induced voltage. Figure 12 from reference [**20**] shows a typical EMF plot from a variable reluctance permanent magnet machine excited by a sinusoidal displacement.

For grid connection, this waveform, which is variable in both frequency and amplitude, must be rectified before conversion into a sinusoidal fixed voltage and frequency waveform using power electronics. The rectification can be passive or active. A passive rectifier can be a simple diode bridge, and this is characterized by having a power factor of one. The active power can be increased if the power factor is not equal to one, which can be accommodated by an active rectifier. The method of converting the current through power electronics is beyond the scope of this review, but is covered in more detail by Baker *et al.* [**65**], Brooking *et al.* [**70**], and Ran *et al.* [**71**].

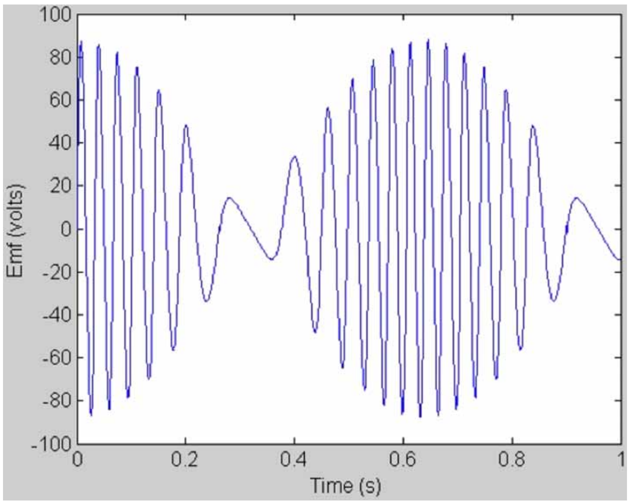


Fig. 12 Typical EMF plot [**20**]

4 CONTROL

In regular waves, energy is captured most efficiently in a point-absorber-type WEC when the undamped natural frequency of the device is close to the dominant frequency of the incident wave [**72**]. At resonance, the velocity of the oscillator is in phase with the dynamic pressure (and hence force) of the incoming wave, resulting in a substantial transfer of energy from the wave to the oscillator [**73**]. The behaviour of the device therefore is dependent on the damping. For most power extraction, damping must be adjusted to achieve maximum energy conversion efficiency. If the damping is too high then the motions are limited and little power is produced. If the damping is too light, then the damper absorbs little power and little power is taken off. With any PTO system, the correct damping is vital for an efficient system.

Real seas, however, rarely exhibit regular conditions. Instead, waves are continually changing in height and frequency, and thus the requirement is a device that can adapt to behave as if resonant over the wide range of frequencies. It is noted that major improvements in efficiency (and hence cost-effectiveness) of WECs are possible with the implementation of active control of the dynamics [**14**], along with potential improvement in year-round productivity [**74**]. The level of device tuning can range from adjusting parameters for a particular sea state to wave-by-wave adaptation (also known as fast tuning). This section covers some of the techniques that can be employed to achieve efficient energy conversion.

Salter *et al.* [**50**] review a range of different control strategies with varying degrees of sophistication. Although many are suitable for specific incident wave frequencies and amplitudes, the range of frequencies and amplitudes that each can deal with gives the more advanced strategies their advantage. Instead of restating the details in this review, more focus is given to some selected strategies that have attracted greater attention in the literature.

4.1 Latching control

Latching control was first examined by Budal and Falnes in reference [**75**]. The objective behind latching control is to stall (i.e. latch) the motion of the device at the extremes of its movement (when velocity is zero), and release it when the wave forces are in good phase to maximize energy extraction. This control strategy

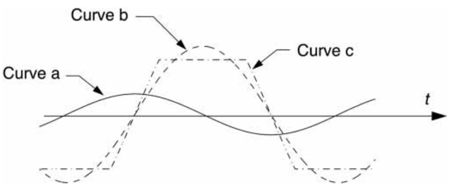


Fig. 13 Latching control

allows for a device whose natural frequency is higher than the exciting wave frequency (and hence, may have a smaller mass). Latching control is discrete, highly non-linear, and by its nature sub-optimal. It is illustrated in Fig. 13 (based on an illustration in reference [**76**]).

In Fig. 13, curve a is the elevation of the water surface caused by the incident wave; curve b is the vertical displacement of a heaving buoy whose mass is so large that its natural frequency matches that of the wave (the ideal condition of resonance); and curve c is the vertical displacement of a body with a smaller mass, and hence a higher natural frequency, being latched at the extremes of travel. The buoy would be released when the wave force had built up to a suitable level, so that its velocity would be nearly in phase with the exciting force of the wave. The velocity of the buoy is at its maximum at the wave crest or trough. A device with negligible mass would follow curve a. Salter notes that the latching system that holds and releases the buoy has to react very quickly, a requirement easily achievable with a hydraulic PTO system [**50**].

Latching control has been the subject of many simulation studies. The challenge with the strategy is determining the optimum time to release the buoy from the latched phase; this is the control variable. In regular waves, using half the difference between the wave period and the natural period of the device gives a good approximation of the latching delay required [**77**].

Babarit *et al.* [**78**] conducted a study to examine three different latching strategies in random seas. Their simulation assumed a single degree of freedom (DOF) heaving body, a simple PTO system, represented as a linear damper, and that the excitation force of the future waves was known (a general assumption in much of the literature); they acknowledge that prediction algorithms exist. They found that the discrete latching control significantly increases the amplitude of the motion, and improves the efficiency of the system over a uncontrolled heave motion by up to three times. Later work by Babarit and Clément [**79**] applied latching control to a four-DOF WEC (dubbed SEAREV). With latching control, the mean absorbed power in a random sea increased by a factor of two over the uncontrolled result.

In reference [**80**], Falcão applies latching control to a wave energy device with a high-pressure hydraulic PTO system, as previously developed in reference [**61**]. He notes that the hydraulic PTO system provides a natural method of achieving latching: the body remains stationary for as long as the hydrodynamic forces on its wetted surface are unable to overcome the resisting force (gas pressure difference multiplied by the cross-sectional area of the ram) of the PTO system. The control strategy was effective, and demonstrated in simulation a significant increase in absorbed energy. The system would need to be optimized through experimental prototype testing, but such a system could be implemented in a real WEC.

Korde [**14**] conducted an experimental study of latching control, demonstrating an efficiency improvement. With irregular waves, some method for predicting the incoming wave profile is necessary. He also notes that the only external force required is to lock the actuator, resulting in easier practical implementation than other control strategies.

In the same paper, Korde also discusses the difficulty of predicting the future wave profile. In regular waves, prediction is not an issue, but in irregular waves, future oscillations cannot be known. Various approaches are reviewed, but the article concludes that attaining accurate and reliable techniques to predict incident waves or device oscillations remains a challenge.

The use of an actively controlled platform has advantages in deep sea offshore sites, as mooring part of the wave energy device on the sea bed is challenging. Korde investigates this in reference [**81**], followed by an examination of latching control of a WEC with an on-board, actively controlled motion-compensated platform as a reference [**82**]. Comparisons are made between this active reference and a sea-bottom fixed reference. For the irregular wave case, the exciting force is assumed to be known far enough into the future. The absorbed energy using the active reference was found to be less than latching using a sea-bottom reference, but worthwhile pursuing in light of the results presented.

The opposite of latching control, dubbed unlatching or declutching is where the primary moving element is allowed to move freely for part of the cycle, with the PTO mechanism only being engaged at the desired velocity. It is the subject of a paper by Babarit *et al.* [**59**], who examined, in simulation, declutching control of the SEAREV device. In this device (which uses a hydraulic PTO system), unlatching is achieved by bypassing the pumps at certain moments, effectively meaning that the PTO force is zero at these times. These moments are determined by the optimal command theory. It is shown that efficiency is improved by a factor of two for some wave conditions.

4.2 Reactive loading control

Reactive loading control is used to widen the efficiency range of a WEC on either side of the resonant frequency [**50**]. This theoretically optimal control strategy involves adjusting the dynamic parameters of the primary converter, such as the spring constant, inertia, and energy absorbing damping, to enable maximum energy absorption at all frequencies. Korde considers reactive control in reference [**14**], and found that velocity feedback could be used to adjust the damping coefficient provided by the PTO system to balance the radiation damping of the device to enable maximum permissible energy absorption. Optimal power absorption requires that the primary converter feels no reactive force (as at resonance) and that the energy absorption rate (damping) equals the rate at which kinetic energy is being radiated from the device.

Reactive loading introduces a phase shift into the PTO force to cancel some of the undesirable stiffness or inertia. Either side of the resonant frequency, the wave force goes into deflecting the 'spring' of the device (a semi-submerged float represents a spring), or accelerating the inertia, reducing overall efficiency. Maximum efficiency is achieved if the force is in phase with the velocity of the device, as at resonance.

Through simulation, Korde studied reactive control of wave energy devices in irregular waves [**74**] and later in reference [**72**], using a time history of past velocity measurements to estimate future velocity of the primary energy converter. In reference [**72**], two approaches are considered: where only the static reactive components due to calm-water inertia and hydrostatic spring are cancelled by the control force at constant damping; and where, in addition, further improvement is sought using estimates of future oscillations (derived from past oscillations). Significant efficiency gains were observed in the first approach, with further gains with estimations of future oscillations. A better prediction strategy or estimation algorithm is needed.

Valério *et al.* [**83**] compares reactive control, phase and amplitude control (another theoretically optimal strategy), latching control, and feedback linearization control (two intrinsically sub-optimal strategies), using the Archimedes Wave Swing as the target device. Reactive control and phase and amplitude control are examined, but since the implementation of these devices require approximations, and both strategies rely on energy to be added to the device (essentially supplying energy to the waves), reducing overall efficiency, the strategies are rendered sub-optimal. Latching is achieved through the use of water dampers so as to prevent the floater from moving. Feedback linearization control aims to provide a control action chosen to cancel the non-linear dynamics of the plant, so that the closed-loop dynamics will be linear. Simulations were carried out to test the strategies, with the assumption that the behaviour of the incident waves is known. All strategies improved the efficiency of the device, with phase an amplitude providing the least improvement, followed by reactive control, with latching increasing the efficiency further, and feedback linearization providing the greatest improvement. Feedback linearization, however, requires detailed knowledge of the machine dynamics and characteristics, and as such is not practical.

Another reason why, in practice, it is not possible for reactive control to be fully optimal, is due to velocities that could become extremely high. As such, constraints are necessary to safeguard against hazards of mechanical/electrical overdriving [**74**].

4.3 Simulation for controller development

Some considerations are necessary concerning the modelling of WECs and the assessment of control strategies using these simulations. Yavuz *et al.* [**84**] present a time-domain model of a single-DOF heaving buoy WEC to investigate the effect on performance of a dynamically changing sea wave frequency. A time-domain simulation study is necessary, as single-frequency-based mathematical models of WECs are not suitable to predict the performance of real systems, as real sea waves are complicated and ever changing. This need is confirmed by Falcão [**61**], who investigates the modelling and control of a heaving buoy WEC with a hydraulic PTO, by stating that the WEC examined is highly non-linear, which requires a time-domain model consisting of a set of coupled equations: (a) an integral-differential equation that accounts for the hydrodynamics of wave energy absorption and (b) an ordinary differential equation that models various aspects of the hydraulic system (including accumulators, valves, flows, and viscosity effects). Josset *et al.* [**85**] constructed a 'wave to wire' time-domain model of the SEAREV WEC, including the PTO system, to study the various elements of the complete device.

With respect to the hydrodynamics, many simulation studies treat the incident waves using linear models. It is generally agreed that this is suitable for relatively calm seas, but in extreme conditions, this linear approximation is not accurate, as non-linear factors dominate (personal communication, Jun Zang, University of Bath, 4 July 2008). Work is ongoing at the University of Bath, and elsewhere, investigating the modelling of these non-linear sea states (for example, see reference [**86**]).

In terms of supplying models with an accurate wave spectrum, many authors have used the Pierson–Moskowitz spectrum [**87**], which accurately models the behaviour of real sea waves [**76**].

5 CONCLUDING REMARKS

The potential for generating electricity from wave energy is considerable. The ocean is a huge resource, and harnessing the energy in ocean waves represents an important step towards meeting renewable energy targets.

This review introduces the current status of WEC technology. The different device types are established and evaluated. The institutions and companies involved in WEC development, as well as collaborative wave energy projects, are also identified.

The possible PTO systems are assessed and classified as hydraulic, linear electrical generator, or turbine based. A hydraulic PTO system is particularly well suited to absorbing energy from a high force, slow oscillatory motion and can facilitate the conversion of reciprocating motion to rotary motion to drive a generator. There are, however, various design challenges such as efficiency and reliability. A linear electrical generator provides an alternative option, but the technology is less mature.

The active control of a WEC can significantly increase its efficiency, and hence cost effectiveness. This research is currently ongoing with latching control being highlighted as a promising, simple method of efficiently extracting energy.

Despite considerable research and development, the concepts for converting a slow, high-force, reciprocating motion to one useful for generating electricity show no signs of converging to a preferred solution. Questions arise over which concept to use, how best to optimize its performance, and how to control such a system. Future research should take a systems engineering approach, as the individual subsystems of a WEC are all intimately related and any one should not be optimized without considering the other subsystems. Furthermore, individual WECs will often operate as part of a wave farm, so future systems analysis must include the interaction between devices.

REFERENCES

1 **Ross, D.** *Power from the waves*, 1995 (Oxford University Press, Oxford, UK).

2 **Salter, S. H.** Wave power. *Nature*, 1974, **249**(5459), 720–724.

3 **Thorpe, T. W.** A brief review of wave energy, Technical report no. R120, Energy Technology Support Unit (ETSU), A report produced for the UK Department of Trade and Industry, 1999.

4 **Duckers, L.** Wave energy. In *Renewable energy* (Ed. G. Boyle), 2nd edition, 2004, ch. 8 (Oxford University Press, Oxford, UK).

5 **Callaghan, J.** and **Boud, R.** Future marine energy: results of the marine energy challenge: cost competitiveness and growth of wave and tidal stream energy, Technical report, The Carbon Trust, January 2006.

6 **Clément, A., McCullen, P., Falcão, A., Fiorentino, A., Gardner, F., Hammarlund, K., Lemonis, G., Lewis, T., Nielsen, K., Petroncini, S., Pontes, M.-T., Schild, B.-O., Sjöström, P., Søresen, H. C.,** and **Thorpe, T.** Wave energy in Europe: current status and perspectives. *Renew. Sust. Energy Rev.*, 2002, **6**(5), 405–431.

7 **Previsic, M.** Offshore wave energy conversion devices, Technical report E21 EPRI WP-004-US-Rev 1, Electrical Power Research Institute, 2004.

8 Wavegen. Available from http://www.wavegen.co.uk/what_we_offer_limpet.htm (access date 24 June 2008).

9 **Falnes, J.** A review of wave-energy extraction. *Mar. Struct.*, 2007, **20**, 185–201.

10 **Pelc, R.** and **Fujita, R. M.** Renewable energy from the ocean. *Mar. Policy*, 2002, **26**(6), 471–479.

11 Power buoys. *The Economist*, 19 May 2001.

12 **Polinder, H.** and **Scuotto, M.** Wave energy converters and their impact on power systems. In Proceedings of the 2005 International Conference on *Future power systems*, 2005, pp. 1–9.

13 **Leijon, M., Danielsson, O., Eriksson, M., Thorburn, K., Bernhoff, H., Isberg, J., Sundberg, J., Ivanova, I., Sjöstedt, E., Ågren, O., Karlsson, K. E.,** and **Wolfbrandt, A.** An electrical approach to wave energy conversion. *Renew. Energy*, 2006, **31**, 1309–1319.

14 **Korde, U. A.** Control system applications in wave energy conversion. In Proceedings of the OCEANS 2000 MTS/IEEE Conference and Exhibition, Providence, Rhode Island, USA, 11–14 September 2000, vol. 3.

15 PelamisWave. Available from http://www.pelamiswave.com (access date 27 June 2008).

16 OPT — Ocean Power Technology. Available from http://www.oceanpowertechnologies.com/ (access date 1 July 2008).

17 Pelamis. Available from http://tinyurl.com/pelamis/ (access date 2 July 2008).

18 OPT Powerbuoy. Available from http://tinyurl.com/oceanpt/ (access date 2 July 2008).

19 Salter's Duck. Available from http://tinyurl.com/saltersduck (access date 31 May 2009).

20 **Baker, N. J.** and **Mueller, M. A.** Direct drive wave energy converters (in French). *Revue des Energies Renouvelables*, 2001, **4**(2), 1–7.

21 Archimedes Wave Swing. Available from http://tinyurl.com/archws1/ (accessed 2 July 2008).

22 Aquamarine Power. Available from http://www.aquamarinepower.com/ (access date 1 July 2008).

23 Aquamarine Power Oyster. Available from http://tinyurl.com/cn9k4k/ (access date 2 July 2008).

24 Oceanlinx. Available from http://www.oceanlinx.com/ (access date 4 September 2008).

25 Oscillating Water Column. Available from http://wavegen.co.uk/images/owc.jpg/ (access date 2 July 2008).

26 Wave Dragon. Available from http://tinyurl.com/wavegen1/ (access date 2 July 2008).

27 Wave Dragon schematic. Available from http://tinyurl.com/wavegen2/ (access date 2 July 2008).

28 EMEC: European Maring Energy Centre Ltd – Wave Energy Developers. Available from http://www.emec.org.uk/wave_energy_developers.asp (access date 1 September 2008).

29 **Tidwell, J.** and **Weir, T.** *Renewable energy resources*, 2nd edition, 2006 (Taylor and Francis, London, UK).

30 The European Wave Energy Centre Ltd. Available from http://www.emec.org.uk/ (access date 4 September 2008).

31 **Taylor, J.** The Department of Mechanical Engineering Wave Power Group. Available from http://www.mech.ed.ac.uk/research/wavepower (access date 2 September 2008).

32 The Digital-Displacement Pump-Motors – A New Generation of Hydraulics. Available from http://www.mech.ed.ac.uk/research/wavepower/ddpm.html (access date 29 September 2008).

33 Artemis Intelligent Power Ltd. Available from http://www.artemisip.com/ (access date 2 September 2008).

34 Peninsular Research Institute for Marine Renewable Energy. Available from http://www.primare.org/ (access date 2 September 2008).

35 South West England Wave Hub Project. Available from http://www.wavehub.co.uk/ (access date 2 September 2008).

36 Wave Energy Planning and Marketing. Available from http://www.waveplam.eu/ (access date 4 September 2008).

37 Wave Energy Centre. Available from http://www.wave-energy-centre.org/ (access date 4 September 2008).

38 EquiMar. Available from http://www.wiki.ed.ac.uk/display/EquiMarwiki/EquiMar (access date 4 September 2008).

39 Marine Energy Accelerator. Available from http://www.carbontrust.co.uk/technology/technologyaccelerator/mea.htm (access date 4 September 2008).

40 SuperGen Marine Energy Research Consortium. Available from http://www.supergen-marine.org.uk (access date 4 September 2008).

41 **Thorpe, T. W.** An overview of wave energy technologies: status, performance and costs. In *Wave power: moving towards commercial viability*, 1999 (Wiley, Chichester, UK).

42 **Mueller, M. A.** Electrical generators for direct drive wave energy converters. *IEE Proc. Gener. Trans. Distrib.*, 2002, **149**(4), 446–456.

43 **O'Sullivan, D. L.** and **Lewis, T.** Electrical machine options in offshore floating wave energy converter turbo-generators. In Proceedings of the Tenth World Renewable Energy Congres (WREC X), 2008, pp. 1102–1107.

44 **Tapia, A., Tapia, G., Ostolaza, J. X.,** and **Saenz, J. R.** Modeling and control of a wind turbine driven doubly fed induction generator. *IEEE Trans. Energy Convers.*, 2003, **18**(2), 194–204.

45 **Ackermann, T.** and **Söder, L.** Wind energy technology and current status: a review. *Renew. Sust. Energy Rev.*, 2000, **4**(4), 315–374.

46 **Thresher, R. W.** and **Dodge, D. M.** Trends in the evolution of wind turbine generator configurations and systems. *Wind Energy*, 1998, **1**(s 1), 70–86.

47 **Curran, R.** and **Gato, L. M. C.** The energy conversion performance of several types of wells turbine designs. *Proc. IMechE, Part A: J. Power and Energy*, 1997, **211**(A2), 133–145. DOI: 10.1243/0957650971537051.

48 **Torresi, M., Camporeale, S. M., Strippoli, P. D.,** and **Pascazio, G.** Accurate numerical simulation of a high solidity wells turbine. *Renew. Energy*, 2008, **33**(4), 735–747.

49 **Kim, T.-H., Takao, M., Setoguchi, T., Kaneko, K.,** and **Inoue, M.** Performance comparison of turbines for wave power conversion. *Int. J. Therm. Sci.*, 2001, **40**(7), 681–689.

50 **Salter, S. H. Taylor, J. R. M.,** and **Caldwell, N. J.** Power conversion mechanisms for wave energy. *Proc. IMechE, Part M: J. Engineering for the Maritime Environment*, 2002, **216**(M1), 1–27. DOI: 10.1243/147509002320382103.

51 **Henderson, R.** Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter. *Renew. Energy*, 2006, **31**(2), 271–283.

52 **Scarr, D., Kollek, R.,** and **Collier, D.** Wave energy: technology transfer & generic R&D recommendations, Technical report ETSU V/06/00187//REP, Arup Energy, Ove Arup & Partners International, Report carried out under contract as part of the Sustainable Energy Programmes, managed by ETSU on behalf of the DTI, 2001.

53 Det Norske Veritas. Guidelines on design and operation of wave energy converters, Technical report, The Carbon Trust, May 2005.

54 **Taylor, J.** *Ocean wave energy: current status and future perspectives*, 2008 (Springer, Berlin, Germany).

55 **Ehsan, Md, Rampen, W. H. S.,** and **Salter, S. H.** Modeling of digital-displacement pump-motors and their application as hydraulic drives for nonuniform loads. *J. Dyn. Syst. Meas. Control*, 2000, **122**, 210.

56 Artemis Intelligent Power Ltd – Digital Displacement Wind Turbine Transmissions. Available from http://www.artemisip.com/appli_renewable.htm (access date 26 September 2008).

57 **Payne, G. S., Kiprakis, A. E., Ehsan, M., Rampen, W. H. S., Chick, J. P.,** and **Wallace, A. R.** Efficiency and dynamic performance of Digital Displacement hydraulic transmission in tidal current energy converters. *Proc. IMechE, Part A: J. Power and Energy*, 2007, **221**(A2), 207–218. DOI: 10.1243/09576509JPE298.

58 Anon. Artemis Intelligent Power Ltd - Marine Energy. Available from http://www.artemisip.com/MarineEnergy.htm (access date 26 September 2008).

59 **Babarit, A., Mouslim, H., Guglielmi, M.,** and **Clément, A. H.** Simulation of the SEAREV wave energy converter with a by-pass control of its hydraulic power take off. In Proceedings of the Tenth World Renewable Energy Congress (WREC X), Glasgow, UK, July 2009, pp. 1004–1009.

60 **Weinstein, A., Fredrikson, G., Parks, M. J.,** and **Nielsen, K.** AquaBuOY-the offshore wave energy converter numerical modeling and optimization. In Proceedings of the OCEANS'04. MTTS/IEEE TECHNO-OCEAN'04, Kobe, Japan, 9–12 November 2004, vol. 4, pp. 1854–1859.

61 **Falcão, A. F. O.** Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator. *Ocean Engng*, 2007, **24**, 2021–2032.

62 **Danielsson, O.** *Ocean wave energy: current status and future perspectives*, 2008 (Springer, Berlin, Germany).

63 **Iwabuchi, N., Kawahara, A., Kume, T., Kabashima, T.,** and **Nagasaka, N.** A novel high-torque reluctance motor with rare-earth magnet. *IEEE Trans. Ind. Appl.*, 1994, **145**(6), 604–614.

64 **Harris, M. R., Pajooman, G. H.,** and **Abu Sharkh, S. M.** The problem of power factor in VRPM (transverse-flux) machines. In Proceedings of the Electrical Machines and Drives, 1997 Eighth International Conference on *(Conf. Publ. No. 444)*, 1997, pp. 386–390.

65 **Baker, N. J., Mueller, M. A.,** and **Brooking, P. R. M.** Electrical power conversion in direct drive wave energy

converters. In Proceedings of the European Wave Energy Conference, Cork, Ireland, 2003, pp. 197–204.

66 **Mueller, M. A.** and **Baker, N. J.** Direct drive electrical power take-off for offshore marine energy converters. *Proc. IMechE, Part A: J. Power and Energy*, 2005, **219**(A3), 223–234. DOI: 10.1243/095765005X7574.

67 **Leijon, M., Bernhoff, H., Agren, O., Isberg, J., Sundberg, J., Berg, M., Karlsson, K. E.,** and **Wolfbrandt, A.** Multiphysics simulation of wave energy to electric energy conversion by permanent magnet linear generator. *IEEE Trans. Energy Convers.*, 2005, **20**(1), 219–224.

68 **Polinder, H., Damen, M. E. C.,** and **Gardner, F.** Linear PM generator system for wave energy conversion in the AWS. *IEEE Trans. Energy Convers.*, 2004, **19**(3), 583–589.

69 **Polinder, H., Damen, M. E. C.,** and **Gardner, F.** Design, modelling and test results of the AWS PM linear generator. *Euro. Trans. Electr. Power*, 2005, **15**, 245–256.

70 **Brooking, P. R. M., Mueller, M. A., Baker, N.J., Haydock, L.,** and **Brown, N.** Power conversion in a low speed reciprocating electrical generator. In Proceedings of the International Conference on *Electrical machines*, Bruges, Belgium, 2002.

71 **Ran, L., Tavner, P. J., Mueller, M. A.,** and **Baker, N. J.** Power conversion and control for a low speed, permanent magnet, direct-drive, wave energy converter. In Proceedings of the Third IET International Conference on *Power electronics, machines and drives*, PEMD 2006, April 2006, pp. 17–21.

72 **Korde, U. A.** Efficient primary energy conversion in irregular waves. *Ocean Engng*, 1999, **26**(7), 625–651.

73 **Budal, K.** and **Falnes, J.** A resonant point absorber of ocean-wave power. *Nature*, 1975, **256**, 478–479.

74 **Korde, U. A.** On control approaches for efficient primary energy conversion in irregular waves. In Proceedings of the OCEANS '98, Nice, France, 28 September–1 October 1999, vol. 3, pp. 1427–1431.

75 **Budal, K.** and **Falnes, J.** Interacting point absorbers with controlled motion. In *Power from sea waves* (Ed. B. Count), 1980, pp. 381–399 (Academic Press, London).

76 **Falnes, J.** *Ocean waves and oscillating systems*, 2002 (Cambridge University Press, Cambridge, UK).

77 **Iversen, L. C.** Numerical method for computing the power absorbed by a phase-controlled point absorber. *Appl. Ocean Res.*, 1982, **4**(3), 173–180.

78 **Babarit, A., Duclos, G.,** and **Clément, A. H.** Comparison of latching control strategies for a heaving wave energy device in random sea. *Appl. Ocean Res.*, 2004, **26**(5), 227–238.

79 **Babarit, A.** and **Clément, A. H.** Optimal latching control of a wave energy device in regular and irregular waves. *Appl. Ocean Res.*, 2006, **28**(2), 77–91.

80 **Falcão, A. F. O.** Phase control through load control of oscillating-body wave energy converters with hydraulic PTO system. *Ocean Engng*, 2008, **35**, 358–366.

81 **Korde, U. A.** On providing a reaction for efficient wave energy absorption by floating devices. *Appl. Ocean Res.*, 1999, **21**, 235–248.

82 **Korde, U. A.** Latching control of deep water wave energy devices using an active reference. *Ocean Engng*, 2002, **29**(11), 1343–1355.

83 **Valério, D., Beirão, P.,** and **Sá da Costa, J.** Optimisation of wave energy extraction with the Archimedes wave swing. *Ocean Engng*, 2007, **34**(17–18), 2330–2344.

84 **Yavuz, H., McCabe, A., Aggidis, G.,** and **Widden, M. B.** Calculation of the performance of resonant wave energy converters in real seas. *Proc. IMechE, Part M: J. Engineering for the Maritime Environment*, 2006, **220**(M3), 117–128. DOI: 10.1243/14750902JEME44.

85 **Josset, C., Babarit, A.,** and **Clément, A. H.** A wave-to-wire model of the SEAREV wave energy converter. *Proc. IMechE, Part M: J. Engineering for the Maritime Environment*, 2007, **221**(M2), 81–93. DOI: 10.1243/14750902JEME48.

86 **Ning, D. Z., Teng, B., Eatock Taylor, R.,** and **Zang, J.** Numerical simulation of 3D fully nonlinear regular and focused waves in an infinite water-depth. *Ocean Engng*, 2008, **35**(8–9), 887–899.

87 **Pierson, W. J.** and **Moskowitz, L.** A proposed spectral form for fully developed wind seas based on the similarity theory of S.A. Kitaigorodskii. *J. Geophys. Res.*, 1964, **69**, 5181–5190.