# A Critical Survey of Power Take-Off Systems based Wave Energy Converters: Summaries, Advances, and Perspectives

Bo Yang [a, b], Jinhang Duan [a], Yong Chen [c], Shaocong Wu [a], Miwei Li [a], Pulin Cao [a, *], Lin Jiang [d].

[a] Faculty of Electric Power Engineering, Kunming University of Science and Technology, 650500 Kunming, China;

[b] Intelligent Electric Power Grid Key Laboratory of Sichuan Province, 610065 Chengdu, China;

[c] Electric Power Research Institute, Yunnan Power Grid Company Ltd., 650217 Kunming, China.

[d] Department of Electrical Engineering and Electronics, University of Liverpool, L69 3GJ Liverpool, UK.

* Corresponding author: Pulin Cao, E-mail: pulincao_kust@sina.com

## Abstract

Being one of the most promising renewable energy sources, ocean wave energy (OWE) demonstrates considerable development and application potential. Consequently, various related technologies have rapidly advanced in recent decades, particularly in the field of wave energy converters (WEC). Power take-off (PTO) stands as a vital element within WEC systems. During the planning and implementation of WEC systems, diverse types of PTO systems and control strategies emerge as crucial factors that impact overall power output and stability. To comprehensively review PTO systems, this paper offers a comprehensive overview and discussion of state-of-the-art development status of PTO, including of based structures, working principles and control strategies. In contrast to prior reviews, a more thorough classification and comparison of different PTO systems have been undertaken in this review with the consideration of seven types of PTO systems in total and detailed control strategies for various PTO types. Besides, the proposed framework includes an evaluation and comparison of advantages/disadvantages, application, complexity, and costs for each controller. Lastly, seven invaluable perspectives are proposed for future research.

**Keywords:** Ocean wave energy; Wave energy converter; Power take-off system; Control strategy; Review

## Nomenclature

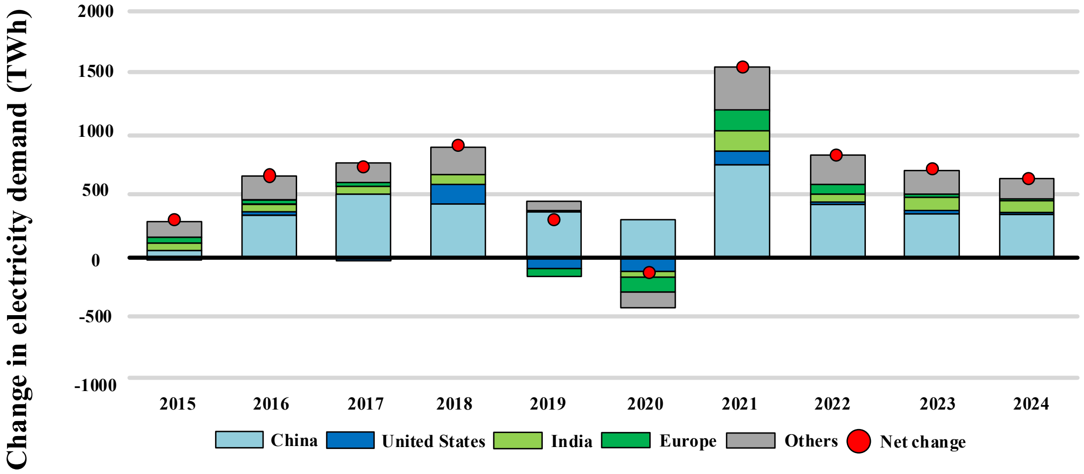
| **Abbreviations** | | | |
|---|---|---|---|
| **AI** | artificial intelligence | **MSC** | machine-side converter |
| **AEP** | annual energy productio | **NMPC** | nonlinear MPC |
| **AWEC** | attenuators WEC | **NSGA-III** | non-dominated sorting genetic algorithm-III |
| **CAPEX** | capital expenditure | **OPEX** | operational and maintenance expenses |
| **CD-DEG** | circular diaphragm DEG | **OWC** | oscillating water column |
| **CNN** | convolutional neural network | **OWE** | ocean wave energy |
| **CGD** | continuous gain-scheduling damping | **OWCWEC** | oscillating water columns WEC |
| **COE** | cost of energy | **OTEC** | ocean thermal energy conversion |
| **CPHPTOs** | constant-pressure HPTOs | **PAWEC** | point absorption WEC |
| **DC** | direct current | **PeWEC** | pendulum wave energy converter |
| **DE** | dielectric elastomer | **PI** | proportional-integral |
| **DEG** | dielectric elastomer generator | **PID** | proportional-integral-derivative |
| **DMDPTO** | direct mechanical drive PTO | **PLD** | passive linear damping |
| **EMG** | electromagnetic generator | **PM** | permanent magnet |

| | | | |
|---|---|---|---|
| **ENFR** | environmental friendliness | **PD** | pressure difference |
| **ESS** | energy storage system | **PTO** | power take-off |
| **ETA** | event tree analysis | **PV** | photovoltaic |
| **FDIG** | doubly-fed induction generator | **PWM** | pulse width modulation |
| **FEC** | fluid energy control | **RD-EMG** | rotary disc EMG |
| **FTA** | fault tree analysis | **RERs** | renewable energy resources |
| **GSC** | grid-side converter | **RPMGs** | rotating PM generators |
| **HBCC** | hysteresis-band current control | **RPL** | rack-pinion-lever |
| **HPTO** | hydraulic PTO | **RPLS** | rack pinion-lever-spring |
| **HSSV** | high-pressure safety valve | **SHCSC** | spatial hysteresis current source control |
| **HTS** | high-temperature superconducting | **SMC** | sliding mode control |
| **HTSLG** | HTS linear generators | **SVM** | support vector machine |
| **ISUIPID** | improved simplified universal intelligent PID | **SVPWMCC** | space-vector PWM current control |
| **IGTO** | improved gorilla troops optimizer | **TCA** | torque control algorithm |
| **LCOE** | levelized cost of energy | **TENG** | triboelectric nanogenerator |
| **LCA** | life cycle assessment | **TECO** | technology cost economy |
| **LPMG** | linear PM generator | **TGD** | two-state gain-scheduling damping |
| **ISWEC** | inertial sea wave energy converter | **TWEC** | terminators WEC |
| **LSTM** | long short-term memory | **VOC** | voltage-oriented control |
| **MBC-TENG** | multilayered soft-brush cylindrical TENG | **VPHPTOs** | variable-pressure HPTOs |
| **MMR** | mechanical motion rectifier | **VRPM** | variable reluctance PM |
| **MPC** | model predictive control | **VSC** | voltage source converter |
| **MPPT** | maximum power point tracking | **WEC** | wave energy converter |
| **MMPC** | multi-objective MPC | **WT** | wind turbine |

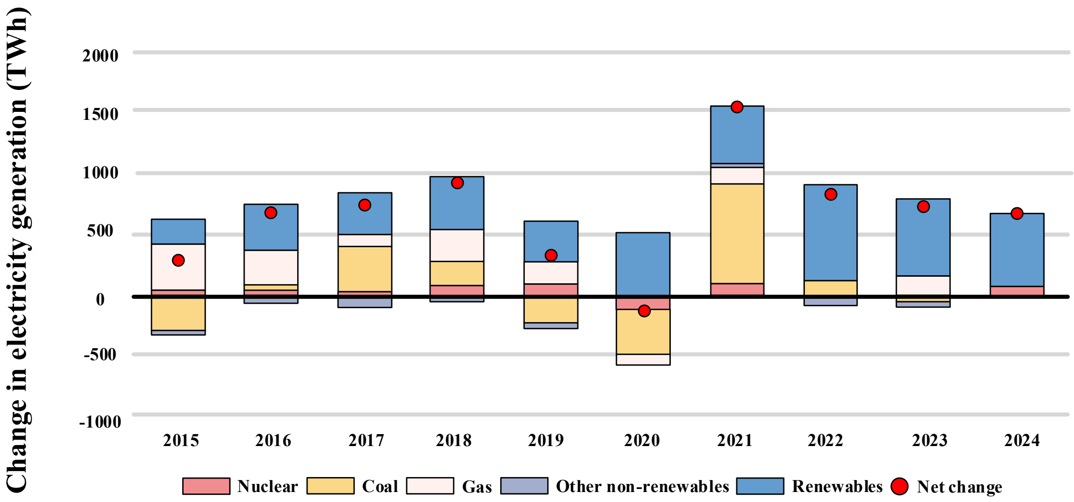
# Contents

# 1. Introduction

Under the circumstances of global energy shortage and environmental protection, after a little decline in 2020, the global energy demand increased by 6% in 2021. This was the highest yearly gain in absolute terms (almost 1,500 TWh) and the most significant increase in recent years, as can be seen in Fig. 1 [1]. Meanwhile, Figure 1 demonstrates that electricity generated from coal is responsible for over half of global demand growth, which inevitably results in $CO_2$ emissions increasing by almost 7%, reaching a record high. To realize the goal of IEA's Net Zero Emissions by 2050, technologies that can promote low-carbon power generation receive worldwide attention, for instance, the application of various renewable energy. According to the Electricity Market Report [1], low-carbon energy production has achieved rapid growth, with 83% coming from renewable energy sources.



(a)



(b)

**Fig. 1.** Global energy pattern transformation from 2015 to 2024: (a) global change in electricity demand and (b) global change in electricity generation [1].

Thanks to the pollution-free and environmentally friendly nature, various renewable energy resources (RERs) are widely used for green and clean power generation [2]. Among them, ocean wave energy (OWE) is a relatively new-emerging RER but contains great potential and promising application prospects thanks to its high energy density and availability [3-6]. As shown in Fig. 2, there are five common power generation forms: tidal, wave energy, ocean current energy, ocean thermal energy conversion (OTEC), and salt difference generation.

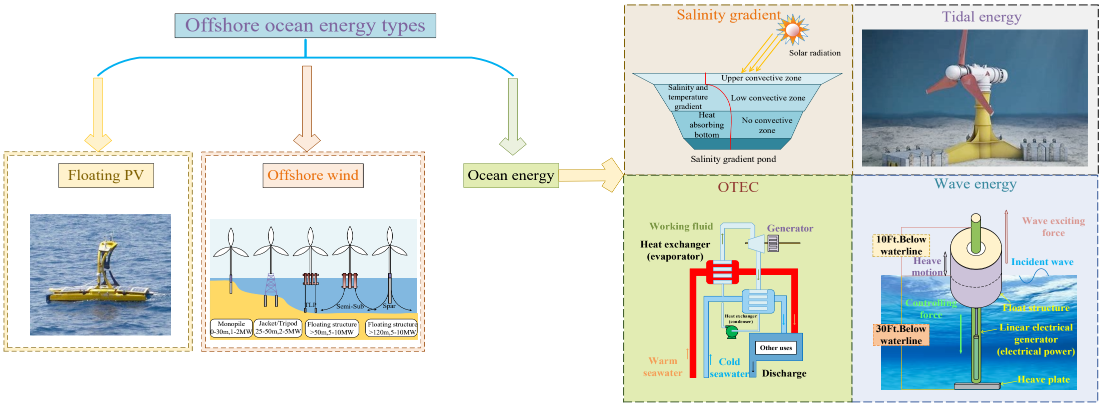


**Fig. 2.** Different offshore energy generation methods [7-10].

Wave energy systems can be categorized based on various criteria, including position, construction, operation principle, size, orientation, and power take-off (PTO) systems [12,13]. For a more explicit illustration, a graphical representation is presented in Fig. 3, in which PTO systems are the core of wave energy converter (WEC) that attract the studies from worldwide researchers and engineers. PTO systems convert mechanical motion into electrical energy. Based on various working principles, PTO systems can be categorized into different types, each employing distinct control strategies such as torque, airflow, current, power, or valve control. Through carefully designed control strategies, WEC can adapt better to varying wave conditions, enhancing energy capture efficiency. So economic viability, efficiency and complexity of WEC configurations depend significantly on the design of their PTO systems [13,14]. So far, only a few articles provide a general introduction to WECs based on PTO systems. Therefore, it is imperative to undertake a more thorough and systematic study of previous and current related works To this purpose, this work intends to offer a detailed study and put forward some novel views concerning the application of PTO systems to WECs, to offer researchers/engineers some practical guidance and sparkle new research activities in related fields [14].

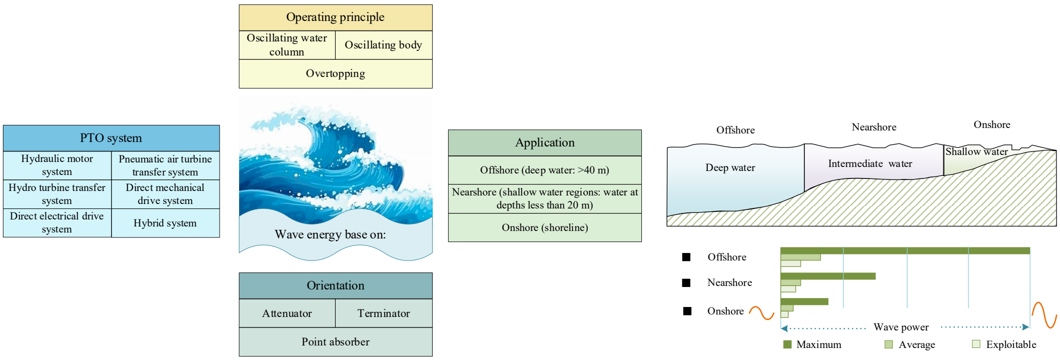


**Fig. 3.** Wave energy classification system.

The rest of this work is organized as follows: Section 2 provides the review screening methods. In Section 3, each type of PTO system is elaborated based on different working principles. Section 4 summarizes and discusses various control strategies applied to different PTO systems.Section 5 briefly discuss the selection criteria for PTO based on five evaluation criteria: energy conversion efficiency, reliability, economic, applicability and environmental friendliness. At last, Section 6 summarizes the whole work and gives some perspectives.

## 2. Review screening methods

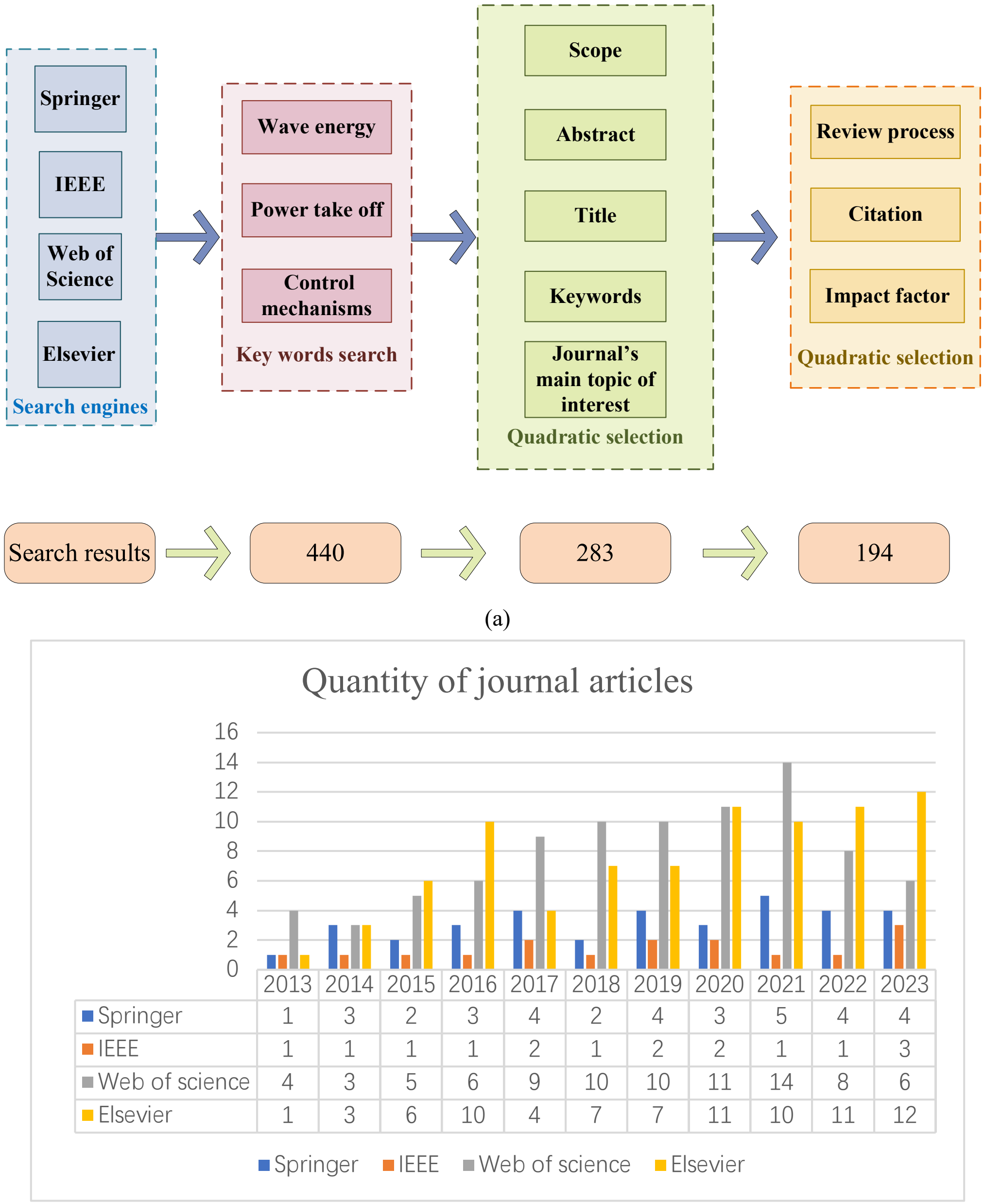
Thus far, there have been several reviews related to PTO systems, however, they all lack a sufficient description of the working principles, application scenarios, and control strategies. Specifically, Table 1 summarizes the main advantages and disadvantages of previous reviews.

**Table 1.** A chronological overview of the five previous PTO reviews.

| Literature | Year | Main work | Advantages | Disadvantages |
|---|---|---|---|---|
| Penalba M, et al. [15] | 2016 | Encompasses all stages of conversion from ocean waves to power grid, identifying necessary components along with dynamics, constraints and grid limitations. | Identifies different control inputs for different components of PTO system. | Summary of the control strategy is overly concise. |
| Wang LG, et al. [16] | 2018 | Briefly introduces characteristics of OWE; Summarizes control strategies for WEC. | Systematically reviews and compares control strategies for WEC. | Lacks of detailed introduction and a summary of advantages and disadvantages for different types of PTO. |
| Jusoh MA, et al.[17] | 2019 | Reviews and analyses concepts of hydraulic PTO (HPTO) system used in various types of WECs. | Outlines control mechanism, advantages, and challenges faced by HPTO. | Summarizes only HPTO, lacks of introduction and summary for other PTO. |
| Liu Z, et al. [18] | 2020 | Reviews different concept PTO systems and simple hydrodynamics of WEC. | Explores strengths and weaknesses of both direct and in-direct drive PTO devices, and mechanisms of PTO system. | Lacks of introduction about control strategies for various PTO systems. |
| Prasad KA, et al. [7] | 2022 | Summarizes a variety of WEC systems and emphasizes a new hybrid wave-photon energy harvesting device. | Consideration of different PTO working methods, especially in hybrid systems. | Insufficient summarization of various PTO and control methods for suggested hybrid system. |

Generally speaking, this work is investigated based on the following three steps: Firstly, four literature searching engines (Springer, IEEE, Web of Science and Elsevier) are used for literature collection based on a number of similar keywords, such as wave energy, PTO, and control mechanisms. Then, titles and abstracts are referenced for further consideration. Finally, 194 publications in total are evaluated based on the impact of citations and journals. Figure 4

(a) describes the procedure of carrying out the searching and reviewing of bibliographic references. Furthermore, Fig. 4 (b) depicts research data in this field over the last 10 years (January 2013 to December 2023).



|  | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ Springer | 1 | 3 | 2 | 3 | 4 | 2 | 4 | 3 | 5 | 4 | 4 |
| ■ IEEE | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 1 | 3 |
| ■ Web of science | 4 | 3 | 5 | 6 | 9 | 10 | 10 | 11 | 14 | 8 | 6 |
| ■ Elsevier | 1 | 3 | 6 | 10 | 4 | 7 | 7 | 11 | 10 | 11 | 12 |

(a)

(b)

**Fig. 4.** Screening process of relevant literature in the previous 10 years: (a) execution process and (b) research statistics.

## 3. Operation principles of PTO systems

WEC converts kinetic or potential energy contained in ocean waves into useful energy, primarily in form of electricity, and is composed of components such as floaters or submerged bodies, PTO units, control systems, power electronics, etc [19].

Currently noteworthy is that WECs such as pendulum wave energy converter (PeWEC) and inertial sea wave energy converter (ISWEC) have undergone extensive research in both numerical simulations and experiments, with successful prototype operation. Unlike other devices, PEWEC and ISWEC units are enclosed within the hull, avoiding contact with seawater, thereby enhancing their durability [20].

PeWEC: Developed collaboratively by W4E, Polytechnic of Turin and ENEA, with TRL5, PeWEC is a floating offshore WEC based on a pendulum mechanism. The device primarily consists of a floating hull moored to seabed and a pendulum connected to generator shaft, seamlessly integrated with hull structure [21]. PeWEC device allows extraction of energy by harnessing forces generated from swinging pendulum enclosed within a sealed casing. Termed as passive, PeWEC operates without the need for external power to induce inertial effects [22].

ISWEC: Originally conceived by Politecnico di Torino, this technology was brought to fruition by the Wave for Energy Company [23]. Internally, an inertial PTO unit transforms pitch motion induced by waves on hull into electrical energy. Externally, it presents itself as a fully enclosed hull, featuring a single cable passing through a joint in the hull. This cable connects to a static cable on seabed, further linking to the island's grid in a transformer chamber [24]. ISWEC falls into the category of a pitch point absorber, and its straightforward design allows for potential cost reduction through the repurposing of decommissioned vessels, thereby facilitating technology adoption [25]. Furthermore, adaptability of this device permits end-to-end arrangements in nearshore installations, maximizing wave energy absorption while concurrently offering coastal protection.

The types of WECs can be classified according to different criteria such as installation location, operating principles, whether the conversion is buoyant or submerged, and the number of degrees of freedom they possess [19]. It is worth noting that currently, there is no single, comprehensive classification method that can cover all concepts of WECs. Below is a brief introduction to the four main types of WECs: Point absorbers WEC (PAWEC), oscillating water columns WEC (OWCWEC), attenuators WEC (AWEC) and terminators WEC (TWEC). Table 2 summarizes types of WECs in recent years along with their corresponding PTO types.

PAWEC: The concept of PA was first defined in 1975, referring to WECs that are relatively small in size compared to the wavelength [26]. This definition is independent of deployment method, degrees of freedom, or hull geometry of PAs. Consequently, PAs can be installed in a floating or submerged manner, oscillating in single or multiple degrees of freedom, and can capture wave energy using a single or multiple PA bodies [27]. Even to date, PAWEC remains one of the "hottest" types of WECs. For this type of WEC, commonly used PTO types include HPTO, linear generator PTO, and direct mechanical drive PTO [28].

OWCWEC: OWC refers to an open structure with an inlet opening used in oscillating wave energy devices to capture internal free water surface and air above the static water level. The trapped air is compressed and released through the alternating cyclic action of waves, opening a valve that directs airflow into a turbine connected to the power plant [29]. This type of WEC, responsive to the seabed, is typically deployed in shallow or moderately deep waters, with deployment depths usually ranging from 20 to 50 m. Additionally, due to the need for mooring/anchoring systems and underwater installation of relevant power generation equipment, their deployment is typically associated with higher costs.

AWEC: A attenuator aligned parallel to the direction of wave propagation is a type of free-floating wave energy conversion device, comprised of a series of interconnected objects linked by hinges [30]. The motion relationship between these objects can provide power to PTO .

TWEC: Similar to AWEC, these devices are elongated structures. However, terminators are positioned vertically to the primary direction of wave propagation, essentially serving the function of wave "termination". Terminator type has the opportunity to harvest more energy than the other types because it absorbs wave energy from its spatial movements [26].

**Table 2.** A overview of the some types of WEC and PTO.

| **WEC name** | **WEC type** | | | | **PTO type** |
|---|---|---|---|---|---|
| | PAWEC | OWCWEC | AWEC | TWEC | |
| CorPower device [26] | √ | | | | Mechanical PTO |
| Archimedes wave swing device [31] | √ | | | | Linear generator |
| CETO 5 (named after a Greek sea goddess) [32] | √ | | | | HPTO |
| CETO 6 (named after a Greek sea goddess) [33] | √ | | | | Mechanical PTO |
| OPT Powebuoy [34] | √ | | | | A ball-screw mechanical PTO |
| Wavebob device [35,36] | √ | | | | HPTO or direct-drive linear generator |
| SEAREV device [37] | √ | | | | HPTO or direct-drive PTO |
| Wello penguin device [38] | √ | | | | Rotary generator |
| WaveStar device [39] | √ | | | | HPTO or linear generator |
| FO3 device [40] | √ | | | | HPTO |
| Parallel configuration WEC [41] | √ | | | | Mechanical PTO |
| 4th-scale BBDB OWC [42] | | √ | | | Wells turbine |
| Mighty Whale [43] | | √ | | | Wells turbine |
| U-shaped OWC [44] | | √ | | | Mechanical PTO |
| Seabreath [45] | | √ | | | Air turbine |
| LEANCON [46] | | √ | | | Air turbine |
| M3 [47] | | √ | | | Air turbine |
| Pelamis [48] | | | √ | | HPTO |
| M4 (a multi-body attenuator type Multi-float and multi-mode-motion -WEC) [30] | | | √ | | HPTO |
| Wave Dragon terminator [26,49] | | | | √ | HPTO |
| Oyster device [50] | | | | √ | HPTO |
| Oscillating wave surge converter (OWSC) [51] | | | | √ | H PTO |

PTO is an important part of WEC. Among all modes of PTO system operation, the working methods of hydraulic motor, turbine transmission, and direct electromagnetically drive are most commonly utilized. Nevertheless, in the past few years, several new technologies, such as triboelectric nanogenerators (TENGs) and hybrid systems have been used to develop PTO systems of WEC. Figure 5 depicts the functioning principles of the PTO system, with different colors representing various types of energy [52].

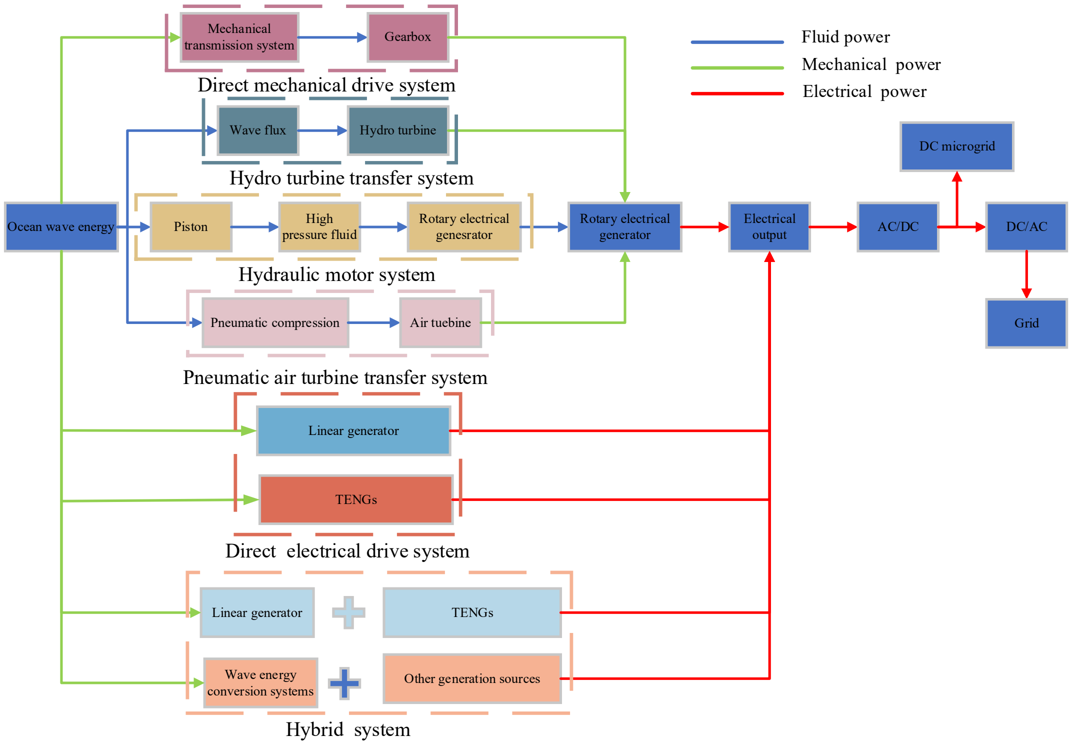


**Fig. 5.** The operation principles of PTO systems.

In general, PTO system firstly converts wave power into mechanical/pneumatic/potential energy, then into electric power via a PTO system, and finally into conventional electricity (including voltage and frequency), which can be conveyed to the micro-grid or public electricity network.

### 3.1 Hydraulic motor system

The hydraulic motor system applies the most appropriate PTO mechanism in the transformation of electric power [7]. The configuration of the WEC with a HPTO system is illustrated in Fig. 6, which consists of four phases, namely, absorption, transmission, generation, and conditioning stage [17].

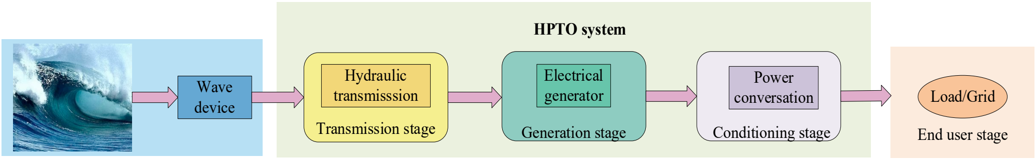


**Fig. 6.** Illustration of HPTO [17].

#### 3.1.1 Type of hydraulic motor systems

According to references [53,50] referring to the hydraulic motor system's ultimate pressure state (i.e., the pressure in the generation module), the hydraulic motor system is categorized to three main groups, i.e., variable-pressure HPTOs (VPHPTOs), constant-pressure HPTOs (CPHPTOs), and the constant-variable pressure hydraulic system. The schematic diagrams of constant-pressure and variable-pressure systems are respectively shown in Fig. 7.

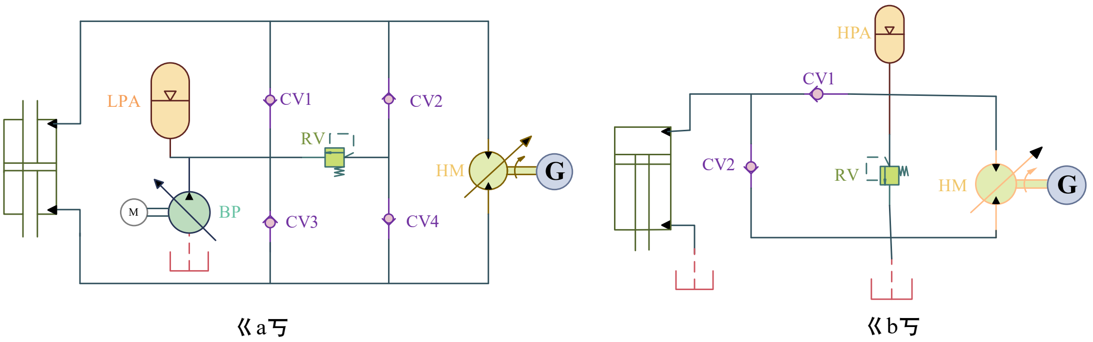


**Fig. 7.** Hydraulic motor system configuration: (a) typical CPHPTOs configuration and (b) typical VPHPTOs configuration [53].

*I. VPHPTOs*

In VPHPTOs, a hydraulic cylinder first produces high-pressure oil, which is then rectified by four check valves before being sent to a hydraulic motor that is coupled to a generator to generate electricity. In order to improve the efficiency of wave energy capture, it is available to regulate the PTO force to optimal degree depending on wave conditions by controlling the motor [54]. Despite the fact that VPHPTO is intended to operate at an optimal operating point with peak efficiency, it is possible that it might operate at a low efficiency under the condition of wave-to-wave changes.

*II. CPHPTOs*

For CPHPTOs, the unidirectional high-pressure oil generated by the hydraulic cylinder and four check valves is first stabilized by a high-pressure accumulator and then transmitted to a hydraulic motor. High-pressure accumulators are able to store energy for a short while and partly filter out variations of pressure and flow rate in the system [54]. As a result, the core energy conversion component, i.e., the hydraulic motor can run under a more stable scenario than the VPHPTO while still achieving high efficiency. In general, CPHPTOs own distinctive advantages in terms of efficiency and flexibility, which efficiency can reach up to 90% [52]. In literature [55], CPHTOs based and VPHTOs based systems are studied and compared, experimental results indicate that CPHTOs show a higher PTO efficiency (30% higher) than VPHTOs, while its electricity generation is 2% lower than VPHTOs.

### 3.1.2 Benefits and challenges of hydraulic motor system

Hydraulic engine systems are often used in converting or rotating types of wave-energy conversion systems due to their advantages of stronger resistance to low-frequency and high-frequency energy waves [56]. Meanwhile, in-compressible fluid utilized in hydraulic motor systems can lead to higher efficiency, for instance, literature [54] indicates that a typical hydraulic motor system's efficiency is close to 90%. In low sea conditions, the efficiency tends to decrease. Literature [56] proposes and designs a HPTO for various WECs. Simulations in low-energy sea conditions suggest that this PTO can achieve 71% efficiency. Literature [57] presents the design and manufacturing of another HPTO, with an average efficiency of about 72% . In such circumstances, both HPTOs have demonstrated satisfactory performance.

Furthermore, in order to optimize energy harvest, the hydraulic motor system has also been employed effectively to regulate WEC movement in line with ocean wave conditions [58].

Besides, the hydraulic motor system can be built utilizing hydraulic components modified from typical commercial applications [57], which further enhance its commercial applicability.

Apart from the aforementioned advantages, the application of a hydraulic motor system also brings some challenges. Firstly, the contaminant of the hydraulic system poses serious potential environmental risks since the marine environment might be severely polluted once a leakage occurs [53]. Moreover, regular system maintenance is a further issue during the operation of the hydraulic engine system, as it is costly, high-risk, and time-consuming to carry out maintenance in the marine environment. In general, the moving parts and fluids in the PTO system require regular necessary inspection and replacement. Besides, the construction and operation of the HPTO unit are more complicated than other types of PTO, thus more components'parameters need to be considered and tuned during the optimization. At last, end-stop concerns are crucial for HPTO system, because when encountering some of the most unexpectedly strong ocean waves, the hydraulic actuator may surpass its maximum displacement limit and perhaps cause a system failure. Fortunately, this problem can be addressed by employing a radial hydraulic piston, attaching a mechanical limit stopper, or utilizing a radial hydraulic piston.

### 3.2 Pneumatic air turbine transfer system

A pneumatic air turbine transfer system is another very well-known type of PTO system for WEC. In general, compressed air systems use air turbines that directly drive generators to generate electricity. As shown in Fig. 8, an air turbine transfer PTO system is shown schematically. Figure 9 shows a schematic of the direct current (DC) grid interface system for an air turbine generator.

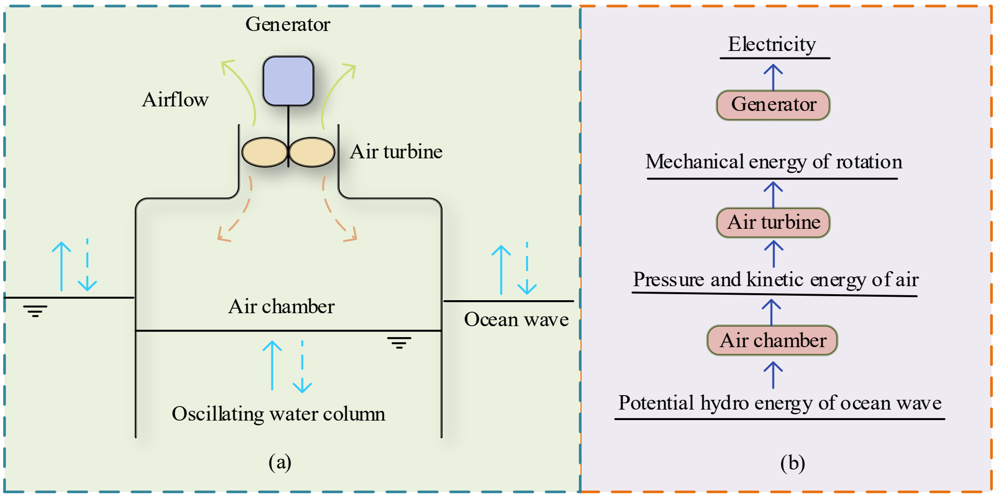


**Fig. 8.** The schematic of the air turbine transfer-based PTO system: (a) schematic view and (b) energy conversion chain [59].

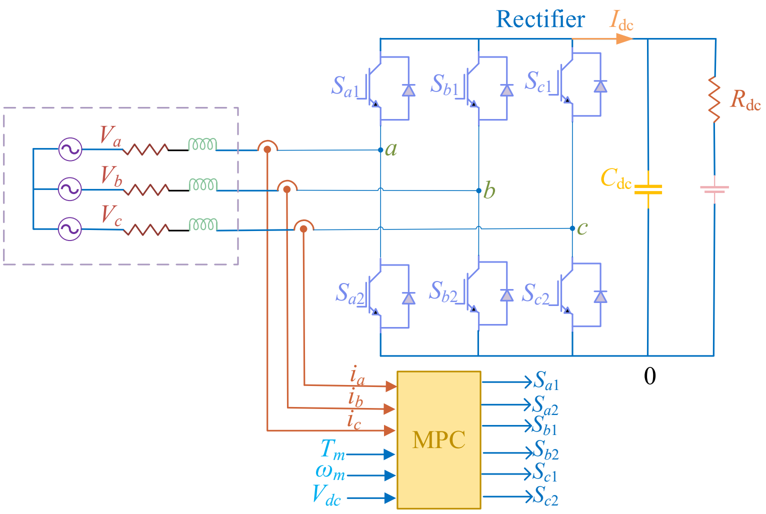


**Fig. 9.** Air turbine generator-DC grid interface system [60].

### 3.2.1 Type of air turbines

Table 3 summarizes different types of turbines, and the basic characteristics of the main four types of air turbines are outlined in Table 4. At the same time, the schematic diagrams of four typical air turbines are shown in Fig. 10.

**Table 3.** Different types of air turbines [59].

| Type | Specific classification |
|---|---|
| Wells turbine | ● Wells turbine with guide vanes;<br>● Turbine with self-pitch-controlled blades;<br>● Biplane Wells turbine with guide vanes;<br>● Contrarotating Wells turbine. |
| Impulse turbine | ● Impulse turbine with self-pitch-controlled guide vanes;<br>● Impulse turbine with active-pitch-controlled guide vanes;<br>● Impulse turbine with fixed guide vanes;<br>● McCormick counterrotating turbine. |
| Radial turbine | ● Radial turbine with fixed guide vanes;<br>● Radial turbine with active-pitch-controlled guide vanes. |
| Cross-flow turbine | - |
| Savories turbine | - |

**Table 4.** Main characteristics of four types of air turbines.

| Turbine type | Characteristic |
|---|---|
| Wells air turbine [7,61] | ● Torque is independent of the direction of airflow;<br>● High peak efficiency;<br>● Low equipment cost;<br>● Relatively low overall efficiency;<br>● Poor starting characteristics;<br>● High noise level. |
| Dennis-Auld air turbine [7] | ● Larger pitch range than Wells turbine;<br>● Self-rectifying turbine;<br>● High efficiency. |
| Impulse air turbine [7,60] | ● Various versions so as to adapt different situations;<br>● High efficiency;<br>● Large aerodynamic losses. |
| Radial-type turbine [7] | ● High efficiency;<br>● Large losses due to bearing friction and rotor disc;<br>● Self-rectifying axial flow turbine;<br>● Simple structure;<br>● High reliability. |

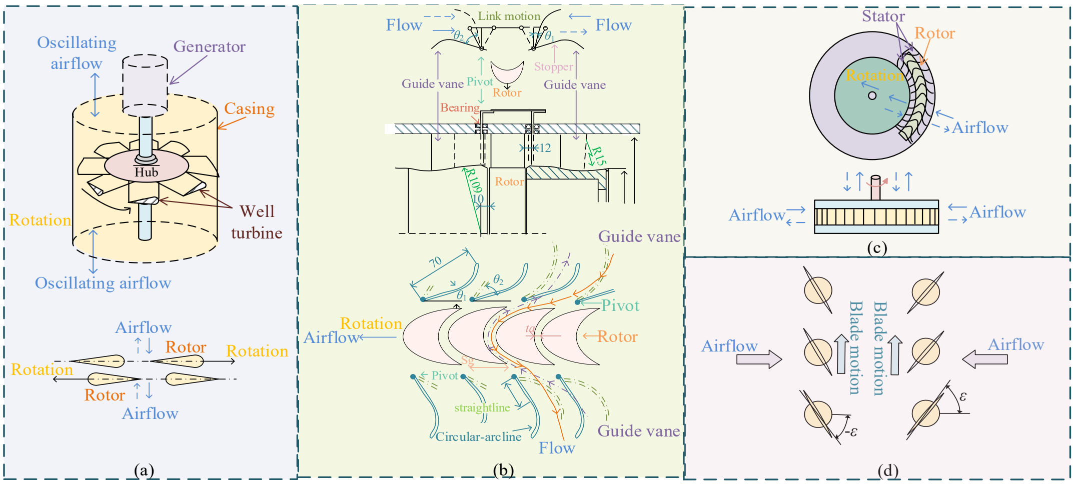


**Fig. 10.** Illustration of four air turbines: (a) a schematic diagram of a Well turbine: outline of Well turbine and contrarotation Well turbine [61]; (b) impulse turbine with self-pitch-controller guide vanes: self-pitch-controller guide vanes connected by link and schematic view [61]; (c) radial turbine with fixed guide vanes [61] and (d) Dennis-Auld air turbine [7].

### 3.2.2 Benefits and challenges of pneumatic air turbine transfer system

Air turbines have the advantage that they can be easily maintained and repaired since their turbine, generator, and related components are far above the waterline, making it relatively easily accessible [62].

The Wells turbines, however, have certain intrinsic drawbacks, including relatively lower efficiency, poorer starting characteristics, and a higher noise level when compared to conventional turbines. Variable voltage and/or frequency are produced at the output due to the functioning of the turbine and the speed of the generator that is attached to it. Consequently, regardless of the grid type, a rectifier needs to be equipped to control the turbine's speed to one or more speed levels in order to maintain the speed at the ideal level and retain the turbine's maximum efficiency. Therefore, extensive research is now being conducted to design an appropriate topological structure to identify the ideal methods for maximizing efficiency and flexibility while decreasing repair and maintenance costs, and the size of the turbine, generator, converters, etc.[12].

### 3.3 Hydro turbine transfer system

Figure 11 depicts a typical hydro turbine transfer system, in which compressed water powers the hydro turbine, which in turn drives the generator to produce energy.

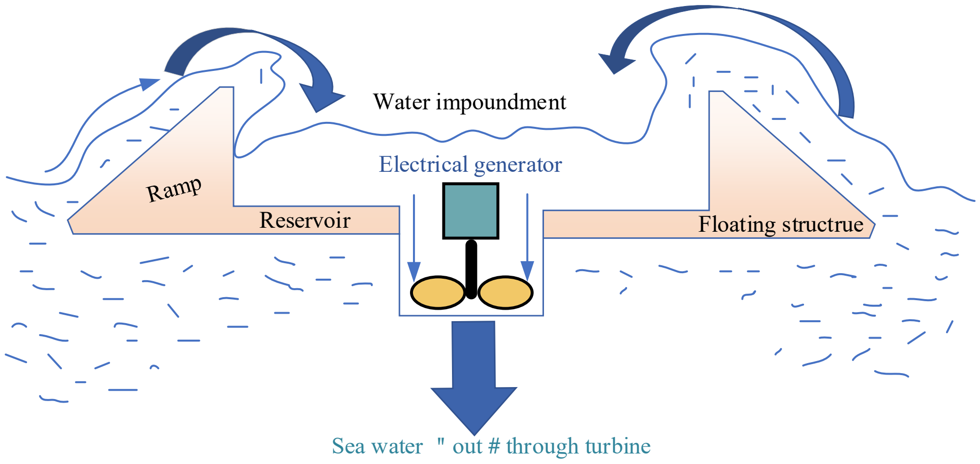


**Fig. 11.** Schematic of the PTO system based on hydro turbines [17].

### 3.3.1 Type of hydro turbines

Figure 12 illustrates some main types of hydraulic turbines and their basic characteristics.

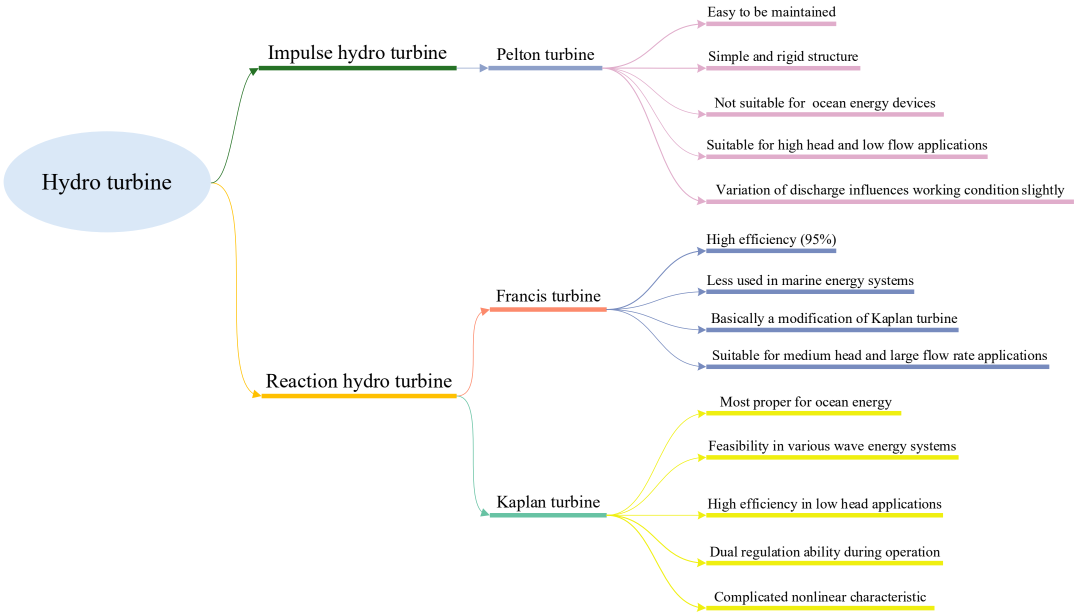


**Fig. 12.** Some types of hydraulic turbines and their characteristics [63-65].

### 3.3.2 Benefits and challenges of hydro turbine transfer system

In applications requiring low power levels (1-3 kW), conditions often involve high pressure heads and low flow rates, typically ranging from 5-20 bar (0.5-2 MPa) and 1-10 $m^3/h$ ($2.7\times10^{-4}$ to $2.7\times10^{-3}$ $m^3/s$). Specific hydraulic converter concepts are necessary, and these operating conditions are primarily associated with low-speed mixed-flow turbines [66,67].The hydro turbine transfer system is different from any other WECs as it uses a one-step energy conversion, which considerably simplifies the overall operation structure. Consequently, its energy conversion efficiency is much higher than an air turbine, which is up to 90% since water flow has a higher energy density compared to that of airflow [68]. Additionally, there is no environmental issue caused by fluid leakage when using the hydro turbine transfer system, thus it could be applied in both fixed and floating WECs on a large scale. As a kind of movable component, hydraulic turbines are vital to the operation of any offshore equipment [66], but are vulnerable to high stresses, fouling, etc.

Turbines must frequently be managed from zero to full load owing to unpredictable wave overtopping as well as low storage [69]. Turbines should be built as simply and robustly as feasible with the least number of moving components possible to maximize the efficiency of WECs [69]. Meanwhile, it is essential to devise an appropriate turbine operating plan to maximize power output while decreasing building, maintenance, and operational expenses.

### 3.4 Direct mechanical drive system

PTO system based on direct mechanical drive has been widely adopted and utilized by 31 developers worldwide. This system may be composed of components such as racks and pinions, slider crank, unidirectional bearings, belt transmission systems, belt pulley systems, or screw mechanisms. Direct mechanical drive PTO (DMDPTO), utilizing the energy of oscillating body, operates via a mechanical setup comprising a pulley and gearbox that drives an electrical generator rotating [70,71].

#### 3.4.1 Type of direct mechanical drive system

*I. Rack & pinion*

A rack-and-pinion PTO system typically involves a mechanism where a rack (a linear gear) engages with a pinion (a small gear). This interplay facilitates conversion of linear motion into rotational motion, and vice versa, providing an effective means to capture and transfer power. The detailed depiction of rack-and-pinion mechanism are visually depicted in Fig. 13. Within this system, a semi-submerged buoy is subjected to the forces of ocean waves, and vertical motion of the buoy is converted into unidirectional rotation through rack-and-pinion mechanism. Subsequently, this rotational motion is transmitted through a gearbox, propelling generator to produce electricity.

In some literatures, a detailed introduction to rack-and-pinion PTO system is provided, and its performance is evaluated. a mechanical motion rectifier (MMR) based PTO system is introduced in literature [72]. This innovative system converts linear motion into rotational motion by utilizing a rack-and-pinion mechanism, enhancing its functionality through incorporation of one-way bearings to rectify the rotational motion. Furthermore, literature [73] presents an inventive adaptive bistable PTO mechanism. This mechanism employs a rack pinion-lever-spring (RPLS) configuration featuring a time-varying potential barrier. Rack-pinion-lever (RPL) mechanism, serving as a displacement amplifier, plays a crucial role in mitigating amplitude sensitivity challenges associated with negative stiffness mechanism.

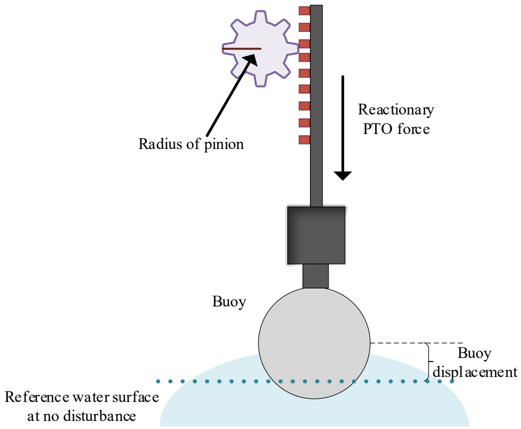


**Fig. 13.** Overall system of rack and pinion mechanism [71].

### *II. Ball screw*

The ball screw is composed of a shaft with an inclined helical groove and a nut concentric with the shaft. Nut also contains small cylindrical steel balls passing through grooves. Detailed structure is shown in Fig. 14. Ball screw possesses characteristics such as high precision, efficient power transmission, cost-effectiveness, and user-friendliness. Therefore, it has firmly established itself as a reliable component in the field of mechanics and plays a crucial role in mechanical manufacturing. Moreover, this mechanism excels in effectively converting rotary motion into linear motion [74]. Due to the efficient energy transmission of ball screw, it has become an attractive choice for scholars interested in WEC. Table 5 provides an overview of four cases employing ball screws in DMDPTO systems. At the same time, the schematic diagrams of three typical Ball screw PTO are shown in Fig. 15.

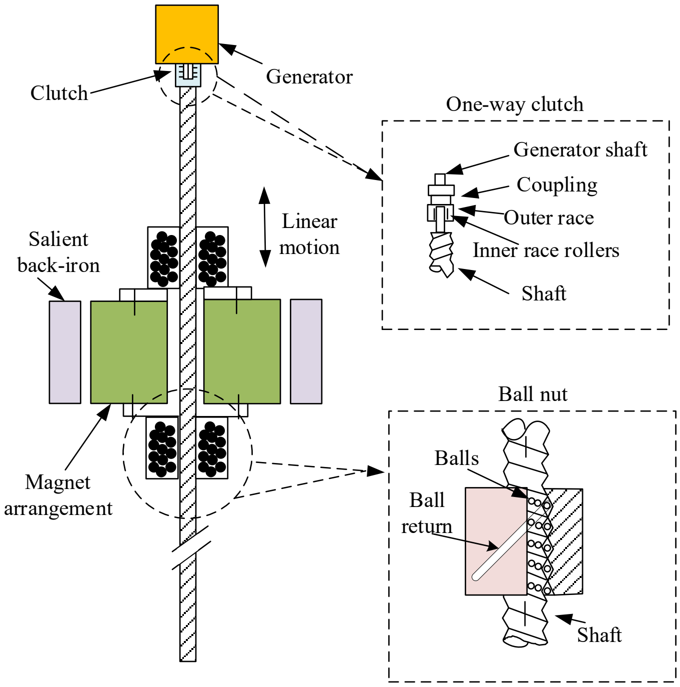


**Fig. 14.** Details of ball crew mechanism [74].

**Table 5.** Introduction of four DMDPTO systems using ball screws.

| Type | Principle | Characteristic |
|---|---|---|
| Non-MMR PTO [75] | Back-and-forth rotation of ball screw serves as a direct driving force for both generator and flywheel. | ●Susceptible to interference;<br>●Shift in peak frequency;<br>●Adjust peak power. |

| | | |
|---|---|---|
| MMR PTO [72] | MMR PTO transfers bidirectional ball screw rotation through the MMR, converting it into unidirectional rotation for electromagnetic generator. | ●High efficiency in high excitation frequencies conditions;<br>●Limited Effectiveness of MMR in low frequency conditions;<br>●Steadier generator rotation speed than a traditional type. |
| Cable-driven PTO [76] | Cable-driven PTO utilizes a ball screw directly linked to generator and reinstated through a tension spring. | ●Great flexibility;<br>●Suitable for harsh marine environments;<br>●Cable slackening can lead to a decrease in power generation. |
| Rectified unidirectional rotary PTO [77] | Ball screw and nut system convert the relative velocity of the two bodies of a WEC into one-directional rotary motion. | ●Simple control process (controlling generator resistance as a parameter, independent of buoy direction);<br>●Small mechanical friction. |

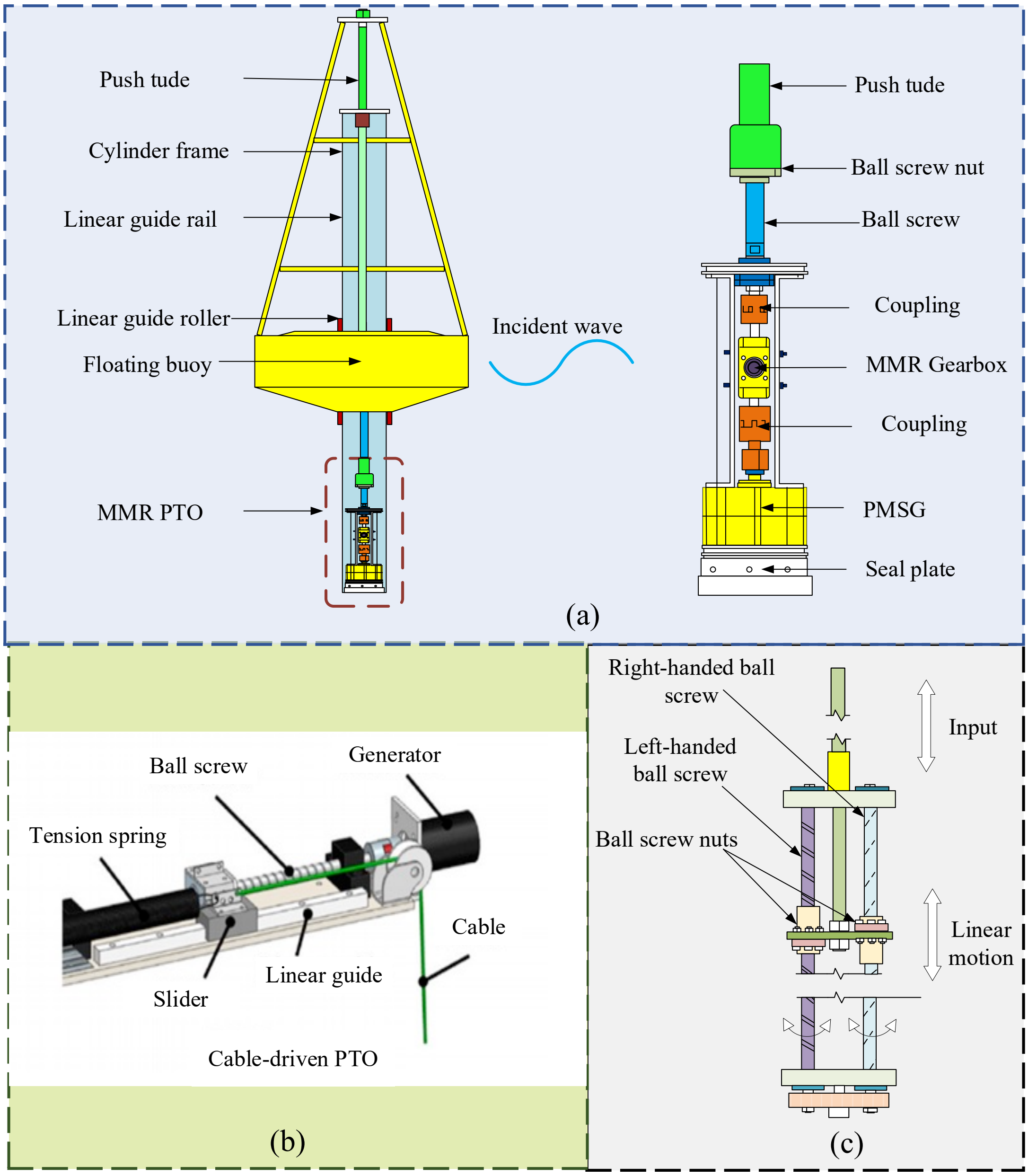


**Fig. 15.** Illustration of three DMDPTO systems using ball screws: (a) detailed designs of proposed two-body WEC and PTO with ball screw [72]; (b) cable-driven PTO [76] and (c) rectified unidirectional rotary PTO [77].

### *III. Slider crank*

Previous research has delved into direct mechanical drive systems such as rack and pinion and traction tire/wheel. However, there has been relatively limited exploration of the slider crank PTO [78]. Illustrated in Fig. 16 (a), the slider crank PTO utilizes ocean waves to exert an excitation force on the buoy. This movement of buoy—upward and downward—is then converted into rotational motion through a slider-crank linkage system and a gear box. This rotation ultimately powers a generator, producing electricity.

Literature [79] presents a slider crank PTO system that closely resembles a single-cylinder internal combustion engine. This system consists of key components such as a piston or slider, connecting rod, slider crank and buoy. Aside from the buoy, these fundamental elements bear a strong resemblance to those found in an internal combustion engine. The model of this slider crank PTO is depicted in Fig. 16 (b). It's worth noting that this system efficiently converts wave energy into electricity through a straightforward design.

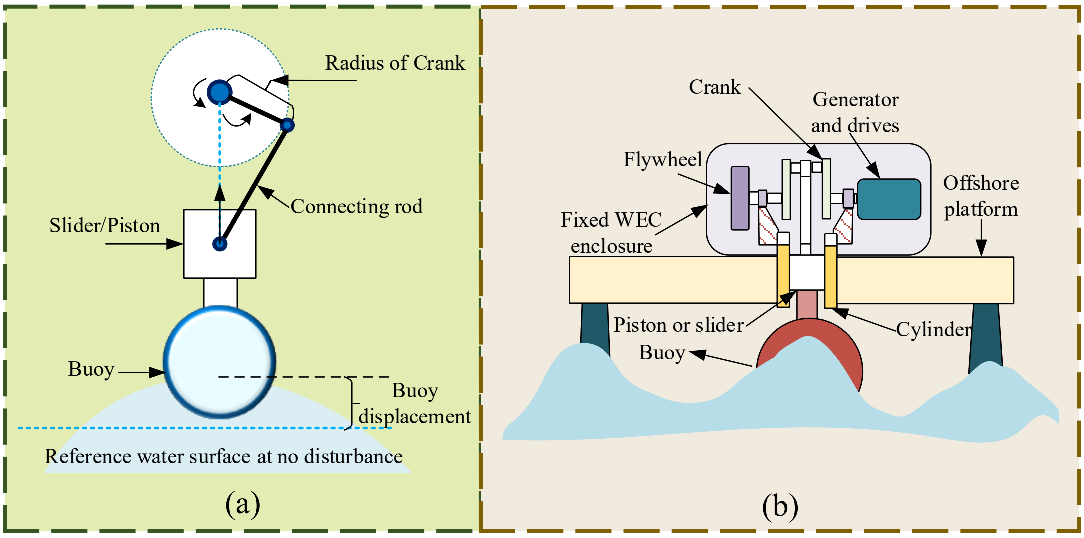


**Fig. 16.** Schematic illustration of slider crank and a type of slider crank PTO: (a) illustration of slider crank [78] and (b) a type of slider crank PTO [79].

### *IV. Dielectric Elastomer Generator*

Dielectric elastomer generator (DEG) is a flexible polymer generator that can convert mechanical energy into electrical energy by utilizing the significant deformation of an elastomer membrane. As a variable-capacitance generator, dielectric elastomer (DE) film undergoes four stages in cyclic energy conversion process: (1) an initial state with no deformation and no charge; (2) stretching under tension to increase film area and decrease the distance between electrodes; (3) injecting charge or applying voltage to generate an electric field on the DE film; (4) returning to the initial state, utilizing elastic potential energy to resist electrostatic forces and generate electricity [80,81]. The working cycle diagram of DEG is shown in Fig. 17.

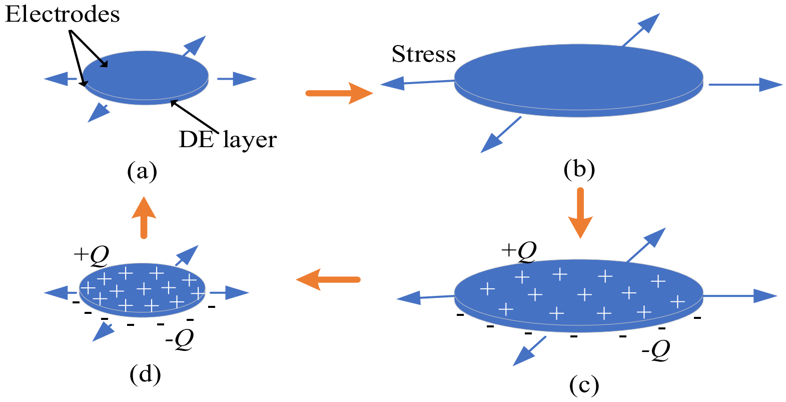


**Fig. 17.** Operating cycle of a DEG:(a) pre-stretched state; (b) the post-deformation state; (c) bias voltage charging; and (d) the elastic recovery state [80,81].

Presently, there exists a specific configuration for DEG that proves especially well-suited as a PTO for harnessing energy from ocean waves. This arrangement is adaptable to various types of WECs. It entails the symmetrical expansion of DEG layers, referred to as circular diaphragm DEG (CD-DEG), which can be seamlessly incorporated into oscillating water column (OWC) and pressure difference systems. The layout and operational diagram of CD-DEG can be seen in Fig.18 [44]. CD-DEG is compatible with diverse WEC systems and can serve as an integral component of PTO systems for various WEC types, falling into two primary categories: (1) the installation of CD-DEG on the chamber top of an OWC (illustrated in Fig.19 (a)) [82], and (2) pressure difference (PD) WEC, wherein CD-DEG is in direct contact with seawater (depicted in Fig.19 (b)) [83].

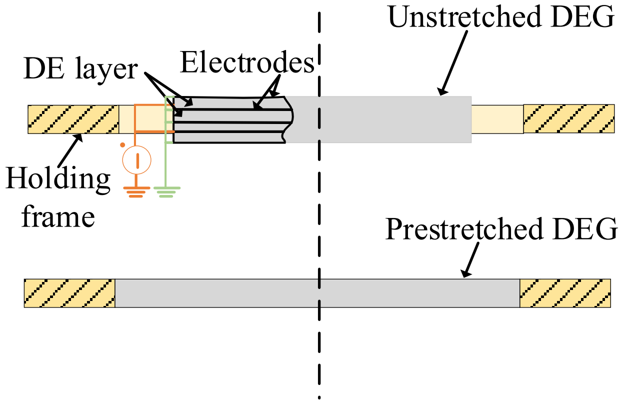
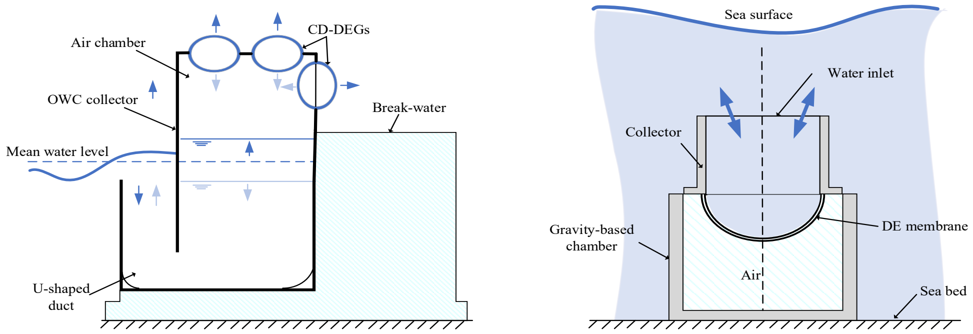


**Fig. 18.** Schematic of the CD-DEG layout [44].



(a) (b)

**Fig. 19.** Examples of WECs with CD-DEGs as PTO system: (a) breakwater integrating a U-OWC with CD-DEGs [82] and (b) architecture of PD-WEC equipped with CD-DEG [83].

### 3.4.2 Benefits and challenges of direct mechanical drive system

Globally, about 31 active companies are involved in the development of DMDPTO. For water turbines, hydraulic systems, air turbines, and direct linear generator systems, the numbers decrease to 21, 13, 13, and 11 active companies, respectively [84].This to some extent indicates that DMDPTO will be the focus of upcoming research, compared to other types of PTOs. Compared with traditional hydraulic transfer systems and pneumatic air turbine transfer systems, instead of turning mechanical energy into air or hydraulic energy, a direct mechanical transmission based system can directly realize transformation from mechanical energy to electrical energy. As a result, transmission efficiency and durability can be improved. As the system is purely mechanical, the mechanical transmission mechanism incorporates a rectification to ensure unidirectional generator rotation regardless of the buoy’s motion, which can reach the higher power production efficiency [15].

The energy conversion efficiency of MMRPTO has been proven to be higher than linear generator systems [85]. Test bench results show that, compared to traditional linear PTOs that utilize ball screws for direct drive of the generator, MMRPTOs, due to their unique free rotational movement, achieve higher efficiency, with energy transfer efficiency reaching up to 81.2%. After integrating prototype PTO with a PAWEC, test results indicate overall efficiency can reach 62.4%, demonstrating good potential for practical application [77]. Some DMDPTOs (such as MMR) are capable of converting bidirectional motion into unidirectional rotation. Moreover, a flywheel can be integrated into system to increase equivalent mass of coupling system and reduce speed fluctuation of generator [86,87].

Pneumatic air turbine transfer system needs three energy conversion processes, including wave energy to pressure, kinetic energy of air to mechanical energy, and finally to electrical energy. In contrast, one advantage of a direct mechanical drive system is only two energy conversions are required, including wave energy to mechanical energy, and then to electrical energy, such that fewer devices are involved in this system to decrease the construction and maintenance costs [18].

Similarly, for WEC, DMDPTO systems for electricity generation is an ideal choice for large-scale WEC deployment exceeding 10 kW [85]. This is because it helps avoid challenges of gap tolerance and linear guidance that linear generators face when operating at high power levels. At the same time, Experimental results demonstrate the feasibility of DMDPTO driven by wave energy in high latitude regions [76].

The primary drawbacks of this system are the limited-service life and high maintenance expenses. Meanwhile, WEC gearbox sizes also need to change according to the overall size and structure of the system, adding extra complexity to the overall system design. By carefully selecting the gear ratio and inertia, the system can adapt to different ranges of wave frequencies and amplitudes, enhancing energy extraction performance while maintaining system stability [88].

### 3.5 Direct linear electrical drive system

The direct linear electric drive PTO system directly converts the motion energy of ocean waves into electrical energy via a linear generator without any intermediate mechanical interface. A schematic illustration of the rotary and linear motor structure is shown in Fig.20 (a). As demonstrated in Fig. 20 (b), the translator attaches to the heaving buoy travels with ocean waves, which causes the translator to move vertically, and thus the generator coils create an electrical current [53].

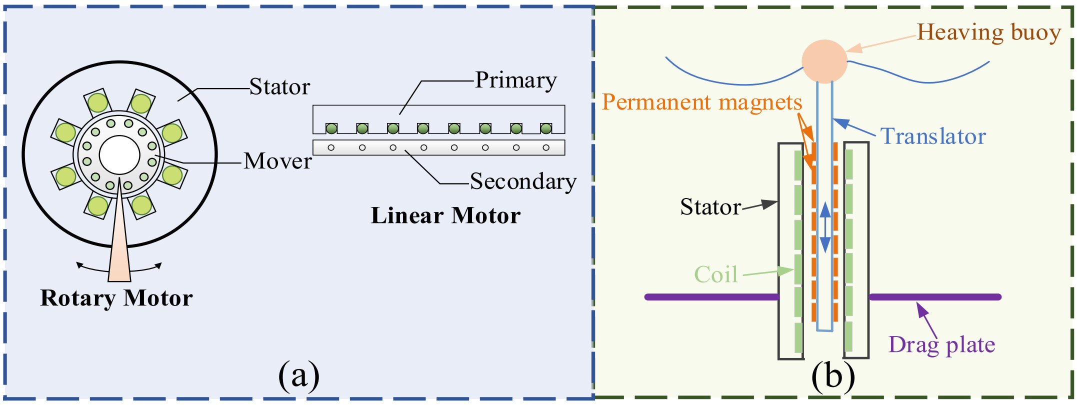


**Fig. 20.** Schematic illustration of rotary and linear motor structure: (a) basic structure of rotary motor and linear motor [89] and (b) basic linear electrical generator [53].

### 3.5.1 Type of linear direct drive generators

*I. Linear induction generator*

In a linear induction generator, an electric current is created by the rotation of the stator in relation to the rotor. The main advantage is its relatively low manufacture costs since slip rings and a collector are not equipped. Due to the poor reactance of the winding, one disadvantage of this device is that a large excitation current is needed, which lowers the device's ability to generate power [90,91].

*II. Linear permanent magnet (PM) tubular generator*

The PM tubular linear machine generates an electromotive force across an electrical conductor in a fluctuating magnetic field using electromagnetic or magnetic induction [92]. The output power of a linear tubular PM generator that comprises an iron core and armature winding may be increased by using various coil types and shapes. Literature [93] compares the performance of different types of coils, which indicates that triangularly-shaped coils output higher power than squared-off windings.

*III. PM linear synchronous generator*

The PMs in a PM synchronous generator give the excitation, and the magnetic and translator fields move at the same speed, which is known as synchronous motion. Literature [94] develops a linear PM synchronous generator, in which the cogging force that is perpendicular to the motion of the translator is reduced.

*IV. Linear switched reluctance generator*

The switched reluctance machines are based on the magneto-resistive minimization concept [95,96] in which the linear switching reluctance generator depends on a rotor position-controlled power electronic converter. Active stator poles attract rotor poles during operation, and when the stator and rotor poles are sufficiently near together, power electronic switches are triggered to transition the current to the next phase. Through a power electronic converter, the active stator propels the rotor [97].

Due to no magnets are equipped, this machine has the highest power generation efficiency, highest torque production, lowest inertia, and lowest manufacturing cost. Since the strict necessity for extremely precise and effective power electronic switches and controllers, it still cannot be effectively implemented. The design of a double-sided linear switching reluctance generator is described in literature [98], where the motor's construction is optimized and electromagnetic properties and generation efficiency are investigated. It is possible to produce energy constantly with a power production efficiency of up to 80.6%.

*V. Linear superconducting synchronous generator*

According to literature [99], superconducting magnets have been employed in place of conventional PM to complete the excitation in linear superconducting synchronous generators because they have a higher capacity to catch magnetic fields and thus perform more efficiently. Commonly, different arrangements of superconducting magnets often lead to different results, while one advantage of a linear superconducting synchronous generator is that its prominent demagnetization effect.

Literature [100] develops a tubular superconducting flux-switching generator that uses MgB2 superconducting windings due to their low manufacture costs and simple manufacture procedure [101]. High-temperature superconducting (HTS) linear generator (HTSLG) owns the inherent advantages of simple design and operation mechanism, and high operation stability, as investigated in literature [102].

### *VI. Variable reluctance PM (VRPM) machine*

VRPM machines are the most reliable OWE converters, and a number of different related machines have been explored in the literature [103,104] revealing that they are powered by reluctance torque. The fundamental benefit of a VRPM machine is that, in comparison to other traditional machines, it exhibits greater shear stress. There are two different types of flux configurations, i.e., transverse and longitudinal. Compared to transverse flux machines, PMs in longitudinal flux topologies are often positioned on the translator, whereas winding is placed on the stator, which increases magnetic coupling.

### *VII. Vernier hybrid machine*

Vernier hybrid machines are variable reluctance machines with magnets on the stator to produce magnetomotive force and slots on the rotor to adjust magnetic field [105,106]. Hybrid Vernier machines are often lighter and cheaper than their pole-splitting PM counterparts. However, the machine has an undesirable low power factor, which may be increased by additional DC field excitation winding [107].

Table 6 summarizes the advantages and disadvantages of several kinds of linear generators, meanwhile, Fig. 21 demonstrates the structure of some of them.

**Table 6.** Summary of seven kinds of linear generators.

| Type | Advantages | Disadvantages |
|---|---|---|
| Linear induction generator [108] | ● Low cost;<br>● Extremely high robustness;<br>● Low cogging force. | ● Need high excitation current;<br>● Low reactance of winding;<br>● Large air gaps have a negative impact on efficiency. |
| Linear PM tubular generator [99] | ● Stable power generation;<br>● Low core losses;<br>● Enhance output power with the use of various coil kinds and shapes;<br>● High output efficiency. | ● PMs lose magnetization after a given period of time;<br>● High total cost of construction;<br>● Significant harmonic content;<br>● Difficult to adapt to harsh working environments. |
| PM linear synchronous generator [99] | ● Low cogging force;<br>● Small bearing load because of the double-sided generator. | ● Complicated structure;<br>● Large air gap so as to decrease the efficiency;<br>● Low operation speed;<br>● Difficulty in manufacturing PM linear synchronous generator. |
| Linear switched reluctance generator [97] | ● High reliability;<br>● Low manufacturing cost;<br>● High efficiency as no wear and lubrication;<br>● Simple construction as each stage may be managed separately. | ●Low accuracy;<br>●Inefficient power electronic switches and controllers. |
| Linear superconducting synchronous generator [99] | ● High stability;<br>● Simple structure;<br>● Reduce the demagnetization effect of the magnet. | ● High construction costs. |
| VRPM machine [99] | ● High Power factor;<br>●High electrical power generation. | ● Need large amounts of expensive PM;<br>●Complicated manufacturing process. |
| Vernier hybrid machine [99] | ●Small overall weight;<br>● High efficiency as it has an excellent magnetic flux path. | ● Low power factor;<br>●High maintenance burden;<br>● Complicated structure. |

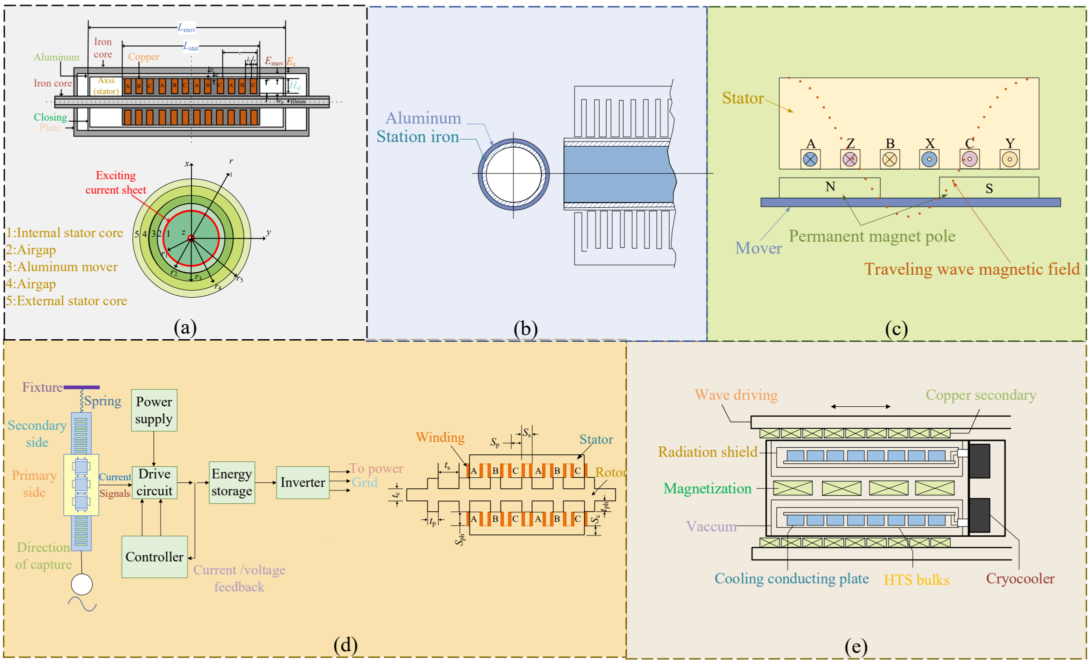


**Fig. 21.** Five types of linear generators: (a) longitudinal section and multilayer transverse section of linear induction generator [109]; (b) linear PM tubular generator [89];(c) PM linear synchronous generator [110]; (d) linear switched reluctance-base generation system [98],[99] and (e) linear superconducting synchronous generator [102].

### 3.5.2 Benefits and challenges of direct linear electrical system

Compared to indirect drive PTO devices, direct linear electrical systems show the benefit of fewer intermediary systems and parts, which increases reliability and robustness [99]. Additionally, by avoiding the losses in conventional PTO systems (such as those using turbines and hydraulic motors), and by eliminating intermediate conversion stages (such as hydraulic, pneumatic, or pumping), direct drive systems have the potential for higher efficiency and reliability, which could reduce the cost of energy (COE) [2]. In general, linear generators have fewer mechanical failure modes, high reliability, and less maintenance needs. As a result, MW-level deployments of renewable energy systems are forecasted to favor linear direct drive generators over rotating generators in the future.

Optimization of electric linear generators in literature [111] has achieved an impressive 96% efficiency under ideal conditions, a noteworthy improvement compared to traditional linear generators. Columbia Power Corporation, in collaboration with Siemens, has developed a large-scale rotary generator for direct drive applications, with a prototype's rated power of 0.65 MW, indicating substantial high-power potential [112]. For low-power wave energy applications (10 kW) employing heave PA, a synchronous PM linear generator proves to be a robust solution. However, at higher power levels, this topology faces challenges such as air gap tolerance and linear guidance, which are difficult to address in an economically efficient manner [110]. At higher power levels (10 kW), double-dynamic reluctance systems have been found to surpass both linear and linear-to-rotary PTO [85].

Since waves travel slowly in general, a direct linear electrical system's motion speed in direct drive WECs is likewise relatively slow, which is the fundamental drawback of a linear generator. Another drawback is that, compared to rotary generators, linear generators have a larger physical mass because they require higher rated force or torque for the machine [15].

Furthermore, the unequal voltage produced by uneven wave motion tends to cause the system of power transmission to be highly complicated [113].

### 3.6 TENG system

TENG begins with no starting charge because when two materials (typically connected to two electrodes) touch, their electronegativity differences produce triboelectric charges on the two surfaces. As the two contacting surfaces separate, a potential difference builds and changes, causing electron flow from one electrode to the other across the external circuit. Charges flow back via the external circuit to adjust for electric potential fluctuation as the two surfaces approach closer [114]. TENG may operate in four distinct modes: vertical contact separation, lateral sliding, single-electrode, and freestanding triboelectric layer, as shown in Fig. 22.

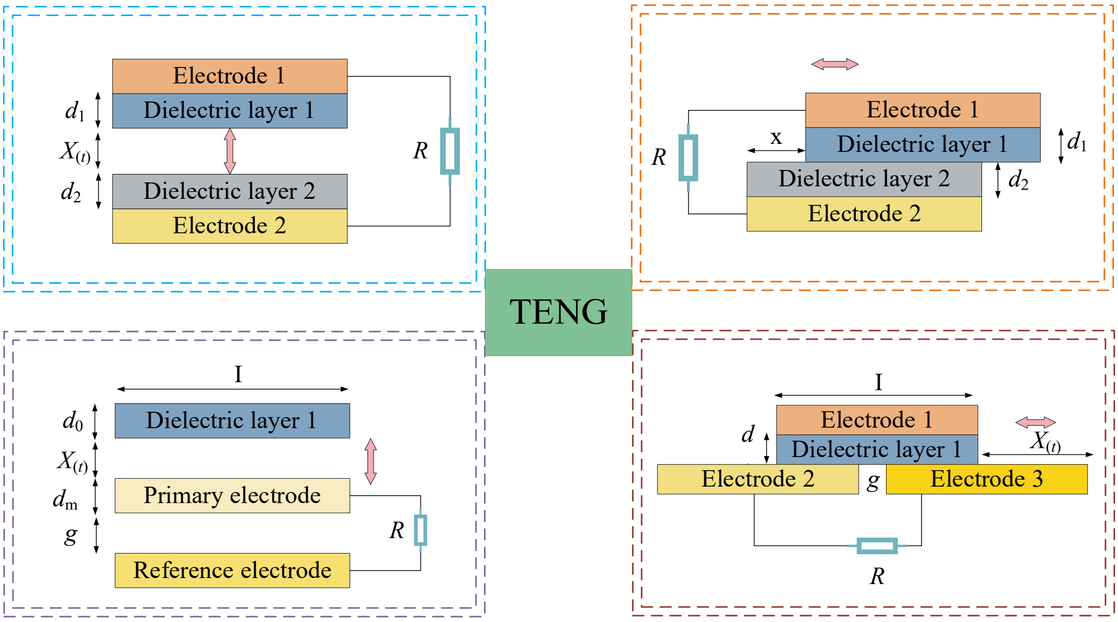


**Fig. 22.** The operating principles of TENG: (a) basic vertical contact-separation working mode; (b) lateral sliding working mode; (c) single-electrode working mode and (d) freestanding working mode of TENGs [115].

#### 3.6.1 Benefits and challenges of TENG-based PTO system

TENG-based PTO systems are emerging as a viable option for PTO aboard tiny maritime buoys because they can easily transform erratic movements into an alternating current in a more constrained environment [116]. Besides, TENG-based PTO system owns the desirable merits of proper size, simple structure, and low costs [117].

However, on the other hand, engineering issues including load matching, system integration, and output stability should be concerned and solved before the real application. Some other challenges on power transmission to shore, device service life in the ocean environment, equipment lifespan expansion costs, and management of large equipment networks still need to be properly dealt with. At present, TENG is utilized to gather energy across all frequency bands, some representative TENG-based PTO systems are tabulated in Table 7.

**Table 7.** Summary of representative TENG-based PTO system.

| Mode | Examples | Characteristics |
|---|---|---|

| | | |
|---|---|---|
| Rolling-structure mode [118] | Rolling-structured freestanding triboelectric-layer-based nanogenerator (RF-TENG) | ●Miniature and light weight;<br>● Low construction cost;<br>● High charge transfer effectiveness at low frequency. |
| Liquid-solid mode [119] | Liquid-solid TENG (LS- TENG) | ● Low impact of electrostatic interference and saltwater corrosion;<br>● High output power. |
| Disk and rotation mode [120] | Swing-structure TENG (SS-TENG) | ● Low friction;<br>●High toughness and durability. |
| Contact-separation mode [121] | A multilayered TENG-based self-powered intelligent buoy system for collecting wave energy. | ● Operate in contact-separation mode;<br>● Average output power density of 13.2 mW/m2 with a 2 Hz wave frequency. |

### 3.7 Hybrid system

Hybrid offshore, wind, and PV systems combine the strengths of each technology. Although hybrid topology is new to wave energy integration, numerous researchers have constructed and installed hybrid WECs for investigation, and some representative hybrid systems are shown in Fig. 23.

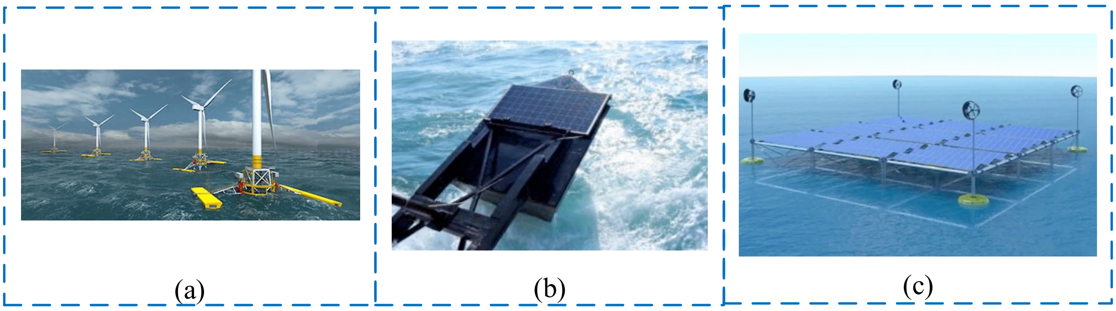

(a)
(b)
(c)

**Fig. 23.** Illustration of hybrid systems: (a) wind and wave system [122]; (b) solar and wave system [123] and (c) wind, solar, and wave system [124].

#### 3.7.1 Type of hybrid systems

*I. TENG and electromagnetic generator (EMG)*

TENG and EMG may be coupled to harvest blue energy to the largest extent in a broad frequency range. TENGs can efficiently capture low-frequency (<0.5 Hz) motion, while EMGs allow them to provide more output at a relatively high frequency, fulfilling the goal of blue energy harvesting within a wide frequency range. Literature [125] proposes a multifunctional hybrid power unit for harvesting blue energy. Literature [126] describes the establishment of a hybrid power unit using a multilayered soft-brush cylindrical TENG (MBC-TENG) and a rotary disc EMG (RD-EMG). MBC-TENG's performance and durability may be greatly improved by soft brushes and the WEC's multilayered construction. Thanks to magnetic coupling, MBC-TENG can be linked with RD-EMG and completely sealed off from the outside world.

*II. Wind and wave*

This hybrid system integrates wind and WECs on the same platform, with Poseidon 37, W2Power, offshore wind power and OWE as representative applications [127].

The W2Power wave-wind system consists of a semi-submersible offshore wind power platform, which is composed of two wind turbines (WTs) and multiple oscillating body WECs [128,129]. W2Power is an ocean demonstration project developed by Norwegian company

Pelagic Power. Full-scale W2Power design aims to generate 10 MW of electricity, including 2×3.6 MW WTs and 2-3 MW of wave energy. A 1:6 scale device has already been tested near the Canary Islands.

Floating power plant Poseidon wave-wind system utilizes a buoyancy-stabilized platform, consisting of 3 WTs and multiple WECs [130]. Poseidon is developed by Danish floating powerboat company. Depending on the site, the full-size Poseidon system can range from 80 to 150 m long, with a 37 m model already tested in Danish waters. The 37 m scale model includes 10×3 kw WECs and 3 ×11 kw WTs [131]. Poseidon features both oscillating bodies and OWCs. The full-size Poseidon system will include 2.6 MW from OWCs and 2.3-5 MW from WTs.

Literature [132] proposes a cutting-edge hydraulic transmission wind-wave hybrid power generation system with four key parts: wave energy harvesting, wind energy harvesting, energy coupling, and power conversion management.

*III. Solar and wave*

By integrating photovoltaic (PV) cells onto the unused open-sky surface of wave devices, a novel idea of wave-voltaic has been presented [133,134]. Jahangir and others considered all possible scenarios for the hybrid PV-WEC system [135]. Literature [136] focuses on hybrid PV-WEC, presenting diverse combinations of offshore hybrid power systems utilizing wind and wave energy. System performance is assessed economically to pinpoint the most cost-effective equipment pairings, considering potential benefits from shared infrastructure and operational costs.

*IV. Wind, solar, and wave*

Currently, it is common to have hybrid systems combining PV with WEC, as well as hybrid systems combining WT with WEC. Of course, there are also hybrid systems that integrate PV, WT and WEC. However, there is limited research on such integrated systems. Literature [137] conducts an analysis of a zero-emission energy system combining Pelamis WEC, WT, PV and batteries from technical, environmental, and economic perspectives. The aim is to provide electricity to 3,000 households in three different regions of Iran (Jask, Genaveh, and Anzali cities). Literature [138] proposes a dynamic modeling and control method for a hybrid system of PVs, wind energy, and wave energy. Researchers from the U.S. Bureau of Statistics analyzed the integration of wave energy with wind and solar energy into the power grid, demonstrating the feasibility of this hybrid system [139]. Literature [7] develops a platform that utilizes wind, PV, and wave technologies, which can endure waves up to 6 m in height. Each module of this ocean hybrid platform by SINN Power contains four WECs with a capacity of 0.75 MW, 20 kW of the PV system, and four wind turbines with a capacity of 6 kWp. It was developed to provide coastal locations with simple access to renewable energy options [7].

### 3.7.2 Benefits and challenges of hybrid system

Due to their hybrid nature, hybrid systems are not prone to the unpredictability of a single resource, leading to higher power efficiency and more seamless integration into the grid network. Meanwhile, offshore farms tend to cut installation and mooring costs by sharing the grid connection, logistics, and similar infrastructure.

However, since hybrid systems usually contain two or even more power generation systems, the structure's complexity will be inevitably enhanced. Thus, one of the challenges is that an advanced control scheme is required to regulate the systems'performance under different operation conditions. Another one is more complex and severe tasks are needed during the installation and removal of hybrid systems, especially under unfavorable weather conditions.

### *I. Wind and wave*

Compared to other hybrid systems, hybrid wind-wave systems are currently the most researched. The future vision of hybrid wind-wave systems includes a offshore platform that can optimize the utilization of ocean space because it can generate a large amount of energy at sea [140]. Compared to two independent systems, a universal platform can simplify maintenance and grid connection, and improve capital expenditure operational and maintenance expenses (CAPEX) and operational and maintenance expenses (OPEX) [141]. In cases studied in literature [142], the combination of 160 MW of wind power generation and 40 MW of wave power generation produced the lowest production cost. When cost is shared at 15%, the average energy cost is EUR 107 /MWh. In the research area, due to European energy crisis, the average electricity price in autumn 2022 exceeded EUR 300 /MWh. Once WEC technology is developed, multiple WECs producing 1 MW of power each will make significant contributions to offshore WTs with capacities of 5-10 MW.

At this stage of development, the biggest advantage of hybrid wind-wave systems is to use WECs to suppress platform motion and provide local power demand. Some studies have found that the motion of offshore WT platforms is reduced by using WECs. Literature [143] studies a hybrid system consisting of a mast-type offshore WT and three WECs, finding that fatigue load of floating offshore WT platform was reduced by 23%. Literature [144] studied a hybrid beam with WECs through numerical and experimental research, finding that a single WEC can reduce 16% of heaving motion, 21% of pitching motion, and 6% of fatigue stress. Literature [145] reduced the pitching motion of a semi-submersible offshore WT group by 50% through WEC control.

There are still some challenges at present. The types of WECs are diverse, lacking integration in design. WECs must economically generate electricity in typical sea conditions and survive in harsh storm conditions. These challenges increase risks, complexity and costs of hybrid systems compared to floating offshore WTs. Additionally, power output of current WECs is an order of magnitude smaller than that of WTs. Ideally, each WEC would generate 1 MW, but currently, their electricity generation is approximately 100-500 kW, whereas offshore wind turbines have a capacity of 5-10 MW [146].

Lastly, more research is needed on motion suppression of marine platforms. Due to the larger safety distance required for WTs compared to WECs, if safety distance is too small, there will be a wake effect between WTs. The two main drawbacks of the wake effect are: (1) a reduction in energy production of the WT field, and (2) an increase in the mechanical load on downwind turbines due to turbulence [147].

### *II. Solar and wave*

The hybrid PV-wave system demonstrates favorable economic performance. According to literature [148], an assessment was conducted on technical and economic impacts of hybrid system under both finite and infinite generator scenarios. The results indicate that in the case of a finite generator, energy cost of hybrid system comprising PV panels, diesel generators, and Wavestar WECs is 0.224 $/kWh, with a renewable resource utilization rate of 82.1%. In the infinite generator scenario, the energy cost for hybrid system incorporating PV panels, diesel generators, and Aquabuoy WECs is 0.209 $/kWh,, yielding a net present value of $103,000, making the hybrid system the optimal choice. Additionally, in the optimal scenario, energy cost of Wavestar converter is 0.385 $/kWh, and the reported percentage of renewable energy equipment usage is 71.4%.

It is noteworthy that the ubiquitous shadows caused by moving objects in this hybrid system are unfavorable because they reduce the efficiency of PV cells, which need to be optimized by proper optimization schemes for optimal power generation [149]. It is anticipated that the next generation of large-scale blue energy harvesting will be inspired by this cost-effective hybrid technology, which can harvest and store the wave and solar energy that is found in the ocean. Currently, the modeling of WECs is predominantly focused on frequency domain modeling. However, for PV systems, their output power varies with changes in temperature, solar radiation angle, and incidence angle, manifesting in the time domain. Effectively integrating these two aspects into a model poses a significant challenge.

*III. Wind, solar, and wave*

Integrating wave, PV and WT into the main DC bus is aimed at enhancing the efficiency of renewable energy systems. The hybrid system can be seen as combining advantages of mixed wind-wave and mixed PV-wave systems. However, it is noteworthy that there is currently no invention that integrates these three onto a single platform. Essentially, these systems are arranged independently at sea to maintain a safe distance.

Currently, the challenges for such a hybrid system are immense. Experimental test beds have been established to research how to integrate the three different types of renewable energy to produce energy cohesively. Wave energy research has been undertaken but faces a prominent challenge: variations in wave intensity, direction and height lead to fluctuations in energy output. Converting this fluctuating energy into electricity poses a challenge. Wind and solar energy are also influenced by different environmental conditions, such as changes in solar radiation and wind speed [138]. Therefore, combining wind, solar, and wave energy is a significant challenge.

WTs may partially obstruct PV panels, affecting the output of solar energy. Due to the smaller safe distance between WEC, which is much smaller than safe distance required for WTs, a smaller safe distance results in the wake effect between turbines, balancing the mutual influences between the three components, ensuring an increase in output power remains a substantial challenge [150].

## 4. PTO control strategies

Control of PTO has a significant impact on the primary energy capture methods and performance of electrical components. Appropriate control methods can enhance key performance indicators of WECs, particularly energy conversion efficiency [16]. Objective of optimal control theory is to achieve phase matching, allowing the WEC to enter a resonant state, amplify its motion, and absorb more energy. Currently, common PTO control methods include the control of generators and turbines torque, airflow, current, power or valves. These control methods are typically employed individually or through a combination of mentioned control objects. The following is a comprehensive description of control strategies adopted by different PTOs.

### 4.1 All-electric PTO

The PTO force, also known as the electromagnetic force on the translator, may be adjusted by modifying the generator's power or current. This kind of regulation is possible for both linear PM generator (LPMG) and rotating PM generators (RPMGs). The power electronic converter is a well-established method for generator-side control, as shown in Fig. 24.

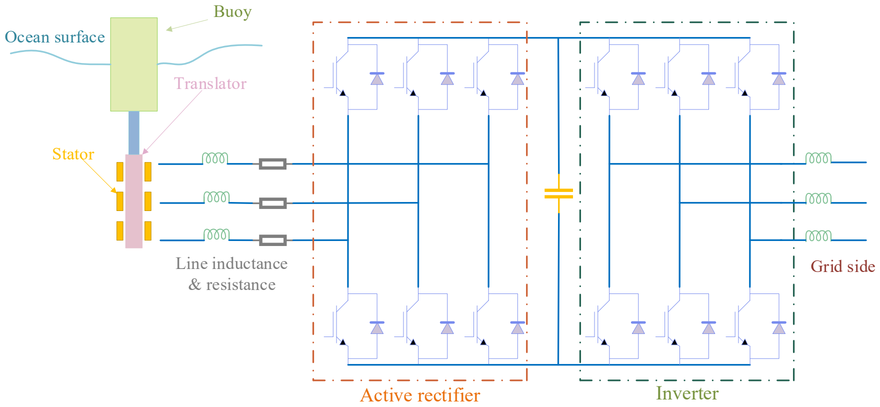


**Fig. 24.** A direct drive linear generator with a back-to-back converter [151].

Table 8 illustrates two control techniques derived from the literature [152], namely, the reactive control approach and the damping control strategy for arrays of WECs. Three current control strategies are proposed in the literature [153], which are summarized in Table 9. Literature [154] proposes that the voltage source converter (VSC) on the LPMG side is a pulse width modulation (PWM) rectifier that permits bidirectional current control by applying a voltage-oriented control (VOC) technique, allowing the LPMG to collect maximum power from waves.

### 4.2 DMDPTO

Currently, the control approach for DMDPTO predominantly employs latching control. This control method maintains oscillating body in a latched state for a specified time interval (latch duration) and releases the oscillating body at a specific moment (unlocking). This is achieved by adjusting phase of oscillation oscillator's speed to wave excitation phase, thereby increasing power absorption of WECs. Locking of the buoy can be provided by PTO system or other mechanisms (such as mechanical brakes or hydraulic systems). However, increasing motion amplitude of buoy is not sole challenge for achieving optimal WEC performance; it also depends on the efficiency of PTO system. Another control strategy is maximum power point tracking (MPPT) technology. MPPT algorithm, widely applied in renewable energy sources such as photovoltaics and wind energy, has subsequently been used in WECs to optimize energy extraction and enhance efficiency. Table 10 provides an overview of two types of latching control and MPPT control for DMDPTO.

### 4.3 Turbine PTO

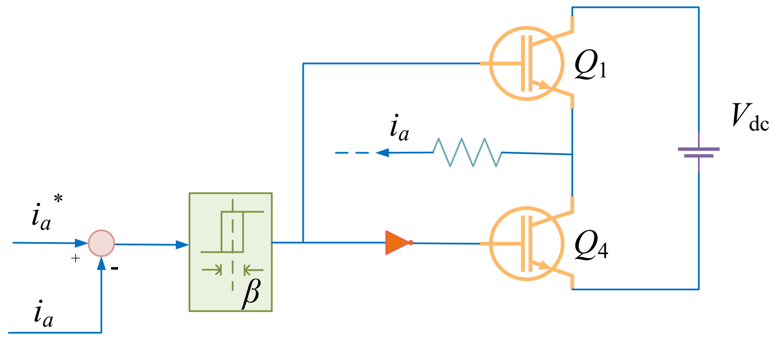
In control of turbine PTO systems, current predominant approaches involve employing various control strategies to regulate valves, torque, air pressure and airflow, aiming to achieve maximum power output. Regarding valve control, different control strategies are applied based on the type of valve, with the high-pressure safety valve (HSSV: one type of valve installed in series with the turbine) being the most commonly used at present. Specific control strategies for these valves are detailed in Table 11. As for torque control, it is the most widely adopted method, primarily achieved by adjusting the speed of generator or turbine, or by regulating air chamber pressure. Torque control solutions for turbines mounted in an oscillating water column are summarized in Table 12.

**Table 8.** Summary of reactive control strategy and damping control strategy.

| Control strategies | Control objective | | Controller design | Parameters | Description | Power production performance | Losses | Complexity | Applicability |
|---|---|---|---|---|---|---|---|---|---|
| | Amplitude | Phase | | | | | | | |
| Reactive control strategy [152] | √ | √ | Load impedance: For$(n = 1, \cdots, 6)$:<br>$Z_{\mathrm{PTO}n} = iwM_{\mathrm{L}n} + B_{\mathrm{PTO}n} + \frac{i}{w}K_{\mathrm{PTO}n}$ | $B_{\mathrm{PTO}}$: damping;<br>$K_{\mathrm{PTO}}$: stiffness force;<br>$M_{\mathrm{L}}$: quantity mass;<br>$n$: numbers of WEC in arrays. | Reference load impedances for each WEC in arrays are computed for optimal control. | *** | *** | *** | ** |
| Damping control strategy [152] | | √ | Load impedance: For$(n = 1, \cdots, 6)$:<br>$Z_{\mathrm{PTO}n} = iwn_{\mathrm{L}n} + B_{\mathrm{PTO}n}$ | $B_{\mathrm{PTO}}$: damping;<br>$K_{\mathrm{PTO}}$: stiffness force;<br>$M_{\mathrm{L}}$: quantity mass;<br>$n$: the numbers of WEC in arrays. | Sub-optimal control: For each WEC in the array, just the PTO damping coefficient (given by the LG impedance) is evaluated. | ** | ** | ** | *** |

*Note. N.P.: not provided; *: very low; **: low; ***: medium; ****: high; *****: very high. Power production performance is judged by average power sent to the grid and peak power; a low generator working power factor, which will increase losses, is used to evaluate losses; complexity depends on how the control strategy works, the control algorithm, and the complexity of the device; applicability is judged by the accuracy of prediction of the incident wave.

**Table 9.** Summary of three current controllers: hysteresis-band current control (HBCC); space-vector PWM current control (SVPWMCC); spatial hysteresis current source control (SHCSC).

| Type | Current controller | Operation principle | Performance |
|---|---|---|---|
| HBCC [153] |  | For this control scheme, one independent controller per phase is used. For each of the three phases, depending on the difference between the instantaneous reference current and the generator terminal phase current, booster switches are actuated according to the hysteresis band. | • Excellent dynamic performance;<br>• Fluctuating switching frequency;<br>• No communication among hysteresis controllers. |

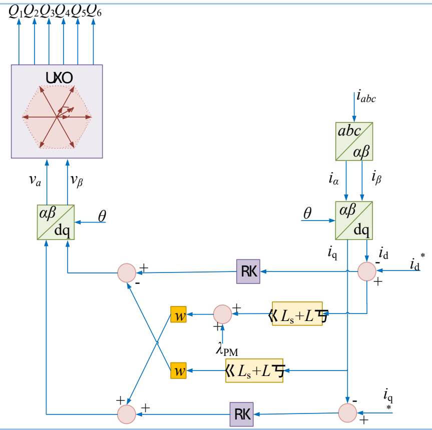
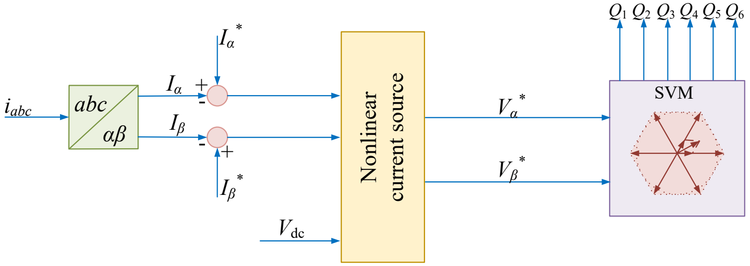
| | | | |
|---|---|---|---|
| SVPWMCC<br>[153] |  | This control technique converts generator terminal currents to $d_q$ components. After that, two proportional-integral (PI) controllers use the resultant $d_q$ voltage references as inputs to a VSC. | • Specific switching frequency;<br>• Constantly changing operating points. |
| SHCSC<br>[153] |  | It combines the hysteresis-based control utilized in traditional nonlinear current sources like the Bang-bang with the support vector machine (SVM) approach. The benefits of both the HBCC and SVPMWCC are combined in this controller using a nonlinear current source and an SVM. | • High out power;<br>• Avoid risk of overcurrent. |

**Table 10.** Summary of two types of latching control and MPPT control for DMDPTO.

| **Control strategies** | **Controller design** | **Parameters** | **Control principles** | **Performance** |
|---|---|---|---|---|
| Non-predictive latching control [155] | Latching duration:<br>$LD = (T_{\mathrm{w}} - T_{\mathrm{n}}) / 2$ | $T_{\mathrm{w}}$ : incident wave period;<br>$T_{\mathrm{n}}$ : buoy natural period. | PTO force decreases to zero in latching stage. | ●Power production of the WEC up to between 38% and 281%;<br>●Short lifetime (working under an average speed of up to 200% large than the control-free condition for a long time may overheat the generator). |
| Latching control [152,156] | latching control force:<br>$F_{\mathrm{c}} = m(v_{\mathrm{f}} - v_0) / \Delta t - (F_{\mathrm{b}} + F_{\mathrm{r}} + F_{\mathrm{e}} + F_{\mathrm{v}} + F_{\mathrm{p}})$ | $m$ : mass of buoys;<br>$v_{\mathrm{f}}$ : buoy velocity at beginning of time step;<br>$v_0$ : buoy velocity at end of time step always equals to 0;<br>$\Delta t$ : time step of numerical solution;<br>$F_{\mathrm{b}}$ , $F_{\mathrm{r}}$ , $F_{\mathrm{e}}$ , $F_{\mathrm{v}}$ and $F_{\mathrm{p}}$ : restoring force, wave radiation force, wave excitation force, viscous damping force and PTO force. | During buoy oscillation, control system is activated only when buoy velocity reaches 0 or becomes very small. Buoy is latched for a predefined time interval (latching duration) and then released. | ●High PTO mean power;<br>●Complex control process (latching control system depends on the gear ratio and flywheel inertial). |
| MPPT perturb and observe (P&O) method [157] | MPPT P&O method:<br>$P_{\mathrm{g}} = K^2 \omega_{\mathrm{g}}^2 R_{\mathrm{g}} / 2((N_{\mathrm{p}} \omega_{\mathrm{g}} L_s)^2 + (Rs + R_{\mathrm{g}})^2)$<br>$T_{\mathrm{g}} = P_{\mathrm{g}} / \eta_{\mathrm{g}} \omega_{\mathrm{g}}$ | $P_{\mathrm{g}}$ , $\eta_{\mathrm{g}}$ , $R_{\mathrm{g}}$ and $\omega_{\mathrm{g}}$ : power, efficiency, resistance and speed of generator;<br>$K$ : back electromotive force constant of generator;<br>$N_{\mathrm{p}}$ : pole pairs number;<br>$L_s$ and $Rs$ : stator inductance and resistance;<br>$T_{\mathrm{g}}$ : generator torque. | MPPT P&O algorithm is utilized to obtain maximum available power by periodically adjusting $R_{\mathrm{g}}$ value, thereby modifying generator torque through a gradient ascent approach. | ●Maximum mean power (approximately 50% of the rated power);<br>●High capture width (approximately 53%). |

**Table 11.** Types of valves and corresponding control strategies.

| Control objective | Characters | Control strategies | Performance | Turbine type |
|---|---|---|---|---|
| A valve installed in series with turbine | ●Quick response;<br>●Precise pressure regulation;<br>●Efficient discharge. | Fuzzy control logic: Main goal in controlling position of HSSV is to discard mechanical turbine power, once the instantaneous turbine torque gets close to the maximal generator torque [158]. | ●High electric efficiency and electric power for low-energetic sea states. | Well turbine |
| | | Peak shaving control managed shutter position of a HSSV to dissipate the pneumatic energy excess [159,160]. | ●Prevent generator overload and turbine-generator overspeed under real bidirectional flow conditions or under control failure. | Air turbine |
| | | Latching control based on sea state data: closes HSSV when chamber relative pressure is near zero. Valve remains closed during latching duration, then returns to open position [161,162]. | ●Not require precise future wave prediction;<br>●High availability PTO system (maintain turbine speed low);<br>●High output of power. | Biradial turbine |

| | | | | |
|---|---|---|---|---|
| A bypass relief valve mounted in parallel with the turbine | ●Substantial amount of space. | Flow control: utilizes valves, either individually or in a configuration, to manage the flow through the turbine, thus preventing or mitigating aerodynamic stall losses in turbine rotor blades [163,164]. | ●Significantly enhance energy output of facility, especially under higher incident wave power levels. | Well turbine |

**Table 12.** Summary of control strategies for torque control.

| **Generic control technique** | **Control objective** | | | **Controller design** | **Parameters** | **Power production performance** | **Reliability** | **Power quality** |
|---|---|---|---|---|---|---|---|---|
| | Speed | Pressure | Airflow density | | | | | |
| Second-order sliding mode control (SMC) [158] | √ | | | Maximal generator torques control signal for generator:<br>$U_{\mathrm{gen},i} = T_{\mathrm{gen}}^{\max} \int u_i dt$ | $T_{\mathrm{gen}}^{\max}$ : maximum counter torque that generator can apply;<br>$u_i$ : time rate of change. | **** | *** | *** |
| Adaptive generator torque control [165] | √ | | | Turbine power:<br>$P_t(\psi_{\mathrm{bep}}, \Omega) = \varrho_{\mathrm{at}} d_t^5 \prod(\psi_{\mathrm{bep}})\Omega^3 = \mathrm{const}\Omega^3$<br>Torque control:<br>$T_{\mathrm{ctrl}} = \min(\alpha\Omega^b, P_{\mathrm{g,com}}/\Omega)$ | $\psi_{\mathrm{bep}}$: best efficiency point;<br>$\Omega$: turbine rotational speed;<br>$d_t$: turbine rotor diameter;<br>$\varrho_{\mathrm{at}}$: air density at atmospheric conditions;<br>$\alpha$ and $b$: generator control law constant and exponent;<br>$P_{\mathrm{g}}$: generator electrical power. | *** | ***** | *** |
| Adaptive generator torque control [166] | | √ | | Generator torque control law:<br>$T_{\mathrm{ctrl}} = k_0 + k_1 p + k_1\lvert p - \bar{p}\rvert$ | $k_0, k_1$ : numerically evaluated biradial turbine characteristics;<br>$p$: absolute air chamber pressure;<br>$\bar{p}$ : 5-minute average absolute chamber pressure. | **** | ** | ** |
| Threshold latching control [167] | √ | √ | | Generator control law:<br>$T_{\mathrm{ctrl}} = \min(\alpha\Omega^b, P_{\mathrm{g,com}}/\Omega)$ | $\alpha$: generator control law constant;<br>$P_{\mathrm{g}}$: generator electrical power;<br>$\Omega$: turbine rotational speed. | ** | *** | ** |
| Torque control based on reinforcement learning [166] | √ | | | Torque law:<br>$T_{\mathrm{ctrl}} = \alpha\Omega^b$<br>Q-Learning algorithm:<br>$S = \{s \mid s_{jl} = (\Omega_j, P_{\mathrm{g},k}), j = 1, \cdots, J, l = 1, \cdots, L\}$<br>Reward function (average output power):<br>$r_{n+1} = \begin{cases} \Delta P_{\mathrm{avg,g},n+1}/1000, \Delta P_{\mathrm{avg,g},n+1} \geq \delta \\ 0, -\delta < \Delta P_{\mathrm{avg,g},n+1} < \delta \\ \Delta P_{\mathrm{avg,g},n+1}/1000, \Delta P_{\mathrm{avg,g},n+1} \leq -\delta \end{cases}$ | $\Omega$: turbine rotational speed;<br>$a$: slope coefficient;<br>$b$: generator control law exponent;<br>$P_{\mathrm{g},k}$: generator electrical power;<br>$\delta$: a design factor;<br>$P_{\mathrm{avg,g}}$: average generator electrical power; | ***** | ** | ** |
| Master-slave torque control [168] | √ | √ | | Control law in regular operation:<br>$T_{\mathrm{gen}}^{\mathrm{RO}} = \min(a_{\mathrm{RO}}(\mathrm{rms}(\Omega))\Omega^2, P_{\mathrm{gen}}^{\mathrm{rated}}/\Omega, T_{\mathrm{gen}}^{\lim})$<br>Control law during safe-mode operation:<br>$T_{\mathrm{gen}}^{\mathrm{SM}} = \min(P_{\mathrm{gen}}^{\mathrm{rated}}/\Omega, T_{\mathrm{gen}}^{\lim})$ | $\mathrm{rms}(\Omega)$ : root-mean-square of rotational speed;<br>$\Omega$: turbine rotational speed;<br>$a_{\mathrm{RO}}$ : control parameter;<br>$P_{\mathrm{gen}}^{\mathrm{rated}}$ : rated power;<br>$T_{\mathrm{gen}}^{\lim}$ : limited counter torque that the generator can apply. | **** | **** | **** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Genetic algorithm (GA)-optimized inverse fuzzy model control [169] | √ | | | Control action:<br>$P_{\mathrm{ctrl}} = \alpha\Omega^{b}$<br>Torque control action:<br>$T_{\mathrm{ctrl}} = \alpha\Omega^{b}$ | $\Omega$: turbine rotational speed;<br>$\alpha$: generator control law constant;<br>$b$: generator control law exponent. | **** | *** | ** |
| Adaptive control based on GA [170] | √ | | √ | Instantaneous rotational speed control:<br>$T_{\mathrm{gen}}(t) = \rho(t)\prod\Phi_{\mathrm{bep}}D^{5}\Omega^{2}(t)$ | $\rho$ : fluid density;<br>$D$ : rotor diameter;<br>$\Phi_{\mathrm{bep}}$ : flow rate coefficient in best efficiency point, 0.0118. | *** | ** | *** |

*Note. N.P.: not provided; *: very low; **: low; ***: medium; ****: high; *****: very high. Power production performance is judged by the total energy generated during sea states, taking into account how often each condition occurred; reliability depends on parameters such as the peaks in generator output and valve operation, which are analyzed to understand how the various control laws cope with operating above the nominal circumstances; Power quality depends on power peaks.

Currently, there’s a trend towards integrating valve control and torque control, creating a novel hybrid control approach. Literature [158] employs second-order sliding mode control (SMC) to generate a smooth torque signal for maintaining reference angular velocity of steam turbine. Given elevated turbine torque in this scenario, a simple feedforward relationship is introduced to control valves, restricting turbine airflow and dissipating mechanical power. Experimental evidence indicates that hybrid control is an effective mean of enhancing WEC efficiency in adverse sea conditions.

In addition to the aforementioned control strategies, there is another type of control strategy known as model predictive control (MPC). MPC involves predicting the pressure or power through modeling and then selecting optimal inputs to optimize system performance. MPC encompasses linear MPC, nonlinear MPC (NMPC), multi-objective MPC (MMPC), and more. Various MPC are employed in turbine PTO control.

A MPC strategy based on short-term air pressure predictions was proposed, with the Mut Riku wave power plant in Spain as a case study. Experimental results indicate that, compared to other strategies, MPC strategy exhibits a non-smooth control response [171]. A NMPC is proposed, which compels WECs to operate with angular velocity, striking a balance between efficiency and maximum power generation, and is capable of real-time implementation. Research results demonstrate that applying NMPC to an array composed of three microgrids can further enhance power generation [172]. Literature [173] proposes a PTO control scheme that includes two MMPC, one for the machine-side converter (MSC) and the other for grid-side converter (GSC). MMPC in MSC minimizes cost function, achieving excellent torque reference tracking and thereby maximizing power generation. GSC is responsible for delivering highly variable input power to the grid. Finally, low-ripple current implemented by MMPC provides high-quality power for PMSG and grid.

Using deep learning algorithms allows for prediction of rotational speed of turbine generator in an OWCWEC. In literature [174], a method employing deep learning algorithms is proposed. This approach anticipates instantaneous speed of turbine generator and utilizes it for rated power control. This allows for precise regulation by activating a HSSV before energy input surpasses the rated value. Analysis indicates that long short-term memory (LSTM) provides the most accurate prediction of instantaneous speed of turbine generator, while convolutional neural network (CNN) demonstrates distinct advantages in scenarios with low data correlation.

### 4.4 HPTO

For WEC equipped with HPTO systems, achieving maximum power output and maintaining system stability can be accomplished by employing advanced control strategies on key components within the HPTO. This includes hydraulic cylinders, valves, accumulators, hydraulic motors and generators. Control can also be exerted by opening and closing valves in the mechanical part of the system, as well as by varying the reverse torque applied by the generator using a frequency converter.

#### 4.4.1 Hydraulic accumulator with an active control valve mechanism

Literature [175] proposes a special “self-hydraulic control system” to control HPTO to release or save energy under maximum and minimum pressures, according to principle of hydraulic balance, system turns on or off the main valve. In order to achieve above-mentioned

0-1 power generation and improve efficiency and reliability. A schematic diagram of self-hydraulic control system as shown in Fig. 25.

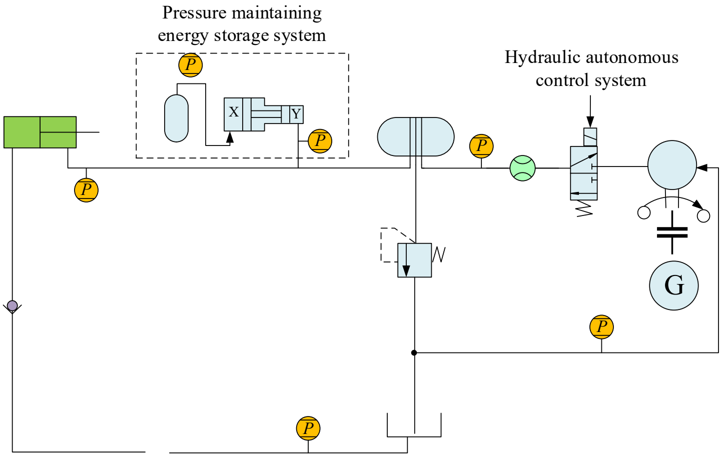


**Fig. 25.** A schematic diagram of self-hydraulic control system [176].

### 4.4.2 Hydraulic cylinder with an active control valve mechanism

Literature [177] introduces a control algorithm for energy extraction implemented across a series of switching valves. This algorithm decouples two hydraulic cylinders driving hydraulic motor and matches wave conditions by varying torque applied by generator.

In literature [178], a pioneering discrete control strategy is introduced. This strategy incorporates use of independent switch valves to regulate operation of each valve. Consequently, each chamber of hydraulic cylinder can actively connect to either a high-pressure or low-pressure accumulator. This advancement substantially enhances flexibility and controllability of PTO system. In comparison to load control and latching control, this novel discrete control strategy significantly enhances energy capture performance of the raft-type WEC. Theoretical efficiencies reach peak values of 2 and 2.5 respectively, in regular and irregular wave conditions. The innovative discrete control possesses a clear advantage over load control and functions as a valuable complement to latching control.

Hydraulic cylinder is a crucial component in HPTO torque control. In terms of torque control, literature [179] proposes a maximum power torque control algorithm (TCA) that is independent of the wave excitation torque period. TCA continuously monitors power generation output and adjusts HPTO damping coefficient in the direction, effectively achieving control over torque. In comparison to traditional TCA, this new TCA has the capability to increase output power generation by 18%.

### 4.4.3 Hydraulic transformer or hydraulic motor with a digital control mechanism

Control strategies for hydraulic motors can be implemented by adjusting the voltage motor’s speed, displacement, or fluid flow and so on. Figure 26 shows a schematic representation of control system for a variable-speed motor.

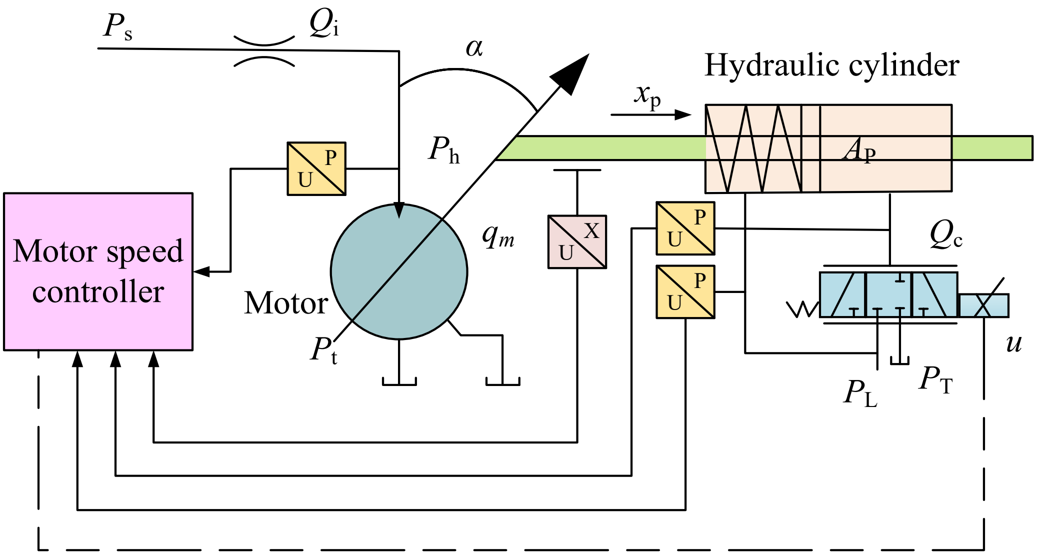


**Fig. 26.** A schematic diagram of the control system for a variable speed motor [176].

In terms of speed control, literature [56] proposes a general HPTO concept and studies its speed control technology, discussing how speed control techniques can maximize grid power. Literature [180] designs a proportional-integral-derivative (PID) controller to regulate motor speed, and experimental results show that PID controller has a noticeable effect on stabilizing speed. Literature [181] introduces a control strategy for an HPTO unit, which can simultaneously achieve flexible rectification and hydraulic motor speed control. It allows for a slow acceleration when unit starts, reducing its impact on the grid.

Concerning displacement control, literature [182] designs a control strategy based on a fuzzy controller to adjust the displacement of the hydraulic motor. Simulation results under irregular wave conditions demonstrate that this strategy effectively reduces fluctuations in the output of unit. literature [183] proposes a MPPT control based, tracking optimal damping point by controlling the displacement of the hydraulic motor. This method is easier to implement than traditional resistance control and significantly improves the output power.

Literature [184] introduces a groundbreaking HPTO control strategy, which fine-tunes both the tilt angle of displacement motor and resistive load of generator for ensuring peak performance across diverse wave conditions. In contrast to alternative control approaches, the suggested control management methodology boosts power generation efficiency by around 10%, especially in low and moderate wave scenarios.

Finally, regarding fluid flow control, literature [185] introduces a novel fluid energy control (FEC) method to regulate the fluid flow entering the hydraulic motor, enhancing the stability of power generation in the HPTO unit. The improved HPTO unit can generate power at rated capacity during 37.3% to 53.7% of the WEC operating time.

### 4.4.4 Control mechanism in conditioning module

At present, besides utilizing diverse control strategies for HPTO devices to boost their efficiency, recent research is concentrated on suggesting improved HPTO systems. These investigations introduce emerging control devices and employ corresponding control algorithms to achieve precise regulation. PTO implementing such control systems are anticipated to evolve into autonomous, stable, efficient and sustainable power supply systems.

To enhance the efficiency and stability of the eccentric rotating WEC, literature [186] develops an adaptive HPTO system equipped with an accumulator. By employing the non-dominated sorting genetic algorithm-III (NSGA-III), optimal combination of control parameters was successfully obtained, leading to a significant improvement in output power and stability.

Literature [187] proposes an improved HPTO system for a point absorption WEC (PA-WEC). Control system was designed using an improved simplified universal intelligent PID (ISUIPID) controller and an integrated improved gorilla troops optimizer (IGTO) for adaptive matching, aiming to enhance and stabilize output power of PA-WEC array. The research findings indicate that IGTO exhibits faster convergence speed and better convergence accuracy in solving optimal linear damping coefficient for the generator. Simultaneously, ISUIPID controller demonstrates superior performance in tracking the speed of hydraulic motor under varying sea conditions.

Literature [188] proposes a maximum power control algorithm tailored for the load control of HPTO systems. The study encompasses speed control algorithms based on perturbation observation and optimal TCA, aiming to achieve precise control of electrical loads. By manipulating electrical load, the algorithm can regulate pressure in hydraulic circuit, thereby achieving accurate management of input power. Throughout research process, a thorough exploration of key parameters of PTO, such as input power, output power, and efficiency, has been conducted.

In literature [189], an optimal latching control law based on the coulomb damping model (HPTO of the coulomb damping model simplifies complexity of finding the optimal latching duration) is proposed. Research indicates that application of latching control law significantly enhances power capture capability of raft-type WEC. Benefits obtained from latching control reach a peak value of 3.04, compared to the improvement brought by load control. Furthermore, even when load control has been implemented, latching control can still provide additional advantages. Figure 27 illustrates a HPTO system with a latching mechanism.

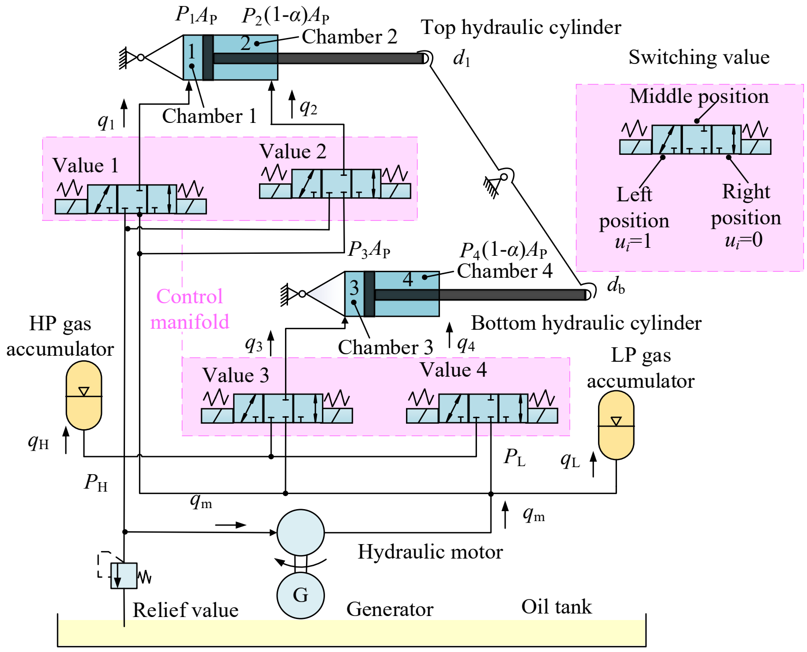


**Fig. 27.** HPTO system with latching control [189].

### 4.5 Hybrid system

At present, there is a relative scarcity of literature on the control of hybrid systems, primarily due to the fact that research on wave energy hybrid systems is still in its early stages. The exploration and proposal of control methods for such systems are extremely limited. In the preceding text, various control methods were mentioned, with phase control being one of the widely acknowledged control methods for OWC WEC. This method involves adjusting air turbine speed or air valve opening ratio to significantly enhance power efficiency. However, for hybrid systems, relying solely on control strategies that maximize wave energy is no longer optimal choice. This is because reducing platform motion and suppressing structural loads are equally crucial design objectives, especially for the long-term operation of hybrid systems.

In literature [190], three control methods for wind-wave hybrid system are introduced:

The first control method employs two active feedback control strategies. Dynamic response and power generation of hybrid power concept are evaluated by manipulating a HSSV installed in series with the air turbine [191]. Simultaneously, passive linear damping (PLD) control with different PTO damping coefficients is used to compare and study behavior of active PTO control.

The second control method utilizes two-state gain-scheduling damping (TGD) control, designed to suppress platform motion [192]. TGD achieves positive damping for platform pitch motion by switching between two different PTO damping configurations.

The third control method proposes continuous gain-scheduling damping (CGD) control, capable of mitigating platform pitch motion and reducing WT structural loads [193].

Research results indicate that TGD and CGD control strategies are more advantageous for platform motion response and WT structural loads. For instance, TGD can reduce platform pitch motion by 15%, while CGD can decrease tower base fatigue loads by 6%. Therefore, it is anticipated that a multi-objective optimal PTO control strategy, considering both motion suppression and power maximization, will contribute to further reducing energy cost balance of hybrid systems.

## 5. Evaluation criteria

In the third section, PTO is categorized into 7 types based on its different operational modes. Different WECs generally choose an appropriate PTO type, and selection of a PTO system involves multiple factors, depending on requirements and environmental conditions of specific applications. Next, the criteria for selecting PTO will be briefly discussed based on five evaluation standards: energy conversion efficiency, reliability, economic, applicability and environmental friendliness .

### 5.1 Energy conversion efficiency

The energy capture efficiency of WECs is product of efficiencies of each component, including energy capture mechanism, transmission mechanism and power generation mechanism. Given differences in existing PTO systems and varied scales and sizes of different WECs, performance indicators for energy capture will also vary.

Damping holds a pivotal significance in evaluating the performance of WECs as it directly influences absorption power and efficiency. Specifically, for floating-point WECs, damping can be categorized into two components: fluid dynamic damping associated with radiation and viscous effects, and non-fluid dynamic damping linked to mechanical and/or electrical losses, along with PTO. Among these elements, only PTO damping has capability to generate useful power [194]. Damping coefficient serves as the representation for magnitude of damping in PTO, acting as a parameter that describes the extent of energy loss during its motion or vibration processes.

In general, damping coefficient is closely associated with system's output power. Literature [195] developed a numerical model for the M3 bottom-fixed pressure-differential WEC and conducted optimization of pertinent parameters influencing energy absorption. These parameters include stiffness and damping coefficients of PTO in each dimension, aiming to achieve maximum absorption power. The absorbed power of WEC can be expressed as:

$$P = \frac{1}{B_{\mathrm{PTO}}}(p_1 - p_2)^2 \tag{1}$$

where $B_{\mathrm{PTO}}$ is the damping coefficient of PTO; $p_1$ and $p_2$ are pressure between the two air chambers.

For OWC system, literature [196] developed a new model that takes into account varying conditions of floater and oscillator under different motion scenarios. Simulation training was conducted, ultimately leading to optimization of both maximum output power and optimal damping coefficient. The power of PTO system can be expressed as:

$$P_{\mathrm{PTO}} = B_{\mathrm{PTO}}(x_2 - x_1)^2 \tag{2}$$

where $x_1$ and $x_2$ are the oscillation speed.

Based on aforementioned content, it can be inferred that output power of WEC is closely related to damping coefficient of PTO. Because of this, some current control strategies employ different methods, such as adjusting damping or using various control approaches based on generation of damping, to enhance output power [197]. However, the analysis in literature [198] indicates that PTO damping is significantly influenced by characteristics of incident waves, accuracy of damping coefficients is crucial evaluating WEC performance, especially in determining optimal operating condition.

### 5.2 Reliability

In design of PTO, efficiency and reliability are crucial considerations. Reliability is one of the most critical factors influencing the life cycle costs and the ultimate electricity generation costs. Different types of PTO have distinct components, and variations in the number and characteristics of these components result in differences in lifespan, thereby affecting their reliability.

The literature [199] creates reliability diagrams, a qualitative comparison of their reliability was conducted. Research results indicate that various subsystems of PTO comprise a total of 31 components, highlighting the complexity of such systems. In comparison, linear generator is much simpler with only 11 subsystems, while well turbine has 14 subsystems. The overall reliability is influenced by number of components, suggesting that HPTO is more susceptible to failure when compared other PTO type.The estimated failure rates for PAWEC and OWC subsystems are presented in Table 13. It is worth noting that, due to the uncertainty associated with environmental and load factors in marine energy applications, these factors have not been considered in these estimates.

**Table 13.** Sub-system failure rate estimation (failures/year) [199].

| | **OWC fixed** | **OWC floating** | **PA direct drive** | **PA hydraulic** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Structure | 0.008 | 0.18 | 0.30 | 0.30 |
| PTO | 1.40 | 0.40 | 0.93 | 0.42 |
| Electric system | 0.30 | 0.30 | 0.30 | 0.30 |
| Low voltage DC system | 0.15 | 0.15 | 0.15 | 0.15 |
| Auxiliary system | 1.74 | 0.74 | 1.74 | 1.74 |
| Grid | N/A | 0.14 | 0.14 | 0.14 |

Although PTO is mainly constructed using commercially available components, the study must take into account reliability considerations, considering offshore operating conditions [200].The greater the number of components in contact with seawater, the higher probability of failure and the lower reliability. For example, certain components in OWC have minimal contact with seawater, allowing integration with breakwaters (overtopping WECs can accumulate seawater along with breakwaters to drive water turbines), thereby enhancing reliability. Energy-capturing components such as PA, terminators, attenuators, and multi-degree-of-freedom devices directly interact with seawater, various failures are more likely to occur when waves are significant [201].

Currently, there are several methods for conducting system reliability analysis, with the most widely used ones including fault tree analysis (FTA) and event tree analysis (ETA), as well as various Bayesian methods. Literature [4] describes a reliability analysis method developed for WEC based on reliability block diagram modeling, and provides information on some key component types within PTO, along with life distribution applicable to these component types. The key components of WEC, along with the applicable life distribution for these components are presented in Table 14.

**Table 14.** Key components of WEC, along with the applicable life distribution for these components [4].

| Component Type | Life Distribution | |
|---|---|---|
| | 1-parameter Exponential | 2-parameter Weibull |
| Automation products (processor modules, I/O modules, communication modules, etc.) | √ | |
| Contactors | √ | |
| Electric generators | | √ |
| Electric motors | | √ |
| Hydraulic accumulators | | √ |
| Hydraulic cylinders | | √ |
| Hydraulic motors | | √ |
| Hydraulic pumps | | √ |
| Relays | √ | |
| Valves (electronic control) | √ | |
| Variable-frequency drives | √ | |

### 5.3 Economic

The economic analysis of WEC typically involves the assessment using levelized cost of energy (LCOE), cost functions, or technology cost economy (TECO). Cost functions are included and the objective function is the ratio between the delivered power and the capital expenditure [202].

The performance index TECO is defined as follows [201]:

$$TECO = \frac{HDE}{S} \tag{3}$$

where $S$ is the scale of WECs. $HDE$ is the energy capture performance index hydro-dynamic efficiency.

LCOE of a wave power farm consisting of $N$ units is computed as follows [203]:

$$LCOE = \frac{CAPEX_{\text{total}} - \sum_{t=1}^{y} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{y} \frac{AEP_t}{(1+r)^t}} \tag{4}$$

where $r$ stands for a discount rate, $CAPEX_{\text{total}}$ and $OPEX_t$ are the capital cost and operational cost of a wave power farm, respectively, $y$ represents for system lifetime in years, $t$ and $AEP_t$

are estimated operating life and annual energy production (AEP) of a wave power farm, respectively.

The latest scientific research indicates that reducing PTO capacity to an appropriate level helps lower LCOE of WECs [204,205]. On the one hand, the capability of PTO is directly related to costs. As highlighted in literature [206], PTO systems typically represent 20% or more of total CAPEX, making oversized PTO economically disadvantageous. On the other hand, PTO capacity reflects physical constraints such as force, peak power and displacement limitations. It is worth noting that larger PTO not only provides greater flexibility for controllers but also has capability to extract more energy. However, such advantages come with higher investment costs.

In fact, OPEX represent a relatively small proportion of overall costs. This is because the absence of moving parts exposed to harsh marine environments (such as saltwater, dust, and debris) in some enclosed WECs (e.g., PeWEC, ISWEC and SEAREV), their operational costs are estimated to account for only about 2% of total expenses, making them generally negligible compared to CAPEX. In fact, for conventional WECs with moving parts exposed to harsh environments, their CAPEX are estimated to represent only 35% [207]. Furthermore, LCOE is primarily sensitive to AEP and CAPEX, while impacts of OPEX, inflation rate, lifespan, and expected internal rate of return are relatively minor [4].

### 5.4 Adaptability

In WECs, adaptability of PTO, referring to output power section of system, signifies its ability to respond to varying wave conditions and changes in energy input. HPTO exhibits excellent adaptability to wave spectrum and wave direction due to its hydraulic system’s ability to adjust output power relatively quickly [208]. Linear generator is suitable for environments with lower wave frequencies and larger wave amplitudes, but its performance may slightly decline when wave direction changes. Pneumatic PTOs are generally suitable for areas with abundant wind and waves, being sensitive to changes in wave direction and wave height.

The methods to enhance adaptability can involve substantial modifications to WECs [209], or adjustments and enhancements to PTO [210-212]. Literature [213] introduces adaptability to PTO and assesses impact of varying degrees of adaptability on the power absorption. Research findings suggest that incorporating adaptability into PTO system can amplify power output, and a higher level of adaptability correlates with increased output power. Nevertheless, heightened adaptability may incur elevated system costs, necessitating development of suitable strategies to ensure optimal economic efficiency while maintaining a sufficiently high level of adaptability.

### 5.5 Environmental friendliness

HPTO and mechanical PTO typically generate noise and vibration. PTO of an air turbine may lead to air emissions, potentially impacting the surrounding air and water quality to some extent. Electromagnetic PTO systems, utilizing electromagnetic generators, may produce electromagnetic radiation. In literature [214], a study focused on linear generator-type PTO, investigating its electromagnetic effects, artificial reef effects and underwater noise on marine environment. The results indicate that transient noise can affect various fish species and marine mammals.

Additionally, as mentioned in literature [215], employing the life cycle assessment (LCA) method—an internationally standardized, scientifically grounded approach to evaluating potential environmental impacts of products, processes, or systems across their entire lifecycle—examined the influence of a WEC on both energy and the environment [216]. Experimental findings underscore significance of choosing materials for enhancing environmental performance of product. Comprehensive LCA studies might also evolve into valuable instruments for crafting eco-friendly wave energy devices.

In order to assess environmental friendliness, literature [4] has defined the environmental friendliness (ENFR) as follows:

$$ENFR = \frac{CAPA}{S} \tag{5}$$

where $CAPA$ is the capacity.

## 6. Summary and perspectives

This work presents a systematic review of advanced research in various PTO systems for wave energy technologies, which classifies PTO systems into seven major groups, i.e., hydraulic motor system, pneumatic air turbine system, hydro turbine system, direct mechanical drive system, direct linear electrical system, TENG, and hybrid system. The basic characteristics of each PTO system, such as advantages, disadvantages, complexity, accuracy, cost, and application are comprehensively discussed, as illustrated in Fig. 28. The main conclusions are summarized as follows:

- Hydraulic motor system is usually located offshore and nearshore, which is suitable for low-frequency and larger ocean waves. Basically, it has a relatively high conversion efficiency, but also poses some threats to marine environment and requires regular maintenance;
- Pneumatic air turbine system is located offshore and nearshore, which is environment-friendly due to harmful fluids are not utilized. However, its conversion efficiency is the lowest, together with some drawbacks such as relatively hard starting, high maintenance cost, and large operation loss;
- Hydro turbine transfer system is widely used offshore which owns high power conversion efficiency (usually around 90%). In contrast, it is generally difficult to be constructed and harmful to environment, and high maintenance costs are needed;
- Direct mechanical drive system is usually employed offshore which owns high power conversion efficiency (up to 97%) and low construction costs, while its drawbacks mainly include short service life, high maintenance cost, as well as relatively low reliability;
- Direct linear electrical drive system is usually installed offshore to increase power generation efficiency, which owns high reliability and strong robustness with relatively low maintenance costs and operation power loss. However, it still remains some disadvantages of complicated structure, complex power transmission system, as well as low power-to-weight-ratio;
- TENG is usually located offshore which possesses the superiorities of high-power conversion efficiency, proper size, low maintenance costs, and simple structure. The main difficulties it faces are load mismatching, power grid synchronization, and power instability;

- Hybrid system can be applied both offshore or nearshore, in which wind or solar energy can be integrated to extract the maximum potential power from nature. It can be extended to the most diverse application scenarios with a quite desirable efficiency. However, a complex structure is needed so that the construction and maintenance costs are also the highest, meanwhile, more advanced control systems are required to achieve an effective and efficient operation.

In summary, most prototype WECs employ one of the three following PTO systems: the hydraulic motor, the turbine transfer, or the direct mechanical drive system. Thanks to higher wave power density and the avoidance of onshore land installation problems, most prototype WECs have been placed offshore. Apart from the summarization of different commonly used PTO systems, main control strategies for PTO systems are also elaborated, including their overall advantages, disadvantages, complexity, accuracy, cost, as well as application scenarios, as presented in Table 15.

To promote further research in this field, seven perspectives on PTO system and control strategies are outlined based on a comprehensive literature investigation combined with future development direction, as follows:

- To reduce the overall cost of WECs arrays caused by the small number of mooring points, PTO systems and/or anchorage points should be shared between nearby devices in arrays. However, buoy arrays'ability to generate electricity is impacted by the intricate interactions among individual buoys, thus the exploitation and refinement of interaction models to allow varying submergence depths are necessary. Meanwhile, the improvement of objective functions, such as considering economic indicators of the array construction and operation is also beneficial for its larger-scale engineering application;
- Geometry, involving both basic shape (e.g., spherical, conical) and specialized geometrical properties (concavity, convexity, and sharp/edged features), tends to affect PTO cumulative and damage equivalent loading that results in reliability decrease. Larger objects with more convex shapes tend to generate more energy, whereas smaller objects have less damage equivalent loading since they are more aerodynamic while moving in the surging direction. So, it is an insightful research direction to design a suitable geometry to balance operation reliability and output power to extract more power from the surge motion;
- The corrosion-related factors in deep-sea environments such as dissolved oxygen, pressure, salinity, and temperature impact the corrosion of metals, alloys, and other materials. To prevent corrosion caused by seawater, the stator is normally sealed with epoxy resin, but the effectiveness is not remarkable. Hence, it is crucial to apply more corrosion-resistant materials to prolong the service life and maintenance costs of PM motor;
- Energy storage systems (ESS) on floating platforms or onshore may enhance power quality or energy management in the short or long term. PTO and ESS models are usually integrated into the buoy dynamic model, thus proper control strategy requirements design can correspondingly increase the precision and reliability of the PTO and ESS design;
- Current main approach of hybrid systems is to combine WEC systems with PV or WT. Common installation method involves placing their systems at a safe distance within designated sea areas. Potential future trend is for three systems to be integrated to form a unified hybrid system. Specifically, there systems may share same floating platform or

anchoring point. However, the integrated hybrid system faces challenges. For instance, hydrodynamic interactions between systems may impact stability. At the same time, effective control strategies should be designed and implemented to ensure coordinated operation of the three systems under varying marine conditions, achieving optimal performance;

- Model predictive control may use wave prediction data to meet the noncausal optimum control criterion and explicitly add limitations to the PTO control issue. However, the direct maximizing control aim of PTO control might lead to a nonconvex optimization issue, thus heavy online computational burden is caused during its implementation. At the same time, due to the complexity of PTO dynamics, a high-order nonlinear model is required to accurately describe them, and preserve modeling integrity and safe operational restrictions. To solve this problem, some advanced nonlinear robust/adaptive control strategies can be developed and combined;
- The main disadvantage of normal control strategies (e.g., suboptimal causal control, latching and model-predictive control, and complex-conjugate control) is that they employ internal models of body dynamics to determine the optimal control settings. Therefore, modeling errors would not only affect the energy absorption of WEC negatively, but also isolate the changes of equipment over time, whether from gradual ocean expansion or abrupt non-critical subsystem breakdown. Model-free artificial intelligence (AI) algorithm can act as an ideal tool for PTO control system design, which is not influenced by the inherent errors of the used models and may easily adjust to the hydrodynamics of the device. For instance, wind/solar/wave forecasting, state monitoring, parameter tuning, and fault diagnosis are some promising research directions.

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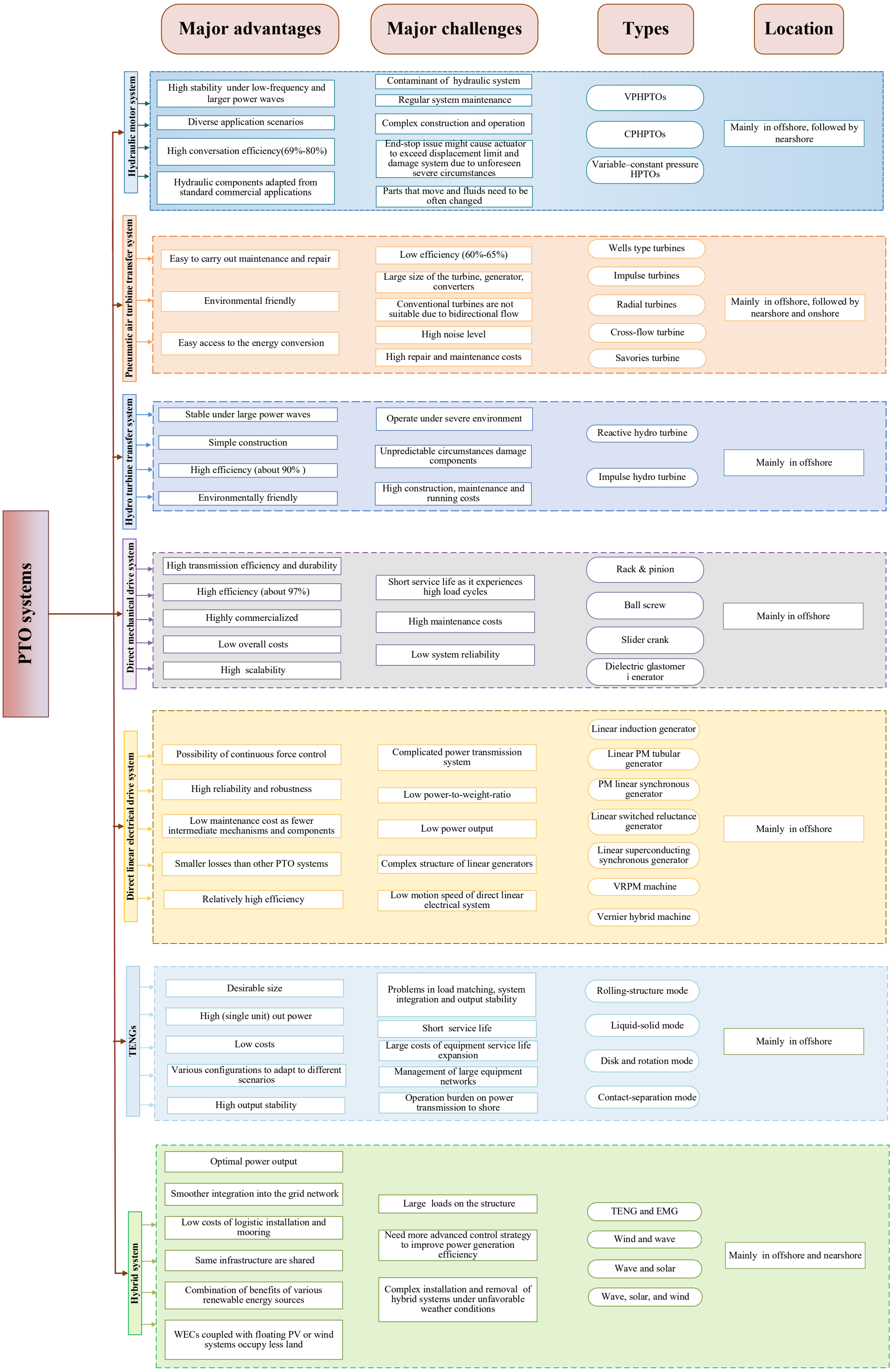

| PTO systems | Major advantages | Major challenges | Types | Location |
|---|---|---|---|---|
| Hydraulic motor system | High stability under low-frequency and larger power waves<br>Diverse application scenarios<br>High conversation efficiency(69%-80%)<br>Hydraulic components adapted from standard commercial applications | Contaminant of hydraulic system<br>Regular system maintenance<br>Complex construction and operation<br>End-stop issue might cause actuator to exceed displacement limit and damage system due to unforeseen severe circumstances<br>Parts that move and fluids need to be often changed | VPHPTOs<br>CPHPTOs<br>Variable–constant pressure HPTOs | Mainly in offshore, followed by nearshore |
| Pneumatic air turbine transfer system | Easy to carry out maintenance and repair<br>Environmental friendly<br>Easy access to the energy conversion | Low efficiency (60%-65%)<br>Large size of the turbine, generator, converters<br>Conventional turbines are not suitable due to bidirectional flow<br>High noise level<br>High repair and maintenance costs | Wells type turbines<br>Impulse turbines<br>Radial turbines<br>Cross-flow turbine<br>Savories turbine | Mainly in offshore, followed by nearshore and onshore |
| Hydro turbine transfer system | Stable under large power waves<br>Simple construction<br>High efficiency (about 90% )<br>Environmentally friendly | Operate under severe environment<br>Unpredictable circumstances damage components<br>High construction, maintenance and running costs | Reactive hydro turbine<br>Impulse hydro turbine | Mainly in offshore |
| Direct mechanical drive system | High transmission efficiency and durability<br>High efficiency (about 97%)<br>Highly commercialized<br>Low overall costs<br>High scalability | Short service life as it experiences high load cycles<br>High maintenance costs<br>Low system reliability | Rack & pinion<br>Ball screw<br>Slider crank<br>Dielectric glastomer i enerator | Mainly in offshore |
| Direct linear electrical drive system | Possibility of continuous force control<br>High reliability and robustness<br>Low maintenance cost as fewer intermediate mechanisms and components<br>Smaller losses than other PTO systems<br>Relatively high efficiency | Complicated power transmission system<br>Low power-to-weight-ratio<br>Low power output<br>Complex structure of linear generators<br>Low motion speed of direct linear electrical system | Linear induction generator<br>Linear PM tubular generator<br>PM linear synchronous generator<br>Linear switched reluctance generator<br>Linear superconducting synchronous generator<br>VRPM machine<br>Vernier hybrid machine | Mainly in offshore |
| TENGs | Desirable size<br>High (single unit) out power<br>Low costs<br>Various configurations to adapt to different scenarios<br>High output stability | Problems in load matching, system integration and output stability<br>Short service life<br>Large costs of equipment service life expansion<br>Management of large equipment networks<br>Operation burden on power transmission to shore | Rolling-structure mode<br>Liquid-solid mode<br>Disk and rotation mode<br>Contact-separation mode | Mainly in offshore |
| Hybrid system | Optimal power output<br>Smoother integration into the grid network<br>Low costs of logistic installation and mooring<br>Same infrastructure are shared<br>Combination of benefits of various renewable energy sources<br>WECs coupled with floating PV or wind systems occupy less land | Large loads on the structure<br>Need more advanced control strategy to improve power generation efficiency<br>Complex installation and removal of hybrid systems under unfavorable weather conditions | TENG and EMG<br>Wind and wave<br>Wave and solar<br>Wave, solar, and wind | Mainly in offshore and nearshore |

**Fig. 28.** Comparison and evaluation results of seven types of PTO systems.

**Table 15.** Chronological summary of forty-one conventional control strategies applied in the PTO system.

| Control strategy | Year | Objective | Advantages | Disadvantages | Complex | Accuracy | Cost | Application | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Direct mechanical drive system | Direct linear electrical drive system | Turbine transfer system | Pneumatic air turbine transfer system | Hydraulic motor system | Hybrid system |
| Flow control [105] | 2011 | • Valve. | • Significantly enhance energy output of facility. | • Short lifetime of components. | **** | *** | ** | | | √ | | | |
| Amplitude control strategy [152] | 2012 | • Load. | • Low losses;<br>• Wide range of applicability. | •Limited applicability. | *** | *** | ***** | | √ | | | | |
| Damping control strategy [152] | 2012 | • Damping. | • Low losses;<br>• Wide range of applicability. | • Low output power. | ** | ** | ***** | | √ | | | | |
| Threshold latching control [167] | 2012 | • Speed;<br>• Pressure. | • Remove constraint of latching threshold;<br>• Simplicity. | • Limited adaptability;<br>• Difficulty in tuning thresholds. | ** | **** | **** | | | √ | | | |
| Self-hydraulic control [165] | 2014 | • Value. | • High efficiency and reliability. | • Complexity and high cost;<br>• High pressure and safety risks. | ***** | *** | **** | | | | | | √ |
| SVPWMCC [153] | 2015 | • Current;<br>• Voltage. | • Switching frequency is specified without frequency prediction. | • Complex structure;<br>• Slow dynamic response;<br>• Constantly change operating points as voltage frequency changes. | **** | *** | *** | | √ | | | | |
| SHCSC [153] | 2015 | • Current. | • Constant switching frequency and high parameter-independent reaction speed;<br>• Avoid overcurrent. | • Complex structure;<br>• High maintenance cost. | ***** | ***** | ***** | | √ | | | | |
| HBCC [153] | 2015 | • Current. | • High dynamic performance;<br>• Simple structure;<br>• Reference signal is almost instantly tracked. | • Unpredictable switching frequency;<br>• No interaction between separate hysteresis controllers. | ** | ** | ** | | √ | | | | |
| Latching control based on sea state data [162] | 2015 | • HSSV. | • Not require precise future wave prediction;<br>• High availability PTO system;<br>• High output of power. | • Short lifetime of components;<br>• Complex structure. | **** | *** | ** | | | √ | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adaptive generator torque control [165] | 2016 | • Speed. | •Small partial load and cost. | • Short lifetime of components;<br>• Large negative and positive air pressure peaks. | *** | ** | ** | | | √ | | | |
| Fuzzy control [182] | 2016 | •Displacement. | • Reduce fluctuations in output. | • High computational costs;<br>• Lack of formal mathematical model. | *** | ** | **** | | | | | | √ |
| Two active feedback control strategies [191] | 2016 | • HSSV. | • High stability of power generation in HPTO unit;<br>• Suitable for complex sea conditions. | • Complex structure and model;<br>• Short lifetime of components. | **** | **** | *** | | | | | | √ |
| VOCl [154] | 2020 | • Voltage. | • Capture maximum power from waves;<br>• High wave-to-wire system stability;<br>• Low generator losses. | • Complex structure;<br>• Low accuracy;<br>• High costs as the system needs supercapacitors. | *** | *** | **** | | √ | | | | |
| Adaptive generator torque control [166] | 2020 | • Pressure. | • Overspeed protection that avoids over speeding under high energetic seas;<br>• High output power. | • Low PTO efficiency;<br>• Low power quality;<br>• Sudden changes in internal pressure. | *** | **** | *** | | | √ | | | |
| Torque control based on reinforcement learning [166] | 2020 | • Speed. | • High output power;<br>• On-line optimization using operational data unbiased by modeling errors or mode changes;<br>• High robustness;<br>• High generator efficiency. | • Low turbine efficiency. | *** | ***** | *** | | | √ | | | |
| Tracking optimal damping point control based MPPT [183] | 2020 | •Displacement. | • High output power;<br>• Simpler implement than traditional resistance control. | • Complex structure. | **** | *** | *** | | | | | | √ |
| Fuzzy logic-based pressure control [53] | 2021 | • Pressure. | • Stable oil pressure fluctuation indicates stability of main power circuit;<br>• High reliability. | • Low efficiency. | *** | **** | ** | | | | | | √ |
| Latching control [152] | 2021 | • Value. | • High PTO mean power. | • Complex control process. | **** | *** | *** | √ | | | | | |
| Non-predictive | 2021 | • Value. | • Power production of the WEC up to | • Short lifetime of components;<br>• High cost. | ** | **** | **** | √ | | | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| latching control [155] | | | between 38% and 281%. | | | | | | | | | | |
| Fuzzy control [158] | 2021 | • HSSV. | • High electric efficiency and electric power for low-energetic sea states. | • High computational costs;<br>• Not suitable for complex systems. | *** | ** | **** | | | √ | | | |
| SMC [158] | 2021 | • Speed. | • Improved tracking performance;<br>• Chattering reduction;<br>• Enhanced Stability. | • Sensitivity to parameter variations;<br>• Limited applicability. | **** | *** | **** | | | √ | | | |
| Maximum power torque control [179] | 2021 | • Value. | • Increase output power generation by 18%. | • Sensitivity to parameter variations;<br>• Limited stability margin. | *** | *** | *** | | | | | | √ |
| PID control [180] | 2021 | • Speed. | • High reliable stabilizing speed;<br>• Simple structure. | • Tuning complexity;<br>• Sensitivity to parameter variations. | **** | *** | ** | | | | | | √ |
| a groundbreaking HPTO control [184] | 2022 | • Tilt angle;<br>• Resistive load. | • Power generation efficiency increased by about 10%. | • Potential sensitivity to environmental variability;<br>• Complex implement. | **** | *** | **** | | | | | | √ |
| FEC [185] | 2022 | • Fluid flow. | • High stability of power generation;<br>• Generate power at rated capacity during 37.3% to 53.7% of WEC operating time. | • Limited range of applicability;<br>• Sensitivity to conditions. | *** | *** | ** | | | | | | √ |
| Adaptive control based on GA [170] | 2022 | • Speed;<br>• Airflow density. | •Maximize each sea state's WEC time-average efficiency;<br>•Simple implementation. | • Sensitivity to initial conditions;<br>• Dependence on representation and operators. | ** | *** | *** | | | √ | | | |
| MMPC [173] | 2022 | • Speed. | • Excellent torque reference tracking;<br>• Maximize power generation;<br>• High-quality power. | • Computational complexity;<br>• Complexity in industrial implementation. | **** | *** | **** | | | √ | | | |
| MPC based deep learning algorithms [174] | 2022 | • Speed. | •Accurate prediction of instantaneous speed of turbine generator;<br>• Precise regulation. | • Computational complexity;<br>• Training data requirements;<br>• Data quality concerns. | *** | ***** | *** | | | √ | | | |
| Pioneering discrete control strategy [178] | 2022 | • Value. | • High flexibility and controllability of PTO system. | • Limited adaptability;<br>• Limited Precision. | ***** | ** | **** | | | | | | √ |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load control based MPPT [188] | 2022 | • Electrical load;<br>• Pressure. | • Achieve accurate management of input power. | • Complex structure;<br>• Low reliability. | *** | *** | *** | | | | | | √ |
| Latching control law based on coulomb damping model [189] | 2022 | • Value. | • High peak value of 3.04 (2 times that introduced by load control);<br>• Reduce complexity of finding optimal latching duration. | • Limited range of applicability. | ** | **** | *** | | | | | | √ |
| TGD control [192] | 2022 | • Pressure;<br>• Platform pitch angular velocity. | • Reduce platform pitch motion by 15%;<br>• Advantageous for platform motion response and WT structural loads. | • Complex model;<br>• Potential Instabilities. | **** | **** | *** | | | | | | √ |
| CGD control [193] | 2022 | • Air pressure;<br>• Platform pitch angular velocity. | • Decrease tower base fatigue loads by 6%;<br>• Advantageous for platform motion response and WT structural loads. | • Limited adaptability;<br>• Challenges in State Identification. | ** | **** | *** | | | | | | √ |
| MPPT algorithms [157] | 2023 | • Generator torque. | • High output of power (approximately 50% of the rated power);<br>• High capture width (approximately 53%). | • Complex structure. | **** | *** | ** | √ | | | | | |
| Peak shaving control [159] | 2023 | • HSSV. | • Prevent generator overload;<br>• Prevent turbine-generator overspeed. | • Complex structure;<br>• Poor technical compatibility. | **** | ** | **** | | | √ | | | |
| Master-slave torque control [168] | 2023 | • Speed;<br>• Pressure. | • Great efficiency and reliability;<br>• Ensure safe and reliable operation of system. | •Complex control mechanism. | **** | *** | **** | | | √ | | | |
| GA-optimized inverse fuzzy model control [169] | 2023 | • Speed. | • High generator power (reaching a maximum of 70%). | •Complex control mechanism. | **** | *** | **** | | | √ | | | |
| MPC [171] | 2023 | • Short-term air pressure. | • Enhance power generation. | • Computational complexity;<br>• Sensitivity to model mismatch. | *** | *** | **** | | | √ | | | |
| NMPC [172] | 2023 | • Angular velocity. | •Keep a balance between efficiency and maximum power generation; | • Lack of universality;<br>• Sensitivity to initial conditions. | *** | *** | **** | | | √ | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | • Real-time implementation | | | | | | | | | | |
| NSGA-III [186] | 2023 | • Trigger pressure;<br>• Delay time;<br>• Open state duration. | • High efficiency;<br>• High stability;<br>• Suitable for complex sea conditions;<br>• Real-time adjustment of control parameters. | • Complex structure and model. | **** | **** | **** | | | | | | √ |
| ISUIPID controller and IGTO controller [187] | 2023 | • Speed;<br>• Value. | • Improve capture power and output power (capture power experiences an increase of over 8.34%, while output power sees a rise exceeding 10.98%);<br>• Facilitate commercialization of WECs;<br>• Fast convergence speed;<br>• Good convergence accuracy;<br>• Reduce average absolute error (79% lower than PID controller and 36% lower than fuzzy PID controller). | • Limited adaptability (only apply to a single WEC);<br>• Potential sensitivity to environmental variability. | ** | **** | *** | | | | | | √ |

*Note. N.P.: not provided; *: very low; **: low; ***: medium; ****: high; *****: very high. Complexity depends on how the control strategy works, the control algorithm, and the complexity of the device; accuracy depends on power production performance that is judged by the sum of energy produced including frequency of occurrence; cost is primarily dependent on the installation and maintenance.

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