

Technology, Geometry, Performance and Challenges in Wave Energy Converters

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Abstract. Recently, the worldwide energy scarcity raised the demand for integrated renewable energy in the modern grid. Considering the potential and ocean areas, wave energy-based power generation becomes an essential sustainable source for industry and academia. Notably, the wave energy converter (WEC) is the most common solution for extracting power from wave energy and convert into electricity. Wave electricity generation is the main method of using wave energy, and wave energy converters that are the core of wave energy technology have been widely and rapidly evolved. In this paper, the state-of-art WECs are reviewed with the classification based on different ways and different principle of operation of capturing energy of waves, including oscillating water column WEC (OWC-WEC), oscillating buoy WEC (OB-WEC) and overtopping WECs (O-WEC) are systematically reviewed in terms of operation principles, geometric structure and power take-off (PTO) strategies. Additionally, the energy conversion efficiency between different technologies is compared and summarized. The challenges and optimization aspects are delivered.

Keywords: Wave energy converters, power take-off, electricity generation, geometry structure.

1. Introduction

Nowadays, there are some imperative problems, including the acute consumption and insufficient supply of non-renewable energy resources, the depletion of traditional fossil energy and the lack of power supply that needs to be resolved. Those problems restrict the development of the economy worldwide, especially in coastal areas. With the increasing global electricity consumption and the urgency of developing renewable and clean energy, wave energy, one of the most potential new sources of energy, has greater energy density, reliability, and cleanliness than solar panel and wind energy power generation. In the field of energy structure optimizations, it tends to become a complement to the energy structure and contribute to a sustainable level of energy consumption. Thus, the progression and utilization of wave energy have attracted the worldwide focus of correlated scholars and have developed rapidly. And the progression and use of wave energy are of great importance in relieving the world energy crisis.

Wave energy is one of the most widely distributed renewable energies with the highest energy flow density. Wave energy is more abundant along the mid-latitude east coast of the Pacific and Atlantic Oceans than in other regions [1]. According to the 2016 research report of the World Energy Commission on ocean energy, theoretically, the annual wave energy potential all over the world is 29500TW/h [2]. The distribution of global wave energy is as demonstrated in Fig. 1 [3]. However, less than 10% of wave energy can be used by current technology per annum. Despite this, the actual obtainable amount of wave energy can still address the issue of insufficient energy supply.

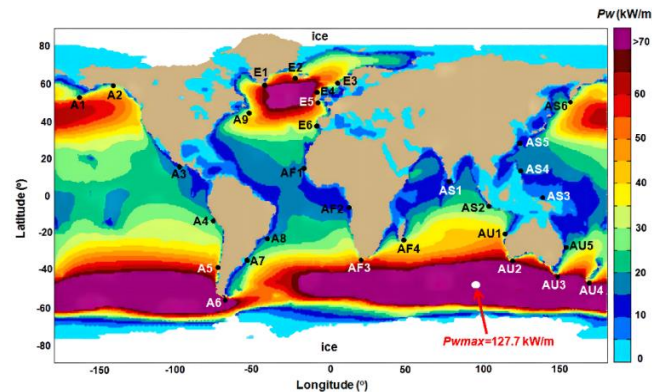


Fig. 1 Average wave energy density [3].

At present, converting wave energy with electricity is the core method for using wave energy, and it is one of the most mature enormous scale marine power generation technologies. Europe has vast oceans and long coastlines with extensive, stable and cheap wave energy resources that can be used [4]. WAVEHUB has been shown using a 10~15 MW device of Carnegie CETO6 for collecting wave energy [5]. In China, a 120kW Eagle device, Wanshan, was implemented in 2013, and another 500kW Eagle Wave Energy Generator, Zhoushan, will launch in 2022 [6]. However, from an environmental protection perspective, conservatively, large-scale construction of ocean energy stations could inevitably aggravate the marine ecosystems already in a difficult situation. Naturally, it is sensible to develop tiny wave energy generation units which provide a lower cost of maintenance, higher mobility and more eco-friendly methods, compared to the collective power station.

Wave energy converter is an important mechanical component in wave energy power generation devices that has been studied by academia and industry. There is a considerable amount of literature on power electricity generation via converting wave energy. The former researchers laid a foundation and developed positive indications among these research results. Studies have shown [7] that these model simulations of WEC have promising results, as well as high power generation efficiency, reflecting their promising development. The work in [8] investigated the PTO characteristics, PTO efficiency and PTO damping coefficient using a two-dimensional CFD model of the Edinburgh Duck WEC, and most numerically experimented to derive its optimal damping coefficient. The work in [9] proposed an OWC-WEC model of CFD-based wave line for coupled air turbine chamber air chambers. Experiments as well as experimental data to validate the model performance for free surface height and chamber air pressure variation, converter conversion efficiency under different sea states, and prediction of the device through case studies, showed that the model has good performance.

However, the limitations of WEC were presented as follows, such as optimizing the performance of the power generation unit, improving the energy conversion efficiency, the selection of durable materials [10], the long-term operational stability of the WEC and the rational geometry design. For this reason, current research indicates that improving the efficiency of converting wave energy to electricity is still a difficult problem, and the conversion efficiency of the WEC is what determines the efficiency of converting wave energy to electricity. As a result of the core of the total wave energy generating electricity device is the WEC. Therefore, the goal of many scholars is to enhance the efficiency of wave energy power generation by optimizing the geometric structure of WEC, improving the hydrodynamic properties, the capture ratio, etc. For example, the work in [11] proposed a new conceptual structure for an oscillating wave surge energy converter, which the authors demonstrated to have good performance and promise for ocean observation, utility power, marine aquaculture, and other applications after extensive analysis. In addition, some scholars have proposed WEC beyond the three principles and basic structures of this paper. The experimental results have also shown superior conversion efficiency and stability, such as the Eagle wave energy converter [12]. After optimizing the shape and experimenting, they were able to obtain high energy conversion efficiency. The work proposed four different geometric shapes of oscillating buoy wave energy converters, forming a buoy design method with high energy collection [13]. A fresh type of WEC for

underwater vehicles is introduced, which was shown to have good power generation performance through simulation and experiments [14]. Prior arts have investigated the hydrodynamic and mechanical dynamics parameters of various WECs. The experiments validate the power generation efficiency.

Various articles have optimized the WECs, and analyzed their hydrodynamic properties and captured energy. Although it appears to be a new device, the principles can be categorized into some existing principles and concepts. WECs can be classified according to their operating principle and how they capture wave energy, the method of converting energy, the location of the WEC in the sea where it is installed, and the frequency at which the WEC resonates with wave energy. This paper classifies WECs according to their operating principle and the form of wave energy capture conversion, and the corresponding basic principle and structure are introduced, gaining a comprehensive review of WECs.

The rest of this paper is organized as follows. The structure and power take-off of wave energy converters are first reviewed and analyzed. We divide the wave energy converter into OWC-WEC, OB-WEC and O-WEC, introducing and analyzing the geometric structure, hydrodynamic performance, power generation performance, PTO and capture wave ratio (CWR) of the devices. Finally, we propose the limitations and problems of the existing WECs. Furthermore, the conclusion is presented.

2. General Principle of WEC

The entire process of generating wave energy electricity generally consists of three energy conversion phases, as shown in Fig. 2. The primary method of converting wave energy is mechanical, pneumatic, or potential energy. The absorbed energy is converted into effective mechanical energy in the second stage using a specific PTO. The final step is to further convert the valuable mechanical energy into electricity by connecting the PTO to the generators [15]. The first stage is where the WEC runs. Factors affecting stage one conversion efficiency include front wall shape and slope, depth of immersion, cavity horizontal area shape, PTO orifice and valve size, PTO damping, mooring system, ballast control, capture width ratio and so on [16].

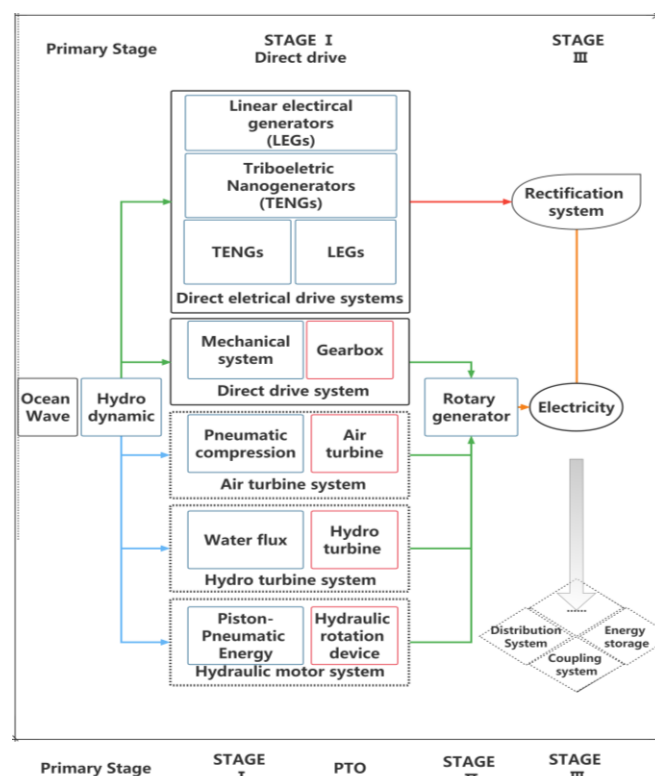


Fig. 2 Various conversion stages of wave energy generation

The capture width ratio (CWR) is commonly used to estimate WEC conversion efficiency. The ratio of absorbing wave power P (in KW) to wave resource J (in KW/m) is defined as CWR,

$$CWR = P/J \quad (1)$$

The efficiency of hydrodynamic capture of energy is a good indicator of the hydrodynamic performance of the WECs. CWR is one measure of hydrodynamic efficiency that reflects the proportion of wave power flowing through and captured by the WEC by dividing the capture width by the device's characteristic length, B [17]:

$$\vartheta = CWR/B = P/JB \quad (2)$$

The conversion efficiency of the stage is usually judged by the CWR, which is the essential characteristic for measuring the performance of the WEC [18]. A key condition for the power generation of the phase one energy conversion is to correctly match the intrinsic frequency of the WEC to the wave frequency, which is ultimately determined via the geometrical structure of the WEC. However, the CWR of a WEC varies from one principle and structure to another and needs to be assessed and calculated based on the specific structure and principle.

3. Geometry Structures of Different WECs

WEC can be classified according to the principle of operation as OWC-WEC, OB-WEC and O-WEC. The form of wave energy capture conversion, as well as the corresponding principle and structures, are investigated in this section.

3.1. Oscillating water column WEC

The OWC-WEC contains a chamber with a portion of water and air. The water column moves up and down in a reciprocating motion under the effect of wave oscillations. The oscillating movement of the air column above the free surface of the water column is caused by the reciprocating movement of the water column. The high-speed air movement is converted into electrical energy by passing it through a reciprocating turbine in the outlet hole above the air chamber. The main difference between the OWC-WEC and other types of WEC is the presence of an air chamber in the inner chamber of the converter. The air chamber is a special structure with an opening underneath where seawater enters the air chamber during oscillation. The OWC has the advantage of converting the energy of low-speed moving waves into high-speed moving air via the air chamber of the air chamber, indicating its high reliability and stability, which can be seen in Fig. 3. The first energy harvesting technology used in wave energy generators was the OWC-WEC. The OWC is divided into two parts: the air chamber and the turbine. When the wave vibrations cause the water column inside the converter to reciprocate, causing the air column at the top of the free surface of the water column to oscillate, and finally, the turbine converts the kinetic energy of the high-speed air into electrical energy.

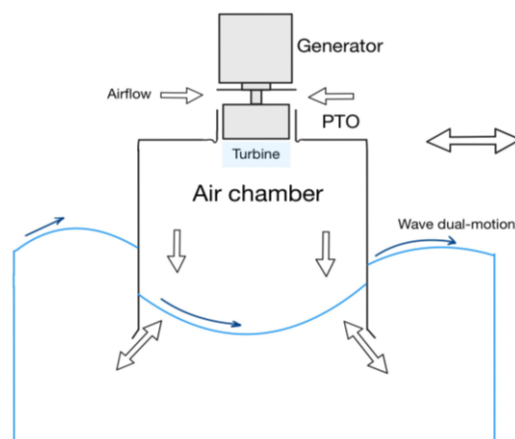


Fig. 3 Principle of OWC-WEC

3.2. Oscillating buoy WEC

In general, the OB-WEC follows the OWC-WEC principle. As illustrated in Fig. 4, the OB-WEC converts wave energy into reciprocating mechanical energy, which is then used to power a hydraulic pump via an oscillating float. The unstable mechanical hydraulic energy is then converted into stable rotating mechanical energy by an energy buffer before being converted into electrical power by a generator. OB-WEC is less costly and challenging to build than other WECs in practice, and the oscillating float type is highly efficient at absorbing wave energy. OB-WEC is classified into three basic types: point absorber, attenuator, and terminator. The basic principle is that wave causes float to vibrate at different degrees of freedom, and converts into electricity through the PTO system.

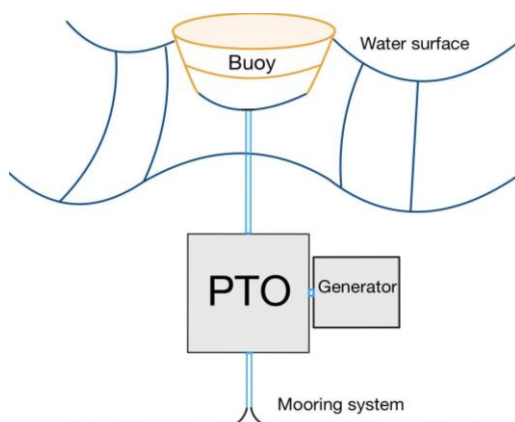


Fig. 4 Principle of OB-WEC

3.3. Overtopping WEC

The O-WEC device has an inclined structure on either side that brings the wave crest, and the sea water on the crest, into the chamber where the sea water is stored. The level within this chamber is above the sea level of the seawater, so that the unstable wave energy in the chamber can be converted into the potential energy of the stable seawater. The seawater in the cavity then impinges on the turbine to rotate. The turbine converts potential energy into mechanical energy, which is then converted into electrical output by the generator. The output of the O-WEC is stable and independent of wave period and height and is suitable for many practical sea conditions, the principle of which is shown in Fig. 5. The O-WEC type converter consists of three parts: a sloping wave gathering section, a reservoir and an outlet pipe. Waves are captured by the wave attraction section and enter the reservoir along the wave gathering section, which then stores the unsteady wave energy as steady potential energy. Due to the head difference, the water in the reservoir flows along the outlet pipe and drives the turbine, which drives the generator to produce electricity.

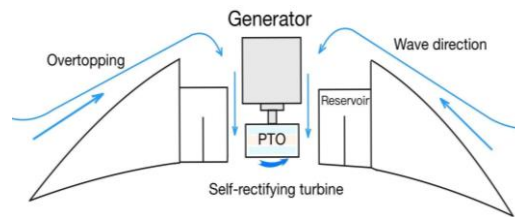


Fig. 5 Principle of O-WEC

3.4. Geometry optimization of WEC

Table 1. Comparison of Different WECs

WEC	Optimization & Discussion	Research Stage	Classification & Ref.
Self-floating oscillating surge WEC	PTO damping Optimization	Numerical analysis, dynamics simulation	OBWEC [11-14] [29, 30, 32, 36]
Eagle type WEC	Optimization of Geometry design, PTO damping Capture width ratio	Numerical analysis, dynamics simulation	
OBWEC and floating breakwater (FB)	Geometric optimization	field test	
Gyroscope WEC	Important parameters, Gyroscope damping discussion	Numerical analysis, dynamics simulation, bench test	
Single body WEC	Geometric optimization	Numerical analysis, dynamics simulation	
Backward Bent Duct Buoy WEC (BBDB-WEC)	Geometric optimization	Numerical analysis, dynamics simulation, field test	
OBWEC	Optimal geometry design, PTO damping	Numerical analysis with algorithm	
Double X wave energy harvest	Optimization discussion final prototype	Numerical analysis, Physical model validation, bench test, field test	
U-shaped OWCWEC	Optimization of Geometry design device efficiency	Numerical analysis, dynamics simulation	OWCWEC [10, 35]
Resonant Airbag WEC	Optimization discussion final prototype	Numerical analysis, dynamics simulation, field test	
OTD-WEC	Optimization discussion final prototype	Numerical analysis, dynamics simulation, field test	OWEC [7, 31]
OWEC	Optimization discussion	Numerical analysis with ANN (Artificial neural networks)	

In order to compensate for the limitations imposed by the oscillating water column, oscillating floating body and transverse wave principles, many new converters based on the oscillating water column, oscillating floating body. Transverse wave principles have been investigated as well as the

geometrical design [19-21], hydrodynamic properties [22-25] and PTO performance of these WECs [26-28], as shown in Table I. For example, based on the up and down wave fluctuations, Mahdi Nazari Berenjkoob et al. [29] optimized the float shape for the purpose of wave energy conversion efficiency and concluded that the appropriate geometry of the float could improve the efficiency of the WEC without changing the PTO specifications or could improve the performance of the PTO system for optimal power absorption. The work in [30] investigated the effect of different air chamber back bottom angle geometries and angles on BBDB OWC under different wave height conditions and concluded that the energy conversion efficiency is closely related to the device's resonant frequency.

Table 2. Classification of PTO Methods

PTO (Applications)	Categories	Outline
Mechanical type (OBWEC)	Gear method	One or multi-stage mechanical energy loss, high maintenance costs
	Pinion-rack method	
	Ball-screw method	
Hydraulic and pneumatic type (OWCWEC)	N/A	Flexible transmission, large torque and stable energy storage
Turbines (OWCWEC, OWEC)	Wells turbine	Unaffected torque, blade-to-air velocity ratio, higher peak efficiency, and lower manufacturing cost
	Self-rectifying air turbine	Better energy absorption compared to Wells turbine
	Denniss-Auld turbine	In comparison to the Wells turbine, the turbine blades have a different staggered angle
	Pelton turbine	The runner blades are installed in the air, and the nozzles are set for the water flow, impacting the runner at a relatively high speed and achieving rotation
	Kascheme turbine	Reactive turbine is completely submerged in water and surrounded by a pressure shell. When the water flows through the runner blades, it causes the pressure difference to generate lift forcing the runner to rotate.
	Francis turbines	
Direct electrical drive (WEC)	Linear electrical generator	LEGs produce electricity without the need for transmission, reducing design complexity, operational requirements, and maintenance costs
	Triboelectric nano-generators (TENG)	High energy density, high system efficiency, reduced weight, and reduced manufacturing costs

With the development of science and technology, computer technology is becoming more and more important and widely used in various fields, and in the field of WEC is no exception, the use of advanced computer technology can promote the development of WEC, improve energy conversion efficiency and power generation efficiency. A successful model with Artificial neural networks (ANN) constitutes the first step of subsequent modification of OWEC structure [31]. Using a CFD model of the WEC float, the geometry of the optimized buoy is derived through multiple iterations of a genetic algorithm, which has been proven to notably improve the efficiency of wave energy conversion [32]. The study in [33] compared six WEC cases and used a genetic DE (Differential Evolution) algorithm to optimize the submerged volume and size of the floats in these WECs, using maximum power as the objective function, to combine cost factors and arrive at an optimal design for a slightly smaller non-optimal submerged volume with a larger PTO damping of the floats. Simulation and analysis by

computer enable optimal solutions to be derived from a wide range of models, on the basis of which actual tests can be carried out, not only increasing the efficiency of research but also reducing the costs associated with actual tests. For example, Chao Zhang [34] proposed four types of semi-submersible barge carriers for the Eagle WEC and conducted performance analysis for each of them to obtain the optimal capture width ratio and energy conversion system damping for the four shapes, and verified the stability and feasibility of their devices under actual sea conditions. WECs with complex geometries bring higher capture efficiency than those with simple geometries and are one effective way to increase the capture energy of WECs. The oscillating water column WEC, such as the U-shape, has superior hydrodynamic performance and allows for higher efficiency in capturing energy [35].

In addition, excellent researchers are no longer satisfied with optimizing existing geometries, but are proposing a new structure of WEC on top of the basic principles and structures, as well as applying it to different scenarios, to fully exploit the potential of the application, and also to provide a richer research direction and ideas for the diversification of WEC structures. For example, the work in [36] investigated a wave energy converter for vibrating buoys utilizing a double X-shaped mechanism and combined with a super supercapacitor as an energy storage element for a self-powered sensor for cross-sea bridges. The device is made up of a wave energy conversion module, a transmission module, a generator module, and an energy storage module, which collects wave energy via a cylindrical buoy, a conventional module that converts the wave energy into mechanical energy, and a power generation module. The conventional module converts wave energy into mechanical energy, which is then converted into electrical energy by the power generation module. The efficiency of the WEC varies from 35.82% to 57.34% depending on the frequency and amplitude of the vibrations, with an average conversion rate of 46.17%. In practical tests, the voltage can reach 3V at a wave frequency of 1.2Hz and an amplitude of 15mm, indicating a high efficiency of power generation and the viability of providing electrical energy for self-powered sensors on sea bridges and a practical function.

These new technological tools, research methods, ideas and directions have contributed greatly to the research in the field of WEC and have contributed to the development of WEC and even wave energy generation technology.

4. Power Take Off

In this section, the classification of different power take off strategies is discussed and summarized in Table II.

4.1. Hydraulic motor system

It has the advantages of flexible transmission, stable energy storage, and high torque, and it is appropriate for wave energy with variable characteristics such as large change amplitude and high change frequency. It can buffer wave energy, improve the quality of electric energy, and accumulate wave energy at low wave speed by converting wave energy into electric energy via a hydraulic or pneumatic system, resulting in continuous and stable energy.

4.2. Pneumatic air-turbine transfer system

According to different WEC structures and working substance, turbines can be generalized into two basic forms, the Air turbine and water turbine. Due to the air flow in water chamber is reciprocating, the front part that can receive energy need self-rectifying turbine to solve the sheer restriction of traditional one-way turbine. There are three types self-rectifying turbines that widely employed in OWCWEC, Wells turbine, Self-rectifying air turbine, Dennis-Auld turbine [37].

4.3. Hydraulic turbine transfer system

Another water turbines, according to the working principal, can be classified: impulse turbine and reactive turbine. The impulse turbines are installed in the air, then nozzles are set to guide water impact the runner blades rotating. The reactive turbines are completely submerged in water. When water flows, due to the water difference caused by reactive turbine blades shape, the runner rotating. Both have been used in hydroelectric power generation for many years and are quite mature. The Overtopping WEC PTO device frequently employs the following three types of turbines: Pelton turbines, Kascheme turbines, and Francis turbines [38].

4.4. Direct mechanical transfer system

PTO devices can convert energy and generate constant electricity. Gearbox is one of the mechanical type PTO, and was widely used in WECs. It can be generalized into gear drive, rack and pinion drive and ball screw drive. A classic example, CECO consists of two floating modules, as well as a gear rack system and a generator module. The two floating modules help to harness the mechanical energy of the waves and generate electrical energy [15].

4.5. Other system

1) Direct drive by linear electrical generator

It generates electricity without the need for transmission, reducing design complexity, operation and maintenance costs. When placed on the seafloor, the linear generator concept is based on the use of a translator and stator, with the translator attached to a floating buoy and the stator fixed or vice versa. The translator is made of permanent magnets, and the stator has coil windings. Because of the hydrodynamic action of the ocean waves, the translator moves up and down with the buoy, creating the magnetic field inside the coil windings and thus producing electric power.

2) Triboelectric nanogenerators (TENG)

It is based on the combination of triboelectrification and electrostatic induction, which has the advantages of high-power density, high efficiency, low weight, and low manufacturing costs. The TENG has the potential to provide a new wave energy conversion method as well as large-scale marine energy harvesting [39].

5. Comparisons, Challenges and Prospective

The focus of this paper's presentation and analysis of WECs is on the capture efficiency and power generation performance of WECs. It is evident from the published papers that Chinese, American and European countries are committed to the development of WECs and case studies illustrate the good dynamic performance and potential development of these devices. In the last few years, numerous new WECs have been investigated and scholars have demonstrated from theoretical studies, experimental simulations and model tests that these WECs achieve very good results. The advantages of these WECs have greatly contributed to the development of wave energy generators and wave energy generation technologies. New technological tools and research methods have also emerged to inform subsequent research, such as optimizing the structure of the WEC, improving the hydrodynamic properties of the WEC to increase its efficiency in capturing wave energy, and using advanced computer technology to drive wave energy converter research and reduce the additional losses associated with extensive practical testing. In addition to this, the use of PTOs plays a very large role in WEC, so there is also a very large amount of research focused on PTOs. This is because the total efficiency of the WEC is the sum of the efficiencies of the individual components.

5.1. Challenges and perspectives for structural optimization

This paper presents and analyses only the optimization of the geometry of the individual WEC itself, which has a very strong influence on the efficiency of the WEC in capturing energy. The geometry of the WEC is optimized according to the characteristics of the waves and the way in which the wave energy is mechanically captured. Research into efficiency improvements in terms of geometry is well established and has demonstrated that these methods and plans are feasible. However, there are still significant challenges in the design of geometries, such as the devices are not currently used in real sea conditions to achieve the desired results. Meanwhile, many projects for wave energy generation have been declared failures within a short period of time when they were put into operation, demonstrating that WECs are not able to operate consistently over long periods of time. The sea climate is variable and often extreme, resulting in the mechanical structure of WECs being prone to damage. This means that a comprehensive and systematic maintenance program should be planned at the time of design, taking into account extreme weather conditions. Although computer technology is now available to simulate WEC installations, installations that work well anyway do not get the same results in real sea conditions. Most of the algorithms used by computers are static, but waves are constantly changing and static algorithms introduce errors. In the future, dynamic algorithms should be developed for simulations or simulations using AI, neural networks, machine learning, etc. More instability factors should be included in the simulation to bring the simulation results closer to the actual sea state operation results. In addition to the structure of the individual WEC, the size of the WEC is critical for improving overall efficiency, with the size of the WEC influenced by many factors such as the power of the installation, cost minimization, the size of the power generation system, and so on. The arrangement of WECs into WEC arrays can also be considered and the array layout extensively studied. In WEC array distribution, the size, number and spacing of WECs and the optimization of the array distribution are mutually constrained, for example, by studies carried out in this regard. Studies on this can both provide stability in the long-term operation of the WEC and improve the efficiency of the WEC in capturing energy. The geometrical optimization of the WEC is not only for the design optimization of the WEC structure itself, but can also be used for the design of the entire WEC system, such as the mooring system and the power take-off system (optimal damping coefficient and damping stiffness of the PTO). The study of WEC mooring systems is still in its initial stages, so the design and optimization of mooring systems to achieve maximum power and optimized structures through the coupling of the various components is one of the trends and directions for future development.

5.2. Challenges and perspectives of PTO

PTOs are the core of energy output of all WECs, and there are many papers focusing on some characteristics of PTOs, such as PTO damping, PTO power performance and the coupling of PTOs with different types of WECs, etc. PTOs are classified into several types, including hydraulic motor system, pneumatic air-turbine transfer system, direct linear electrical motor drive system, direct mechanical transfer system, hydraulic turbine transfer system and so on. The following summarizes and analyses the challenges and future directions of the various PTOs. Classification reference [39].

The hydraulic motor system has hydraulic oil stored inside the hydraulic unit, which flows inside the hydraulic chamber and is constantly compressed during operation, which may lead to excessive forces on the hydraulic unit resulting in hydraulic oil leakage [27], therefore polluting the marine environment. Secondly the structure of the hydraulic motor system is more complex compared to other types of PTOs. Thus, the requirements for its stiffness and strength are very high. Future research will focus on how to stiffness and strength of the hydraulic motor system, design a more reasonable mechanical structure and reduce the number of maintenances in operation. Pneumatic air turbine transfer system is more commonly used for oscillating water column WECs, which use the system to convert wave energy into kinetic energy of high-speed air through the reciprocating motion of wave energy. The flow of high velocity air at the turbine is bi-directional, which is clearly not possible for a unidirectional turbine, and although Wells turbines are now available, they still have

some drawbacks [28]. In the future research should be focused on turbines. How to research turbines that can solve the problem of bi-directional air flow and guarantee efficiency is the next way forward. Direct mechanical drive system has the most efficiency. Therefore, it is widely used in WEC. However, the system has to withstand more frequent motion cycles during operation. This leads to the system being faced with short service life of mechanical components and the need for regular maintenance. It also places higher process requirements on some components such as gears which are prone to wear and tear. This can also lead to significantly higher costs. It is therefore necessary to improve the wear resistance of the mechanical components to increase the service life of the entire installation as well as to reduce the maintenance costs of the installation. Hydro turbine in comparison is mature technology and are now widely used in multisite scenarios. The disadvantage of the WEC, which is mainly used in overtopping WECs, is that the movement of the sea water is variable. This can lead to certain structures of the turbine and also its hydrodynamic properties in operation need to be improved. Thus avoiding damage to some structures. So future research into turbines will be to strengthen some of these structures that are susceptible to damage. And also, to improve its ability to adapt to sea conditions. The linear electrical drive system converts wave energy directly into electrical energy. The structure of this system is relatively simple compared to the above-mentioned ones. Therefore, there are no problems with short service life and high maintenance costs. The problem is that the specific power of the system is relatively low at low frequencies of wave motion. This means that very large machines are required to achieve the same efficiency as other types of PTOs. In addition to this, wave energy is an intermittent source of energy and driving the system with a linear electrical motor would produce unstable electrical energy. If stable power is required, a complex power output system is needed. The above results in high manufacturing costs and system complexity. In the future there is a need to increase the specific power, to reduce the size of the device and to come up with a more rational design of the power output system.

The PTOs required for WECs with different energy capture methods and operating principles are different. Alternatively, one of the PTO types can be combined with a specific WEC to achieve the highest efficiency. In addition to the research and optimization of the PTO itself, finding the best combination of PTO and WEC coupling is also a direction and trend for future research, and the theoretically most suitable combination of WEC and PTO can be found quickly through computer simulation techniques and some specific model building. Currently it is more common to use only one type of PTO for energy conversion, but hybrid PTOs are an important direction for the future and new types of PTOs, such as nano-friction generators, are also being actively developed. These active research efforts will contribute significantly to the development of WEC.

In summary, there are still some unresolved issues with wave power technology compared to other relatively mature and large-scale commercial green energy generation technologies. In addition to the technical challenges, there are also economic aspects. The climate at sea is highly variable and prone to extremes. This can result in WEC installations being vulnerable to damage and incurring high investment costs. The need to also consider the effects of seawater corrosion, maintenance costs, etc., means that a reasonable solution and maintenance strategy for the factors that hinder stable WEC operation and maintenance needs to be additionally planned during the converter design phase. Integration of WECs with conventional coastal or offshore structures is an alternative that significantly reduces the cost of WECs. There is a need to further research and propose superior solutions to prepare for better use of wave energy in the future. After continuous innovation and development, these technologies have matured and the way forward is to fully utilize these wave energies for power generation, which will greatly alleviate the problem of energy crisis and is of great importance for energy conservation and new energy development and exploitation.

6. Conclusions

Because of the scarcity of traditional energy sources and the need to develop green power generation methods, wave energy power generation technology has received attention and has been

rapidly developed with the support of various policies. This paper introduces the recent progress of wave energy converters, the basic structure and principle of oscillating water column type, oscillating buoy type, and overtopping type WEC, as well as the direction and trend of wave energy converter research in recent years, such as improving wave energy converter efficiency by optimizing geometry, inventing new geometry of WEC, and coupling various principles of WEC to improve wave energy efficiency. Then the classification of PTO for WEC and their principles and structures are presented and supported by a list of literature, and it is pointed out that the future direction and trend of PTOs is hybrid PTOs or the use of new types of PTO such as using Triboelectric nanogenerators for energy conversion, which can achieve higher efficiency. Finally, the prospects and challenges faced by WEC at all levels are summarized and presented. It can be seen that although wave power technology has good potential for application, there are still some problems that need to be solved, resulting in greater difficulties for wave power generation compared to solar and wind power technologies, which are used on a larger scale, but with the development of technology, the widespread use of wave power technology will become possible.

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