The development of power take-off technology in wave energy converter systems: A Review

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Abstract. Utilizing ocean wave energy as a renewable energy source has become the object of rapid research. Energy conversion technology continues to evolve to seek more efficient, cheaper forms of investment, operation, and maintenance and are environmentally friendly. The converter type and PTO hold the key to the efficiency of the whole system. This literature review paper examines various general concepts and innovations of wave activated body converters and commonly used and innovative power take-off systems with a focus on controlling efforts in maximizing the generated power, challenges and efforts to develop a PTO control system as well as various research conducted by various parties.

1. Introduction
Oceans, where there is a very wide and untapped source of renewable energy, account for about 70 percent of the earth's surface. The potential energy available from the oceans can be in the form of ocean waves, currents, differences in temperature and salinity. Due to the interaction of winds at sea level, ocean waves are one of the greatest potentials of ocean energy, with many significant advantages such as high source availability, high load factors, less environmental impact and predictability of sources compared to other renewable energy sources [1]. In addition, the energy density contained by ocean waves is higher than solar and wind energy [2], which is an average of 100 kW / m. The global energy potential currently reaches 10 TWh, with an annual energy potential that can be generated as much as 93,000 TWh [3]. So it is not wrong if the energy potential of this sector is expected to contribute to replacing the use of fossil-based energy, along with other renewable energies.

Many parties have conducted various researches on ocean wave energy extraction technology. The number of patents for this technology has also been registered in various countries around the world. More than a thousand wave energy conversion technology techniques patented around the world, especially in Europe, North America and Japan, have been identified in a recent study [4].

In general, ocean wave power generation systems consist of a wave converter system, power take-off, control system, and electrical transmission. This paper specifically discusses the wave activated body type wave energy generation system, then various types of power take-offs, and the control strategy of the WEC system especially in the PTO section which aims to increase the power generated.

2. Ocean Wave Energy Conversion Technology
2.1. History of Wave Energy
With the first patent registered in Paris in 1799 under the name Girard pere et philosoph, ocean wave energy has been investigated since the late 18th century. There are now thousands of registered patents, with pioneers such as Yoshio Masuda (Japan), Stephen Salter (UK) and Michael McCormick
making most of the inventions in the last forty years (USA). Owing to the 1973 oil crisis, study in the UK started mainly in the 1970s, leading to increased interest in renewable energy sources such as wave energy and other energies. Stephen Salter of the University of Edinburgh, who drafted the 'Salter Duck' idea, which is said to have 90 percent efficiency for ocean wave energy extraction, is Britain's key pioneer.

However when the government planned to shift towards financing large-scale 2 GW generation systems, such as coal and nuclear power plants, research funding was limited in the early 1980s. This practically stops almost all research. Government spending has risen again since the 1990s, with the threat of global warming and increasing fossil fuel prices resulting in an increase in the amount of research and development. This suggests that, compared to that of the wind industry 30 years ago, awareness and understanding in the country has greatly improved. There are however, still several different concepts that developers have designed to turn energy from ocean waves into electricity. This involves systems with distinct operating principles and power take-off mechanisms and no integration with one single device configuration at the moment, which is a normal phenomenon in most emerging industries.

And at this time, there should still be a lot of it at the prototype scale, but there have been many references discussing the energy conversion of ocean waves. From various references, in general, the conversion of ocean wave energy can be classified into Wave Activated Body, Point Absorber, Oscillating Water Column and Overtopping. Various modifications and innovations are carried out while remaining based on these four basic technologies. There are also those who try to add such as, [5] grouping them again into six types of ocean wave power converter concepts. While EMEC on its website explains 8 types of wave converter devices, apart from the six, with the addition of bulge waves and rotating mass [6].

![Various WEC Concepts](image1.png)

*Figure 1. Various WEC Concepts [5]*

![Bulge wave and Rotating mass wave device](image2.png)

*Figure 2. Bulge wave and Rotating mass wave device [6]*

### 2.2. Wave Energy Converter

There are many papers that describe in great detail the types of wave energy converters that have been developed by the WEC developers. For example [7] details various typical WEC devices, such as WEC wave activated bodies, point absorber, oscillating water column and overtopping, along with power capacity, depth of installation in the sea, and other technical characteristics. Also included are
other efforts of WEC technology by utilizing breakwaters to save construction, installation, maintenance and operational costs.

2.3 Several WEC innovations

Besides the typical technologies that have been commonly used in the generation of ocean wave energy, there have been many innovations in how ocean wave energy is captured. This section attempts to provide an overview of these innovations.

For example, a new research is called the Articulated Tower Ocean Wave Energy Converter (AT-OWEC) [4]. This converter modifies the structure commonly used for offshore oil and gas exploration equipment into an electrical energy converter. AT supports a deck at the top, on top of the mast or upper shaft. The upper mast is supported by a buoyancy chamber, which provides hydrostatic lift. The float cylinder is supported by a lower pole or lower shaft, connected to the ballast tank cylinder or ballast chamber. The ballast cylinder can be filled with seawater or emptied, to adjust the location of the center of gravity of the entire system, so that the stability of the AT will be maintained. At the bottom, the ballast cylinder is supported by a connecting pole or connector to a universal hinge or universal joint. The existence of a universal joint, which is located on the basic foundation or base, allows the AT to move rotational dynamically in response to wave excitation.

![Figure 3. Articulated Tower (a) AT–OWEC (b) System [4]](image)

Another research is related to the shape of the rotor to increase the capture of ocean wave energy by optimizing the shape of the salter duck by examining changes in its geometric parameters [8]. The salter duck shape is a geometric shape that produces the largest energy catch among other shapes, such as cylinders, spheres and ellipses.

Each technology has been applied to successful projects with data on the capacity and average power that can be generated. An important result of these studies, among others, is that most of these integrations are that at present the integration of power plants and breakwaters, mostly, uses OWC type WEC and overtopping with large power output targets and large additional civilian structures and is even planned from the start, not using the existing breakwater. For the wave activated body type, there are several studies related to other techniques on how to harvest energy from ocean waves by combining it with an existing breakwater structure [9]. Another form of this type of research is the integration of a fixed box floating breakwater with a heave-type Oscillation buoy installed in front of the breakwater [10]. A Power Take-off (PTO) system is attached to the top of the breakwater, which harvests energy from the up and down motion caused by the incident wave.
3. Power Take-off
A power take-off system in a marine energy converter is part of the ocean wave power generation system that converts mechanical power into electricity. Currently, there are several types of power take-off technology used in the conversion of ocean wave energy, namely the hydraulic system in the oscillating body system, wind turbines in the OWC system, Low head water turbines in the overtopping system, linear generators commonly used in point absorber systems, triboelectric nanagenerator and PTO hybrid system. Figure 6 shows the working principles of the various existing PTO systems.
3.1 Hydraulic PTO System

The hydraulic motor based PTO system is one of the well-known methods that can be used for converting wave energy in WEC to transform low-speed oscillating motion into energy. The hydraulic motor-based PTO system especially for wave-energy conversion systems of the wave-activated body type, is the most suitable device to generate usable wave-energy electricity. The hydraulic form of a PTO system typically comprises a hydraulic cylinder or ram, hydraulic motor, accumulator and generator. Figure 7 shows a schematic diagram of a typical hydraulic motor of the PTO system sort. In order to raise the working medium pressure (usually hydraulic oil), the hydraulic ram is usually pushed by sea waves, which means that the hydraulic cylinder of the PTO system transforms the translator or rotational motion into the hydraulic energy that drives the hydraulic motor. Then the hydraulic motor drives the generator to generate energy [12].

Figure 6. Principles of work for PTO systems [11]
In most Wave Energy Converters, high pressure oil hydraulic is the most dominant type of PTO among hydraulic power take-off types [14]. Using a hydraulic piston and a hydraulic motor to drive an electric generator, this unit converts the slow, high-power WEC motion into a high-speed rotary motion to generate electricity.

There is no industry standard design for hydraulic PTOs at present. And some companies are trying to use simple systems with limited energy storage to power variable speed generators. In order to drive synchronous generators, others are trying more complex hydraulic systems with integrated energy storage. The most common current approach to large gas accumulators used to provide the energy storage needed to smooth the irregular force gases captured from the waves is shown in Figure 7. In order to ensure that the motor rotates in the same direction regardless of the float movement, the non-return valve improves the flow from the piston.

There are several related issues, which must be considered when deciding and designing a hydraulic unit. The first is the liquid reservoir. It is important to make sure this device is very watertight. The entry of sea water should be avoided, which can damage the device's internal operation, cause corrosion, adjust the buoyancy and even submerge the device. Similarly, if oil is used in the PTO as a working fluid (which would be a natural choice), which is undesirable, there will be oil leaks which can have a negative impact on the environment in the surrounding waters.

Secondly, about maintenance. It is a costly and risky job to perform marine equipment maintenance, particularly if it is far offshore. Maintenance can only be carried out using specialist ships and engineers to do the work during the weather-dependent time window. This can imply high costs, so when considering more complex hydraulic devices that require more moving parts and may require more regular maintenance, the overall design should be carefully taken.

Efficiency is third point. PTO efficiency is its ability to convert the energy it receives from the ocean into power that can be transmitted to the grid. A coupled variable displacement pump and motor commonly use hydrostatic transmissions, which have an ideal operating point with a peak efficiency of around 60 percent [15]. However, due to the losses associated with leakage, friction and compressibility in hydraulic machines, the efficiency can be poor at times in systems away from this point in the load section.

PTO design is very important because it affects the hydrodynamics of electrical energy capture and generation. Between designing the PTO, a balance must be reached. The options are straightforward and less reliable, but require minimal maintenance. Or a more complicated but more powerful PTO that could need more regular maintenance.
3.2 Air Turbine PTO
Another type of PTO system for WEC is the Air Turbine PTO. The air turbines in the system are usually powered by compressed air, and the turbines directly drive a generator to generate electricity. The schematic of the PTO transfer turbine air-based device is shown in Fig. 8. In the Oscillation Water Column (OWC) system and in integrated breakwater with OWC wave energy converters, air turbines are commonly used.

![Air Turbine PTO Diagram](image1)

**Figure 8.** How the OWC converter works with the air turbine PTO [16]

3.3 Hydro Turbine PTO
In this type of PTO, the turbines used are almost the same as the turbines used in hydropower plants on land. The WEC technology that uses this type of turbine is called WEC overtopping. In essence, waves that come and pass through the central wall of the generator will enter and be accommodated in a reservoir under which there is a low head turbine or a French turbine which rotates due to the flow that is passed and discharged back into the sea.

![Hydro Turbine PTO Diagram](image2)

**Figure 9.** Overtopping type wave energy converter with hydro turbine PTO [16]

The innovation in PTO for hydro-turbines is the emergence of several designs in the form of a double acting piston pump and rack [8]. One motion back and forth activated body (heave or flap) can be optimized. Some of the designs include the following:
Figure 10. Seven piston pump designs for the wave energy converter [8]

In contrast to the high pressure hydraulic system, these seven double-acting piston pumps are intended to pump seawater to drive the turbine directly or through a reservoir placed on the support structure.

Figure 11. Application of piston pump and rack in WEC heaving and surge [8]
3.4 Direct Mechanical PTO
In this type of PTO, the heaving or surge of the device is translated through a mechanical device system, directly. Furthermore, through a gearbox mechanism, this translational movement is converted into a rotational motion. Figure 12 shows the basic schematic of this direct mechanical PTO system.

![Figure 12. Direct mechanical type PTO system [16]](image1)

3.5 Direct Electrical System PTO Using Linier Generator
In this type of PTO, a linear generator is used. Unlike conventional generators that generate electricity from the rotational interaction between the magnetic field and the coil, in linear generators, this interaction is carried out translational. The strong magnetic field that is in a straight translator moves back and forth in a stator which is the main material of the conducting coil. The electrical energy produced depends on the quality of the magnet and the coil, it also depends on the relative velocity of motion between the translator and the stator. The typical form of this PTO can be seen in Figure 13.

![Figure 13. PTO type direct electric (linear generator) [16]](image2)

3.6 Static Electric Material Type Static PTO
Elementary electricity can be generated from certain materials, such as wool, plastics and other materials which are moved relative to other materials. Recent developments have been made by [17]–[19] who exploit the latest materials with nanotechnology, to generate more than just elementary electricity. They call it a triboelectric nano generator. But electricity with enough power to be harvested and amplified in large quantities. This technology requires a continuous, large and free energy source of motion. Ocean energy is the ideal choice for this source of mechanical energy.
3.7 Efficiency of a PTO

PTO from the wave-activated body is the most powerful when only one degree of freedom of movement is limited to [7]. Otherwise the wave-activated body will often prefer to shift towards the least resistance and thus prevent interactions between PTOs. In addition, it restricts the movement to one degree of freedom:

- Reduces the PTO device complexity and the potential number of cases of load.
- Optimizes its efficacy and simplifies its control

In general, the WEC PTO system is needed to convert slow oscillating motion in combination with high power (from waves) to rapid rotation in one direction (required by an electric motor). As such, there are numerous types of PTO systems, all of which present performance, control, complexity and cost benefits and disadvantages. Typical efficiency values (from the absorbed wave energy to the generator) for these different forms of PTO are as shown in Table 1. It should be mentioned that there can be very significant other aspects of the PTO system, such as the ability to:

- Storing temporary / smooth energy.
- Handling short-term overload of power.
- Handling sudden system fault and possible losses control.

| Type of PTO | Typical $\eta$ (%) |
|-------------|-------------------|
| Direct Drive| 95                |
| Hydraulic   | 65                |
| Water       | 85                |
| Mechanical  | 90                |
| Air         | 55                |

Usually, the strategy of continued control of the wave absorber via the PTO system will significantly increase the overall output of electricity. It will also, however, demand substantially greater loads and wear on the structures and components of the device.

In working against fixed references, PTOs are also much more efficient. A seabed or a large structure immovable under the operation of a wave-absorbing device may be this fixed reference. Otherwise, much of the available energy would be redirected to other motions associated with the body.

4. The Control of PTO

Ocean waves have a wide frequency band that varies with time and season, as well as extreme events. On the other hand, wave energy converters are often designed with oscillations over a narrow...
frequency range, with a maximum absorption efficiency of wave energy close to its natural frequency \((\omega_0)\) [20]. Generally, PTO control techniques are classified as generally referred to as damping control, reactive control, latching, and predictive control MPC models [21]. Meanwhile, in terms of the approach to applying the above control techniques [22] divides the PTO control generation into 3 basic approach generations, namely the classical era with many analytical approaches, then the numerical era with various numerical calculations, including MPC, and the modern era with the approach. model-free based on machine learning or artificial intelligence.

4.1 Damping Control

Damping control or also known as linear control or also resistive control is a conventional control which is currently widely used in practice. Here the PTO force is proportional to the oscillation speed and the damping coefficient \((B_{pto})\), formulated:

\[
f_{pto} (t) = -B_{pto} \cdot v (t)
\]

where \(B_{pto}\) is the damping coefficient. This technique does not need excitation force prediction, making it an simple control strategy to be implemented. And in fact this technique is usually found in pre-commercial devices that are currently used all over the world. Conventionally, it is only necessary to know the instantaneous value of the PTO velocity, which can usually be measured easily. The damping here is kept constant, to keep it simple.

Variable damping control is a further development of the constant damping control technique. Passive damping controls, based on for example, the Hilbert-Huang transformation (HHT) as performed by [23], are analyzed and contrasted with real-time passive (PC) controls. The damping coefficient varies over time for this solution and is set instantaneously, depending on the excitation force frequency. Because the excitation force must be known, this solution adds a degree of difficulty to the damping control. The results of this study show that the proposed solution increases from 21 \% to 65\% of the results that can be achieved with classical damping control methods with real-time damping coefficient tuning.

4.2 Reactive Control

This control technique generally includes changing the resistance and reactance of the PTO \((B_{pto} \text{ and } K_{pto})\), taking into account constraints such as the PTO power rating or displacement limits.

\[
f_{pto} (t) = -B_{pto} \cdot v (t) - K_{pto} \cdot x (t)
\]

Reactive power is a back and forth interaction between the PTO and the oscillating system and does not contribute to the output of electricity. Any hydraulic, compressed-air, thermal, chemical, kinetic, electrostatic, electromagnetic storage source or grid can supply this energy [24]. The key weakness of the reactive approach comes from the method of dissipative reactive energy exchange (wasting power).

4.3 Latching / Declutching Control

Latching control is based on the ability, through the clamping mechanism, to obtain WEC resonance, stopping a certain timing device from the wave oscillation cycle [25]. When the device is removed, linear damping typically controls the power of the device. In this way, without the need for reactive power management, the system delivers resonant activity. However when the speed of the unit is zero, some energy needs to be drawn from external sources to activate the clamping mechanism. How to compute the latching-unlatching time period is the critical point for this control strategy. In the same way as reactive power, the latching control prevents two-way energy transfer and energy dissipation, so a wider range of PTO systems running only in generator mode can be used under this control strategy.

The performance improvement when the latching control strategy is applied is then calculated by creating a simple case scenario of a passive damping control strategy. The results show a 70 percent rise in capture width and a 60 percent decrease in the optimal damping coefficient [21].
4.4 Model Predictive Control

The predictive model uses predictive results in issuing control inputs. This input control is the optimal control for control based on the prediction results generated for some time to come. This technique has been widely applied in industry and was initially applied to chemical processes.

MPC uses a cost function to produce the optimal control input values for some time to come (predicted results), but only current control inputs are applied to the factory. Next time, the calculation based on the cost function is repeated and only the current input controls are applied, and so on. One of the advantages of MPC is the technique of calculating the limits of input and output values. In fact, the input and output values are subject to certain limitations that should not be violated. These limits can be saturation, security reasons, etc.

Many researchers have performed many MPC-related studies, including [26] comparing MPC control and classical control (complex conjugate control) for PTO forms of linear permanent magnets.

Another research, a prediction strategy analyzed by [27] to improve reactive control efficiency, in which machine learning-trained neural networks are used to predict future waves (height and time), influence WEC and optimize the related parameters for wave energy absorption in real time (PTO damping coefficient and PTO stiffness coefficient).

Another inventive MPC solution proposed by [28]. It incorporates a predictive controller that takes into account the limits of the PTO, ensures optimum power absorption while keeping practical, and an advanced model for solving several parametric uncertainties and model mismatches, called the Robust Model Predictive Control (R-MPC). Future wave frequency prediction is used in [29] to calculate the optimum PTO damping coefficient and stiffness in real time, using Fuzzy Logic power. The approach suggested incorporates many regular tuning techniques with a novel methodology for slow tuning.

IFP Energies Nouvelle (IFPEN) is one of the first winners of the WECCCOMP competition, organized by the Center for Marine Energy Research (COER, Ireland), the National Renewable Energy Laboratory (NREL, USA), Sandia National Laboratory (USA), and Aalborg University (Denmark), which is an open competition comparing the energy maximization controller for the wave energy converter (WEC), both in simulation, real time, and using a tank test scale device. In this case IFPEN uses the MPC control technique which increases efficiency by at least 10% compared to conventional control techniques.

4.5 Control using Artificial Intelligence

In this approach, an important aspect of interest is that instead of adding complexity, a reduction in complexity is carried out here, by avoiding the need to estimate or predict the excitation force of waves and the need for numerical optimization which has difficulty consequences in terms of convexity and convergence [22].

Some research related to artificial intelligence for WEC or PTO control applications, among others, was applied by [30], which uses the Internal Model Control (IMC) structure, applying phase and amplitude control, to combine the neural network model from Archimedes Wave Swing. More recent applications include the use of a neural network model by [27], using a simple Complex Conjugate controller (single frequency). The causal inference approach from [31] is used by avoiding the need for forecasting, and is then corrected by including nonlinear dynamics and PTO losses [32], and finite stroke constraints [33]. WEC Controller with Causal Inference from [34].

5. Conclusion and Future Works

Power Take-off technology has developed rapidly along with the rapid pace of WEC technology itself. This paper has presented general forms of WEC technology and several innovations related to the design of WEC devices. The various power take-off technologies commonly used with WEC devices have also been discussed.

Efforts to maximize the power generated, apart from the design of WEC devices, are also carried out on the PTO that will be used. The basic concept of the overall conversion system optimization today is how to make or force a resonant WEC device with a wave frequency, which is then called the control strategy. The trick is to adjust the damping coefficient and the stiffness coefficient of the PTO
(B_{pto} and K_{pto}). So various suboptimal control techniques developed, such as damping, reactive, latching, MPC and the idea of modern artificial intelligence-based control.

- In terms of simplicity and ease of implementation, damping control techniques are still the choice for many wave energy converter developers. Although in many studies, currently developed technology has a higher efficiency than damping control.

- Reactive control is a natural development from damping control, providing any WEC prototype used for the pilot phase with a tabular approach. A PTO capable to switch itself from motor to generator mode, in multiple times in one wave oscillation requires such a control strategy.

- Latching control addresses the PTO limitations of reactive control, but involves installing and energizing an external clamping mechanism on the WEC device, resulting in additional costs while reducing reliability. Because of the extreme ambient salinity, offshore equipment, especially mechanical parts, is prone to failure.

- The MPC control technique is the best approach when it comes to optimal control. The activation excitation force prediction applies to any step of the optimal PTO force for maximum energy absorption, thus taking into account the current constraints (non-linear model). The MPC has been the scientific community's most interesting subject [21]. This is marked by the large number of MPC-based WEC system optimization research, both at the simulation and tank test stages, although currently not many have entered the industrial scale in the field. ocean energy.

- Control using Artificial Intelligence has also been applied to marine energy conversion systems. The model-free approach, and the development of new algorithms that continue to evolve, are expected to result in increased efficiency as well as reliability in the existing WEC system.

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