energies

MDPI

Review

A Review of the Optimization Design and Control for Ocean Wave Power Generation Systems

Juanjuan Wang [1,2], Zhongxian Chen [1,2,*] and Fei Zhang [2]

[1] School of Information Engineering, Huanghuai University, Zhumadian 463000, China; wangjuanjuan@huanghuai.edu.cn
[2] School of Intelligence Manufacturing, Huanghuai University, Zhumadian 463000, China; zhangfei@huanghuai.edu.cn
* Correspondence: chenzhongxian@huanghuai.edu.cn

Abstract: Ocean wave power generation techniques (converting wave energy into electrical energy) have been in use for many years. The objective of this paper is to review the design, control, efficiency, and safety of ocean wave power generation systems. Several topics are discussed: the current situation of ocean wave power generation system tests in real ocean waves; the optimization design of linear generator for converting ocean wave energy into electrical energy; some optimization control methods to improve the operational efficiency of ocean wave power generation systems; and the current policy and financial support of ocean wave power generation in some countries. Due to the harsh ocean environment, safety is another factor that ocean wave power generation systems will face. Therefore, before the conclusion of this review, a damping coefficient optimization control method based on the domain partition is proposed to improve the efficiency and safety of ocean wave power generation systems.

Keywords: wave power generation; generator design; optimization control; efficiency; safety

check for updates

Citation: Wang, J.; Chen, Z.; Zhang, F. A Review of the Optimization Design and Control for Ocean Wave Power Generation Systems. *Energies* **2022**, *15*, 102. https://doi.org/10.3390/en15010102

Academic Editor: Duarte Valério

Received: 4 December 2021
Accepted: 18 December 2021
Published: 23 December 2021

1. Introduction

After the widespread utilization of hydropower and wind energy, ocean wave energy is regarded as a new renewable source to meet the world's energy shortage. One way to utilize ocean wave energy is to convert wave energy into electrical energy, which is called 'ocean wave power generation' in this paper. Ocean wave energy results from wind energy or solar energy and is mainly stored in ocean surface waves [1]. Ocean wave energy has a higher energy density than wind energy and solar energy. The evaluation data indicates that ocean wave energy is about 2000 TWh/year, which accounts for 10% of the world's total electrical energy utilization [2]. So far, various ocean wave power generation systems have been proposed, such as oscillating water column, floating buoys, and so on. Usually, most of the oscillating water columns were installed on the shoreline or near shore, and the buoys were located offshore [3]. Some prototypes of the oscillating water column prototypes were built in the UK (the LIMPET near a rugged rock coastline of Isle of Islay, initially rated at 500 kW, Scotland [4]), Australia (MK3 installed offshore from the eastern breakwater of Port Kembla Harbour, one-third scale of the 2.5 MW full-scale prototype [5]), and Spain (a power capacity of 300 kW, near the shore of Mutriku [6]). Some buoy prototypes were built in Sweden (a single buoy system installed 2 km offshore of Sweden's west coast [7]), Portugal (multi-buoys named Pelamis installed at Agučadoura Wave Park [8]), and the USA (two-buoy system named 'PowerBuoy' prototype installed and tested off the Hawaii coast [9]).

According to the theory of mechanical vibration, only when the wave power generation system resonates with the ocean wave can the energy of the ocean wave be converted into electric energy to the greatest extent. However, due to the irregularity and nonlinearity of ocean waves, the operation efficiency of ocean wave power generation systems is

low [10]. Besides, under severe marine environment conditions (typhoons, storms, etc.), the motion distance of the wave power generation system is too large, resulting in unsafe conditions. Therefore, some optimization control methods have been investigated to improve the operating efficiency of the ocean wave power generation system. The optimization control methods are generally classified into two categories: (1) based on the generator's electromagnetic force, the speed phase difference between the ocean wave power generation system and the ocean waves is reduced, and thus resonance occurs between the ocean wave power generation system and ocean waves. (2) on the basis of buoys, some control algorithms are proposed to optimize the motion process between the buoy and ocean waves. The buoys are the transmission devices that drive the generator of the ocean wave power generation system [11–13].

The aim of the present work is to summarize some optimization design and control methods of ocean wave power generation systems, including generator design and system control. The layout of the rest of the paper is as follows. The second section is the current ocean wave power generation system test, especially in the real ocean waves. The third section is the optimization design of the linear generator of the ocean wave power generation system. The fourth section introduces some optimization control methods of ocean wave power generation systems, including generator control and float buoy control. Before the conclusion, an optimization control method based on domain partition is proposed to improve the operation efficiency and safety of ocean wave power generation system, and the current policies and financial supports for ocean wave power generation in some countries are also discussed.

2. Ocean Wave Power Generation System Tests

Despite a wide variety of design methods, and more than 1000 patents having been proposed for ocean wave power generation systems, few prototypes have been tested in real ocean environments [14]. Ocean wave power generation systems can be classified into three predominant types according to their location.

2.1. Tested in the Shoreline

An example of the ocean wave power generation system installed on the shoreline is the Wavegen Limpet. The system has a power capacity of 500 kW, and is installed on the island of Islay, Scotland [15]. Wavegen Limpet is the world's first commercial ocean wave power generation system connected to the British National Grid. Figure 1 shows a sketch of Wavegen Limpet, which has two Wells turbine generators. The rise and fall of water column drive air into and out of the wells turbine generator through the pressure chamber. Regardless of the direction of air flow, the well turbine generator can be rotated in the same direction. Therefore, without considering the direction of the generator current, the ocean wave energy can be converted into electrical energy [16].

The prototype of the Wavegen Limpet has been constructed and tested in several other countries—such as Japan, Norway, Australia, China, and so on. Besides, an ocean wave power generation system equipped with 16-well turbine generators was installed on the shoreline of Biscay, Spain [17].

2.2. Tested near the Shore

A representative prototype of an ocean wave power generation system installed near the shore is Archimedes Wave Swing (AWS). The concept of AWS originated from F. Gardner and H. van Breugel [18]. Figure 2 shows the sketch of AWS. Generally, the AWS is a completely submerged cylindrical ocean wave power generation system, the basement part is fixed on the sea bed, and the buoy is connected with the piston of the linear generator. During the operation process of the AWS, the buoy can be pushed down by the wave crest (the pressure of wave crest is larger than the buoyancy of buoy), or it can be pushed up by the wave (the pressure of wave though is smaller than the buoyancy of buoy). Therefore, the buoy can reciprocate with respect to the basement part,

thereby driving the piston parts of linear generator to convert ocean wave energy into electrical energy.

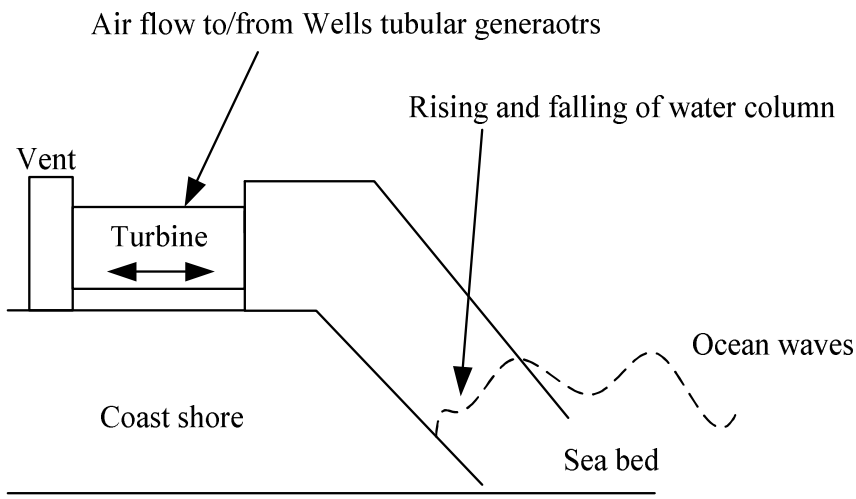


Figure 1. Sketch of Wavegen Limpet.

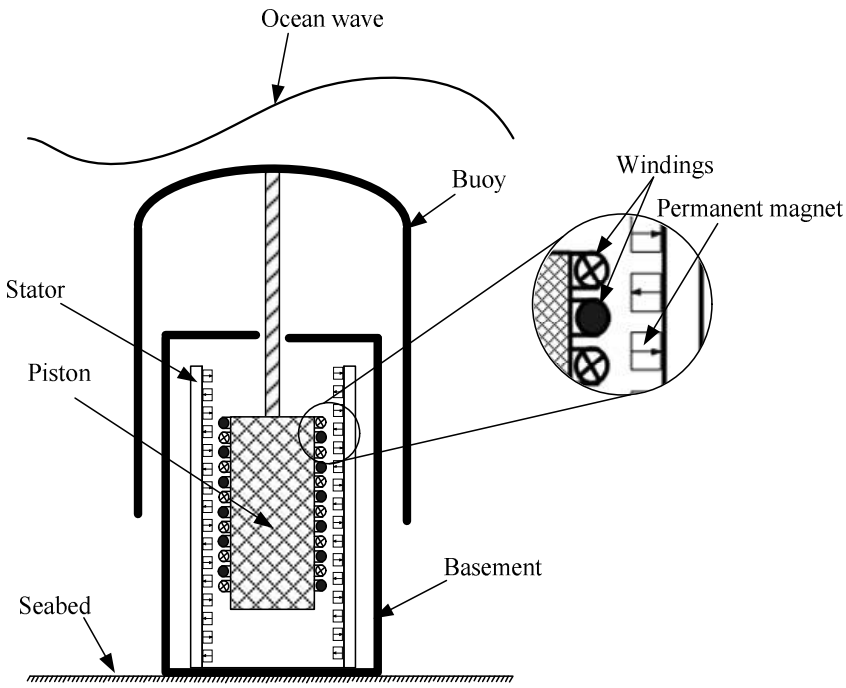


Figure 2. Sketch of AWS.

In order to verify the feasibility of the AWS, some small-scale prototypes of AWSs were tested. In 2004, an AWS pilot plant was installed near the northern shore of Portugal [19]. The experimental results indicate that the AWS was proved to be feasible near a shore exposed to ocean waves.

H. Polinder et al. designed and built a double-sided permanent magnet linear synchronous generator (PMLSG) to improve the performance of AWS, as shown in Figure 3. In Figure 3, the permanent magnets is installed on the PMLSG's stator, the translator (piston) moves inside the stator, and the permanent magnets of the stator generates a varying flux, which induces voltage in the windings of the translator. The PMLSG has the advantages of high force density, reasonable efficiency, and low manufacturing costs [20].

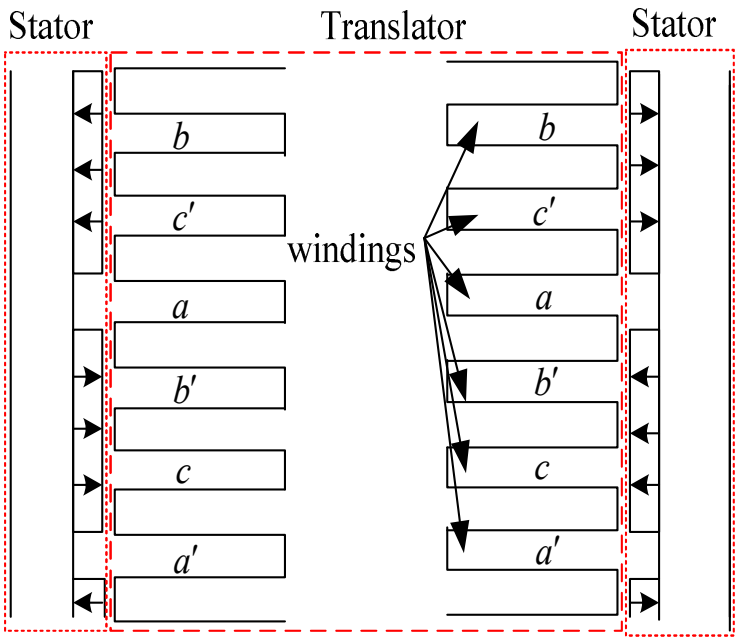


Figure 3. Cross-section of PMLSG.

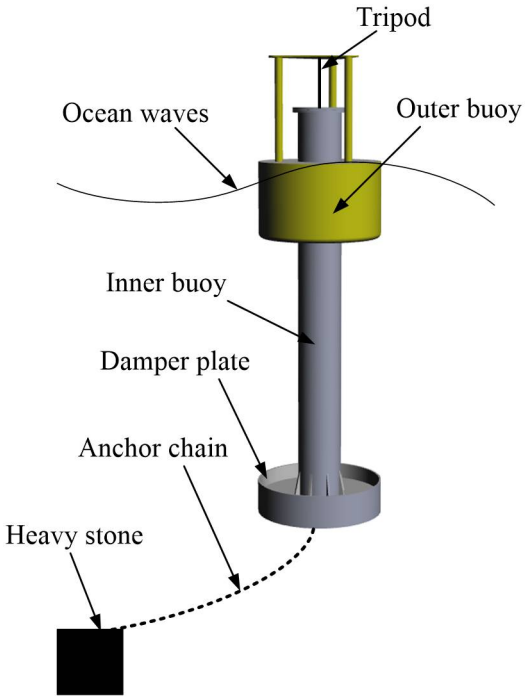
2.3. Tested Offshore

One famous example of ocean wave power generation system installed offshore is the PowerBuoy prototype, designed and constructed by Ocean Power Technologies Inc., and installed off of the northern shore of Spain [21]. Pelamis is another offshore ocean wave power generation system, which has also been investigated in many countries, such as Portugal, UK, and China, among other [22]. China designed and tested a two-buoy offshore ocean wave power generation system, as shown in Figure 4. In Figure 4, the diameter of the outer buoy is 2.4 m, the diameter of inner buoy is 0.83 m, the linear generator is installed in the inner buoy, and the linear generator's piston is connected to the outer buoy by a tripod.

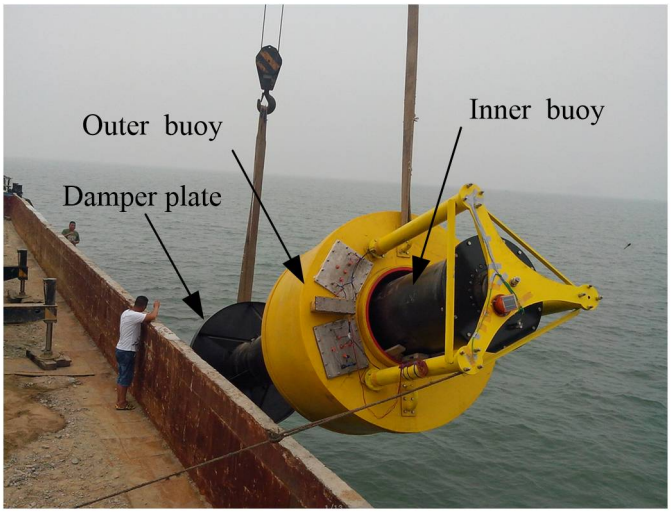
Due to the depth below the ocean's surface being greater, the amplitude of motion of the ocean waves in the vertical direction is smaller. Therefore, the relative motion of two buoys in the vertical direction occurs (the bottoms of the inner buoy and outer buoy below the sea level are different, see Figure 4a), which drives the linear generator to convert ocean wave energy into electrical energy [23].

In August, 2014, the two buoys offshore ocean wave power generation system was installed in the East China Sea (see Figure 4b). According to the experimental results, the maximum instantaneous power is 2.3 kW, and the average power is about 1 kW [23,24].

Besides, another type of offshore ocean wave power generation system is Pelamis, which was designed by the British Ocean Power Delivery Ltd. (Edinburgh, UK), and tested in Agucadoura Wave Park, Portugal [8]. Figure 5 shows the structure of Pelamis, which consists of several buoys, hinged joints, generators, and an anchor. During operations, the relative vertical direction motions of buoys were restricted by the hinged joints, and drive the generators to convert ocean wave energy into electrical energy (the generators were installed in the hinged joints). Pelamis has the advantages of high power capture/unit weight, and was the first offshore ocean wave power generation system to convert ocean wave energy into the grid.



(**a**)



(**b**)

Figure 4. The two-buoy offshore ocean wave power generation system. (**a**) General scheme; (**b**) Installation process.

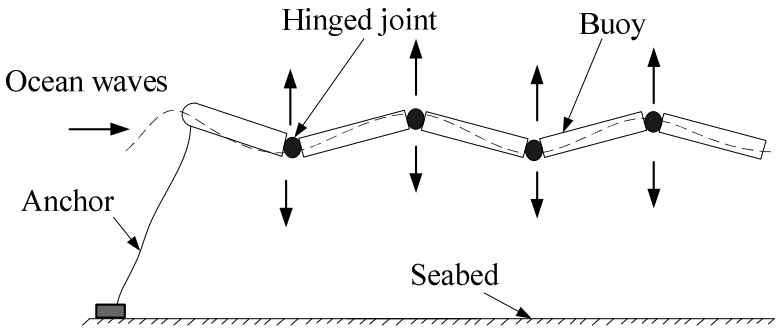


Figure 5. Structure of the Pelamis.

3. Optimal Design of Linear Generator for Ocean Wave Power Generation System

As a part of ocean wave power generation system, the generators play a significant role in the conversion efficiency from wave energy to electrical energy. Usually, there are two kinds of generator that apply to the ocean wave power generation system, namely rotary generators and linear generators [24,25]. For rotary generators, some transmission systems are required to couple the linear motion of ocean waves and the rotary motion of the rotary generators. For the linear generator, the movement direction between waves and linear generators can be identical (without any linear to rotary conversion devices). In comparison with the conventional rotary generators, high efficiency and easy construction made the linear generator an attractive candidate for an ocean wave power generation system [26]. In this section, some linear generators are reviewed.

3.1. Linear Magnetic-Geared Generator

A permanent magnet is an object made from some material—such as iron, nickel, etc.—which can keep its persistent magnetic field for more than 10 years. Therefore, permanent magnet is one of the appropriate materials to produce magnetic source for generators. Figure 6 shows the basic structure of tubular linear magnetic-geared generator. It consists of a linear magnetic gear and a linear permanent magnet generator. Usually, the operation process is that the low-velocity piston reciprocates with the ocean waves by buoy. Then, under the condition of magnetic gear effect, the velocity of the high-velocity piston is amplified correspondingly. Therefore, the tubular linear magnetic-geared generator produces a higher output voltage [27]. The modulation rings are made from steel, and fixed between the high-velocity piston and low-velocity piston by epoxy.

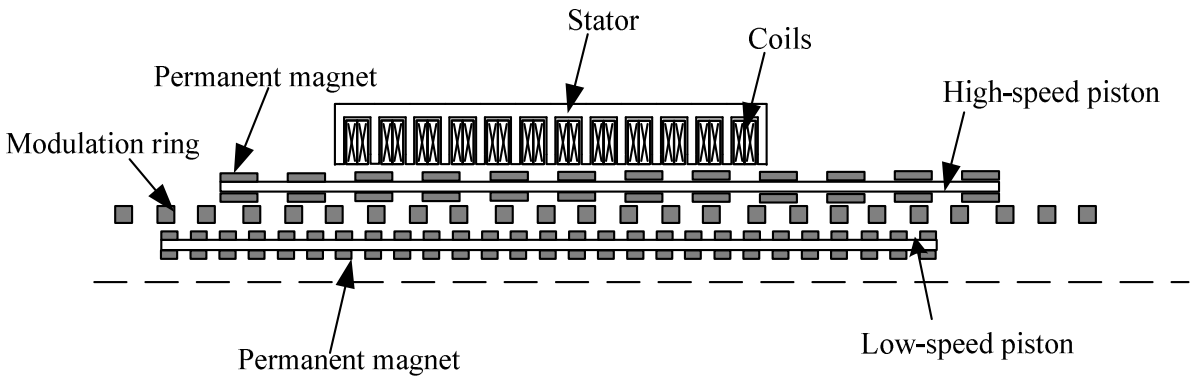


Figure 6. Basic structure of tubular linear magnetic-geared generator.

The theoretical analysis and simulation results indicate that the tubular linear magnetic-geared generator has higher efficiency than conventional rotary generators and linear permanent magnet generators. However, the tubular linear magnetic-geared generator requires some high-precision technology during its production process.

3.2. Linear Switched Reluctance Generator

The linear switched reluctance generator is a special linear generator without a permanent magnet, and it has the advantages of simple structure, good thermal performance, and low cost [28,29].

Figure 7 shows the sketch of a linear switched reluctance generator, which consists of a stator (static part) and a piston (movable part). Usually, the stator is housed by electrical phase windings, and the piston has no magnetic field source. Since the piston has no magnetic field source, some control methods need to be adopted to make the device as a generator. For example, provided that the linear switched reluctance generator runs at high velocity, the method of position control should be adopted, or the method of pulse width modulation (PWM) chopper control should be to be adopted to keep the generator running at low velocity.

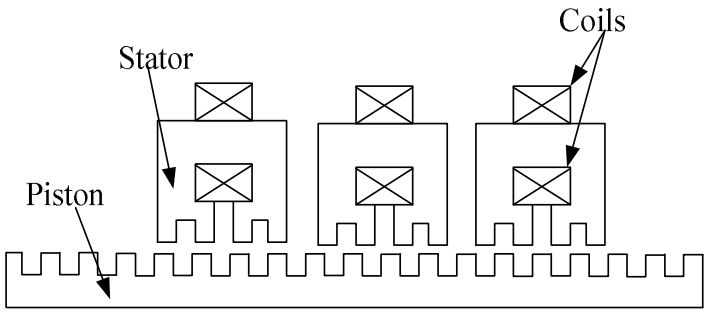
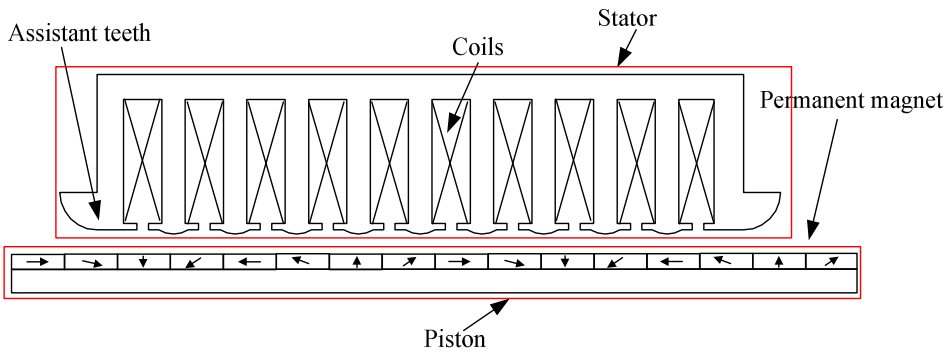


Figure 7. Sketch of the linear switched reluctance generator.

Besides, some other control methods have been proposed for the optimal design and operation of linear switched reluctance generator [30,31].

3.3. Halbach Magnetized Linear Permanent Magnet Generator

A significant advantage of Halbach magnetized linear permanent magnet generator is that the arrangement permanent magnets increase its air-gap flux density. The gap flux density distribution of Halbach magnetized permanent magnet generator is better than that of an ordinary linear permanent magnet generator. Figure 8 illustrates the sketch and prototype of a Halbach magnetized linear permanent magnet generator designed by Southeast University in China [32]. In Figure 8a, the Halbach magnetized linear permanent magnet generator adopted assistant teeth to reduce its detent force.



(**a**)

(**b**)

Figure 8. Halbach magnetized linear permanent magnet generator. (**a**) Sketch; (**b**) Prototype.

The installation site of the Halbach magnetized linear permanent magnet generator in an ocean wave power generation system is shown in Figure 9. In August 2014, the ocean wave power generation system was installed and tested in the Yellow sea near Lianyungang, China. The experimental results indicate that the ocean wave power generation system has low efficiency in ocean waves [24]. The main reason for its low efficiency is that the phase difference between the ocean wave power generation system and the ocean

waves. Therefore, some optimization control methods should be proposed to improve the operational efficiency of ocean wave power generation system.

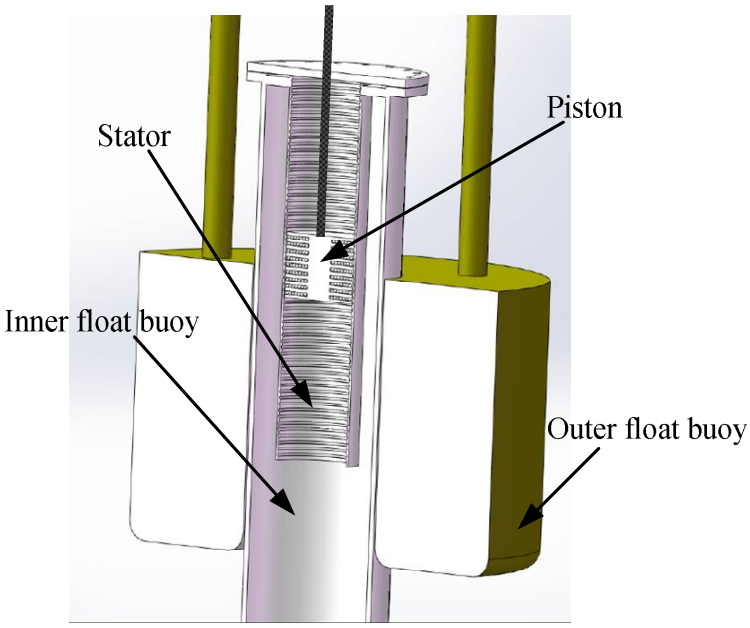


Figure 9. Installation site of Halbach magnetized linear permanent magnet generator.

Table 1 shows the optimization design classification of linear generator of the ocean wave power generation system in the reference [25–31], including the structure, electromagnetic field, force, and operation control of the linear generators.

Table 1. Optimization of linear generator for ocean wave power generation system.

Reference Number	Main Research Contents
Reference [25]	Structure comparison of iron-cored linear permanent magnet generator and semi iron-cored linear permanent magnet generators
Reference [26]	Analysis of multi-physical coupling field of a permanent magnet linear synchronous generator
Reference [27]	Analysis of air gap flux density, thrust force characteristics, no-load and load performances of linear magnetic-geared interior permanent magnet generator
References [28,29]	Multi-objective optimization design and simulation calculation of linear switched reluctance generator
References [30,31]	Structure and operational control of linear switched reluctance machines

4. Optimization Control Methods for Ocean Wave Power Generation System

Due to the irregularity and nonlinearity motion of ocean waves, some optimization control methods were proposed to improve the efficiency of ocean wave power generation system [33–35]. The purpose of optimization control methods is to make the ocean wave power generation system resonate with the ocean waves. Generally, there are two kinds of optimal control methods, which are depicted as follows.

4.1. Optimization Control of Generator

The forces exerted on ocean wave power generation systems include ocean waves' force, generator's detent force, generator's load force, system's friction force, buoy's radiation force, etc. [36]. In order to make the ocean wave power generation system resonates

with the ocean waves in the vertical direction, a method of q-axis current control of generator was proposed [37,38]. By Park transformation, the load force of the generator can be written as

$$\hat{F}_u = -\frac{3}{2}\frac{\pi\psi}{\tau}\hat{i}_q \tag{1}$$

where ψ is the magnetic linkage of generator, τ is the pole pitch of generator,ˆrepresents the complex representation, and $\hat{i}_q$ is the q-axis current of generator. According to the structure of ocean wave power generation system and the theory of mechanical vibration, if the velocities of buoy and ocean wave are identical, there will be resonance between the ocean wave power generation system and ocean waves.

In the vertical direction, the acceleration formula of buoy can be described as

$$m\hat{a}_z = \hat{F}_z + \hat{F}_r + \hat{F}_b + \hat{F}_f \tag{2}$$

where m is the mass (in kilograms), $\hat{a}_z$ is the acceleration in the vertical direction, $\hat{F}_z$ is the vertical direction ocean wave force, $\hat{F}_r$ is the radiation force from the relative motion between buoy and ocean waves, $\hat{F}_b$ is the hydrostatic buoyancy force, and $\hat{F}_f$ is the friction force.

The diameter of buoy is smallest than the wavelength of ocean waves, thus the method of Froude–Krylow force and small object approximation can be used. Therefore, the vertical direction ocean wave force $\hat{F}_z$ can be written as

$$\hat{F}_z = \left[\rho g S_w - \omega^2 \rho V(1+\mu_z)\right]\hat{\eta} \tag{3}$$

where ρ is the density of ocean water, g is the acceleration of gravity, S_w is the horizontal cross-section of buoy, ω is the angular frequency of ocean waves, V is the volume of buoy below the ocean waves surface, μ_z is the added mass coefficient of buoy, and $\hat{\eta}$ is the wave amplitude of ocean waves.

Besides, the radiation force $\hat{F}_r$, the hydrostatic buoyancy force $\hat{F}_b$, and the friction force $\hat{F}_f$ can be written as

$$\hat{F}_r = \left(\omega^2 m_z - i\omega R_z\right)\frac{\hat{a}_z}{-\omega^2} \tag{4}$$

$$\hat{F}_b = -\rho g S_w \frac{\hat{a}_z}{-\omega^2} \tag{5}$$

$$\hat{F}_f = -i\omega R_f \frac{\hat{a}_z}{-\omega^2} \tag{6}$$

where m_z and R_z are the added mass and damping coefficient of buoy respectively, R_f is the friction resistance coefficient of double buoys type ocean wave energy extraction system.

According to the relationship between speed and acceleration, the vertical direction acceleration $\hat{a}_z$ can be written as

$$\hat{a}_z = i\omega\hat{v}_z \tag{7}$$

where $\hat{v}_z$ is the vertical direction speed. Substitute Equations (3)–(7) into (2), the vertical direction speed of buoy can be described as

$$\hat{v}_z = \frac{\hat{F}_z + \hat{F}_u}{i\omega[m_m + m_z] + R_z + \frac{S_{wp}}{i\omega}} \tag{8}$$

From the velocity of buoy $\hat{v}_z$ (see Equation (8)), it can be concluded that the resonance between ocean waves and buoy can be occurred by adjust the load force of generator $\hat{F}_u$.

In Equation (1), the load force of generator $\hat{F}_u$ can be changed by adjusting the q-axis current $\hat{i}_q$. Therefore, based on the above equations, the optimization control diagram based on q-axis current of generator is shown in Figure 10, which consists of the inverse direction transformation, the current distribution, the space vector pulse width modula-

tion (SVPWM), the power inverter, the generator, the inverse Park transformation, and the inductance compensation. In Figure 10, θ is the electric angle of generator in operational process, PI is the proportional integral regulation, dq and α-β represent the coordinate system.

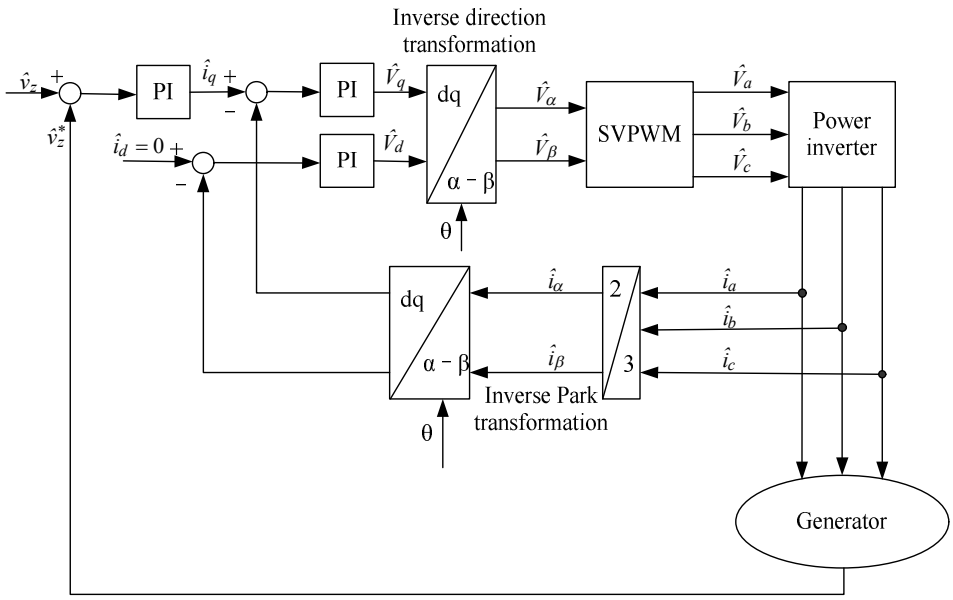


Figure 10. Optimization control diagram of ocean wave power generation system based on the *q*-axis current of generator.

By employing load current control of the generator, the efficiency of the ocean wave power generation system can be significantly improved. The buoy's heave excursions and the peak-to-average power ratio are reduced.

4.2. Optimization Control of Float Buoy

Usually, the buoy of ocean wave power generation system oscillates in the vertical direction. Therefore, some optimization control methods based on the buoy are proposed to improve the operational efficiency of ocean wave power generation system. One optimization control method is the internal model proportion integration differentiation (IM-PID). Figure 11 shows the block diagram of IM-PID control [39]. In Figure 11, the input $R(s)$ is the velocity of ocean wave, and the output $Y(s)$ is the velocity of buoy. The relationship among output $Y(s)$, input $R(s)$ and disturbance $D(s)$ can be written as

$$Y(s) = \frac{G(s)G_{IMC}(s)}{1 + \left(G(s) - \hat{G}(s)\right)G_{IMC}(s)}R(s) + \frac{G(s)\left[1 - G_{IMC}(s)\hat{G}(s)\right]}{1 + \left(G(s) - \hat{G}(s)\right)G_{IMC}(s)}D(s) \quad (9)$$

where $G_{IMC}(s)$ is the IM-PID controller, $G(s)$ is the plant (buoy) to control, and $\hat{G}(s)$ is the mathematical model of $G(s)$. After the formula derivation from Equation (9), the dynamic performance of buoy can be optimization controlled (makes the velocity identical between ocean waves and buoy) by adjusting the filter coefficient ε of $G_{IMC}(s)$.

Figure 12 shows the simulation model of an ocean wave power generation system based on the IM-PID control. The purpose of IM-PID control is to make the buoy of ocean wave power generation system resonate with the ocean waves, so as to improve the efficiency of ocean wave power generation system. Figure 13 shows the simulation result of IM-PID. The simulation result indicates that the resonance between ocean waves and buoy can be realized by adjusting the filter coefficient ε of $G_{IMC}(s)$, and the ocean wave power generation system has good robustness and high operational performance.

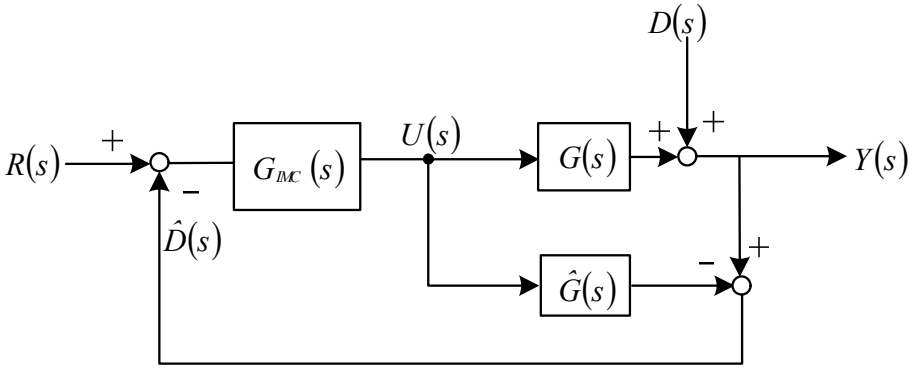


Figure 11. Block diagram of IM-PID control.

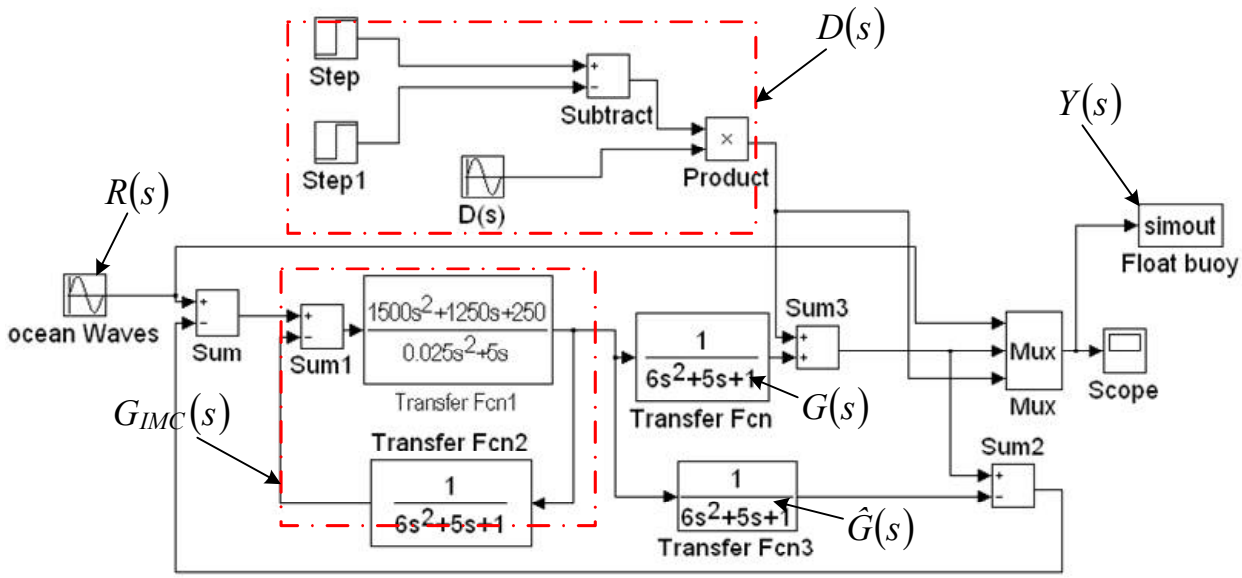


Figure 12. Simulation model of ocean wave power generation system based on the IM-PID control.

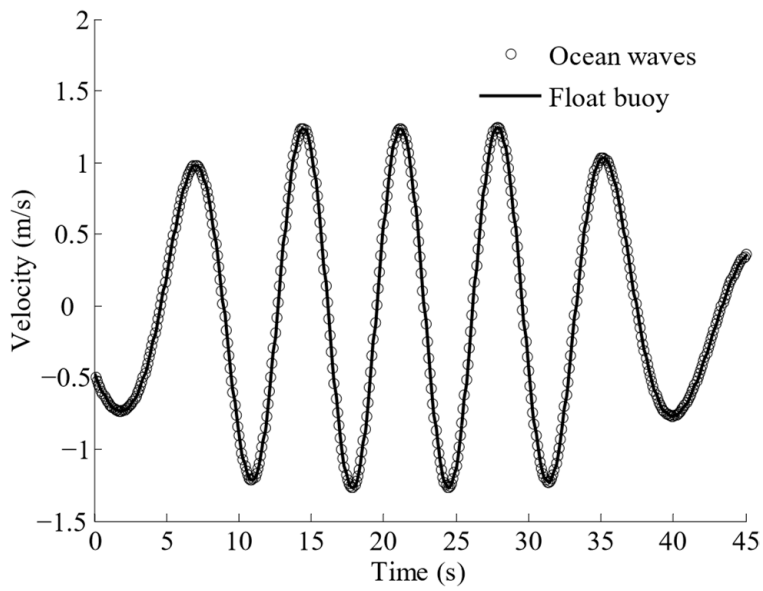


Figure 13. Simulation result of IM-PID control ($\varepsilon = 0.01$).

Some other optimization control methods for ocean wave power generation system are proposed. For example, the maximum power point tracking (MPPT) method was

proposed to eliminate the faults of the AWS-based ocean wave power generation system, and maximum power extraction from ocean waves [40]; the method based on learning vector quantitative neural network (LVQNN) was proposed to improve the efficiency of an adjustable slope angle type ocean wave power generation system [41]; the latching control method is proposed to improve the operational performance of the oscillating-body-type ocean wave power generation system [42,43]. Table 2 shows the optimization control classification of ocean wave power generation system in reference papers [33–43].

Table 2. Optimization control classification of reference papers [33–43] for ocean wave power generation systems.

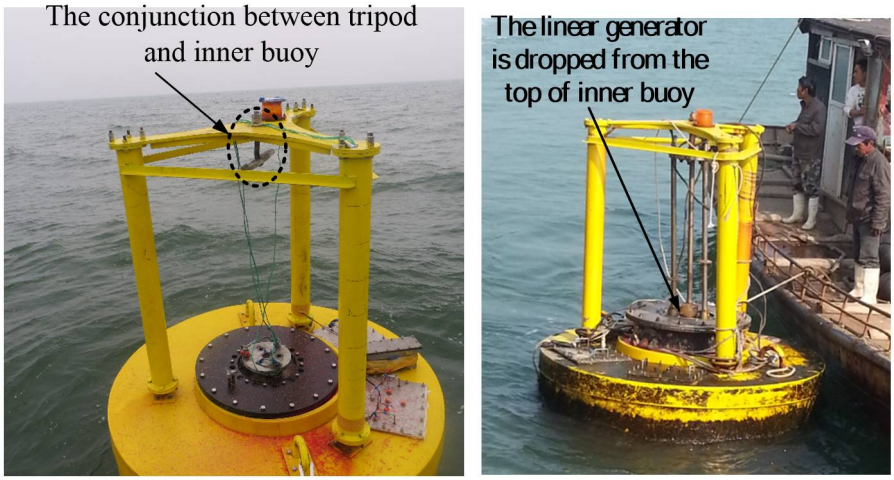
Reference Number	Main Research Contents
References [33–36]	Overall system optimization control of ocean wave power generation system, including the power output, transmission and grid connection, etc.
Reference [37]	Analysis of the forces that exert on ocean wave power generation system.
References [38,39]	Q-axis current control of linear generator for the stable operational and maximum power output of ocean wave power generation system.
Reference [40]	Optimization control of float buoy to improve the power output of ocean wave power generation system.
References [41–43]	Other optimization control methods—such as maximum power point tracking (MPPT), learning vector quantitative neural network (LVQNN), and latching control—to improve the power output of ocean wave power generation system, but still in the stage of theoretical research.

However, the above optimization control methods are still in the stage of theoretical research. Before applying these optimization control methods in the real test of ocean wave power generation system, it is also necessary to solve the problems of hardware design, construction implementation, corrosion protection from ocean water, ocean environmental adaptation, and waterproof sealing. In addition, the difficulty level, economic cost, maintenance cost, and actual efficiency of ocean wave power generation systems should also be considered.

In order to improve the effect of optimization control of ocean wave power generation systems, some other mathematical modeling of ocean wave power generation systems were provided. Such as the mathematical modeling of mooring system [44,45], nonlinear approaches [46,47], mathematical modeling of single point mooring wave energy converter [48], mathematical modeling of wave impact on wave-energy buoys [49], multi-oscillating water columns of wave energy converter [50], and so on.

5. Safety of Ocean Wave Power Generation Systems in Ocean Waves

In harsh ocean environments, many kinds of ocean wave power generation systems were destroyed by the large ocean wave height, typhoons, or hurricanes. In August 2014, the two-buoy offshore ocean wave power generation system was destroyed by large ocean wave height, as shown in Figure 14a. In Figure 14a, due to the amplitude of ocean waves being greater than that of the ocean wave power generation system, the conjunction between the tripod and inner buoy was broken. Subsequently, the ocean wave power generation system was repaired, and tested in the same sea area again. However, the ocean wave power generation system was damaged by a typhoon, as shown in Figure 14b.



(**a**) (**b**)

Figure 14. Tests of ocean wave power generation system. (**a**) The first test; (**b**) The second test.

Therefore, in addition to operational efficiency, safety is also another factor to promote the development of ocean wave power generation technology. In this paper, a damping coefficient optimization control method based on the domain partition is proposed to improve the efficiency and safety of ocean wave power generation system. Figure 15 shows the phase relationship between the exciting force of an ocean wave power generation system and its velocity. Generally, the exciting force F_{exc} legs behind the velocity v_z (in Figure 15a), the exciting force F_{exc} ahead of the velocity v_z (in Figure 15b), and the exciting force F_{exc} is identical to the velocity v_z (in Figure 15c). The domain between exciting force F_{exc} and velocity v_z are divided as T_1, T_2, T_3, T_4 and T.

According to the phase relationship between exciting force F_{exc} and velocity v_z, a certain damping coefficient B_{pto} can be obtained. The relationship between the linear generator's q-axis current and damping coefficient can be written as

$$\hat{i}_q = -\frac{B_{pto}\hat{v}_z\tau_p}{0.5\pi\psi_{PM}} \tag{10}$$

where B_{pto} is the damping coefficient, τ_p is the length of the permanent magnet of the linear generator. Equations (1) and (10) indicate that the generator's load force $\hat{F}_u$ can be adjusted by the damping coefficient B_{pto}. In the ocean wave power generation system, the generator's load force $\hat{F}_u$ is an important force to eliminate the phase difference between the exciting force F_{exc} and velocity v_z. Under this condition, the resonance between the ocean wave power generation system and ocean waves can improve the operational efficiency of ocean wave power generation system.

Based on the exciting force F_{exc} and velocity v_z, the damping coefficient optimization control method is described as follows. For domains T_1 and T_3, the constant damping coefficient control method is adopted. For domains T_2 and T_4, the optimization damping coefficient control method is adopted. For domain T, the zero damping coefficient control method is adopted. Furthermore, under the extreme ocean environment conditions, the maximum damping coefficient control method is adopted to ensure the safety of an ocean wave power generation system. The diagram of the damping coefficient optimization control method is shown in Figure 16.

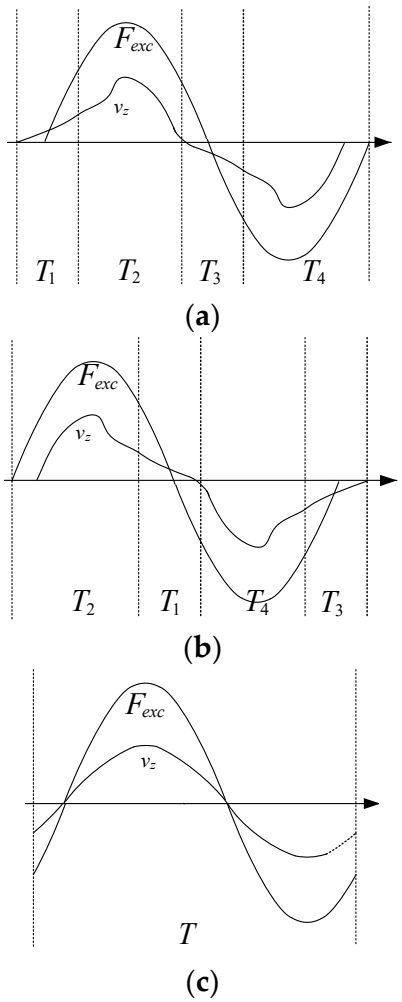


Figure 15. Phase analysis and domain partition of ocean wave power generation system. (**a**) Exciting force F_{exc} legs behind the velocity v_z; (**b**) Exciting force F_{exc} ahead of the velocity; (**c**) Exciting force F_{exc} is identical to the velocity v_z.

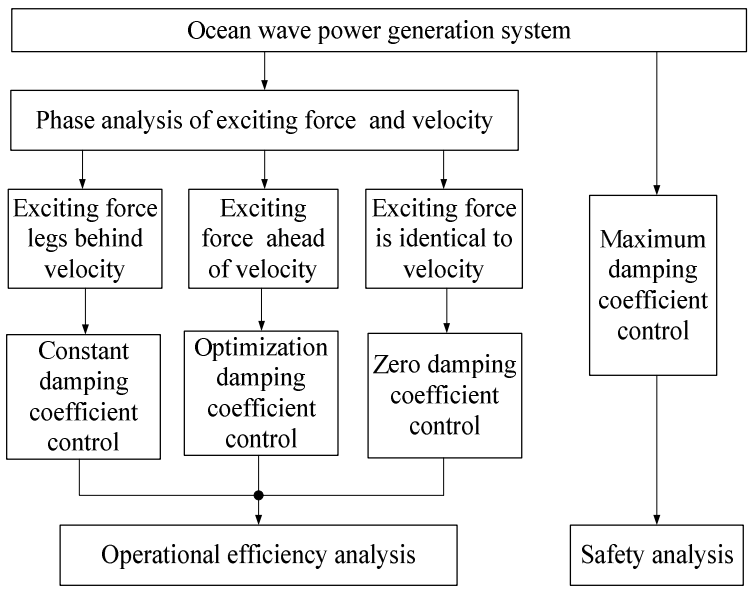


Figure 16. Diagram of damping coefficient optimization control method for ocean wave power generation system.

6. Policy and Financial Support for Ocean Wave Power Generation

In the past decade (2010–2020), there have been many policy and financial supports for the development of ocean wave power generation projects.

In the United States, a lot of government and research departments provide the financial or technical support for ocean wave power generation, including the Department of Energy (DOE), National Science Foundation (NSF), National Laboratories, and so on. For example, in order to support the "Hydropower" and "MHK" projects, DOE has invested $116 million in 95 MHK projects in 2008–2014, most of which were used for technology research [51].

Around 2015, both Britain and Denmark released technical roadmaps of wave energy (or ocean energy), and established policy support, economic investment, development objectives, etc. [52]. In 2010, the European Ocean Energy Association (EOEA) released the European Marine Energy Roadmap 2010–2050, wherein it was stated that financial support in the research and development of marine energy extraction will be increased, and the installed capacity will reach 3600 MW by 2020 and nearly 188,000 MW by 2050 [53].

In Australia, many renewable energy development and utilization funds have been established, such as the Renewable Energy Fund, Energy Innovation Fund, and Renewable Energy Industry Development Fund, etc. [54].

In Asia, South Korea released a medium- and long-term development plan of ocean energy extraction in 2015, which determined the government's new task of developing ocean energy, that is to increase the investment in ocean energy infrastructure, promote the commercialization of ocean energy industry, and cooperation with Pacific Island countries in ocean energy [55]. In 2015, China issued the renewable energy development plan (2016–2020), which aims to improve the management system of ocean wave energy, full acquisition of ocean energy power generation, tax relief, etc. [56].

7. Conclusions

This review shows the current situation of ocean wave power generation system tests. The optimization design and control methods to improve the operational efficiency of ocean wave power generation systems are also illustrated—mainly including the generator design, float buoy control, and generator control. The safety of ocean wave power generation systems in ocean environments is discussed, and a damping coefficient optimization control method based on the domain partition of phase is proposed to improve the stability and safety of ocean wave power generation system. The current policies and financial support for ocean wave power generation in some countries were also elaborated.

According to the current development status of ocean wave power generation systems, this review shows that the optimization control techniques of ocean wave power generation systems needs further investigation and ocean testing.

Author Contributions: Conceptualization, J.W. and Z.C.; Methodology, J.W.; Writing—original draft preparation, J.W.; Writing—review and editing, Z.C and F.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Scientific and Technological Project in Henan Province under grant no. 212102210255, and the key laboratory of new permanent magnet motor, Zhumadian.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data, models generated, or used during the study are available in a repository or online.

Acknowledgments: The authors would like to acknowledge The Key Laboratory of New Permanent Magnet Motors, Zhumadian, Henan province, which provided the support and facilities in conducting this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, S.M.; Li, Z.Y.; Yu, T.; Ma, C.B. A review of research on multi-energy complementary ocean energy integrated power generation technology. *Mar. Sci. Bull.* **2019**, *38*, 241–249.
2. Khan, N.; Kalair, A.; Abas, N.; Haider, A. Review of ocean tidal, wave and thermal energy technologies. *Renew. Sustain. Energy Rev.* **2017**, *72*, 590–604. [CrossRef]
3. Gradowski, M.; Gomes, R.P.F.; Alves, M. Hydrodynamic optimisation of an axisymmetric floating Oscillating Water Column type wave energy converter with an enlarged inner tube—ScienceDirect. *Renew. Energy* **2020**, *162*, 1519–1532. [CrossRef]
4. Currie, M. Hydrogen, Fuel Cells and the Optimisation of the LIMPET 500 on Islay. Master's Thesis, University of Strathclyde Glasgow, Glasgow, UK, 2002.
5. Falcão, A.F.O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **2010**, *12*, 899–918. [CrossRef]
6. Ning, D.Z.; Wang, R.Q.; Zou, Q.P.; Teng, B. An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter—Science Direct. *Appl. Energy* **2016**, *168*, 636–648. [CrossRef]
7. Heath, T.V. A review of oscillating water columns. *Philos. Trans. R. Soc. A* **2012**, *370*, 235–245. [CrossRef] [PubMed]
8. Rizal, A.M.; Ningsih, N.S. Ocean wave energy potential along the west coast of the Sumatra island, Indonesia. *J. Ocean. Eng. Mar. Energy* **2020**, *6*, 137–154. [CrossRef]
9. Abanades, J.; Greaves, D.; Iglesias, G. Wave farm impact on beach modal state. *Mar. Geol.* **2015**, *361*, 126–135. [CrossRef]
10. Lin, L.; Yu, H. Offshore wave energy generation devices: Impacts on ocean bio-environment. *Acta Ecol. Sin.* **2012**, *32*, 117–122. [CrossRef]
11. Özkop, E.; Sharaf, A.; Altaş, İ.H. An adaptive fuzzy PI controlled bus quantity enhancer for wave energy systems. *Turk. J. Electr. Eng. Comput. Sci.* **2016**, *24*, 2454–2468. [CrossRef]
12. Oikonomou, C.L.; Gomes, R.P.; Gato, L.M. Unveiling the potential of using a spar-buoy oscillating-water-column wave energy converter for low-power stand-alone applications. *Appl. Energy* **2021**, *292*, 116835. [CrossRef]
13. Huang, W.; Yang, J. A Novel Piecewise Velocity Control Method Using Passivity-Based Controller for Wave Energy Conversion. *IEEE Access* **2020**, *8*, 59029–59043. [CrossRef]
14. Hong, Y.; Pan, J.; Liu, Y.; Wang, C.; Li, C.; Fu, P. A Review on Linear Generator Based Wave Energy Conversion Systems. *Proc. CSEE* **2019**, *39*, 1886–1899.
15. Abraham, E.; Kerrigan, E.C. Optimal active control and optimization of a wave energy converter. *IEEE Trans. Sustain. Energy* **2013**, *4*, 324–332. [CrossRef]
16. Trivedi, K.; Koley, S. Mathematical modeling of breakwater-integrated oscillating water column wave energy converter devices under irregular incident waves. *Renew. Energy* **2021**, *178*, 403–419. [CrossRef]
17. Ahmed, N.; Mueller, M. Impact of varying clearances for thewWells turbine on heat transfer from electrical generators in oscillating water columns. In Proceedings of the IEEE International Conference and Exhibition on Ecological Vehicles and Renewable Energies, Monte Carlo, Monaco, 27–30 March 2013; pp. 1–6.
18. Ren, Y.; Zhao, J.; Qin, C.; Zhu, L. Small signal stability analysis and optimal control of AWS based wave energy conversion system. In Proceedings of the 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Nanjing, China, 20–23 September 2020.
19. Beiro, P.; Valério, D.; Costa, J. Linear model identification of the archimedes wave swing. In Proceedings of the International Conference on Power Engineering, Energy and Electrical Drives, Setubal, Portugal, 12–14 April 2007; pp. 660–665.
20. Wahyudie, A.; Jama, M.; Susilo, T.B.; Mon, B.F.; Shaaref, H.; Noura, H. Design and Testing of a Laboratory Scale Test-rig for Wave Energy Converters using a Double-sided Permanent Magnet Linear Generator. *IET Renew. Power Gener.* **2017**, *11*, 922–930. [CrossRef]
21. Edwards, K.; Mekhiche, M. Ocean power technologies powerbuoy: System-level design, development and validation methodology. In Proceedings of the 2nd Marine Energy Technology Symposium, Seattle, WA, USA, 15–18 April 2014.
22. Reddy, K.S.; Prajwal, K.S.; Satwik, T.S. A review on the gradiation towards pelamis wave energy converter. In Proceedings of the 4th International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli, India, 15–17 June 2020.
23. Chen, Z.; Yu, H.; Hu, M.; Meng, G.; Wen, C. A review of offshore wave energy extraction system. *Adv. Mech. Eng.* **2013**, *5*, 623020. [CrossRef]
24. Chen, Z.; Yu, H.; Liu, C.; Hong, L. Design, Construction and Ocean Testing of Wave Power generation system with Permanent Magnet Tubular Linear Generator. *Trans. Tianjin Univ.* **2016**, *22*, 72–76. [CrossRef]
25. Azhari, B.; Wijaya, F.D.; Yazid, E. Performance of Linear Generator Designs for Direct Drive Wave Energy Converter under Unidirectional Long-Crested Random Waves. *Energies* **2021**, *14*, 5098. [CrossRef]
26. Liu, C.; Rui, D.; Zhu, H.; Fu, W. Multi-Physical Coupling Field of a Permanent Magnet Linear Synchronous Generator for Wave Energy Conversion. *IEEE Access* **2021**, *9*, 85738–85747. [CrossRef]
27. Feng, N.; Yu, H.; Hu, M.; Liu, C.; Huang, L.; Shi, Z. A Study on a Linear Magnetic-Geared Interior Permanent Magnet Generator for Direct-Drive Wave Energy Conversion. *Energies* **2016**, *9*, 487. [CrossRef]
28. García-Tabarés, L.; Lafoz, M.; Blanco, M.; Torres, J.; Obradors, D.; Nájera, J.; Navarro, G.; García, F.; Sánchez, A. New Type of Linear Switched Reluctance Generator for Wave Energy Applications. *IEEE Trans. Appl. Supercond.* **2020**, *30*, 5207105.

29. Zhao, S.; Chen, H.; Nie, R.; Liu, J. Multi-objective optimal design of double-sided switched reluctance linear generator for wave power generation. *COMPEL* **2019**, *38*, 1948–1963. [CrossRef]
30. Huang, X.; Lin, Z.; Xiao, X. Four-quadrant force control with minimal ripple for linear switched reluctance machines. *CES Trans. Electr. Mach. Syst.* **2020**, *4*, 27–34. [CrossRef]
31. Qiu, L.; Shi, Y.; Pan, J.; Zhang, B.; Xu, G. Collaborative Tracking Control of Dual Linear Switched Reluctance Machines Over Communication Network With Time Delays. *IEEE Trans. Cybern.* **2017**, *47*, 4432–4442. [CrossRef]
32. Liu, C. Research on the Tubular Permanent Magnet Linear Generator Using Direct-Driven Wave Power Take-Off System. Ph.D. Thesis, Southeast University, Nanjing, China, 2015.
33. Talaat, M.; Sedhom, B.E.; Hatata, A.Y. A new approach for integrating wave energy to the grid by an efficient control system for maximum power based on different optimization techniques. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106800. [CrossRef]
34. Guo, B.; Ringwood, J. Non-Linear Modelling of a Vibro-Impact Wave Energy Converter. *IEEE Trans. Sustain. Energy* **2021**, *12*, 492–500. [CrossRef]
35. Zabihi, M.; Mazaheri, S.; Namin, M.M.; Mazyak, A.R. Irregular wave interaction with an offshore OWC wave energy converter. *Ocean. Eng.* **2021**, *222*, 108619. [CrossRef]
36. Falnes, J. *Ocean Waves and Oscillating Systems*; Cambridge University Press: Cambridge, MA, USA, 2002.
37. Bariša, T.; Sumina, D.; Kutija, M. Control of generator-and grid-side converter for the interior permanent magnet synchronous generator. In Proceedings of the International Conference on Renewable Energy Research and Applications, Palermo, Italy, 22–25 November 2015; pp. 1015–1020.
38. Xu, Q.; Li, N.L.; Xu, Y. Flutter Control of the Wind Turbine Blade Based on IMC-PID Control. Measurement & Control Technology. *Meas. Control. Technol.* **2017**, *36*, 70–73.
39. Chen, Z.; Yu, H.; Wen, C. An Optimal Control Method for Maximizing the Efficiency of Direct Drive Ocean Wave Energy Extraction System. *Sci. World J.* **2014**, *2014*, 480916. [CrossRef]
40. Marei, M.I.; Mokhtar, M.; El-Sattar, A.A. MPPT strategy based on speed control for AWS-based wave energy conversion system. *Renew. Energy* **2015**, *83*, 305–317. [CrossRef]
41. Tri, N.M.; Truong, D.Q.; Binh, P.C.; Dung, D.T.; Lee, S.; Park, H.G.; Ahn, K.K. A novel control method to maximize the energy-harvesting capability of an adjustable slope angle wave energy converter. *Renew. Energy* **2016**, *97*, 518–531. [CrossRef]
42. Kim, J.; Cho, I.H.; Kim, M.H. Numerical calculation and experiment of a heaving-buoy wave energy converter with a latching control. *Ocean. Syst. Eng.* **2019**, *1*, 1–19.
43. Shadman, M.; Avalos, G.O.G.; Estefen, S.F. On the power performance of a wave energy converter with a direct mechanical drive power take-off system controlled by latching. *Renew. Energy* **2021**, *169*, 157–177. [CrossRef]
44. Davidson, J.; Ringwood, J.V. Ringwood Mathematical Modelling of Mooring Systems for Wave Energy Converters—A Review. *Energies* **2017**, *10*, 666. [CrossRef]
45. Amaechi, C.V.; Chesterton, C.; Butler, H.O.; Wang, F.; Ye, J. Review on the design and mechanics of bonded marine hoses for Catenary Anchor Leg Mooring (CALM) buoys. *Ocean. Eng.* **2021**, *242*, 110062. [CrossRef]
46. Penalba, M.; Giorgi, G.; Ringwood, J.V. Mathematical modelling of wave energy converters: A review of nonlinear approaches. *Renew. Sustain. Energy Rev.* **2017**, *78*, 1188–1207. [CrossRef]
47. Giorgi, G.; Penalba, M.; Ringwood, J. Nonlinear hydrodynamic models for heaving buoy wave energy converters. In Proceedings of the Asian Wave and Tidal Energy Conference, Singapore, 25–27 October 2016.
48. Amaechi, C.V.; Wang, F.; Ye, J. Mathematical Modelling of Bonded Marine Hoses for Single Point Mooring (SPM) Systems, with Catenary Anchor Leg Mooring (CALM) Buoy Application—A Review. *J. Mar. Sci. Eng.* **2021**, *9*, 1179. [CrossRef]
49. Kalogirou, A.; Bokhove, O. Mathematical and numerical modelling of wave impact on wave-energy buoys. In Proceedings of the International Conference on Ocean, Offshore and Arctic Engineering, Busan, Korea, 19–24 June 2016.
50. Doyle, S.; Aggidis, G.A. Development of multi-oscillating water columns as wave energy converters. *Renew. Sustain. Energy Rev.* **2019**, *107*, 75–86. [CrossRef]
51. Lehmann, M.; Karimpour, F.; Goudey, C.A.; Jacobson, P.T.; Alam, M.R. Ocean wave energy in the United States: Current status and future perspectives. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1300–1313. [CrossRef]
52. Zhang, X.; Zhang, P. Comparative Analysis of Domestic and Overseas Current Marine Energy Policies. *Mar. Econ.* **2018**, *8*, 48–56.
53. European Ocean Energy Association. Oceans of Energy—European Ocean Energy Roadmap 2010–2050. Strategy International Communications, Belgium. 2010. Available online: https://www.icoe-conference.com/publication/oceans_of_energy_european_ocean_energy_roadmap_2010_2050/ (accessed on 21 December 2021).
54. Hemer, M.A.; Manasseh, R.; McInnes, K.L.; Penesis, I.; Pitman, T. Perspectives on a Way Forward for Ocean Renewable Energy in Australia. *Renew. Energy* **2018**, *127*, 733–745. [CrossRef]
55. Park, J.I.; Kim, T. Institutional improvement measures for environmental assessment in the pursuit of eco-friendly ocean renewable energy development in South Korea. *Renew. Sustain. Energy Rev.* **2016**, *58*, 526–536. [CrossRef]
56. Wu, X.D.; Chen, G.Q. Energy and water nexus in power generation: The surprisingly high amount of industrial water use induced by solar power infrastructure in China. *Appl. Energy* **2017**, *195*, 125–136. [CrossRef]