Power Transmissions for Wave Energy Converters: a Review

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Abstract

Ocean wave power is a huge, largely untapped energy resource, and is considered a viable option for future renewable energy generation by many nations. This review describes the state-of-the-art for devices and systems designed to convert wave energy to electrical energy, focusing on the transmission of wave interface motion to generator motion. Hydraulic power take-offs (PTOs) are often preferred, and hydraulic circuit design options are described. The PTO design needs to be closely linked to the control strategy employed to maximize energy capture. The interaction between the wave interface, the PTO, and the electrical generator creates a complex dynamic system and thus design optimization is difficult. This is further hampered by a lack of experimental data due to the size and cost of land-based test rigs, and the fragility of prototypes in sea-based trials.

KEYWORDS: wave power, wave energy converter, WEC, power take-off, hydraulic PTO

1. Introduction

Modern research into harnessing energy from waves was stimulated by the oil crisis of the 1970's. With global attention currently 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 development. It is estimated that the potential worldwide wave power resource is 2 TW /1/. In the UK, up to 15 % of current electricity demand could be met by wave energy /2/. There are several reviews of wave energy converter concepts /1, 3-7/. These show that many wave energy devices are being investigated, but only a few have been tested at large scale at sea.

The benefits of wave power are:

- Sea waves offer the highest energy density among renewable energy sources /3/: solar power intensity is typically 0.1 - 0.3 kW/m^2, near-surface wave power is typically 2 - 3 kW/m^2 through a vertical plane perpendicular wave travel /8/.
- Limited negative environmental impact in use.
- Waves can travel large distances with little energy loss.
- It is estimated that wave power devices can generate power up to 90 % of the time, compared to approximately 20 - 30 % for wind and solar power devices /9/.

There are several technical obstacles. A significant challenge is the conversion of the slow (approximately 0.1 Hz), irregular, oscillatory motion into useful motion to drive a generator with output quality acceptable to the utility network. Ideally, the variable input should be converted into smooth electrical output and hence energy storage is needed, or other means of compensation such as an array of devices appropriately arranged. Efficient conversion of variable power levels is also a challenge. Around the western coasts of Europe, the most common offshore wave fronts are around 30 - 70 kW/m /10/, and so a device must operate efficiently in these conditions. 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. Lack of robustness in rough seas has often prevented long term sea trial measurements to be made. Ultimately, for commercial viability, devices must be highly reliable and have maintenance intervals of several years.

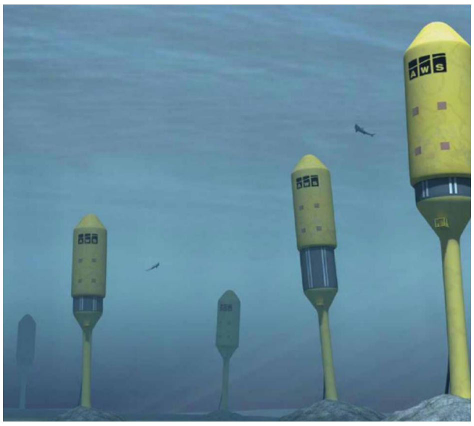
2. WEC types

Wave energy converters (WECs) can be classified as shoreline, nearshore (typically attached to the seabed), or offshore (e.g. 40 m depth or more) /6/. Offshore devices experience considerably higher wave power levels, but maintenance and electrical power connection is more problematic. The main device designs are:

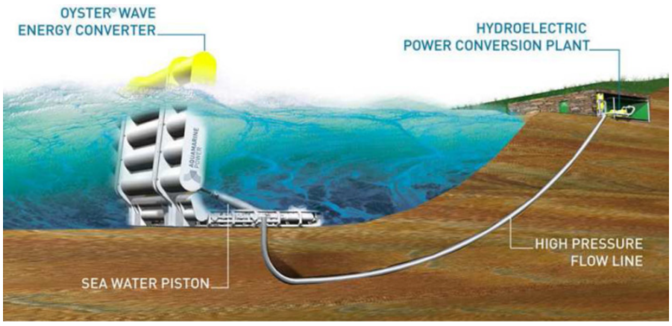
- Point absorbers: these are heaving devices of small width compared to the wavelength, e.g. OPT Powerbuoy /11/, Wavebob /12/.
- Attenuators: these lie parallel to the predominant wave direction and `ride' the waves, e.g. Pelamis /13/.
- Terminators: these are perpendicular to the wave direction, appearing to block the wave. Examples are Salters duck /14/, and flap-type oscillating wave surge converters such as the Aquamarine Power Oyster /15/.

- Oscillating water column devices: in these air is forced through a turbine by varying water level in a chamber. They are typically shoreline, such as the Wavegen Limpet /16/.
- Overtopping devices: these capture water from incident waves which is released through a turbine (e.g. the Wave Dragon /17/)

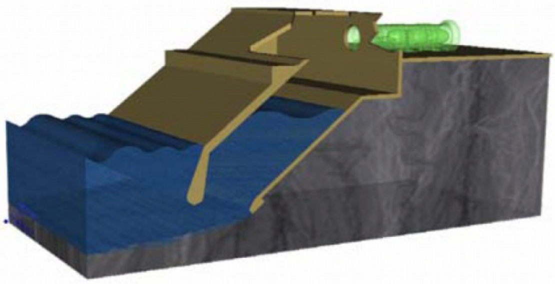
Some examples are shown in **figure 1**.

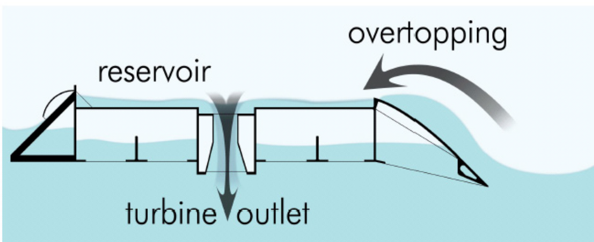


(a) Point absorbers (AWS) **(b) Point absorbers (OPT)**



(c) Attenuators (Pelamis) **(d) Terminator (Aquamarine Power)**





(e) Oscillating water column (Wavegen) **(f) Overtopping device (Wave Dragon)**

Figure 1: Example wave energy converters (artist impressions)

3. Power take off overview

Current WEC designs differ widely in their energy extraction technique, however most require a power take-off (PTO) system for converting the irregular motion of the primary wave interface into a smoothed, controlled motion for use by the high speed electrical generator. PTO options are shown in **figure 2** /6/. Turbine systems are not discussed here – instead the focus is on point absorbers, attenuators or terminators which require power take off from a low frequency mechanical oscillation.

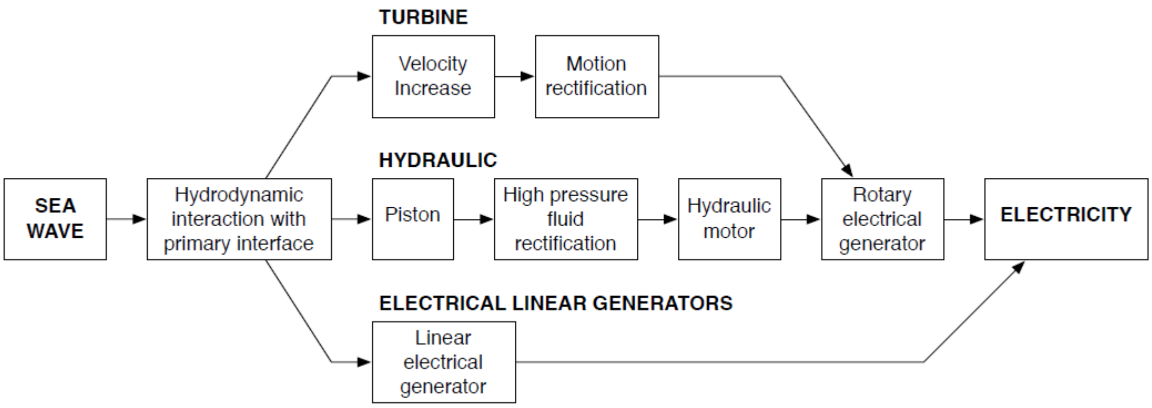


Figure 2: Alternative PTO concepts

3.1. Linear electric generators

A linear generator offers the possibility of directly converting movement of the primary wave interface (e.g. buoy) into electrical energy. During early wave power research this option was investigated, but it was concluded that these machines would be too heavy, inefficient and expensive /14/. However, new rare-earth permanent magnet materials and the reduced costs of frequency converter electronics means that this possibility is now being reconsidered. The air gap speed between the rotor and stator in conventional rotary generators is high (upwards of 50 m/s) giving high rates of change of flux. Linear oscillatory motion from a wave energy converter, however, is expected to have a peak of only about 2 m/s, and an average of considerably less /18/. So this is even lower than the air gap speed for direct drive generators being developed for wind turbines (around 5 - 6 m/s).

A trial was conducted with a large linear permanent magnet generator PTO in the Archimedes Wave Swing submerged point absorber /19/. The generator had a 7 m stroke, 1 MN maximum force, and 2.2 m/s maximum velocity; the total moving mass was 400 tonnes. An average electrical power output of about 200 kW was predicted based on the trial results /20/. The basic concept of a linear generator for a point absorber is to have a translator 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 (either connected to a drag plate, a large inertia, or fixed to the sea bed), as in **figure 3**.

The design of electrical generators for direct drive wave energy converters was examined by Mueller /18/, by comparing the longitudinal flux permanent magnet machine with the transverse flux permanent magnet machine. He identified 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 /21/), their topology requires structural support and they suffer from a low power factor requiring reactive power compensation /22/.

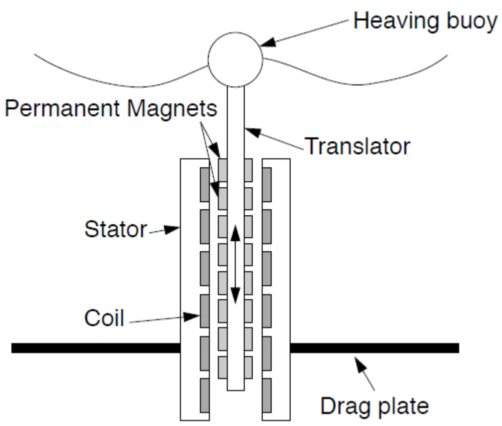


Figure 3: A schematic of a linear electrical generator based on a permanent magnet generator

3.2. High speed rotary electrical generators

Traditional power stations use synchronous generators 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 possible generator types are: Doubly-Fed Induction Generators, Squirrel Cage Induction Generators, Permanent Magnet Synchronous Generators, and Field Wound Synchronous Generators. O'Sullivan and Lewis discuss these generator options in terms of suitability for an oscillating water column application, by examining the advantages and disadvantages in terms of environmental, electrical and cost factors, and by using a time-domain model /23/. There are similarities in this application with the mature technologies currently used in wind turbines. The favoured generators used in wind turbines (Doubly Fed Induction Generators (DFIG) driven via a gear box, and direct drive low speed Synchronous Generators (SG) with dedicated power electronics) are possible candidates for use in wave energy converters. O'Sullivan and Lewis's study concludes that the latter, the synchronous generator, is 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 to cope with rotary speed variations.

3.3. Hydraulic PTO concepts

Hydraulic transmissions are usually favoured for the conversion of the low speed linear wave motion to high speed rotary motion to drive the generator due to their high power density, robustness and controllability. As yet, an industry standard design configuration or control strategy for hydraulic PTOs is far from being established. As sizes of trial WECs increase towards peak powers of 1 MW, serious challenges in PTO design are being encountered.

There is a trade-off between the complexity (and efficiency) of the hydraulic system and the electrical generation system. Two possible approaches are:

- a simple hydraulic system with limited energy storage, driving a variable speed generator.
- a more complex hydraulic system, designed to store the variable supply of power from the wave, and release smoothly to a constant speed generator.

In both cases, control of force or torque on the primary wave interface (e.g. buoy) is required to extract maximum energy from the prevailing waves within the stroke and velocity limits of the PTO.

In the following, the example of a point absorber WEC will be used. For a point absorber, power is extracted from the vertical motion of a buoy relative to the seabed, a submerged reaction plate (drag plate), or a large reaction mass. **Figure 4** shows a point absorber with a simple hydraulic PTO. Only limited control over the cylinder force is possible, which is achieved by managing the state of charge of the accumulators. An alternative design which allows force control is shown in **figure 5**. A control strategy which switches the valves to vary the effective total piston area gives force control in discrete steps with a constant hydraulic pressure. However frequent switching may ultimately give reliability problems, and switching can cause large force or motion transients /24/.

A further option is to use a hydraulic motor and pump, or hydraulic transformer, as shown in **figure 6**. With an over-centre pump, varying pump displacement can be used to give control of force as well as to provide unidirectional flow. However, losses in such a system (particularly part load losses) have been shown to be potentially quite high /25/.

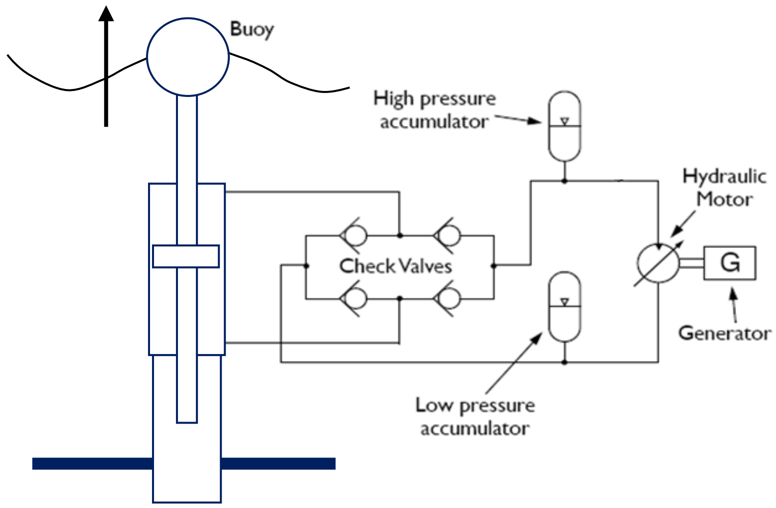


Figure 4: Simple hydraulic PTO

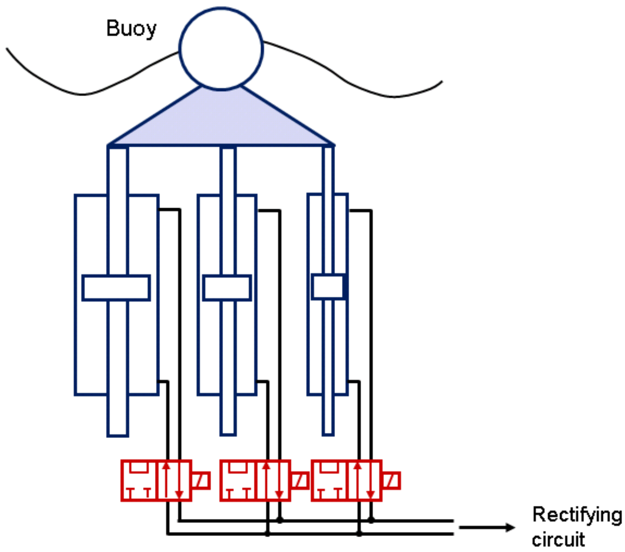


Figure 5: Discrete-level force control PTO

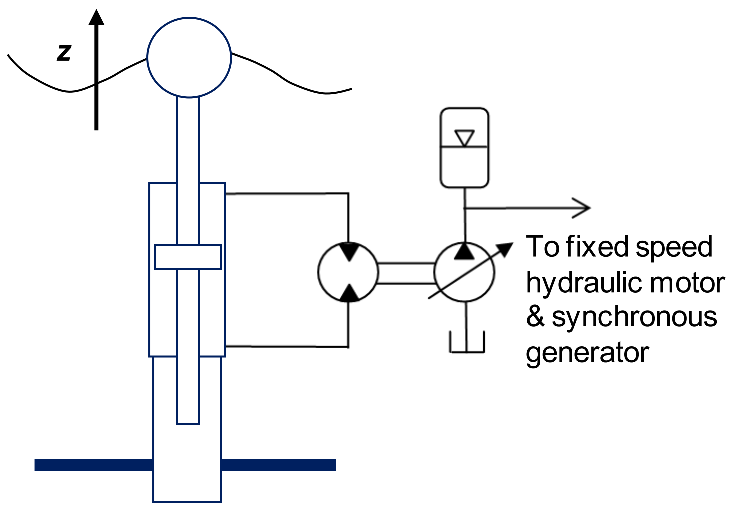


Figure 6: Variable displacement pump PTO

4. Control for maximum energy capture

A variety of control concepts for maximising energy capture have been studied, and the two most prominent ones are described here. Both relate to matching the characteristics of the WEC to the predominant frequency of the incident waves so that it behaves as though at resonance. A point absorber, such as that shown in figure 6, is used for analysis. Understanding the practicalities of these approaches, particularly the effect of PTO limitations and losses, is still at an early stage.

4.1. Reactive control

Using a linear hydrodynamic model,

$$(Ms^2 + Cs + K)z = f_e - f_p \tag{1}$$

where M is the buoy mass and added hydrodynamic mass, C is a linearized radiation resistance/drag term, and K is the buoyancy stiffness. The buoy upward displacement is z, upward wave excitation force is f_e, and downward PTO force is f_p.

Assume the PTO force can be controlled to be a linear function of buoy position. The following relationship is sufficient to demonstrate reactive control /26,27/:

$$f_p = (C_p s + K_p)z \tag{2}$$

Thus the PTO behaves like a damper in parallel with a spring (with either positive or negative spring constant). The damper force component, in phase with velocity, relates to resistive (absorbed) power, and the spring force component, lagging the velocity by 90°, gives reactive power which averages to zero over one cycle.

From Eq. (1) and (2), the buoy velocity is:

$$v = \frac{s}{Ms^2 + (C + C_p)s + (K + K_p)} f_e \tag{3}$$

A method for choosing C_p and K_p is required. Consider a regular (sinusoidal) wave of frequency ω. In the frequency domain, the amplitude of velocity and excitation force are related by:

$$V = \frac{1}{\sqrt{(C + C_p)^2 + \left(\frac{K + K_p - M\omega^2}{\omega}\right)^2}} F_e \tag{4}$$

or

$$V = \frac{1}{\sqrt{(1 + r_c)^2 + \left(\frac{K + K_p - M\omega^2}{C\omega}\right)^2}} \frac{F_e}{C} \tag{5}$$

where $C_p = r_c C$ (thus PTO damping is chosen as a multiple r_c of hydrodynamic damping). The average power absorbed from the buoy by the PTO is the averaged product of the damping force $C_p v$ and velocity v, which for a sinusoid is:

$$P_{av} = \frac{1}{2} r_c C V^2 \tag{6}$$

so

$$P_{av} = \frac{4r_c}{(1 + r_c)^2 + \left(\frac{K + K_p - M\omega^2}{C\omega}\right)^2} \left(\frac{F_e{}^2}{8C}\right) \tag{7}$$

It can be shown that to maximize the power from the buoy (i.e. maximize P_{av}):

$$K_p = K - M\omega^2 \tag{8}$$

$$r_c = 1 \tag{9}$$

K_p (which is usually negative) alters the natural frequency of the WEC to match the wave frequency i.e. the buoy is in resonance. The ‘reactive term’ – the second term in the denominator of Eq. (7) – disappears because the inertia and stiffness forces cancel.

However this choice for K_p and r_c will often give too large a motion amplitude in heavy seas (from Eq. 5). To reduce the amplitude K_p or r_c can be increased, but it is clear from Eq. (7) that the latter is best as r_c also appears in the numerator and power will not be so greatly affected. Note that this control strategy requires an estimation of the dominant wave frequency.

4.2. Latching control

Reactive control requires relatively high resolution PTO force control, and also an oversized PTO to handle large reactive powers. A simpler alternative is latching control, applicable to devices with resonant frequencies higher than the wave frequency, which is the normal situation.

Phase control by latching was first introduced by Budal and Falnes in 1980 /28/. It consists of locking the buoy in position at the instant when its velocity is zero and releasing it after a certain delay such that the wave force is in phase with the body velocity (**figure 7**). The latching duration effectively increases the resonant period of the device to match the frequency of the wave, and this tends to maximize the buoy motion amplitude. The release time of the body represents the control variable and studies have been undertaken to determine the best way to calculate this; prediction of the future wave excitation force is necessary to determine the optimum value /29/. The method gives significant power capture improvement in regular and irregular waves with release timing strategies to maximise buoy amplitude or keep buoy velocity and wave excitation force in phase giving similar improvements /30/.

5. Hydraulic PTO studies

5.1. Force control

The PTO in the Pelamis WEC is described in Henderson /32/. A pair of single-ended cylinders mounted across each segment joint pumps fluid, via control manifolds, into high pressure accumulators. These accumulators provide energy storage and in turn provide smoothed flow to hydraulic motors which drive grid-connected generators. Thus the generators are rated for the mean incident power.

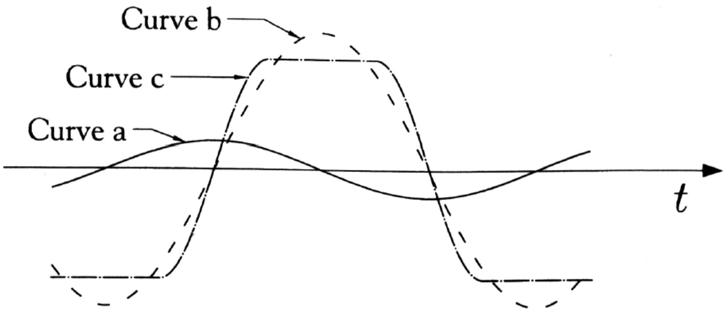


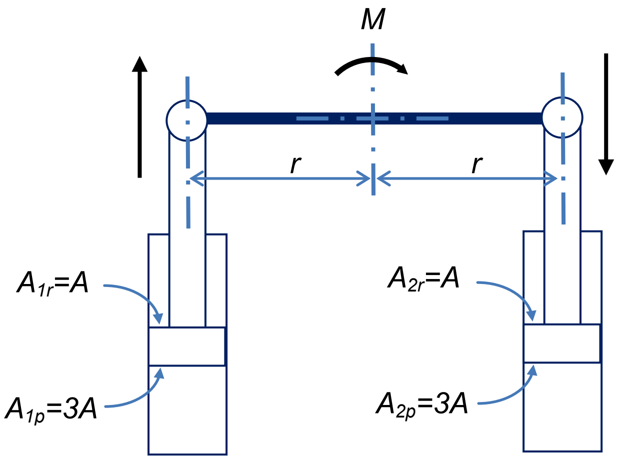
Figure 7: Latching control displacements (adapted from /34/)
a) Wave height; b) Resonant WEC;
c) WEC of higher resonant frequency, with latching

Pelamis uses reactive control. However, the device is designed to have a resonant frequency close to the incident wave frequency, so the reactive power can be kept small. The PTO can control the moment about each joint to four discrete levels in each direction by switching different actuator chambers into the high pressure line. Four equispaced levels can be achieved using 3:1 area ratio cylinders, as shown in **figure 8**.

Measured PTO efficiencies in a test rig are reported to be around 90 % for mechanical to fluid power conversion, and predicted at over 80 % in a range of in-service conditions (with greater reactive power) /32/. Pressure drops in valves, manifolds and pipes are the main losses, with seal friction accounting for an estimated 5 %. As suggested in the paper, the efficiency of a conventional variable hydrostatic transmission (or transformer) used to convert a constant high pressure source to variable cylinder force, in a range of operating conditions, is likely to be much less than 60 %.

The idea of electronically switched cylinder chambers for WEC control originated in the 1970's in Salter's group in Edinburgh, with the need for a very efficient high power (> 1 MW) rotary PTO for the Duck /14/. This led to the Digital Displacement® approach latterly developed by Artemis Intelligent Power, in which electronically controlled poppet valves were provided for each pumping chamber in a piston pump /33-35/. Initially ring cam pumps, and later radial piston pumps were developed.

Reactive control is also the focus of /36/, in which the Wavestar device – an array of point absorbers – is modelled. In this study, each absorber drives an over-centre variable displacement swashplate motor such that the output shaft can be controlled to always rotate the generator in the same direction (**figure 9**). PTO force is controlled by a combination of motor displacement and generator torque control. Maximising motor displacement, and thus relying on generator control much of the time, was found to be the most efficient control strategy. When the power direction is reversed, i.e. the generator becomes a motor, its stored kinetic energy reduced the need for electrical power input. Simulation results predicted overall conversion efficiencies (buoy input to electrical output) of 52 % to 68 % for a range of wave conditions, which the authors considered inadequate. Part of the challenge with this design is the need to handle large peak powers as there is no hydraulic accumulation for smoothing.



Connection to high(P_s) or tank (0) pressure				Moment, M x P_sAr
A_{1p}	A_{2r}	A_{1r}	A_{2p}	
P_s	P_s	0	0	4
P_s	0	0	0	3
P_s	0	P_s	0	2
0	P_s	0	0	1
0	0	0	0	0
0	0	P_s	0	-1
0	P_s	0	P_s	-2
0	0	0	P_s	-3
0	0	P_s	P_s	-4

Figure 8: Pelamis moment control concept

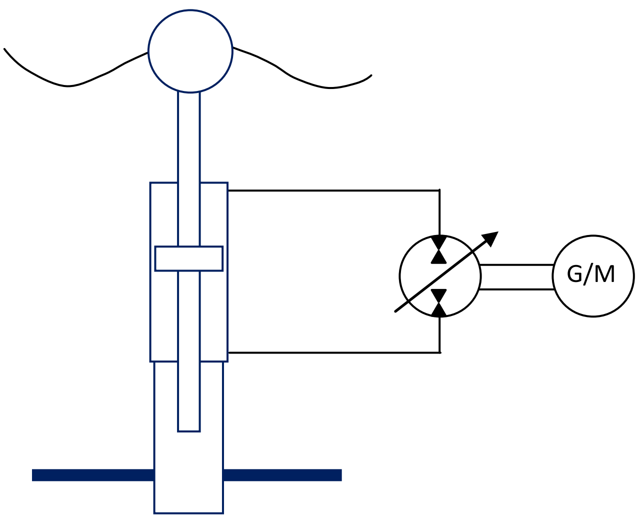


Figure 9: Force control by varying motor displacement and generator torque

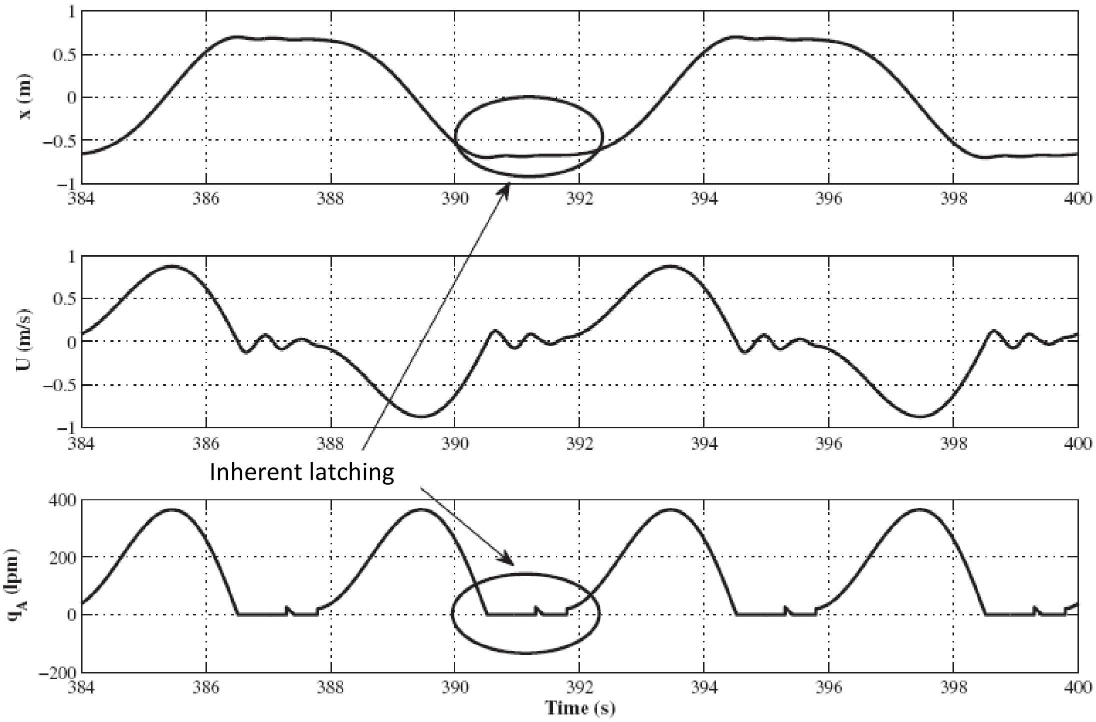


Figure 10: Buoy position, velocity, and flow to HP accumulator for simple hydraulic PTO of figure 4. /40/

5.2. Resistive PTOs

A number of papers have considered, in simulation, the simple rectifying/smoothing circuit of figure 4 /37-43/. In this circuit, the piston is hydraulically restrained unless the force is high enough to overcome the accumulator pressure. This gives a latching effect, and also a resistance force akin to Coulomb friction, as shown in **figure 10**. Note that the latching force may be much smaller than the optimum, but power capture can still be higher than just a viscous damper for a device operating below its resonant frequency /40,43/. For the SEAREV point absorber, results indicate that two design parameters of the PTO (high pressure level and generator rated power) have a large influence on the power generated and these parameters can be optimised to sea state. It has also been shown that parameters in a PTO can be optimised for a given wave condition in /39/. Some controllability might be possible by altering motor displacement to reach a different accumulator state of charge and hence pressure, to match characteristics to different wave periods /40/.

Design concepts for the hydraulic PTO of the Wavebob point absorber are discussed in /44/. Using a hydraulic transformer, in an arrangement similar to figure 6, is considered, but dismissed due to the need for a motor rated to peak powers, and reliability concerns associated with its intermittent operation. Instead, a rectifying circuit charging a high pressure accumulator, as in figure 4, is proposed, but with a check valve before the accumulator, and an extra flow path from the cylinder through a second hydraulic motor. Both motors are variable displacement, and drive the same generator. The extra motor allows the generator to be driven in small sea states where the wave force is below the equivalent accumulator force. Additional flexibility is provided by having two pump/generator modules of different size, and either or both can be operative at any time. Thus a reasonable degree of versatility in damping force control is possible, but reactive control is not proposed.

Three PTO designs are simulated for a terminator WEC in /45/. A constant pressure system (figure 4), is compared with linear damping (PTO force proportional to velocity) implemented by removing the accumulation and varying hydraulic motor displacement and generator torque with constant generator speed. The terminator simulated has no inherent stiffness and thus no resonance, so the latching effect of the constant pressure system is of no benefit, and linear damping is found to be best. Connecting four terminators to a single centralised, on-shore, hydraulic motor plus generator, as in figure 1d, is also studied. The terminators can be positioned to operate out of phase with one another. Linear damping at the individual terminators can no longer be achieved, but controlling pressure to be proportional to total flow into the central motor gives good power capture.

5.3. System modelling

Until recently, there has been very little published research on detailed dynamic predictions of complete system behaviour, incorporating both hydrodynamic and PTO modelling. Many control studies have assumed the PTO can provide a user-defined mechanical impedance, and PTO efficiency is not considered. Some of the first papers to include a reasonable PTO model are by Falcão /37,38/. Equations for a heaving buoy attached to a simple rectifying hydraulic PTO (as in figure 4) are presented, but there are significant simplifications in the PTO model, such as loss-less components. A more detailed hydraulic PTO unit is presented in /43/, but critical characteristics, like hydraulic motor losses, are represented just by a constant efficiency value. Convincing system simulation results, incorporating sophisticated PTO characteristics, have only been published since 2010 /36, 39, 40, 42, 44, 45/.

Whole system simulation is important to predict absorbed power. The PTO cannot be optimised in isolation, for changing a PTO design to increase its own efficiency will alter the wave-buoy interaction force and motion, which may reduce absorbed power (demonstrated in /36/). Accurate PTO simulation is also necessary to enable the best control method to be selected. Losses and non-ideal characteristics such as friction, leakage, compressibility, inertia, and valve/pipe pressure drops may mean that accurate force control is not achieved open loop /25/. Simulating such characteristics can also show that larger PTO's, designed to handle reactive power, have larger losses and so the advantage of reactive control is lost.

6. Conclusions

WEC PTO design and control is an immature field. However most PTO's for large scale reciprocating WEC's under development are hydraulic. Only very recently have there been serious attempts, with the help of simulation, to analyse and optimize PTO design and control properly accounting for hydrodynamic, hydraulic, mechanical and electrical characteristics. Nevertheless, experimental validation of models and results for many types of WEC at large scale is still almost non existent. Some of the challenges facing WEC PTO designers are:

- Ensuring extremely high robustness and reliability, despite extreme environmental condition.
- Maximizing power absorption with highly variable seas (long periods with small seas states, and short periods with large waves and massively increased input power).
- Balancing the benefits of achieving ideal PTO behaviour (e.g. reactive control) with the consequences for PTO design (e.g. larger, more expensive PTO with higher losses).
- Determining the benefits of energy storage (typically hydraulic accumulation) to allow sizing motors/generators for mean rather than peak powers, improving efficiency and reliability through constant speed running, but making buoy force control more difficult.
- Improving part-load efficiency of components (e.g. variable displacement hydraulic motors).
- Considering implications of arrays (farms) of WEC's working together.
- Developing controllers which automatically adapt to wave conditions.

7. Acknowledgements

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8. References

/1/ Thorpe, T.W. 1999 “A Brief Review of Wave Energy”. Technical Report R120, Energy Technology Support Unit (ETSU). A report produced for the UK Department of Trade and Industry.

/2/ Callaghan, J. and Boud, R. 2006 “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.

/3/ Clement, A., P. McCullen, A. Falcao, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M.-T. Pontes, B.-O. Schild, P. Sjostrom, H.C. Soresen, and T. Thorpe. 2002 “Wave energy in Europe: current status and perspectives”. Renewable and Sustainable Energy Reviews, 6(5):405-431.

/4/ Previsic, M. 2004 “Offshore Wave Energy Conversion Devices”. Technical Report E21 EPRI WP-004-US-Rev 1, Electrical Power Research Institute.

/5/ Salter, S.H. 1974 “Wave power”. Nature, 249(5459):720-724.

/6/ Drew, B., Plummer, A. R., Sahinkaya, M. N., 2009 “A review of wave energy converter technology”. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 223(8):887–902.

/7/ Cruz, J (Editor) 2008 “Ocean Wave Energy, Current Status and Future Perspectives”; Springer-Verlag. ISBN978-3-540-74894-6.

/8/ Falnes, J. 2007 “A review of wave-energy extraction”. Marine Structures, 20:185-201.

/9/ Pelc, R., Fujita, R.M. 2002 “Renewable energy from the ocean.” Marine Policy. 26(6):471-479.

/10/ Polinder H., Scuotto. M. 2005 “Wave Energy Converters and their Impact on Power Systems”. In Proceedings of the 2005 International Conference on Future Power Systems, 1-9.

/11/ www.oceanpowertechnologies.com

/12/ www.wavebob.com

/13/ www.pelamiswave.com

/14/ Salter, S.H., Taylor, J.R., and Caldwell, N.J. 2002 “Power conversion mechanisms for wave energy”. Proc. IMechE, Part M: J. Engineering for the Maritime Environment, 216(M1), 1–27.

/15/ www.aquamarinepower.com

/16/ www.wavegen.com

/17/ www.wavedragon.net

/18/ Mueller,M. A. 2002 “Electrical generators for direct drive wave energy converters”. IEE Proc. Gener. Trans. Distrib., 149(4), 446–456.

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

/20/ Polinder, H., Damen, M. E. C., and Gardner, F. 2005 “Design, modelling and test results of the AWS PM linear generator”. Euro. Trans. Electr. Power, 15, 245–256.

/21/ Iwabuchi, N., Kawahara, A., Kume, T., Kabashima, T., and Nagasaka, N. 1994 “A novel high-torque reluctance motor with rare-earth magnet”. IEEE Trans. Ind. Appl. 145(6), 604–614.

/22/ Harris, M. R., Pajooman, G. H., and Abu Sharkh, S. M. 1997 “The problem of power factor in VRPM (transverse-flux) machines”. In Proceedings of the Eighth International Conference on Electrical Machines and Drives, (Conf. Publ. No. 444), 1997, pp. 386–390.

/23/ O’Sullivan, D. L. and Lewis, T. 2008 “Electrical machine options in offshore floating wave energy converter turbogenerators”. In Proceedings of the Tenth World Renewable Energy Congress (WREC X), 1102–1107.

/24/ Roberts, A., Schlotter, M., Plummer, A., Tilley, D., 2010 “CFX/Simulink co-simulation of a wave energy converter”. Bath/ASME Conference of Fluid Power and Motion Control, Bath, Sept 2010.

/25/ Plummer, A.R., Schlotter, M., 2009 “Investigating the Performance of a Hydraulic Power Take-Off.” Proceedings of the 8th European Wave and Tidal Energy Conference (EWTEC), Uppsala, Sweden, Sept 2009.

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

/27/ Budal, K. and Falnes, J. 1975 “A resonant point absorber of ocean-wave power”. Nature, 256, 478–479.

/28/ Budal, K. and Falnes, J. 1980 “Interacting point absorbers with controlled motion”. In Power from sea waves (Ed. B. Count), 381–399 (Academic Press, London).

/29/ Babarit, A. and Clement, A., 2006 “Optimal latching control of a wave energy device in regular and irregular waves”, Applied Ocean Research, 28, 77-91.

/30/ Babarit, A., Duclos, G., and Clement, A. 2005 “Comparison of latching control strategies for a heaving wave energy device in random sea”, Applied Ocean Research, 26, 227-238.

/31/ Falnes, J. 2002 “Ocean waves and oscillating systems” Cambridge University Press, Cambridge, UK.

/32/ Henderson, R. 2006 “Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter”. Renew. Energy, 31(2), 271–283.

/33/ Rampen. W.H.S., 2010 “The Development of Digital Displacement Technology”. Bath/ASME Conference of Fluid Power and Motion Control, Bath, Sept 2010

/34/ Ehsan, M., Rampen, W. H. S., and Salter, S. H. 2000 “Modeling of digital-displacement pump-motors and their application as hydraulic drives for nonuniform loads”. ASME J. Dyn. Syst. Meas. Control, 122, p210.

/35/ Rampen. W. H.S., 1992 “The Digital Displacement Hydraulic Piston Pump” PhD Thesis, University of Edinburgh.

/36/ Hansen, R.H., Andersen, T. O., Pedersen, H.C. 2011 “Model Based Design of Efficient Power Take-off Systems for Wave Energy Converters” 12th Scandinavian Conference of Fluid Power, May 2011, Tampere.

/37/ Falcao, A.F.O. 2007 “Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator”. Ocean Engineering, 34:2021–2032.

/38/ Falcao, A.F.O. 2008 “Phase control through load control of oscillating-body wave energy converters with hydraulic PTO system”. Ocean Engineering, 35:358–366.

/39/ Livingstone, M. and Plummer,A.R., 2010 “The Design, Simulation and Control of a Wave Energy Converter”. Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, 2010.

/40/ Cargo, C. J., Plummer, A. R., Hillis, A. J. and Schlotter, M., 2011. “Determination of optimal parameters for a hydraulic power take-off unit of a wave energy converter in regular waves”. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. DOI 10.1177/0957650911407818.

/41/ Plummer, A. R., Cargo, C. J., Hillis, A. J. and Schlotter, M., 2011. “Hydraulic Power Transmission and Control for Wave Energy Converters”, 52nd National Fluid Power Conference, Paper 2099, Las Vegas, USA, March 2011.

/42/ Cargo, C. J., Plummer, A. R., Hillis, A. J. and Schlotter, M., 2011. “Optimal design of a realistic hydraulic power take-off in irregular waves” in Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC), Southampton, UK, September 2011.

/43/ 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.

/44/ Schlemmer, K., Fuchshumer, F., Bohmer, N., Costello, R. , and Villegas, C., 2011, “Design and Control of a Hydraulic Power Take-off for an Axi-symmetric Heaving Point Absorber”, in Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC), Southampton, UK, September 2011.

/45/ Kamizuru, Y., Murrenhoff, H. 2011 “Improved Control Strategy for Hydrostatic Transmission in Wave Power Plants”, 12th Scandinavian Conference of Fluid Power, May 2011, Tampere.

9. Symbols

C	Linearized hydrodynamic radiation damping
C_p	PTO effective viscous damping coefficient
f_e	Wave excitation force
F_e	Amplitude of sinusoidal wave excitation force
f_p	PTO force acting on buoy
K	Hydrostatic stiffness of buoy
K_p	PTO effective stiffness
M	Buoy mass, including added mass
P_{av}	Average absorbed power
r_c	Ratio of damping coefficients C_p/C
s	Differential operator
v	Buoy velocity
V	Amplitude of sinusoidal buoy velocity
z	Buoy displacement
ω	Frequency