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A Survey of Power Take-off Systems of Ocean Wave Energy Converters

Zhenwei Liu[a], Ran Zhang[a], Han Xiao[a] and Xu Wang[a*]
[a*]School of Engineering, RMIT University, Australia
Telephone: 03 9925 6028
Fax: 03 9925 6108
Email: xu.wang@rmit.edu.au

Abstract

Ocean wave energy conversion as one of the renewable clean energy sources is attracting the research interests of many people. This review introduces different types of power take-off technology of wave energy converters. The main focus is the linear direct drive power take-off devices as they have the advantages for ocean wave energy conversion. The designs and optimizations of power take-off systems of ocean wave energy converters have been studied from reviewing the recently published literature. Also, the simple hydrodynamics of wave energy converters have been reviewed for design optimization of the wave energy converters at specific wave sites. The novel mechanical designs of the power take-off systems have been compared and investigated in order to increase the energy harvesting efficiency.

Keywords: power take-off, wave energy converters, direct-drive, indirect drive, linear generator, hydrodynamics, energy harvesting efficiency

1. Introduction

The energy production from ocean waves has been becoming one of the most promising technologies and attracting research interests of many people since the oil crisis in 1973. Nowadays, due to the energy crisis and environmental awareness, researches on the wave energy conversion technology have received more and more attention [1, 2]. A study back in

2010 theoretically estimated the potential of total ocean energy resource in the world to be about 29,500 TWh/yr, with the realistic potential energy demand of Australia, New Zealand and Pacific Islands being 5600 TWh/Yr [3]. Many researchers of different countries have conducted researches and developments in installation, planning, and operation of wave energy converters (WEC). Although the WEC operation in practice is still limited compared with the operation of other renewable energy conversion devices such as solar or wind devices, the research progress shows that more attention and awareness are paid in the exploitation of the ocean wave energy source. It is because the wave energy source has more advantages than other renewable energy sources. For example, the wave energy source has a higher energy density than other renewable energy sources [4] and has a limited environmental impact [3]. The wave energy has very little loss in the long distance travel and could be exploited in almost 90 percent of time each year, while there is only ~20–30 percent of time each year for utilising the wind and solar power devices [5, 6].

In this paper, different concepts of power take-off of the wave energy converters were reviewed. The conversion technologies also include the hydrodynamics of the WECs interacting with the ocean environment.

1.1 Wave energy resource assessment

In terms of ocean wave energy conversion, the power per unit wavefront length $(^{W}/_{m})$ is defined as [7, 8, 9]:

$$J = \frac{1}{64}\rho g^2 {H_s}^2 T_e \qquad (1)$$

where ρ is the density of water, g is the gravitational acceleration, H_s is the significant wave height and T_e is the wave energy period. The significant wave height H_s being defined as the mean wave height of the third highest waves is mathematically calculated as four times the standard deviation of the ocean surface wave elevation. The sea state is described as a sine wave with the energy period T_e. Mathematically, the energy period T_e is equal to the peak wave period of the spectrum multiplied by 0.86.

It is seen from Equation (1) that the propagating wave height and period of ocean waves determine the available wave power for conversion. The characterization of the wave varies depending on the locations of the wave energy sources. Take the WERATLAS program (European Wave Energy Atlas) as an example, the program is designed to analyse and calculate the available wave energy for conversion on the shores of European ocean. The power of ocean waves can be derived using the mean values of the significant wave height and period in specific regions around the world [10, 11]. Ocean wave characterization data are normally collected from weather stations, ocean buoys and the satellites [12]. According to Evans [9], Australia is suitable for wave energy conversion because of higher wave energy potential in the southern hemisphere and less seasonal variations of the wave energy potential on average during the annual period. Barstow et al [13] studied the wave energy resources in Australia, and Illesinghe et al [11] studied a single body point absorber which is specifically designed for the shores of Australian ocean. It is found that the energy potential in southern Australian shorelines have the largest amount with 8 s -12 s peak wave periods and 2 m - 4 m significant wave heights respectively.

1.2 Challenges:

There are many challenges to design an efficient and robust wave energy converter. The first challenge is to harvest the energy from the wave motion of low frequency, random and large displacement. The ocean waves change in both heights and periods, so it is hard to convert the kinetic energy of the waves into smooth electric energy. The second challenge is that the ocean wave energy converters are usually located in severe offshore environments. The corresponding mooring system and the consummate anti-corrosion design are critical. The third challenge is the optimized design of the wave energy converter because the efficiency of the

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WEC could be affected by its design. The WEC is a comprehensive system which involves multi-disciplines of hydrodynamics [9], fluid mechanics [14], mechanical design [108], power electronics [15] and control theories [16]. A power take-off system, for example, has various ways of converting wave energy into electricity. Therefore, only a few commercial products have been established for ocean wave energy conversion, as most WEC devices have low efficiency and life cycle [17]. Although there are some scaled down prototypes built, the existing full-sized prototypes are still very limited as benchmarks because of limitation of the financial cost and test locations in the ocean.

2. Wave energy converters

There are more than 1000 techniques for ocean wave energy conversion which have been patented in the world. They are categorised into three types according to their application locations which are: onshore devices, nearshore devices and offshore devices. The main advantages of the onshore wave energy converters are their easy maintenance, installation and not requiring any mooring systems to operate. However, waves contain less energy at the shallow water area and the places such as breakwater, dam or fixed cliff are usually needed to install the ocean wave converters [108]. Nearshore devices can be mounted on the sea bed but the structure must be robust enough to sustain the impact of waves. For example, the CETO from Australia Carnegie Wave Energy Ltd is a nearshore device. Some small and simple floating wave energy converters could be used nearshore [26]. The offshore devices are usually located in deep waters which are more than 40 meters deep as shown in Figure 1. The offshore devices consist of floating buoy and submerged bodies which are moored to the bottom of the sea. They have the potential to exploit the vast wave energy but are lack of reliability and survivability and the maintenance of the devices is expensive and complex. Moreover, the high cost and long seabed cables are required to transmit the converted electricity to the electric grid. [18]

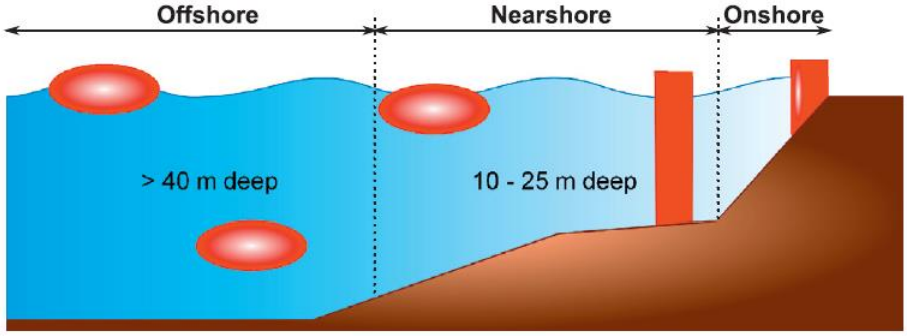

Figure 1. Classification of wave energy converters according to their location [19].

2.1 Operation modes of power take-off systems

Power take-off systems of ocean wave energy converters are categorised into the four types according to the working principles of the operation modes as:

1. Pressure differential type
2. Floating structures type
3. Overtopping type
4. Impact type

2.1.1 Pressure differential:

A converter of the Archimedes effect utilizes the oscillating peaks and troughs of the device pushed by waves to create pressure difference. The air inside is compressed and expanded when the peak and trough of the device pushed by waves are respectively reached as shown in Figure 2. Because of the water pressure, the device moves up and down. They are usually submerged point absorbers near shore located and fixed [20].

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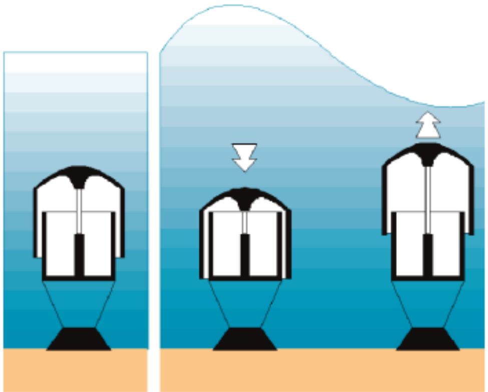

Figure 2. Operating principle of the Archimedes wave system (AWS) [20]

Oscillating water columns (OWCs) are also applied based on the same principle as AWS. The first device of this type is a navigation buoy equipped with an air turbine and was named as a (floating) oscillating water column (OWC) later. This type of converters was developed by Yoshio Masuda and commercialized in Japan since 1965 [21]. Masuda promoted this type of devices as a larger device named Kaimei with different types of air turbines in OWCs on a floating testing platform house [22]. Most of these devices are mounted on the ocean bottom near the shore, so they have the advantage of easy installation for the existing coastal structures. Some common examples are WaveGen Limpet [23], Energetech [24], Pico OWC [25], OceanLinx [26] and Yongsoo power plant [27]. There is also a floating type of OWC, such as Backward Bent Duct Buoy [28], Mighty Whale [29] and the Spar Buoy [30].

OWC uses a half-submerged chamber which is open at the bottom, the internal air volume which drives a uni-directional turbine was flowing with the reciprocating movement of the water therein. [31]. Some researches focused on the capture width ratio under different wave periods and heights while the nonlinear power take-off (PTO) damping conditions are also simulated. For example, Elhanafi and Kim [32] used an orifice to simulate the OWC system and found out that when the wave frequency is higher than the device resonant frequency, the capture width ratio of OWC device is decreased as the wave height increased. However, when the wave height is doubled, the OWC device could extract about 7.7 times of

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the maximum wave energy throughout the whole frequency range. The experiment result was verified by the simulation results of the 3D CFD model.

2.1.2 Buoy structures:

The devices of this type are installed in a floating body being moved along with the ocean waves. They are usually driven by wave heave, surge, pitch and roll motions or their combination. Moreover, the devices are driven either by an absolute motion of the floating buoy with respect to an external fixed reference or by the relative movement of the two or more floating bodies [33, 34]. Zhang, et al [35] studied a power conversion device with two interconnected floaters horizontally, the electricity is generated through the relative pitch motion of two floaters as a power take-off (PTO) system. The floating structures operate in different directions, for example, Gao et al [36] designed a converter consisting of two bodies in a vertical direction. Trapanese et al [37] designed a WEC system with internal horizontally mounted permanent magnet linear generator (PMLG) that utilizes the surge and pitch motion of sea-waves.

2.1.3 Overtopping devices:

Overtopping devices are those which have a structure to increase the potential energy, kinetic, or both the potential and kinetic energy of the ocean waves. Overtopping system consists of a water pool that is above the ocean surface level and forces the pool water to pass over the turbine structure to the sea. Wave Dragon is a popular application using overtopping devices, the structure of Wave Dragon can be seen in [38, 39]. Wave Dragon is a multi MW production plant which has a high power take-off output and is easy to maintain. However, Wave Dragon is complex and expensive because of its massive structure. Wave Dragon occupies a large area in the ocean that has an impact on the environment.

2.1.4 Impact devices:

Impact devices are placed in the perpendicular direction to the wave propagating direction with articulated or flexible structures. The deflector sways forth and back due to the

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impact of the waves. The working principle of the impact device can be seen in [40]. BioWave is an Australian technology which naturally sways swell waves forth and back beneath ocean surface through the surge motion [41].

2.2 Rotational mechanisms of power take-off systems

There are many ways to take the power out from the waves where three of them are main ways of the power take-off. The three main power take-off ways are pneumatically, hydraulically and mechanically. In order to illustrate the above definitions and classifications, the following examples of the power take-off systems are given below. The power take-off systems consist of the primary and secondary conversion stages which are illustrated below:

- Primary conversion:

Using pneumatic, hydraulic or mechanical systems to rectify the air or water flow. The aim is to convert the slow oscillatory motion of the low-frequency waves (~1.2 Hz) into a fast-oscillatory motion [19]. The working principle of the primary conversion can be seen in Figures 3 & 4 below.

- Secondary conversion:

This stage converts the energy from the working fluid that is generated in the previous step, into useful electric energy. The speed amplified working fluid that is generated in the first stage will drive the rotary generators.

2.2.1 Air-turbines:

Air turbines of self-rectifying function are recently used in OWC WECs. The air turbines are illustrated below, where Dennis-Auld turbines [44], the wells turbines and impulse turbines [42, 43] are relevant and shown in Figure 3 (a)-(c) respectively.

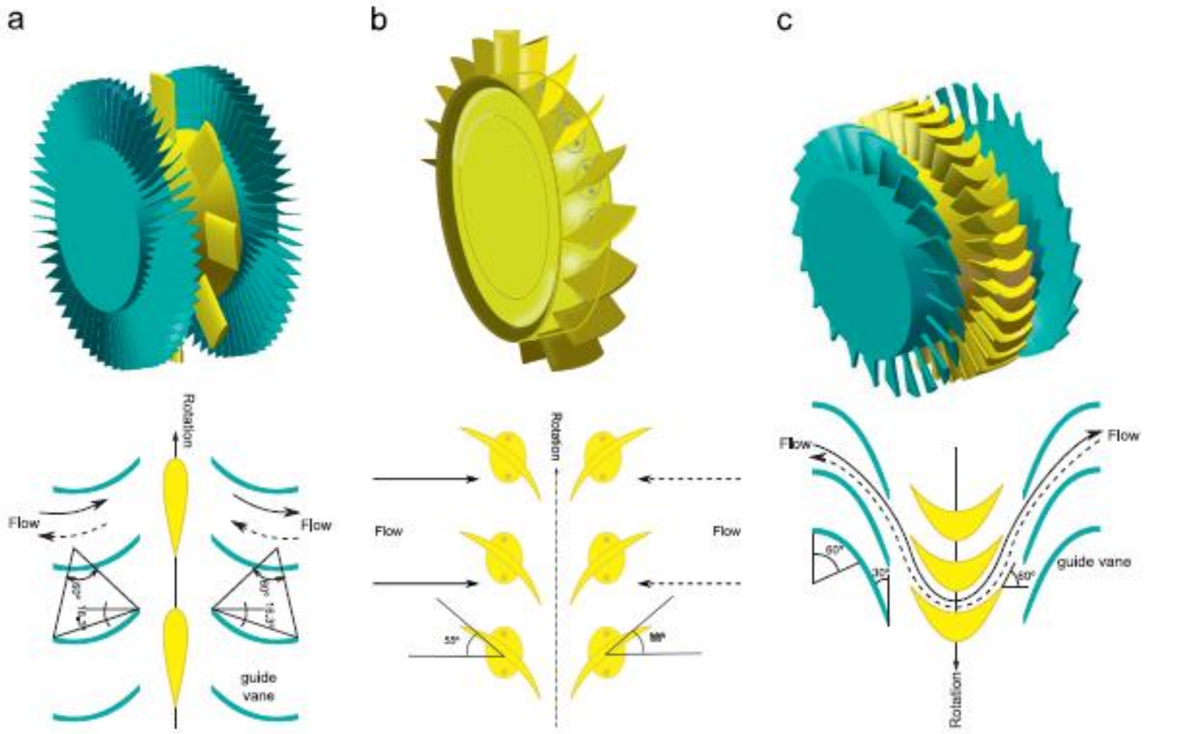

Figure 3. Air turbines for WECs. (a) Wells turbine, (b) Denniss-Auld turbine and (c) impulse turbine [19].

2.2.2 Hydraulic turbines:

This turbine will swirl when water flows through the guide vanes of the turbine. This is a well-established equipment and has been used widely in hydropower generation plants. Francis turbine, Kaplan turbine and Pelton turbine operate when water flows inwards into the runner radially and drives the blades being mounted around a wheel as shown in Figure 4 (a)-(c) respectively. [45]

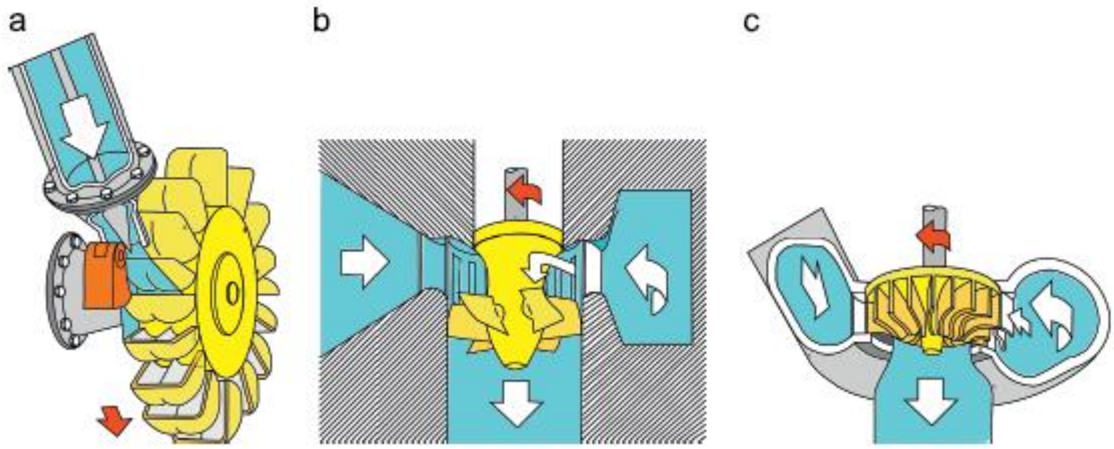

Figure 4. Hydro turbines for WECs. (a) Pelton turbine, (b) Kaplan turbine and (c) Francis turbine [19]

2.2.3 High oil pressure hydraulic cylinders

Another energy conversion method is to employ the pressure difference of the high oil pressure hydraulic cylinders which drive the hydraulic motor and generators. These hydraulic systems are generally applied for slow oscillating bodies which need the speed amplification of translation or rotation. PowerBuoy [48], Pelamis [47] and Aquabuoy [46] are examples of the hydraulic systems to illustrate the working principle of high oil pressure hydraulic cylinders where the liquid pressures are different in the three hydraulic systems. The difference of the high oil pressure hydraulic cylinders from air turbines and hydraulic turbines is that the power take-off of the high oil pressure hydraulic cylinders is hydraulic motor or pump while the power take-off of the air turbines and hydraulic turbines is the fluid and turbines although they all use the mature generator technology.

2.2.4 Electricity generator:

The electricity generator is rotating electrical equipment which is driven by a mechanical mechanism such as air or hydraulic turbines, or hydraulic motors. A lot of research works study converting the ocean wave vibration energy into electrical energy using electromagnetic [36, 37], electrostatic [49] and piezoelectric [50, 51] devices. The most popular type of devices is the electromagnetic one because of its design flexibility for huge ocean wave

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energy converters. Because initial cost calculations showed the large WEC systems were unlikely to be economic, therefore, the small WEC systems will be focused. Take the point absorber as an example, the resonating device can capture more energy when it is smaller than the wavelength. When the device is resonating near the predominant wave frequency and the wave force in phase with the device velocity continuously and with very small viscous damping losses, the conclusion could be drawn. WEC devices are moving slowly (1 m/s for heave, less for roll), and so large powers can either be achieved by large reacting high forces (e.g. 1MN for 1MW) or by speed amplification. Electrical machines are sized for torque and for a given power, torque required reduces inversely with speed.

2.3 Direct drive and in-direct drive power take-off systems

There are two types of power take-off systems: direct drive and in-direct drive power take-off systems. Direct drive power take-off system is to directly convert the kinematic energy of ocean waves into electrical energy based on the electromagnetic induction principle without any intermediate mechanical interfaces. Direct drive power take-off does not require a mechanical interface and does not have the losses in turbines and hydraulic motors that are produced in the mechanical machines operation. While the sizes of the direct drive power take-off will be increased when high power is generated. The in-direct drive generator is to convert the bi-directional oscillation of primary mover into uni-directional rotational motion of an electrical generator through intermediate mechanical interfaces, thus convert the kinematic energy of ocean waves into the electrical energy with a rotational generator. The in-direct drive power take-off has the disadvantage of having too many intermediate mechanisms and components which may cause the non-negligible friction losses between the primary mover and the rotational generator and degrade the reliability and robustness, although the efficiency and power output of the in-direct drive power take-off are not restricted by the limited displacement stroke of the translator. For the same power output, the in-direct drive power

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take-off tends to have a smaller size and volume. The in-direct drive power take-off has a mature generator technology which has a higher generator efficiency.

A majority of full-scale wave energy converter devices to date have adopted the in-direct power take-off systems which apply a complex mechanical drive train to convert the slow device motion into high-speed rotary motion. Direct drive linear electrical machines are a preferred power take-off technology because they are likely to be more efficient and more robust than the indirect drive power take-off system equipped with conventional rotational generators which require the gearboxes or hydraulic systems. Prototyped novel high torque dense electrical machines have been developed for low-speed high torque applications e.g. [52]. Slow speed direct drive electrical machines have been designed specifically for WECs [53], although demonstrators have always had the tight moorings to the sea bed to provide the reaction force. Linear machines have been proven to be capable of being tuned for power-take-off of WECs.

The most widely used linear generators are the permanent magnetic (PM) synchronous generator [54], flux-switching permanent magnet linear generators (FSPMLGs) [55, 56, 57], switched reluctance linear generators [58, 59], and Vernier hybrid machines [52]. The heavy weight of translators and stators, low power efficiency and high cogging force are the main problems of the direct drive linear machines. The flux-switching permanent magnet linear generators (FSPMLG) have the advantages of lower cogging force, fewer harmonic content of electromotive force (EMF), higher efficiency and simpler translator structure than normal linear PM synchronous generator. The switched reluctance linear generators (LGs) are easier to manufacture and control because of the simple and robust structure, cheaper because of the absence of permanent magnets. Vernier magnet linear generators simplified mover's structure, reduced the thermal instability and demagnetisation problem. An example of FSPMLG configuration is shown in Figure 5. Table 1 lists the model and performance details of different flux-switching permanent magnet linear generators reported in the literature.

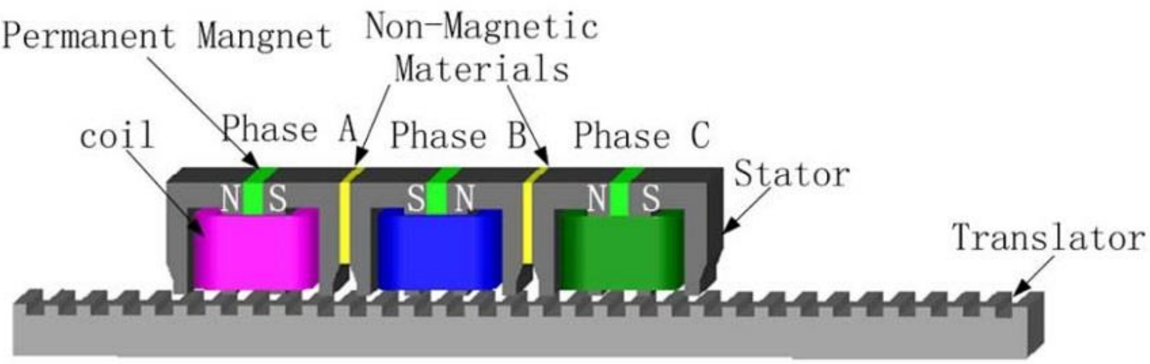

Figure 5. Configuration of a single-side FSPMLG [60].

Table 1 Model and performance details of flux switching permanent magnet linear generators (FSPMLG) reported in the previous literature.

Presenters	Model description	Output power	Load
Huang [60]	The one side single-side FSPMLG has a stator with six U-shaped stacks	75 W	10 Ohm
Farrok [61]	a clipped off translator and a special m-shaped main stator	150 W	8 Ohm
Huang [62]	A tubular primary-permanent magnet linear generator where the magnets and armature windings are placed in the primary buoy which is a translator or mover.	155 W	5 Ohm
Huang [57]	A tubular superconducting flux-switching linear generator (TSFSLG) with direct current superconducting windings to increase the magnetic energy and decrease the demagnetization.	N/A	N/A

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Omar [89]	Used the superconducting magnets instead of permanent magnets to increase the magnetic field.	125 W	2.2 Ohm
Sui [63]	A tubular dual-stator FSPMLG has two flux-switching linear machines sharing the common mover.	1095 W	N/A
Omar [64]	Proposed an optimized design for the stator and the translator using human intervened genetic algorithm.	20 W	5 Ohm

It is seen from Table 1 that Sui [63] achieved the maximum output power of 1095 W through a tubular dual-stator FSPMLG with two flux-switching linear-machines sharing the common mover where the external load resistance was not specified. Huang [62] achieved the second maximum output power of 155 W through a tubular primary-permanent magnet linear generator and an external load resistance of 5 Ohm where the magnets and armature windings are placed in the primary which is a translator or mover.

The model and performance details of different switched reluctance linear generators reported in the literature are summarised in Table 2. An example of a switched reluctance LG configuration is shown in Figure 6.

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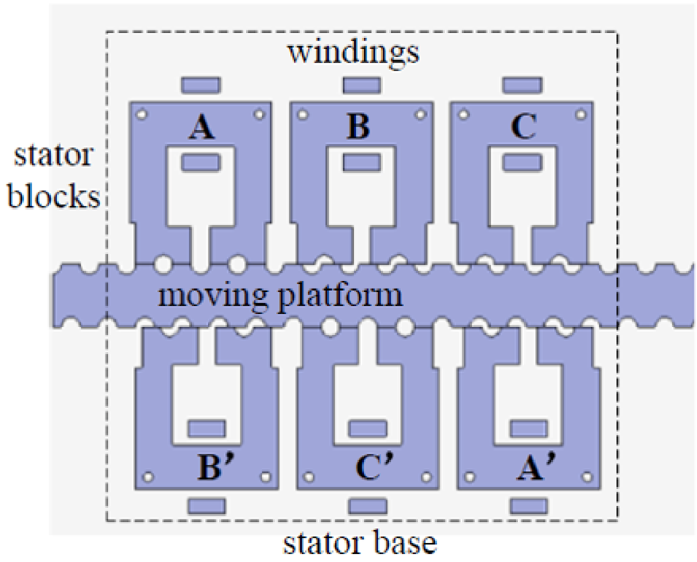

Figure 6. Switched reluctance linear generator [67].

Table 2 Model and performance details of different switched reluctance linear generators reported in the previous literature

Presenters	Model description	Output power	Load
Blanco [66]	employing a direct-drive linear switched-reluctance machine which optimized the dimensions of the WEC	100000 W	N/A
Pan [67]	a two asymmetric bilateral linear switched reluctance generators (ABLSRGs) with complementary power is proposed	5.76 W	25 Ohm
Pan [68]	bilateral planar switched reluctance generator (BPSRG) is developed	0.78 W	8 Ohm
Pan [69]	A linear switched reluctance direct-drive generator for wave energy utilization.	160 W	N/A
Sun [70]	A double-sided linear switched reluctance generator.	N/A	N/A

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Pan [71]	A direct-drive double-sided linear switched reluctance generator (LSRG) with a moving track is designed	150 W	N/A
Di Dio [72]	a bilateral switched reluctance linear generator for special cases	N/A	N/A
FANG [73]	A wave power generation system using the gravity, buoyancy and drag force acting on the switched reluctance generator (SRG) is analysed.	3000 W	N/A

It is seen from Table 2 that Blanco [66] achieved the maximum output power of 100 KW through a direct-drive linear switched-reluctance machine which optimized the unpractical dimensions of the WEC and its power take-off. FANG [73] achieved the second maximum output power of 3000 W without specifying the external load resistance where a wave power generation system with the gravity, buoyancy and drag forces acting on the switched reluctance generator (SRG) is analysed.

Table 3 lists the model and performance details of different Vernier hybrid machines reported in the literature. An example of a Vernier hybrid machine configuration is shown in Figure 7.

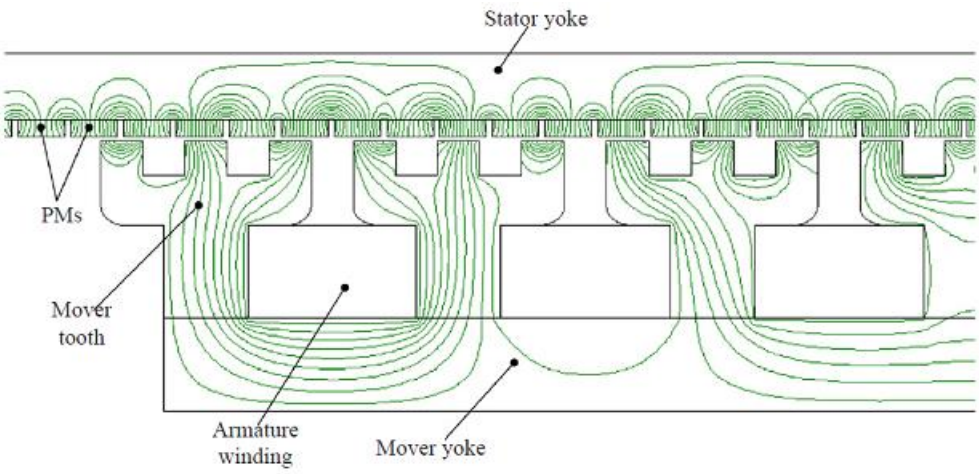

Figure 7. Flux distribution of a typical linear Vernier permanent magnet machine [79].

Table 3 Model and performance details of different Vernier hybrid machines reported in the previous literature

Presenters	Model description	Output power	Load
Toba [74]	A toothed-pole stator with windings in slots and surface permanent-magnet poles rotor structure Vernier machine.	N/A	N/A
Brooking [75]	A generator with a linear toothed translator and two coils wound C-cores and magnets mounted on the pole face.	607 W	N/A
Du [76]	A linear primary permanent magnet Vernier machine	43 V	N/A
Du [77]	A machine which	152 V	N/A

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	is composed of a tubular stator and a tubular translator		
Vining [78]	A double-sided, dual airgap linear Vernier generator for wave energy conversion.	500 W	12 Ohm
Li [79]	the linear Vernier permanent magnet machine	N/A	N/A

It is seen from Table 3 that Brooking [75] achieved the maximum output power of 607 W from a generator with a linear toothed translator and two coils wound C-cores and magnets mounted on the pole face where the external load resistance was not specified. Vining [78] achieved the second maximum output power of 500 W with the external load resistance of 12 Ohm where a double-sided linear Vernier generator with dual airgap was applied for wave energy conversion. As seen, the switched reluctance linear generators have the potential of producing higher output power, but it has a complex control system and the requirement of dimension is very strict. The flux switching permanent magnet linear generators and Vernier hybrid machines are more suitable for the off-shore wave energy converter, because of the easy operation and potential economic benefit.

Some researchers are focused on the designs for reducing the cogging force. These designs include the pole shifting, skewed permanent magnets (PMs), fractional pitch winding, fractional and assistant slots and semi-closed slots. Liu, et al [65] designed an external tubular linear permanent magnet generator with an assistant tooth, 68.98% detent force had been greatly reduced by changing the length of the assistant slots located at the end of winding armature. Liu, et al [80] used an optimised bulged stator and reduced the cogging force by 87.18%. They also compared different air gap widths, which will affect the amplitudes of the voltage and cogging force. Du, et al [76] designed the closed slots to create saturation for the low permeability. The slot harmonics in the magnetic flux density will be reduced but the flux leakage between the stator teeth will be increased, therefore the cogging force and the harmonics of the magnetic flux density in the air-gap will be reduced. Danielsson, et al [81] optimized the permanent magnet (PM) size by changing the length or height, which could change the flux density and reduce the cogging force but increase the PM cost. Bianchi et al [82] used the technique of the pole-shifting and reduced the cogging force by 60%-90% but the output voltage was not harmonic. The primary structure or translator of the linear generator also has an influence on the cogging force where the coils, cores and magnets are placed. For example, the 9-pole 10-slot structure has better performance than the 12-pole 9-slot one [83]. Lejerskog and Leijon [84] used the closed stator to have reduced the cogging force but the harmonics of the magnetic flux density in the air-gap were also reduced. Some of the designs were made based on the optimization of the magnet arrays. Zhang et al and [85] and Xia et al [86] improved the air flux density and the efficiency of the generator. They used T-shaped permanent magnet (PM) structure and claw-shaped permanent magnet (PM) structure to improve the Halbach PM Arrays and compared the air flux density and the efficiency of the slot-less linear generator with the normal Halbach PM Arrays as shown in Figure 8. Wang et al [87] proposed a tubular linear switch reluctance generator (TLSRG) with ferromagnetic rings which is superior to the teeth-type generator as linear generation systems. Zhang et al [88] changed the geometry parameters of the slot so that the effect of the Halbach PM array configuration on the electromagnetic properties of the generator and design guides were established for optimization of the key design parameters. There are also studies on how to avoid the irreversible demagnetization of magnets using the superconducting windings [57, 89, 90, 91].

Field-modulated tubular linear generators are designed to overcome the disadvantages of the heavy generator and low frequency of ocean waves [86, 92, 53]. Some new excitation winding configurations were used to improve power density [93] where Du et al proposed a direct-drive mutually coupled linear switched reluctance machine (MCLSRM) which had better utilized the magnetic and electric circuits and generated a higher voltage than the field-modulated tubular linear generators.

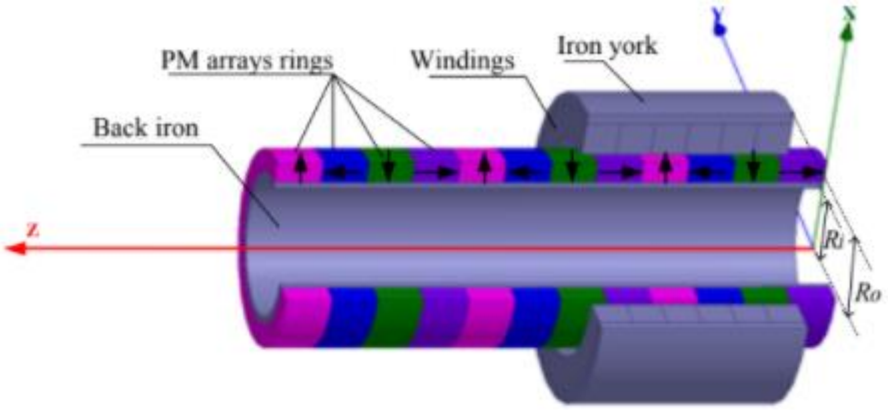

Figure 8. 3D Model of a slot-less linear generator [85].

2.4 Mechanisms of the power take-off system:

2.4.1 Two-body systems

Two-body systems were studied in recent years because the two-body systems have lower natural resonant frequency and higher potential power than normal one body systems. It was found that the two-body systems were able to absorb higher power significantly than the single buoy systems with the same floating buoy in both regular and irregular waves and had a resonant frequency close to the low excitation frequency of real ocean waves [94]. The dual-buoy system where the relative heave motions between the dual buoys are amplified through highly amplified internal-fluid motions is shown in Figure 9 [95]. Al Shami, et al [96] studied the effect of different design parameters on wave energy conversion performance using Taguchi method. The optimized combination of the PTO parameters was identified, which could increase the generated power and harvesting bandwidth. Gao [97] designed a direct-driven linear wave energy converter where a fully floating magnet was supported by springs and the coils moved with another floater. The direct-driven linear wave energy converter is a two-body system.

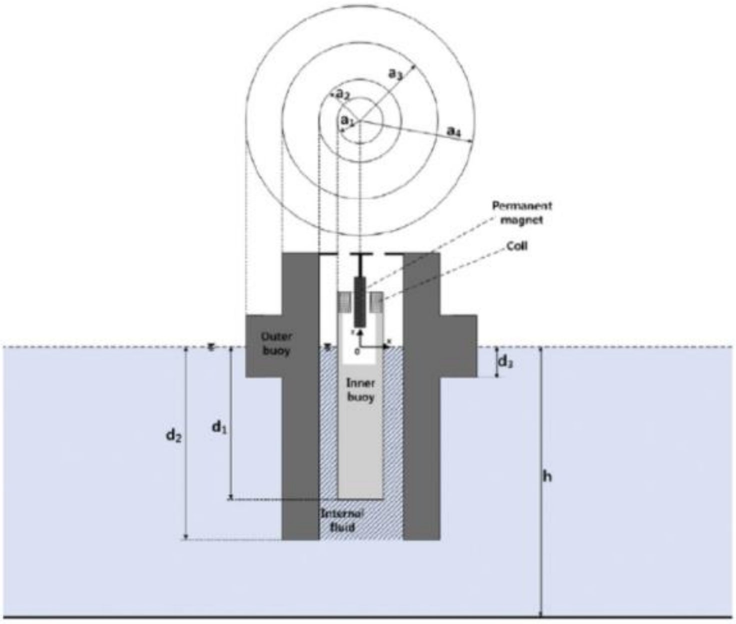

Figure 9. The schematic of a dual-buoy WEC [95].

2.4.2 Pendulum systems

The SEAREV wave energy converter is a floating device enclosing a heavy horizontal axis wheel serving as an internal gravity reference. The centre of gravity of the wheel being off-centred, this component behaves mechanically like a pendulum. The rotational motion of this pendular wheel relative to the hull activates a hydraulic Power Take Off (PTO) which, in turn, set an electric generator into motion. In other words, SEAREV is a pendulum system with the axis of rotation orthogonal to a gravity vector, using the surge or pitch motion to rotate the pendulum [98]. ISWEC is the gyroscopic system composed of a platform with the spinning flywheel along the generator axis as shown in Figure 10 [99]. When the device is working, a torque along the horizontal central line was created from the combination of the flywheel spinning velocity φ and the wave induced pitching velocity δ. Using this torque as the input of

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an electrical generator, the extraction of the energy from the waves is possible [99]. There are some other designs using the pendulum systems [100-104]. For example, Guo et al [104] designed an ocean wave energy harvester that consists of a swing body, a rack, transmission gears and electromagnetic power module. The swing body connected to the outer rack drives the gear to rotate where the shaft of the gear is the input shaft of the generator.

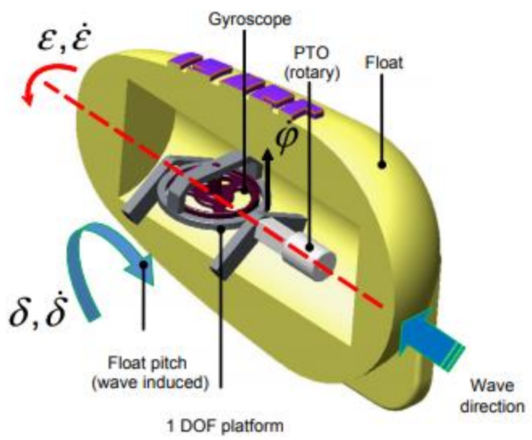

Figure 10. Gyroscopic mechanism [99]

2.4.3 Ball-screw or rack and pinion systems

Ball-screw or rack and pinion systems can transfer the linear motion into rotational motion which increase the input velocities. One design consists of a point pivoted floater which oscillates due to waves [105] where an electromechanical generator linked to the buoyant body converts buoy oscillating movements caused by the wave into electrical power as shown in Figure 11. Zuo also used the ball screw mechanism in the PTO system with a simpler design [106] where a ball-screw mechanism and two one-way clutches were used. The rack and pinion and bidirectional clutch gearbox mechanisms were widely adopted in some researches, as they can transfer the reciprocation motion to the one directional rotation, and generate power during the motions in both the directions as shown in Figure 12 [107 -109]. Another application is the pulley system, normally the counterweight is connected to one end of the pulley and the other side is connected to the excitation part [110-111]. The drawback is that the generator should be fixed on cliff or platform in the ocean. Some researchers designed the built in PTO prototype using pulley system to create a WEC of dual resonance. The authors used a damping system in place of the PTO and verified their design through experiment [119].

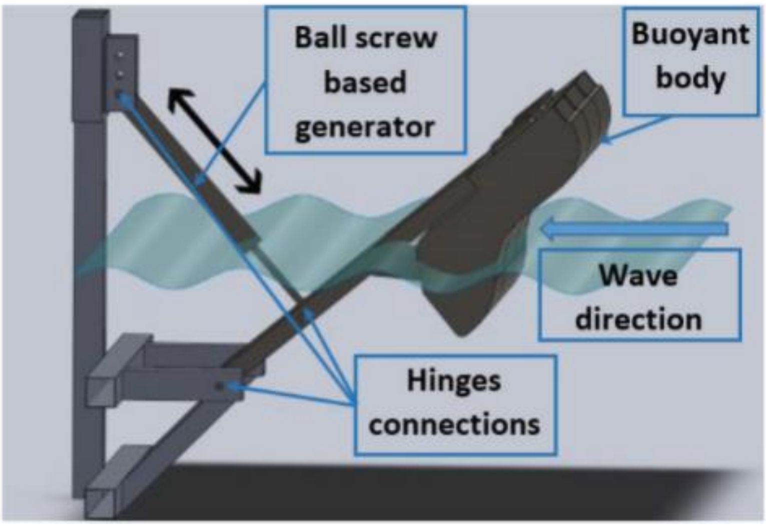

Figure 11. Wave-To-Wire Oscillating system and its main components [105].

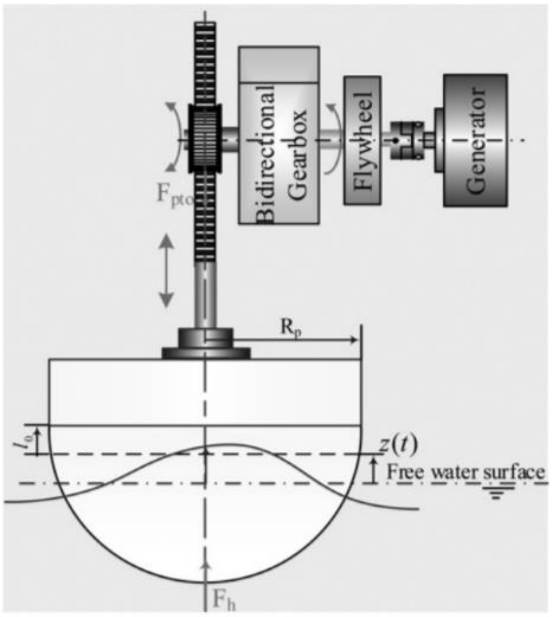

Figure 12. The configuration of the WEC with bi-directional gearbox [107].

2.4.4 Rotational vane wheel systems

In terms of the rotational characteristics of the guide blades of a wave energy converter, Yu [110] designed a novel wave energy converter with variable guide vane, the waves drive the vane wheel to rotate, generating electricity as shown in Figure 13. Joe [111] proposed a

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mooring-less wave energy harvesting system, which utilized the excitation force on the buoy to push the structure up and down. Some researchers [112-115] employ a pivot structure to utilise the heaving or surging motion to drive the generator. The disadvantage of the pivot mechanism is that there should be a fixed support on the cliff or boat. Yang et al [116] used the cup blades of the motor laid out around its shaft. The rotors achieved a profound unidirectional rotation under all testing conditions by using the single directional clutch bearings. The parametric study of the blade diameters such as the rotor diameter, the rotor spacing gap and blade angle revealed the effect of the parameters on the rotor's mean angular velocity.

In addition to the above literature for PTO system mechanisms, more literature are categorized and listed in Table 4. It can be seen the mechanisms have their own different particular benefits and it is hard to define which one is the best. The design of a PTO mechanism should be based on different wave conditions (wave height, wave period, locations etc.). None of PTO system mechanisms is commercialized as the cost of the WEC PTO is very high, so the optimised WEC PTO design are desired.

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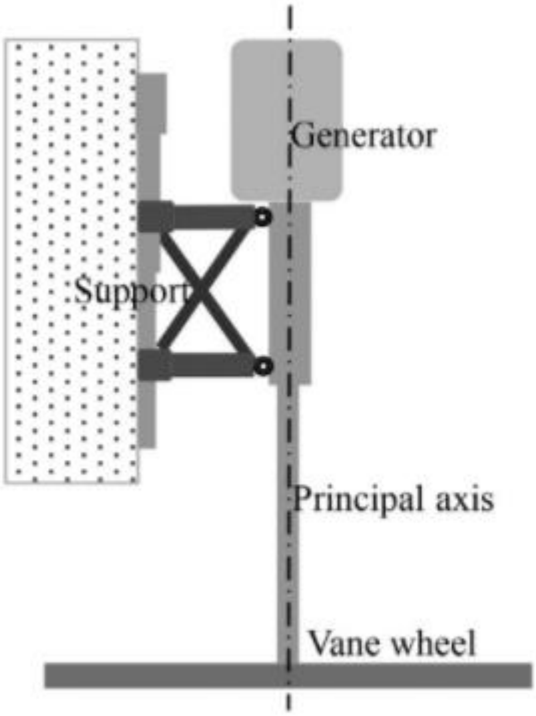

Figure 13. Structure of the guide vane wave energy converter [110].

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Table 4. Relevant literature for four mechanism catalogues.

Year	Two-body system	Pendulum	Ball screw & rack and pinion	Rotational wheel
2010		Ruellan, et al. [98]		
2011		Bracco, et al. [99]		
2014			Lok, et al. [109]	Barbarelli, et al. [114]
2015		Battezzato, et al. [100]		
2016	Gao, et al. [97]		Coiro, et al. [105]	
2017	Liang & Zuo [94] Kim, et al. [95]	Boren, et al. [101]	Liu, Lin and Zuo [106] Porter, et al. [117] Albert, et al. [108]	Joe, et al. [111]
2018	Chen et al. [117]	Yurchenko & Alevras [102] Crowley, et al. [103] Guo, et al [104]		Yu, Shi and Song [110] Chow, et al. [112] Chen, Gao and Meng [113] Wang, et al. [115] Yang et al. [116] Sun, et al. [118]
2019	Al Shami, et al. [96]	Chen, et al. [119]	Shi et al. [120]	

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3. Point Absorber WEC Design

In order to design a point absorber WEC, the energy properties and resources, site assessment, and other factors should be considered because these factors determine the survivability and successful operation of the point absorber WEC in the target site. It was learned from the recently published literature [121] that numerical simulation and basic theoretical analysis could be applied to calculate the potential captured energy and energy conversion efficiency of a point absorber WEC. The simulation software of the boundary element method such as WAMIT or Ansys Aqwa can be used to predict the coefficients of the hydrodynamics of the WEC systems. Simulations using the software were relatively fast and efficient [96]. Most Point Absorber systems were scaled down and tested in laboratory wave tanks [86]. Some tests were performed considering a point absorber WEC as a complete whole device, while some tests elaborated different modules of a point absorber WEC separately, such as hydrodynamic, PTO and electrical systems. The more detailed results of the modules gave more insights into point absorber WECs' behaviour and performance [122].

The WEC dynamic equation of a single body point absorber can be established and solved in the time or frequency domain. From the solution, the vertical response amplitude operator (RAO) could be calculated to estimate the motion behaviour. The input of this equation is the wave excitation force on the buoy which is proportional to the wave displacement amplitude. The outputs could be the oscillator displacement, velocity, acceleration, output voltage and output power etc. either in the time or frequency domain. The WEC dynamic equation of a single body point absorber is given by

$$M\ddot{y} + k_p y + c_p \dot{y} + k_{hs} y + c_{vd} \dot{y} + c_r \dot{y} = F_{we} \tag{2}$$

where y is the displacement, $\dot{y}$ is the velocity and $\ddot{y}$ is the system acceleration in the vertical direction of heave; M is a sum of the dry and added masses of the single body point absorber WEC, k_{hs} is the coefficient of the hydrostatic stiffness, c_r is the coefficient of the radiation damping, c_{vd} is the coefficient of the linearized viscous damping, F_{we} is the force of the wave excitation, and k_p and c_p are the coefficients of the PTO's stiffness and damping which are used to calculate the PTO force: $F_{pto} = k_p y + c_p \dot{y}$. Except for the viscous damping coefficient, other hydrodynamic parameters could be calculated from the software of ANSYS AQWA using the boundary element method.

The Cummins equation [123] which was originally used to study ship motions can be used to obtain the time domain solution of the point absorbers. The input could be the regular wave or irregular wave excitation force in the time domain and the output could be the oscillator displacement, velocity, acceleration, output voltage and output power etc. The Cummins equation can be given by:

$$(m + m_a^{\infty})\ddot{y_{(t)}} + \int_{-\infty}^{t} RIF(t-\tau)\dot{y_{(t)}}d\tau + k_{hs}y_{(t)} = F_{(t)}^{wave} - F_{(t)}^{ext} \quad (3)$$

where $y_{(t)}$ is the instantaneous position, $\dot{y_{(t)}}$ is the instantaneous velocity and $\ddot{y_{(t)}}$ is the instantaneous time domain acceleration of the single body buoy; m is the dry mass of the physical system, m_a^{∞} is the hydrodynamically added mass at the very large frequency, the radiation impulse function (RIF) is the inverse Fourier transform of the radiation damping coefficient c_r from the frequency domain to the time domain, $F_{(t)}^{wave}$ is the instantaneous wave excitation force, and $F_{(t)}^{ext}$ is the external forces acted on the system, for example, PTO forces (linear or nonlinear PTO system), viscous damping forces of waves, mooring forces, etc.

Eriksson et al [124] studied the generator as a viscous damper and showed the power capture ratio of the system at resonance. It was found that the PTO damping coefficient can be tuned for better performance under different wave climates. Zurkinden et al [120] used the numerical modelling method to study the non-linear hydrostatic stiffness and viscous drag force of a point absorber with a spherically shaped bottom. The numerical model was validated by the laboratory test results. It was found that the numerical model considering the non-linear

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hydrostatic restoring moment can effectively predict the dynamics of the wave energy converter where the viscous drag damping loss can be neglected.

4. The Contributions

The two-body point absorber WECs have been studied and optimized by our research team who have the capacity to improve the efficiency of the WECs which are suitable for the sites around Australia [96]. Our focus in terms of the hydrodynamics now is to optimize different WECs based on wave height and frequency of specific sea areas. The novel PTO concepts for point absorbers have been studied where a speed amplified PTO with pulley system has shown the advantage of being able to collect more energy. The novel wave energy conversion systems have been developed with speed amplified mechanism and optimized topology of stator and translator where the parameter sensitivity study of the speed amplified PTO system is also important [125]. The experimental validation will be conducted this year. Finally, power electronics has been studied for WECs on electrical energy storage, smooth power transmission from PTO to grid and supply stability as a power source [126]. The team are working hard to identify research gaps for the point absorber WECs out of which some of the research questions are raised. Our future researches will be focused on:

1. How will the linear electromagnetic generator be designed to achieve high efficiency and low cogging force for well enhanced wave energy conversion performance?
2. How can one overcome the shortcoming of low ocean wave excitation frequencies of WECs through novel design and optimized oscillating body weight?
3. How can one accurately predict and evaluate wave energy conversion performance of the proposed linear electromagnetic generator?

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5. Conclusions

The design and optimization of the power take-off systems of ocean energy converters have been studied from reviewing the recently published literature. The arrangement of magnets and coils and novel designs of conversion devices are the key factors to improve the conversion efficiency. Large magnetic flux density and relative motion of the PTO primary mover, reasonable mechanical and electrical damping coefficients are the key to increase the converted power. The resonant frequency of the WECs could be designed by tuning the design parameters of the buoy or PTO. The high relative speed between the stator and translator has the potential to increase the efficiency of WEC.

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