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REVIEW

Direct-Drive wave energy conversion with linear generator: A review of research status and challenges

Jing Zhang[1] | **Haitao Yu**[2] | **Minshuo Chen**[2]

[1]Department of Electrical Engineering, Jinling Institute of Technology, Nanjing, China

[2]School of Electrical Engineering, Southeast University, Nanjing, China

Correspondence
Jing Zhang, Department of Electrical Engineering, Jinling Institute of Technology, Nanjing 211169, China.
Email: phillish@126.com

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Abstract
Ocean wave energy is sustainable and renewable energy, wave energy conversion (WEC) effectively solves the disadvantage of traditional power system with fossil energy. WEC system is the power generation process that converts wave kinetic energy of undulation and swing into electric energy, and direct-drive WEC system (D-DWEC) converts wave energy into electric power directly by linear generator to improve the efficiency. At present, the research of WEC system has the characteristic of interdisciplinary, multi-system integration, engineering application, and commercial operation. This paper summarizes the types, principle, and classification of WEC system, mainly focusing on the aspects of the kinds and characteristics of linear generators used in D-DWEC system, power post-processing, and power control methods. At the end of the paper, giving the development trend and challenges of D-DWEC technology, the research of ocean complementary energy generation platform with offshore wind, solar and ocean wave energy is analysed. It shows that the platform has advantages owing to stable power output, efficient utilization, ocean saving-space, and power generation cost reduction.

1 | INTRODUCTION

Overusing fossil energy for industrial development has led to the deterioration of the human living environment. At the same time, the continuous consumption of fossil energy has become a vital issue restricting the growth of the global economy and society [1–3]. To solve the problems above, the effective action and utilization of renewable energy have become an essential issue of energy development. Ocean wave energy is a kind of clean and renewable energy, and the ocean covers about 70.8% of the earth's surface area [4, 5]. It has become more attractive because of low carbon emissions and the depletion of non-renewable energy resources such as oil, gas and coal. Meanwhile, compared with other renewable energy, such as wind energy and solar energy, the energy density of sea wave is much higher, the density of wave energy power is 2–3 kW m^{-2}, wind energy is 0.4–0.6 kW m^{-2}, and solar energy is 0.1–0.2 kW m^{-2} [6–8].

Based on the survey of the International Energy Agency, the potential wave energy of the earth's surface is about 3 billion kW, and the annual average power is about 40 MW km^{-1} based on the coastline length of the world, the data is shown in Figure 1 [9, 10]. According to the research of the World Energy Council, 2×10^{12} kW of wave energy would be obtained in one day, and 1.752×10^{15} kW of wave energy can be obtained within a year, among which 2×10^{14} kW of wave energy can be converted into electric power [11, 12]. Nowadays, the independent WEC system can provides power for the islands, the beacon lights and the marine observation equipment. So it reduces the cost of battery maintenance and maintenance. However, with the development of marine energy, the ocean space is decreasing day by day, the separate independent energy conversion units and power transmission systems in the ocean also increase the cost of electricity production and output. So, the energy complementary generation platforms consisting of wind energy, wave energy and solar energy have been proposed by many research institutes, such as MARINA by European Union [13], POSEIDON by Denmark [14] and Wave Treader by Scotland [15]. By sharing energy generation platforms and transmission systems, the platform can provide better power quality and higher energy density than independent WEC system or wind system. Due to the removal of the middle machine section, the D-DWEC

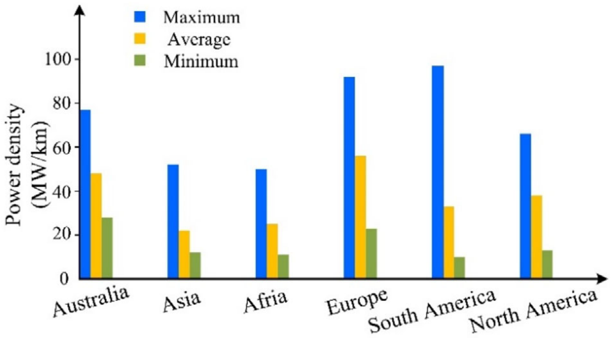

FIGURE 1 The average wave energy distribution in the word [9, 10]

system with linear generator can promote the conversion peak efficiency to more than 90% [7]. In addition, the D-DWEC device is easier to install because of its simple structure and principle. But it would also face many technical problems and challenges.

This paper summarizes the classification, operation principle and some typical engineering application of WEC systems, especially D-DWEC devices and linear generators for it. The current trend, technology challenges of D-D WEC system and linear generators for D-D WEC are introduced respectively. The purpose of all the cases and illustrations is to recognize the linear generators and D-D WEC systems with great promise.

2 | OVERVIEW OF WEC SYSTEM

2.1 | Principle of WEC system

Wave energy refers to the kinetic and potential energy of wave at the ocean surface, which is proportional to wave height, wave period, and wave-facing width. It is also affected by wave power density, external wind speed, wind direction, wave velocity and so on. Based on the law of energy conservation, the working process of WEC system can be divided into three stages, as shown in Figure 2. Wave energy is captured and stored in the first stage, and the wave energy captured is transformed into mechanical energy, then is converted into electric power in the second stage. Or the wave energy captured is directly converted into electric power in this stage (D-DWEC system). In the third stage, electric power is transmitted to the external grid, DC microgrid or power storage devices by power converter lastly.

From Figure 2, some WEC systems convert wave energy into mechanical energy by using air turbines, hydraulic turbines or hydraulic motors, then mechanical energy is converted into electric power by rotary generators. There will be a series of problems in the whole conversion system, for example, low conversion efficiency and high cost by the middle hydraulic or transmission mechanism [23, 25]. To solve the above problems, the mechanism in the second stage is discarded, the conversion efficiency of D-D WEC system is improved significantly, and the cost of the whole system is also decreased [16].

2.2 | Classification and typical devices of WEC

2.2.1 | Classification for WEC system

WEC devices can be classified by principle, such as oscillating water column (OWC), oscillating bodies and overtopping. WEC devices can also be classified into on shore, near shore and offshore by installation site. Based on the fixation methods, WEC devices are classified into fixing and floating. By the energy transmission, WEC devices are classified into pneumatics, hydraulics and mechanical drive. The classification above is shown in Figure 3.

2.2.2 | Non-direct WEC system

Energy conversion process of non-direct WEC (N-DWEC) system includes the first stage and the second stage, as shown in Figure 2. The typical N-DWEC system includes OWC, overtopping and a part of oscillating bodies as follows.

OWC WEC system: In OWC system, the water column compresses the air in the air chamber, then drives the air turbine to generate electricity. Typical OWC system includes Land Installed Marine Power Energy Transformer (LIMPET), LeanCon, Sakata, Pico, Mutriku, U-OWC and so on. In LIMPET, the max-power can reach 500 kW, as shown in Figure 4a [17]. Besides, LeanCon is a floating WEC system near shore as shown in Figure 4b [18]. For 8 turbines and power sets in LeanCon, the max-power can reach 4.6 MW. OWC devices are usually built on cliffs or breakwater dams along the coast, so they have high reliability and strong resistance to the storm. However, there are air chambers and turbines in OWC devices, the large volume of OWC system is the major defect.

Oscillating bodies WEC system: The relative motion of the bodies including heaving, pitching and rolling converts wave energy into electric power by hydraulic motor and rotary generator in oscillating bodies WEC system, such as power buoy in UAS with a capacity of 40 kW [20], shown in Figure 4d. Oscillating bodies WEC systems are usually installed on large power ships or platforms in the deep sea, or floating in the ocean areas with the depth more than 40 m. In these areas, wave energy density is high, so the device has usually a large installed capacity. For instance, the max-power of the AWS offshore in Portugal is 2 MW [23].

Overtopping WEC system: As shown in Figure 4e,f, Wave Dragon and Sea Slot-cone Generator (SSG) are categorized into overtopping WEC system. The Wave Dragon device in Denmark is floating offshore, and the max-power is 7 MW [21], while SSG device is fixed on the dams, and the max-power is 50 kW [22]. They all take advantage of the difference in water levels between inside and outside to drive water turbine to generate electricity. This type of device has simple structure and

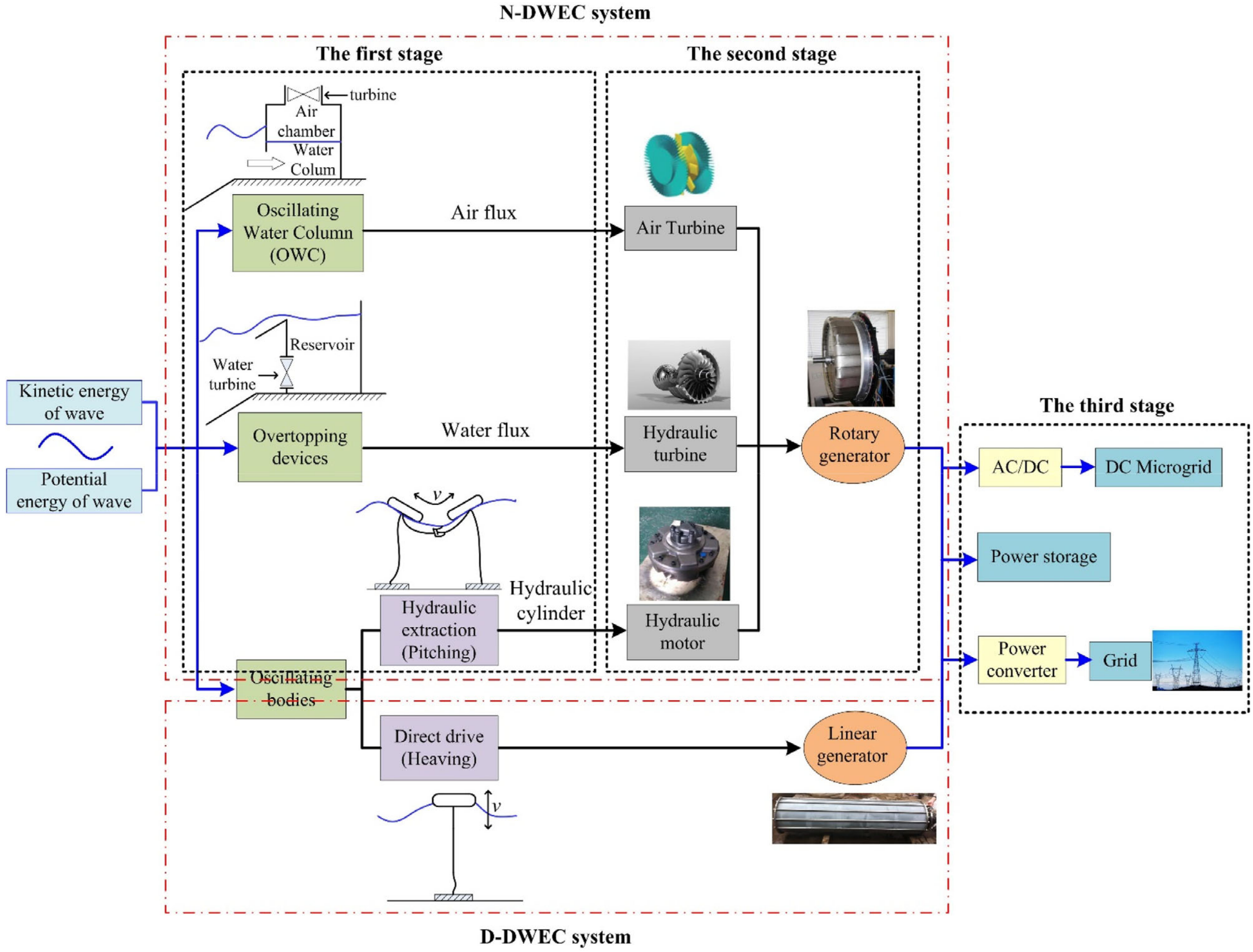

FIGURE 2 Energy transmission of WEC system

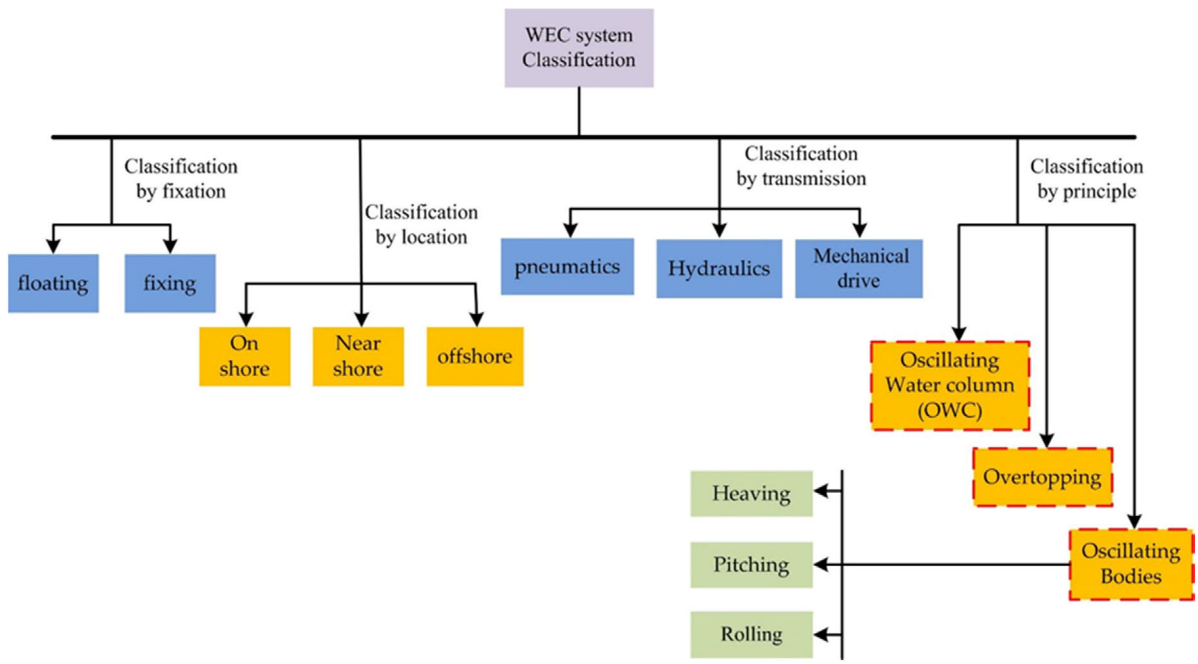

FIGURE 3 Classification of WEC system

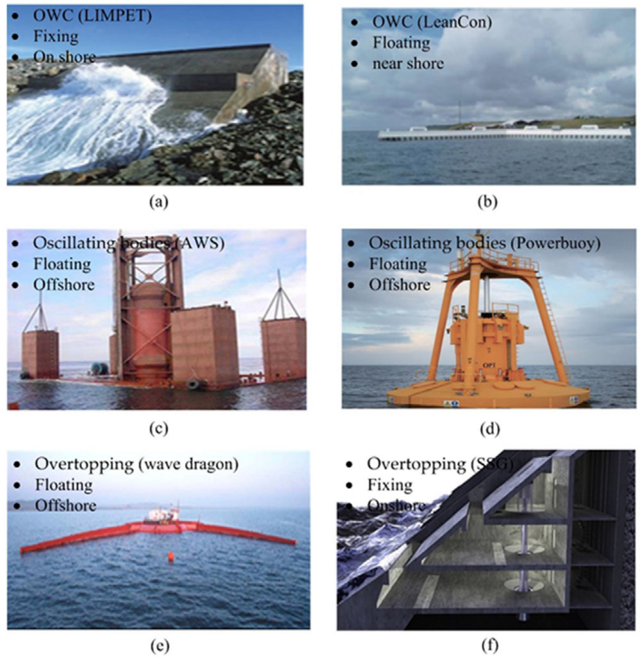

FIGURE 4 Typical WEC devices: (a) LIMPET in Scotland [17], (b) LeanCon in Denmark [18], (c) AWS in Portugal [19], (d) Power buoy in USA [20], (e) Wave Dragon in Denmark [21], (f) SSG in Norway [22]

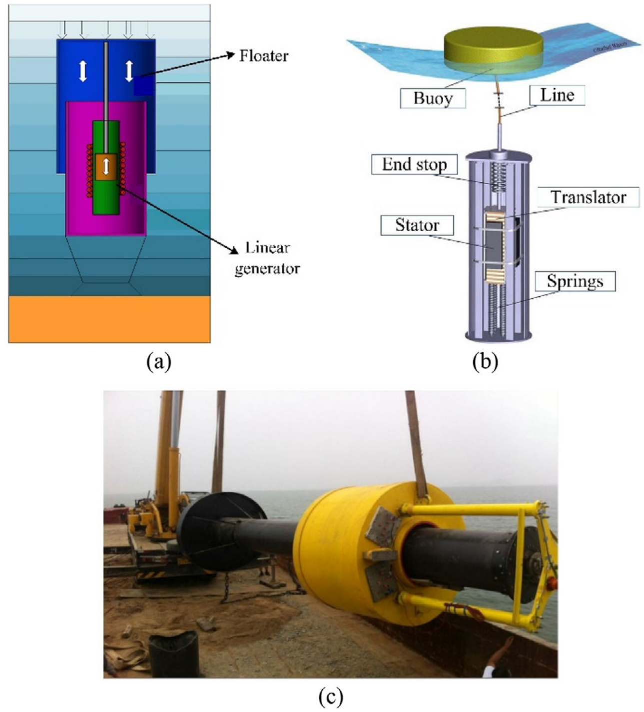

FIGURE 5 D-DWEC device (a) AWS [23], (b) Floating D-DWEC device with single floater [25], (c) D-DWEC device with dual floaters [67]

strong resistance to wind and waves, but the wave energy utilization rate is lower than the other WEC devices in deep sea area.

2.2.3 | Direct-drive WEC system

Due to the mechanical interface deleted in D-DWEC system, wave energy is converted into electric power directly. The structure of D-DWEC system mainly includes floater, linear generator, anchor or supporting platform structure, waterproof shell etc. The floater immersed in the sea obtains kinetic energy of the wave and drives the linear generator to generate electric energy. According to the different structure of D-DWEC systems, it can be divided into three types, submerge D-DWEC, point absorber D-DWEC and double floaters heaving D-DWEC.

Submerge D-DWEC: Typical submerge D-DWEC is Archimedes wave swing (AWS) in Portugal as shown in Figure 4c [19]. The maximum power can reach 2 MW, and the principle of AWS is shown in Figure 5a [23]. With the undulating movement of the floater underwater, the translator of the linear generator is driven to produce electricity.

Point Absorber D-DWEC: Point absorber D-DWEC devices with linear generators are mostly floating or point-suction power generation mechanisms [24]. The principle of it is shown in Figure 5b [25]. The floater is directly connected with the translator of the linear generator on the sea by the line, the reciprocating movement of the floater drives the translator of the linear generator, and then, the induced electromotive force (EMF) is generated in the stator windings. On the premise of solving reliability, the manufacturing cost of point absorber D-DWEC devices is low. The volume of the device is small compared to the wave, it is particularly suitable for regions with low wave energy density.

Double floaters heaving D-DWEC: In order to overcome the problems of the traditional single floater D-DWEC device, such as mooring, maintenance, corrosion and low power, Southeast University in China proposed a floating double floaters D-DWEC device with linear superconducting generator, as shown in Figure 5c [66]. The device uses the relative motion of the outboard floater and the inboard floater to drive the generator to produce electrical power, and the peak power output can reach 2 kW.

2.3 | Summary and analysis of the WEC system

According to different classifications and characteristics of WEC systems mentioned above, Table 1 summarises various WEC systems and their parameters with project cases. Literature [6] calculates the statistics and evaluations for the existing WEC system, the peak efficiency of OWC is about 29%, that of overtopping is about 29%. The efficiency of oscillating bodies (pitching) is less than 20%, and rolling is less than 40%. In [7], the efficiency of AWS with linear generator is more than 90% by sea testing with full scale. Literature [8] evaluates different WEC from the aspects of energy capture, technology cost, economy, reliability and environmental adaptability. The data shows that compared with other WEC types, oscillating bodies

TABLE 1 Typical projects of WEC

Name	Classificationby principle	Classificationby fixation	Country	Max-power	Classificationby location	Reference
AWS	Oscillating bodies (D-DWEC)	Floating	Portugal	2 MW	Offshore	[23]
Oregon L10	Oscillating bodies (D-DWEC)	Floating	USA	10 kW	Near shore	[27]
Ne Zha	Oscillating bodies(D-DWEC)	Floating	China	20 kW	Offshore	[28]
Power buoy (M3)	Oscillating bodies	Floating	USA	866 kW	Offshore	[26]
Pelamis	Oscillating bodies	Floating	Scotland	750 kW	Offshore	[29]
Wave bob	Oscillating bodies	Floating	Ireland	500 kW	Offshore	[30]
IPS	Oscillating bodies	Floating	Scotland	200 kW	Offshore	[31]
Wave star	Oscillating bodies (point-array)	Floating	Denmark	600 kW	Offshore	[32]
LIMPET	OWC	Fixing	Scotland	500 kW	Onshore	[17]
Pico	OWC	Fixing	Portugal	400 kW	Onshore	[33]
Sakata	OWC	Fixing	Japan	50 kW	Onshore	[34]
U-OWC	OWC	Fixing	Italy	2 kW	Onshore	[35]
Mutriku	OWC	Fixing	Spain	300 kW	Onshore	[36]
LeanCon	OWC	Floating	Denmark	4.6MW	Near shore	[18]
Wave dragon	Overtopping	Floating	Denmark	7 MW	Offshore	[21]
TAPCHAN	Overtopping	Fixing	Norway	350 kW	Onshore	[37]
SSG	Overtopping	Fixing	Norway	50 kW	Onshore	[22]

have the best comprehensive performance and wide application, especially when linear generators are used in oscillating bodies (heaving) for their high efficiency. The second types are OWC, overtopping and other types for their comprehensive performance. In addition, WEC with multi degree of freedom has a good foreground in the application [8, 9].

3 | LINEAR GENERATORS FOR D-DWEC SYSTEM

Compared with induction generators and synchronous generators, linear permanent magnet generators (LPMG) are suitable for the requirements of D-DWEC systems with different structure [38, 39]. In order to solve the problems of the traditional linear generators, such as large volume, large materials, high electromagnetic force, high cost and limited efficiency, this section summarizes and classifies different structures of linear generators, so as to find the topology and performance optimization methods that have advantages for D-DWEC system. The classification of linear generators applied in D-DWEC system by principle, configuration and excitation modes is illustrated in Figure 6.

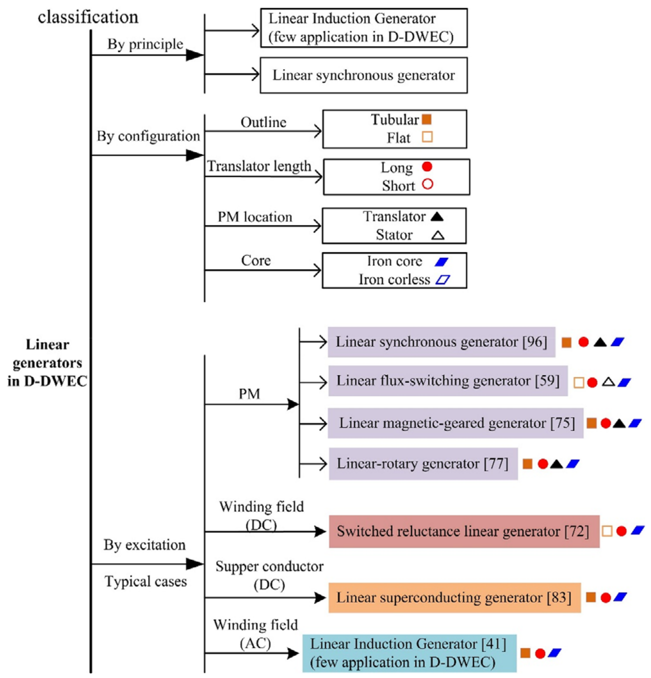

FIGURE 6 Classification of the linear generator in D-DWEC system

3.1 | Classification of linear generators

3.1.1 | Classification by principle

There are great differences between linear induction generator and linear synchronous generator in structure, principle and application field. For simple structure, the cost of linear induction generator is less than the other machines. As a linear induction motor, it is preferred as Maglev train's power traction. Meanwhile, as a linear induction generator, it has few engineering applications. In [40], Phillips Reed has sought a patent of linear faraday induction generator for electrical power generation from ocean wave kinetic energy and arrangements thereof. In [41], a linear induction generator is proposed only for teaching laboratory. The structure of linear synchronous generator is transformed from the rotary motor, and its principle is same as the synchronous rotary motor. The magnetic field is usually excited by AC or DC current, PMs and DC supper conductor. By adjusting the excitation, the output voltage of the generator can be easily controlled. PM synchronous generator is widely used in the field of power generation, especially in wind power and thermal power [42, 43].

3.1.2 | Classification by configuration

Classification by outline structure—tubular versus flat: The structure of linear generator in D-D WECs may be tubular or flat. The flat structure has the advantage of simple manufacturing process and low manufacturing cost. However, the flat linear generator has to overcome the end effect for its asymmetry magnetic field structure. At present, the method to decrease the end effect is to increase the number of sides, such as the structure of double sides or multilateral sides [44, 45]. As the number of sides increases, so does the manufacturing process and cost of the generator [46, 47]. The end effect can be eliminated in the tubular construction, which can effectively improve the output efficiency to 85.5% [48–52]. However, the manufacturing process especially for PM rings is more complex, and the cost of the whole generator is increased for PM rings structure. The detent force of the tubular linear generator in [51] is reduced to 40 N. But, the flat linear generators are more suitable for high power generation than the tubular type, the average power of that in [44] can reach 1 MW.

Classification by translator—long versus short: In order to obtain more wave energy, the translator and stator of the linear generator is long as possible. In the process of full stroke motion, induced current is generated in stator windings. Compared with short translator, long translator is more widely used in D-DWEC system [53]. Nevertheless, short PM translator is made to reduce the weight and cost of the translator in some case. In [54], a flux switching linear generator is proposed, in which the stator structure embedded with steel core is used to reduce the mass of the translator and improve the magnetic circuit distribution. In addition, the translator of linear generator may be internal translator or external translator [55, 56]. In [55], the researches show that the power density of the external translator is 7–8 times that of the internal translator in the case of same volume. Most generators have single translator but in [57], a linear generator with double translators is proposed to obtain high magnetic field energy, and it shows that the flux density is 1.67 times higher than that of single translator when the structure of the stators are same.

Classification by PM location—translator PM versus stator PM: There are two types of generators according to the installation position of PM, one is translator PM and the other is stator PM. The armature windings of the former is placed in the stator, it has the advantages of being waterproof and anticorrosive.

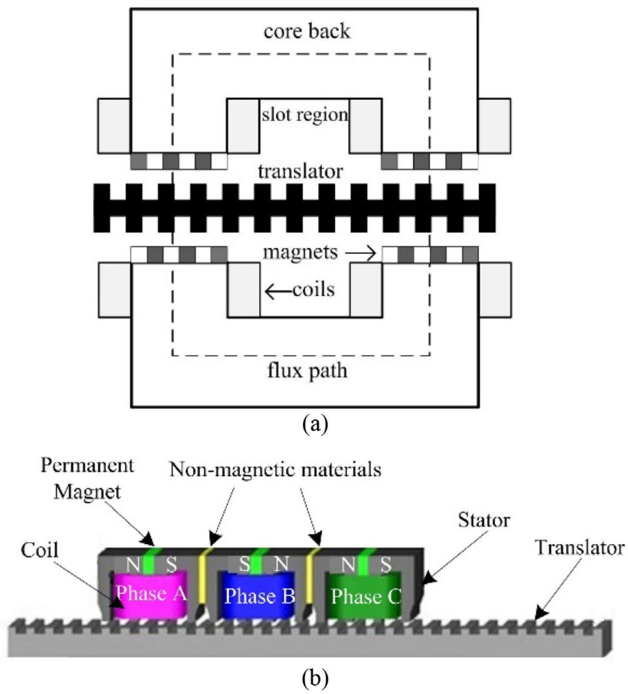

FIGURE 7 Linear generators with stator PM (a) Single phase LVHM, (b) three phase LFSPM generator

However, it also has the disadvantage for the complexity and high cost of translator, especially for the long translator [55, 57]. In order to solve the problems above, both the armature windings and PMs need to be placed in the stator. In [58], a single phase linear vernier hybrid machine (LVHM) has been proposed as shown in Figure 7a, PMs are placed on the teeth of the stator. With movement of the translator, LVHM offers the peak shear stress of 140 kN m^{-2}. In [46], the stator of a three phase linear flux switched PM (LFSPM) generator has been separated by non-magnetic materials, and PMs are placed in the core yoke of the stator, so the closed magnetic path is built through the teeth of the translator, as shown in Figure 7b. The cogging force of LFSPM is reduced to 10 N. In [54], an improved LFSPM generator with two stators has been proposed, the maximum value of magnetic flux density is raised to 1.6 T.

Classification by core—Iron core versus iron coreless: As we have shown, the generator with iron core has high flux density per unit volume due to low magnetic resistance of the core material. However, it has some problems such as low power factor, large electromagnetic resistance and high cost of core materials. The problems mentioned above can be solved by the generator with iron coreless. In [59], a novel tubular linear generator is proposed with iron coreless, which removes the end effect and the cogging force of iron core, as shown in Figure 8. The main materials of the generator are non-magnetic material and a tiny amount of steel, the power of the porotype is 1 kW and the winding resistance is 2.1 Ω. In [60–62]. Several different cooling methods have been studied to solve the windings thermal dissipation of iron coreless, and the research shows that the winding is fully flooded and is more suitable for WEC applications.

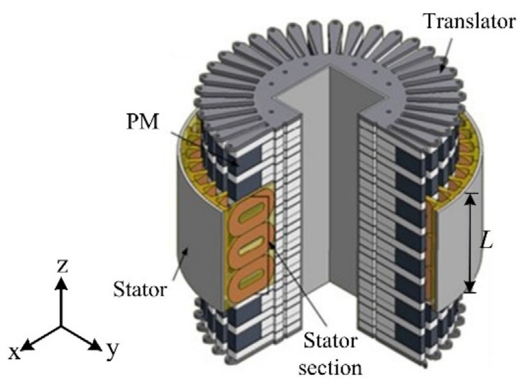

FIGURE 8 Tubular linear generator with iron coreless [53]

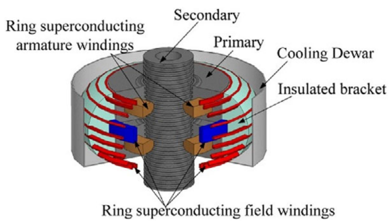

FIGURE 9 The structure of TSFSLG) [66]

3.1.3 | Classification by excitation

There are four excitation types in the design of linear generators for D-DWEC system, PM, winding field with direct current (DC), winding field with alternating current (AC) and superconductor with direct current (DC). Compared to the other three excitation, PM excitation produces higher power density and eliminates commutator brush and slip ring. In [57, 63], the analysis for a tubular PM linear generator has shown that Halbach PM array can effectively improve the magnetic field distribution, enhance the flux density to 1.4 T, reduce the total harmonic distortion (THD) of the output power to 6.7%. However, cogging force in PM linear generator decreases its conversion efficiency. At present, the methods to reduce cogging force are skewing PM, PM pole shifting or optimizing the number of slots and pole, and so on [64, 65]. Apart from PMs excitation mode, a tubular superconducting flux-switching linear generator (TSFSLG) is proposed in [66], the primary of that uses DC superconductor of MgB2, as shown in Figure 9. Comparing with LVHM and LFSPM, the cogging force amplitude of TSFSLG is reduced to 5 N, while that of PMFSLG is 25 N and LVHM is 160 N.

3.2 | Typical linear generators for D-DWEC system

3.2.1 | Linear switched reluctance generator

The salient pole structure is usually used in the stator and the mover of linear switch reluctance generator (LSRG), the amount of PMs is largely reduced, so the cost of PM materials decreases

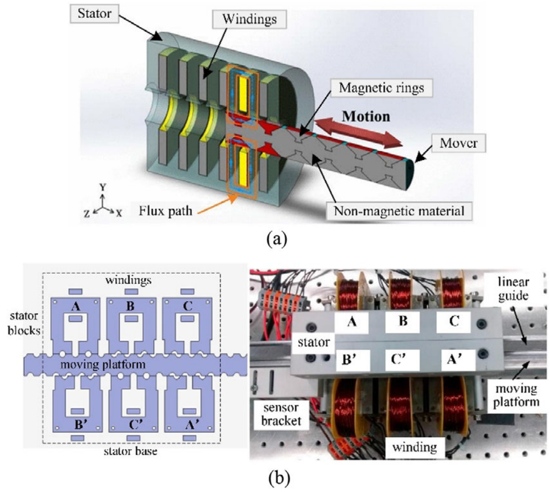

FIGURE 10 LSRG for D-DWEC (a) tubular LSRG [70], (b) flat-panel LSRG [71]

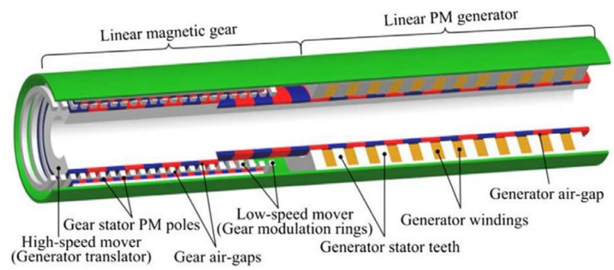

FIGURE 11 The machine consisting of TLMG and linear PM generator [73]

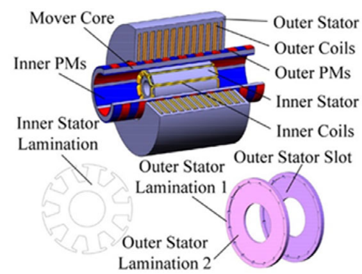

FIGURE 12 Linear-rotary generator [76]

significantly [67–69]. Ref. [70] proposed a tubular LSRG as shown in Figure 10a, the generator is tubular, pie windings are placed in circular slots, and the peak phase current is 5 A, the average load force is 100 N. For without any electrical isolation, it enhances the capability of flux carrying and fault tolerance. Due to non-ferromagnetic material applied in the translator, the material cost is reduced. In [71], a flat-panel LSRG with DC bus voltage of 40 V is proposed, as shown in Figure 10b. Three concentrated windings are placed in the stator, and the salient pole structure without PMs is used in the translator. In addition, ref. [71] also conducted experimental research on the LSRG in AWS D-DWEC system. It shows that the generator used no winding structure, and it obtained high thrust density and robust mechanical structures.

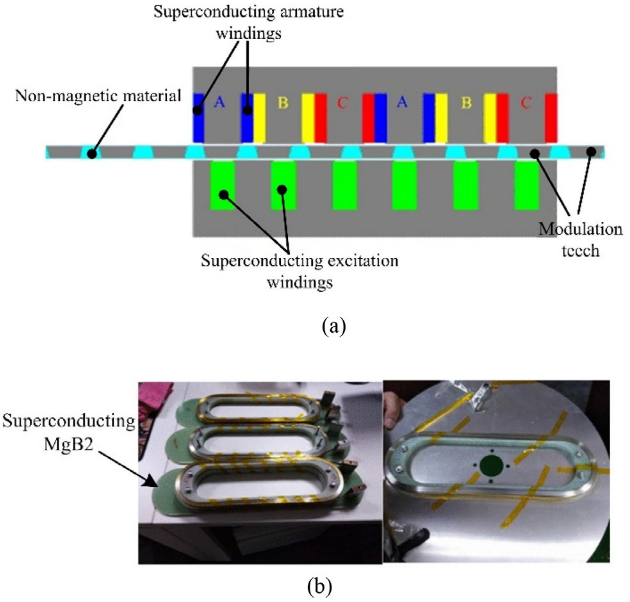

FIGURE 13 LFSPM with superconductivity coils [82] (a) structure of the generator (b) superconducting windings in the generator

3.2.2 | Linear magnetic gear

The construction of magnetic gear transmission mainly includes the coaxial magnetic gear and the tubular linear magnetic gear (TLMG) [72]. The research shows that the structure of magnetic gear can effectively improve the power density of the machine, and it is suitable for high-speed wind power plant. The TLMG is applied in tidal current power generation and WEC, it improves the power density of D-DWEC system at low speed. In [73], a machine consisting of a TLMG and an LPMG is proposed in D-DWEC system, as shown in Figure 11. The high-speed mover of TLMG and the translator of LPMG are connected into an overall structure. After the low-speed mover is driven by the wave, the magnetic field is modulated, and then the high-speed mover of the machine drives the LPMG to product electrical power. Then, the peak value of EMF is 110 V when the speed of low-speed mover is 0.4 m s^{-1}. However, the axial length of the machine and the amount of PM materials are both large, and the processing technology is also complex. In addition, in order to adapt the ocean environment of D-DWEC system, refs. [74, 75] have studied two types of linear generators with integrated magnetic gear respectively, and the purpose is to have simple structure, simple processing, high reliability and low cost.

3.2.3 | Linear-rotary generator

The D-DWEC system using linear-rotary generator can convert the oscillating kinetic energy and the tidal energy of the wave into electrical energy directly. It obtains energy collection of linear free degree and rotational free degree, so the output power is improved. As shown in Figure 12 [76], a linear and rotary permanent magnet generator (LRPMG) with dual-stator is proposed in joint wind and wave energy conversion system. PMs are placed on the rotor (translator) in the linear-rotary generator, the stator windings include the rotating windings and linear windings. Through the linear motion and rotary motion driven by the floater, the EMF in the two windings are obtained. The output power is promoted to 2 kW when the rotational speed is 1000 r min^{-1} and linear speed is 1 m s^{-1}. The electric power can also be obtained by spiral motion of the floater in an improved floating generation platform combined wave and offshore wind energy [77, 78]. Ref. [79] proposes a tubular PM linear-rotary generator with two stators, one stator has 8 poles and 6 slots and the other stator has 7 poles and 6 slots, PM structure was placed on the translator and induced EMF was obtained in the two stator windings respectively through the linear motion or rotary motion of the translator. However, the configuration of rotary linear machine needs to match with the entire power system structure. The operating characteristics, operating condition, operating mechanism and the output power quality need further research [80].

3.2.4 | Linear superconducting generator

Use of high temperature superconducting materials (HTS) makes the generators smaller and lighter for large current carrying capacity [81]. The metal superconductor MgB_2 is preferred for engineering applications due to its low cost and low conversion temperature. In [82], a cylindrical LFSPM generator with superconductivity coils MgB_2 was proposed in double floaters D-DWEC system and a fully flat superconducting linear generator prototype for testing is proposed as shown in Figure 13. The superconductivity armature windings and the superconductivity excitation windings are also placed in stator to reduce the cooling problems of the superconducting coils. The no-load peak value of induced EMF is 245 V, and the total loss of each superconductor winding is reduced to 3.265 W. In [83], a high temperature superconductor (HTC) material of Yttrium Barium Copper Oxide (YBCO) is used in superconducting switched reluctance machine (SSRM) for D-DWEC system. Instead of PMs, high efficiency of 96% and low core loss of 0.5 W kg^{-1} are obtained in it. Different from the superconducting generators mentioned above, superconducting coils are placed in the stator and the translator of a linear generator in order to obtain strong magnetic field of 2.7 T in [84]. Meanwhile, the whole generator is placed in the thermostat to solve cooling problems. In addition, the two silicon steel materials Armco DI-MAX27 and DI-Max HF10 are applied to reduce the heat dissipation of core due to using of superconducting coils in [85]. More on HTC synchronous reluctance linear generator topologies for D-DWEC system have been described in [86].

3.3 | Comparison of linear generators in D-DWEC system

The merits and drawbacks of linear generators with various types are illustrated in Table 2. From Table 2 it can be seen that the different structure and excitation methods applied have

TABLE 2 Merits and drawbacks of various linear generators

Type	Merits	Drawbacks
Tubular	• No end effect • Less copper losses, the leakage inductance, and the radial forces	• Fabrication cost especially for LPMG
Flat	• Simple manufacturing process • Low manufacturing cost	• Low stability of support structure • End effect
Long translator	• High utilization rate of winding • Less conduction losses	•Heavy translator structure • High cost especially for translator PM
Short translator	•Low cost especially for translator PM	• Low utilization rate of winding • Complicated control system for stator windings
Translator PM	• Conducive to waterproof and anticorrosive	• High complexity of translator structure •Heavy translator structure • High cost of translator
Stator PM	• Less mass of translator • High utilization rate of PMs	•Low cost of translator • Complex structure of stator
Iron core	• High flux density per unit volume • Low magnetic resistance	• Low power factor • Large electromagnetic resistance • High cost of core materials
Iron coreless	• No end effect • No cogging force • No cost of core materials	• Additional cooling for windings thermal dissipation • Less magnetic flux varies and induced voltage amplitude
PM excitation	• Higher power density • No commutator brush and slip ring • Low THD of the output power	• High amplitude of cogging force • High cost of PMs
Winding field (DC) excitation	• Low of material cost • Simple and robust mechanical structures	• Low efficiency
Supper conductor (DC) excitation	• Low ohmic loss • Small size and low mass Per power capacity (ignore cooling system)	• Complex cooling system • Low operation stability
Winding field (AC) excitation	• No merits	• Low power generation efficiency • External exciting windings

advantages, but also have disadvantages under some special circumstances.

In this review, performance characteristics of the main linear generators applied in D-DWEC are evaluated based on the contrastive analysis in literatures. As seen in Table 3, the synchronous LPMG of ID 4 has the largest power, but it has been replaced by AWS N-DWEC system for its high maintenance. On the premise that cryocooler and cooling system can be simplified, TSFSLG of ID 9 is a more promising type because of its high efficiency. Though the generating efficiency of LSRG of ID 1 is lower than the other LPMG, the cost of manufacture and material is reasonable. So LSRG is more suitable for the deployment of D-DWEC in large numbers. TLMG of ID 7 is more suitable for the sea condition, such as low wave velocity or instable wave velocity. Linear-rotary generator of ID 8 is a novel structure combining linear generator and rotary generator in recent years. In laboratory studies, linear-rotary generator with Halbach PM array has excellent performance parameters for two free degrees. It will be a promising types in WEC system, if the processing technology problem can be solved.

4 | ELECTRICAL POWER PROCESSING CONTROL FOR D-DWEC SYSTEM

Compared with wind power and photovoltaic power, WEC system has the disadvantages of instantaneous power fluctuation for the randomness of wave. Especially in D-DWEC system, the wave energy has been not stored before conversion, the electrical power output is low-frequency alternating current with frequency and peak value fluctuation. To solve the problem, several solutions have been proposed now, such as grid-connection of wave energy farm, bus-bar capacitance adjustment, and external energy storage devices.

4.1 | Grid-connection of wave energy farm

Due to the floater diameter of the D-DWEC system is usually smaller than the wavelength of input wave, the capture width of wave energy is limited through a separate D-DWEC device. To improve the energy capture efficiency, several

TABLE 3 Linear generators developed for D-DWEC

ID	Type	Structure	Excitation	Core type	PM location	Max-Power	Reference
1	Switched reluctance	Flat (two sides)	Winding field (DC)	Iron core	/	/	[71]
2	Switched reluctance	Tubular	Winding field (DC)	Iron core	/	/	[70]
3	Flux-switching	Flat (one side)	PMs	Iron core	Stator	75 W	[46]
4	Synchronous	Flat (two sides)	PMs	Iron core	Translator	1 MW	[44]
5	Synchronous (single-phase)	Tubular	PMs	Iron core	Translator	45 W	[63]
6	Magnetic-gear	Tubular	PMs	Iron core	Translator	250 W	[74]
7	Magnetic-gear	Tubular	PMs	Iron core	Translator and stator	/	[73]
8	Linear-rotary	Tubular	PMs	Iron core	Translator	2 kW	[76]
9	Supper conductor	Tubular	Supper conductor (DC)	Iron core	/	3.5 kW	[82]
10	Supper conductor	Flat (two sides)	Supper conductor (DC)	Iron core	/	125 W	[83]
11	Synchronous	Tubular	PMs	Iron coreless	Translator	1 kW	[59]
12	Synchronous	Flat (two sides)	PMs	Iron coreless	Translator	50 kW	[87]

separate D-DWEC devices form a point-array wave energy farm, and Swedish Renewable Energy Centre has proposed such a wave energy farm. By detecting the wave condition and optimizing the point-array distribution in the wave energy farm, the power fluctuation among the separate devices is decreased and the power output of the wave energy farm is smoothened. The wave energy farm with the rated power of 160 kW has been built near the coast, and the performance tests have been completed [88]. Ref. [89] has analysed the site selection of the point-array wave energy farm. To achieve the optimal arrangement of the independent WEC devices, the influence of wave conditions on the site selection is studied. Ref. [90] conducts experiments on the offshore substation of the point-array wave energy farm, and studied the grid-connection characteristics and influencing factors of total system efficiency. It shows that the reasonable plan of wave energy farm improves the energy conversion efficiency and decreases the fluctuation of output power. However, this method is still in research stage, and now it has not yet formed a commercial point-array wave energy farm.

4.2 | Electrical energy processing

In addition to the optimization configuration of the wave farm, the method to reduce power fluctuation in engineering is using electrical energy processing devices before the grid. Electrical energy processing devices mainly include energy storage, voltage conversion device, rectifier and inverter. At present, the energy storage devices include superconducting energy storage, capacitor energy storage and battery energy storage.

Superconducting energy storage: Superconducting energy storage is to store the power in the magnetic field around the superconducting coil generated by direct current (DC). Now the

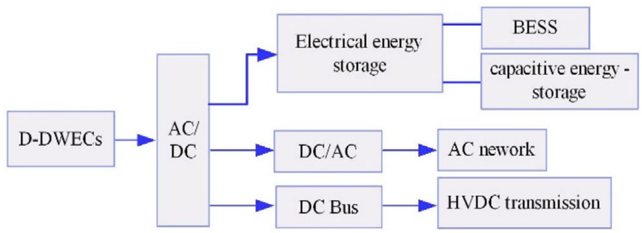

FIGURE 14 Power processing method for D-DWEC system

application cost of superconducting energy storage is high, and meanwhile, it is difficult to be realized in offshore WEC system. It requires more space and mechanical support structure, so it is seldom applied in D-DWEC system [91].

High-power capacitor energy storage: High-power capacitor energy storage has been effectively applied in the field of photovoltaic power generation, which can be used as an effective supplement to battery energy storage, and it improves the life of the power processing device [92]. The capacitors have low energy density but high power density, which are suitable for short-term energy storage in D-DWEC system.

Battery energy storage system (BESS): BESS has been widely used in the field of electric vehicles. With the development of LiFePO4 (LFP) battery, BESS is also used in renewable energy generation system to smooth out the output power fluctuations. Due to the limited service life of the battery cell, it is often applied in the grid side and independent energy storage power stations [93].

The mixed application of the three methods mentioned above is applied in the D-DWEC system, as shown in Figure 14. The topological structure based on power electronics have been studied in [94], which can effectively smoothen the power and improve the quality of output power.

5 | CHALLENGES AND TRENDS OF D-DWEC SYSTEM

5.1 | Challenges of D-DWEC system

According to the analysis above, it is shown that D-D WEC system has been widely exploited at the technical application level, and it has formed commercial operations in some countries. However, there are some problems to solve in the future as follows.

Lower stability: The key issue is the technology required for the installation and maintenance of D-DWEC system in harsh Marine environments, especially for the D-DWEC devices offshore. Additionally, in order to obtain the maximum efficiency of wave energy capture, the installation location and extreme weather should be considered in the design of D-DWEC devices. In [57], when the wave parameters including wave width, wave depth, wave period and wave height are different, the data of the output power are studied by D-DWEC system experiment.

Higher costs: The output power quality and stability of D-DWEC system need to be further improved before connected to the grid. It is essential how to determine the maximum energy capture and smooth power output in the complex marine environment. At present, energy storage and frequency conversion modulation are mainly used to solve the problems of unstable output power and poor output power quality of D-DWEC system. So the cost of D-DWEC system is higher than solar power and wind power generation, it is an important obstacle to the commercialization process of the D-DWEC system. Compared with levelized cost of energy (LCOE), stability and survivability of WEC devices are more significant key performance indicators (KPI) [95, 96].

Power density of linear generators: Linear generators used in D-DWEC system usually operate at varied speed and high thrust, so the design needs to match the WEC device structure and operating environment. In addition, considering the high requirements for waterproofing, corrosion protection and sealing of the linear generators in D-DWEC system, the air gap of generators is larger than that of the ordinary generators, which leads to the reduction of the power density of the generators. Ref. [97] analyses the performances of linear generators for D-DWEC system under different air gaps, and it shows that under the same structure and operating parameters, the output power of the linear generators is reduced with the increasing air gap.

Environmental compatibility: With the further development and utilization of ocean resources and energy, ocean space is dwindling, the separate WEC devices and the independent offshore wind power system take up more ocean space. Meanwhile, the installation of separate energy generation units and submarine transmission and transformation systems in the ocean also increases the cost of electricity production and output. In addition, the development of WEC further should consider the distribution of power grid, ocean geographical environment, optimal distribution of wave energy farm, ocean biotic environment and other factors.

5.2 | Research trends of D-DWEC system

The complementary energy generation platform takes full advantage of the strong ocean energy complementarity in terms of resources and seasons to reduce the construction and maintenance costs for power stations and power transmission system. Due to complementary energy, it reduces instantaneous power fluctuation and energy storage capacity on the premise of the same load demand.

In America, the energy island has been firstly proposed to collect wind energy, wave energy and solar energy to generate electricity [98, 99]. However, practice engineering research shows that energy island is difficult to implement because of its high cost and long construction period. Marine renewable integrated application platform funded by European Union proposes many concept designs of ocean complementary energy generation. In Denmark, a floating power plan proposed a marine renewable integrated application platform (named Poseidon) combining wave energy generation and offshore wind power generation. The platform with high stability is equipped with wind generator and hydraulic turbine, and the platform prototype has been developed and in the testing stage now. Scottish green marine energy company proposed a complementary energy generation platform (named Wave Reader), and it has been already constructed now. The power generated by wave energy and wind energy share the seabed transmission structure, and the total installed capacity reached 500 kW. In addition to Poseidon and Wave Reader, typical energy complementary platform systems also include Wind Float, W2Power, STC, SFC etc. as shown in Figure 15 [100–13].

Figure 16 shows the power take-off (PTO) system of complementary energy generation platform. The electric power obtained by wind energy and wave energy is converted into direct current (DC) and transmitted to the DC bus grid, or be stored in energy storage devices by bidirectional converters. In addition, WEC system and large floating platform integration brings many benefits owing to space-sharing, cost-sharing, and multiple functions of the integrated system. Ref. [103] reviews semi-submersible power generation floating platforms with a variety of renewable energy generation and comparative analysis of the data.

6 | CONCLUSIONS

This paper reviews many scientific literatures and classifies WEC devices according to their installation location and operating principle. Based on analysing different types of WEC systems, the dynamic theory, the power processing methods and the output power fluctuation of the D-DWEC system

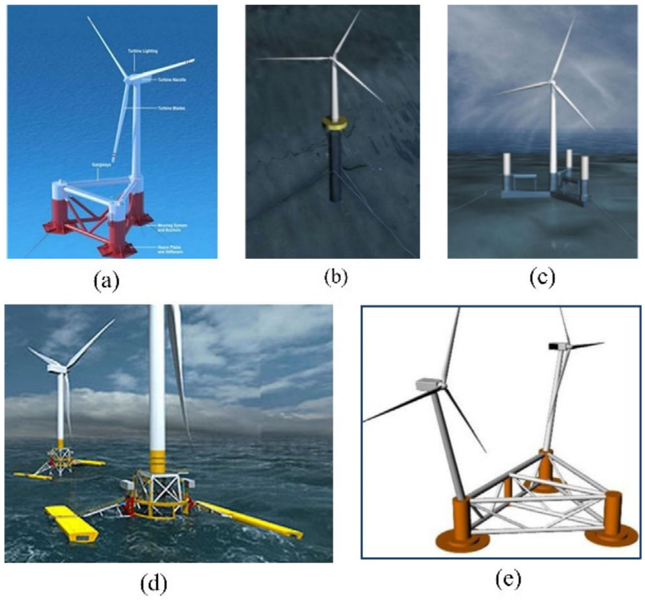

FIGURE 15 Offshore wind and wave energy combined power generation system platform. (a) Wind Float [14], (b) STC [101], (c) SFC [100], (d) Wave Reader [102], (e) W2Power [15]

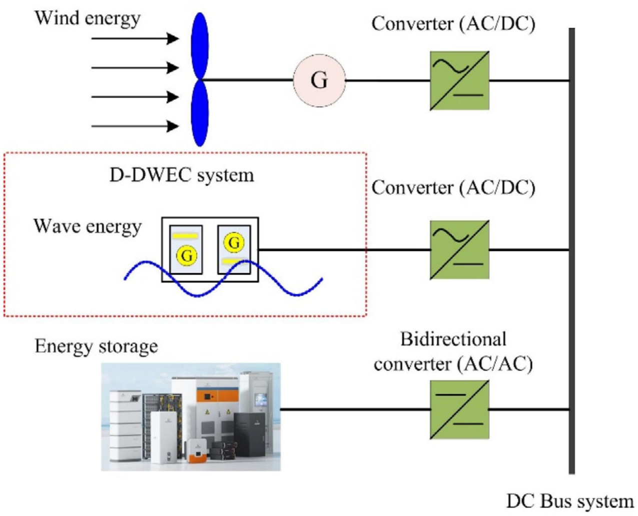

FIGURE 16 PTO system of complementary energy generation platform

are summarized. The main factors including the ocean climate condition, the structure performance of linear generator, and efficiency of wave energy capture, output power control, power transmission and grid connection of the D-DWEC system will directly affect the development of it.

Compared with traditional fossil energy generation, wave energy generation has excellent development potential. D-DWEC system using linear generator has the advantages of simple overall mechanical structure, small volume, flexible installation, and low manufacturing and maintenance costs. Meanwhile, it also faces the following challenges.

1. The output power of the linear generator depends heavily on the parameters of the input wave, and the rectification control is required before the power is transmitted and applied, hence it is the key issue to improve the stability of the output power of D-DWEC system. At present, WEC research focuses on the real-time control technology of the output power.
2. Since there is no intermediate energy transfer, the energy conversion efficiency of D-DWEC using the linear generator is higher than the N-DWEC system using turbine generator. However, the capacity of D-DWEC individual power generation is still smaller. It is one of the critical ways to improve the output power and the characteristics of the linear generators by adopting novel structures.
3. At present, the related research of the D-DWEC system is at the stage of numerical simulation analysis and laboratory test. Whether it is applied in marketization and engineering is still facing more practical problems, such as the regional cycle of marine climate, ocean geographical environment, optimal distribution of wave energy farm, ocean biotic environment and other factors.

The last part of the paper summarizes the development of marine renewable integrated application platform with offshore wind, solar and ocean wave energy. If the issues about the platform construction and power grid transmission in complex ocean condition are overcome, marine renewable integrated application platform will be an important application approach in the future.

AUTHOR CONTRIBUTIONS

J.Z.: Project administration; Writing – original draft; Writing – review & editing. M.C.: Data curation; Writing – review & editing

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors declare the data of this review is availability.

ORCID

Jing Zhang https://orcid.org/0000-0001-7879-1277
Minshuo Chen https://orcid.org/0000-0001-6344-845X

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