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Ocean's Renewable Power and Review of Technologies: Case Study Waves

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1. Introduction

In last decades, in effect of high price of fossil fuel, environmental pollution due to fossil fuel utilization and greenhouse effect, renewable energy resources are considered as an alternative energy resource to the World's excessive energy demand. Nowadays, different technologies are utilized to energy generation from hydro power, fuel cell and hydrogen, biomass, geothermal, solar thermal, photovoltaic and wind, while the technology for converting ocean powers are still in infancy. The aim of this chapter is to introduce potential renewable power sources of ocean, mostly ocean wave power, as well as available technologies for extracting wave power. Due to high energy amount available in ocean, the issue has a strong importance to investigate. Furthermore there are variety of technologies that are developed for harnessing wave power each of which has an individual mechanism. Harvesting ocean wave power and converting to electrical power is a challenge for marine, mechanical, electrical and control engineers and we hope to give essential information about ocean wave, methods of energy extracting from wave and related electrical equipment.

1.1. Ocean

The oceans contain 97.2% of total world water which are covering 71% of Earth's surface [1]. Also the oceans intrinsically are couple with atmosphere via air-water interface and they exchange heat, moisture, momentum and trace constituents by means of air-water interface [2]. The fundamental processes that transfer energy from atmosphere to ocean are energy input to ocean by wind and net surface heat flux [3]. Furthermore, ocean absorbs heat of geothermal energy via geothermal vent in ocean bed. So that, oceans are vigorous and ubiquitous sources of renewable energy which contain 93100 TWh of energy annually [4]. Energy in oceans comes in various forms such as tides, surface wave, thermal gradient,

ocean circulation and salinity gradients. It is apparent that ocean with its high amount of energy and global realm on Earth surface can be appropriately utilized for generating electric power. To date, diverse technologies has been developed for extracting different energy forms of ocean most of which are in infancy stage and there is a challenging road before scientists and engineers to generates electricity from ocean in a cost-effective manner.

1.2. Ocean waves

The most potent form of ocean energy is ocean wave. According to the International Energy Agency report, It is estimated that ocean waves have approximately 10000-15000 TWh of energy annually [4], also last researches clarified that 2.11±0.05TW (to 95% confidence) of ocean waves power facing total coastlines of the world [5].

Ocean wave is created by wind, as a byproduct of the solar energy. As solar energy is converted to wind energy, the time-averaged power flow is spatially concentrated, from an intensity of typically 0.1–0.3 kW/m² horizontal surface of the earth to 0.5 kW/m² envisaged area perpendicular to wind direction. As wind energy is converted to wave energy, even more spatial concentration takes place. Just below the ocean surface, average power flow intensity is typically 2–3 kW/m²of envisaged area perpendicular to direction of wave propagation [6]. Because of increase in power intensity, the wave energy is more persistent than wind energy or solar energy. In addition to wind, passing ships and subsea earthquakes generate waves while their contribution in total generated ocean wave power is negligible in comparison to wind.

When wind generates disturbance on ocean surface, gravity or surface tension act as restoring forces that tend to drive water toward its equilibrium state consequently ocean waves manifest themselves. Ocean waves can travel thousands of kilometers with little energy loss. When a wave is propagating, the water particles are not traveling, in fact they move clockwise around a small ellipse with the same period as the progressive wave which drives the motion [7]. The ellipse has its axes vertical and horizontal. By approaching to the seabed, the ellipses become progressively thinner in the vertical direction. At the sea bed, the water particles slip back and forth horizontally. Since the entire particle paths are closed loops, there is no net mass transport by the wave. Equation of water particles' pathway while taking part in a gravity wave motion is as follow;

$$\left(\frac{X_1}{\cosh(Z_0+h)} - \frac{A_I gk}{\omega^2 \cosh(kh)}\sin(kX_0)\right)^2 + \left(\frac{Z_1}{\sinh(Z_0+h)} + \frac{A_I gk}{\omega^2 \cosh(kh)}\cos(kX_0)\right)^2 = \left(\frac{A_I gk}{\omega^2 \cosh(kh)}\right)^2 \qquad (1)$$

Where A_I is amplitude of wave, X_0 and Z_0 are the initial position of water particle in x (wave propagation direction) and z (gravity acceleration direction) directions in Cartesian coordinates respectively, h is ocean depth, ω is angular velocity of ocean wave harmonics, g is gravity acceleration and k is wave number which is achieved from dispersion relation. Ac-

cording to the Eq. (1), by approaching to the sea bed $Z_0 \rightarrow -h$ so that $\sinh(Z_0 + h)$ and Z_1 tend to zero and water particle displacement abates in vertical direction.

Another important characteristic of gravity waves is propagation velocity of ocean waves. The importance is due to intrinsic relation of ocean wave power with group propagation velocity. Angular velocity for different harmonics of ocean waves is calculated according to the Eq. (2), so called dispersion relation, and phase velocity is achieved from Eq.(3);

$$\omega^2 = gk \tanh(kh) \tag{2}$$

$$v_p = \frac{\omega}{k} = \sqrt{\frac{g\lambda}{2\pi} \tan(\frac{2\pi h}{\lambda})} \tag{3}$$

In above equation, v_p is phase velocity of ocean wave harmonics and λ is wavelength of ocean wave. As Eq. (3), the phase velocity depends on ocean depth so that a distinct wave propagates in different depth of ocean with different velocities. There are two possible values for phase velocity. In shallow water, where ocean depth is significantly less than wavelength ($h \ll \lambda$), the phase velocity is;

$$v_p = \sqrt{gh} \tag{4}$$

And phase velocity in deep water, where ocean depth is more than wave length ($h \gg \lambda$), is as follow;

$$v_p = \sqrt{\frac{g\lambda}{2\pi}} \tag{5}$$

With respect to Eq. (4), in shallow water, wave is not dispersive and various harmonics of wave propagates with same velocity, while in deep water, according to Eq. (5), waves are dispersive. It means wave with different wavelength propagate with different velocities proportional to their wavelength.

Total power that is carried by one harmonic of wave in unit length of wave crest, called wave energy transport, is as below equation;

$$J = \frac{\rho g^2 A_I^2}{4\omega} \left(1 + \frac{2kh}{\sinh(2kh)}\right) \tan(kh) = \frac{\rho g A_I^2}{2} v_g \tag{6}$$

While, ρ is density of ocean water and v_g is group velocity of wave that is equal to phase velocity in shallow water $v_g = v_p = \sqrt{gh}$ and in deep water is equal to half of phase velocity

$2v_g = v_p = \sqrt{g\lambda / 2\pi}$. According to different wave propagation velocity in deep and shallow waters and related energy transport by wave in these environments and by considering various methods of extracting wave power by different devices and related commercial, installation and maintaining issues, ocean waves study is divided to three different areas called; shoreline, near-shore and off-shore.

Off-shore is a location of ocean in where depth is more than 40 meters. In this location ocean waves have the most power.

Near-shore is location with ocean depth of 10-30 meters and typically has a distance of 0.5-2Km from coastline. In near-shore, seabed fraction is the major source of incident wave power reduction. For instance, in location with ocean depth of 10 meters, different harmonics of ocean waves losses 2-10% of their total power [8].

Shoreline is the location of ocean where depth is less than 10 m. In this location most of the wave power is declined due to seabed fraction and wave breaking.

Not only amount of wave power is various in off-shore and in-shore (shoreline and near-shore) but also ocean wave power is not uniformly separate in all oceans. Fig. 1 illustrates global distribution of wave power density [5]. The arrows on the plot show the mean best wave propagation direction. This figure represents that most of wave power is concentrated in western part of continents which is due to west to east winds. The highest levels in the Northern Hemisphere are off the west coast of the British Isles, Iceland and Greenland, with somewhat lower energy levels in the Pacific off the western seaboard of the US and Canada in Southern Hemisphere Chile, South Africa and the entire south and south west coasts of Australia and New Zealand.
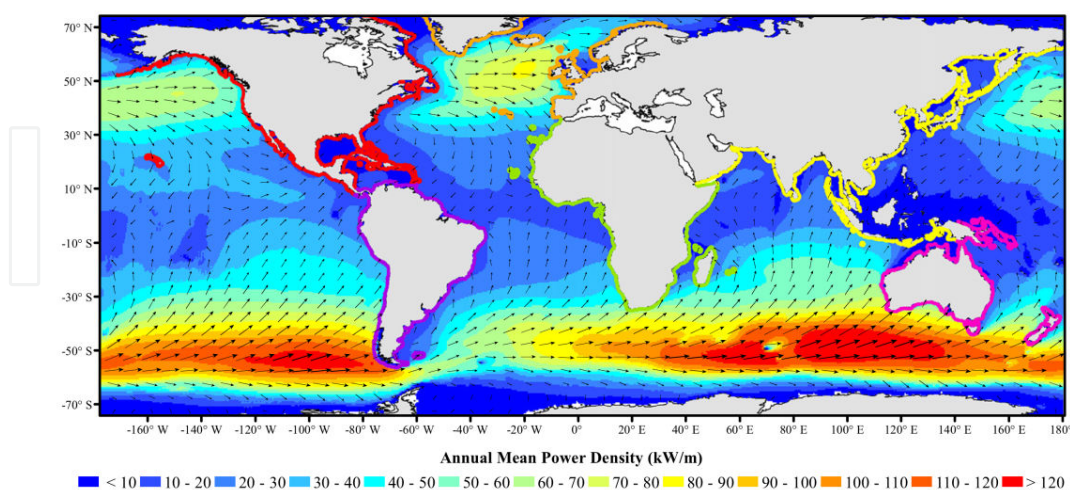

Figure 1. Global annual mean wave power density and annual mean best direction (arrow) [5].

In other point of view, ocean wave power is denser between 40º-60º latitudes in both Northern and Southern hemisphere. Stephen Barstow et al. represented relevance of annual mean

ocean wave power density to latitude as Fig. 2. It is shown that ocean wave power is mostly travelling between 40º-60º latitudes [9].
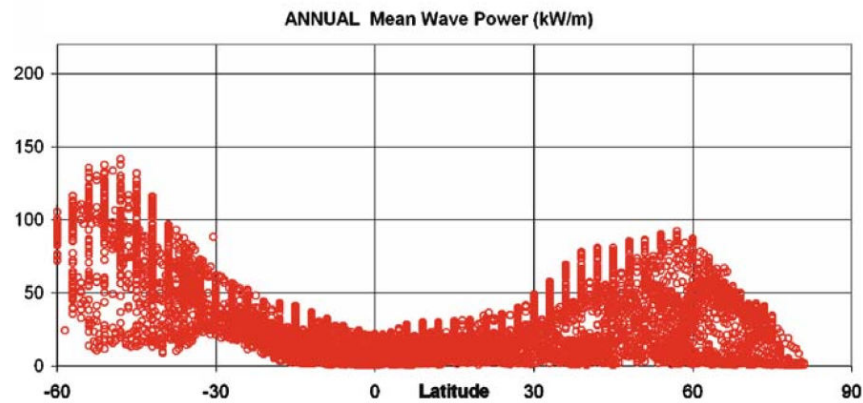

Figure 2. Global annual mean wave power density with respect to latitude [9].

Ocean waves are variable in different time scales. The average wave energy for a winter month can be 5–10 times the mean value for a summer month. The wave energy can vary 10 times from one week to the next. The wave energy during one storm can be five times higher than the mean value for the week the storm occurs. Wave energy in a wave group can be up to 50 times the wave energy between wave groups [10]. In Fig. 3, Monthly mean ocean wave power is plotted for different months of year. According to this figure ocean wave power in both Hemispheres is significantly higher in winter season in comparison to summer. Also seasonal variation of wave power in southern Hemisphere is lower than northern one.
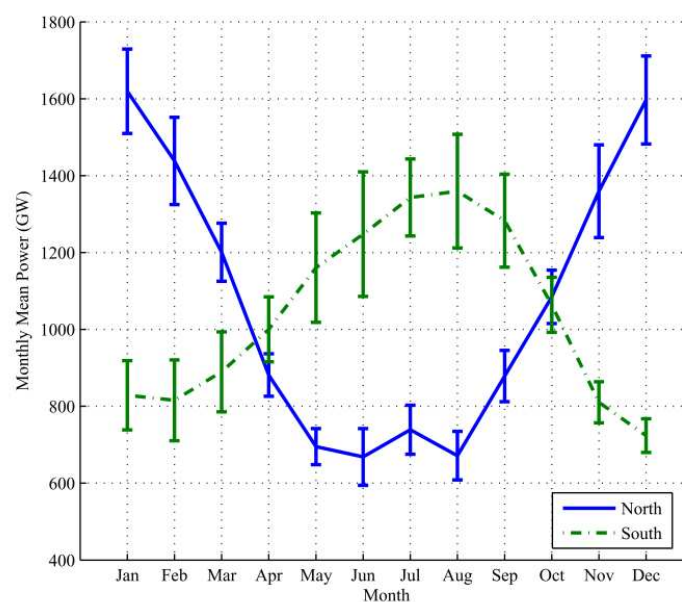

Figure 3. Monthly mean wave power for Northern and southern Hemispheres [5].

1.3. Wave measurement and prediction

Ocean waves are variable in different time scales. Not only wave elevation and wave length (wave power) but also wave propagation direction varies with time. These detailed statistics are important for designing and controlling of particular Wave Energy Convertor (WEC). In most of cases, WECs extract wave power with oscillation in special directions and these WECs absorb maximum power whereby are adjusted in the resonance frequency, a restricted frequency span that WECs oscillation frequency is equal to exciting wave frequency. Implementing upcoming characteristic parameters of ocean wave (amplitude, propagation direction and wave length or period) has a significant impact on capture width of WECs. This information can be used for generator speed control. In all WECs, rotating or linear electric generator is utilized for generating electrical power, implementing information of upcoming wave can be used for speed control of generator and adjusting system in resonance frequency [11]. Briefly, measurement and anticipation of upcoming ocean wave parameters play a significant role in controlling of a WEC. To date, there are various instruments for measuring and predicting ocean wave some of which are described as follow;

1.3.1. Buoy

Buoys are the oldest method for measuring wave parameters. Buoys can measure wave amplitude and wave period but for detecting wave propagation direction at least two buoys are needed. Different sensors have been used on buoys for measuring such as down looking laser profiles, current meter triplets, pressure transducers.

However, when using buoys to measure the waves, these tend to drift with the water particle motion and give imprecise spatial measurement (see Fig.4 left side). In order to solve these problem different methods have been offered as an example see ref. [12]. In Fig. 4 right side a measurement buoy named WaveScan is depicted, this buoy measures heaven and sway acceleration [9].

1.3.2. Synthetic aperture radar

It has been amply demonstrated that synthetic aperture radar (SAR) data can be used to estimate parameters of the two-dimensional (2-D) sea surface elevation field [13, 14]. Due to their high spatial resolution and all-weather and daylight capabilities, spaceborne SAR systems are the only sensors that can provide directional ocean wave information on a continuous and global scale.

The SAR radar sends a pulse down to the ocean surface at nadir. The significant wave height is obtained from the slope of the leading edge of the return pulse, while the total backscatter gives us the wind speed. The major goals of the variable SARs were applications in ocean wave research and wave forecasting. Two-dimensional ocean wave spectra can be derived from SAR images by inversion of the SAR imaging mechanism.
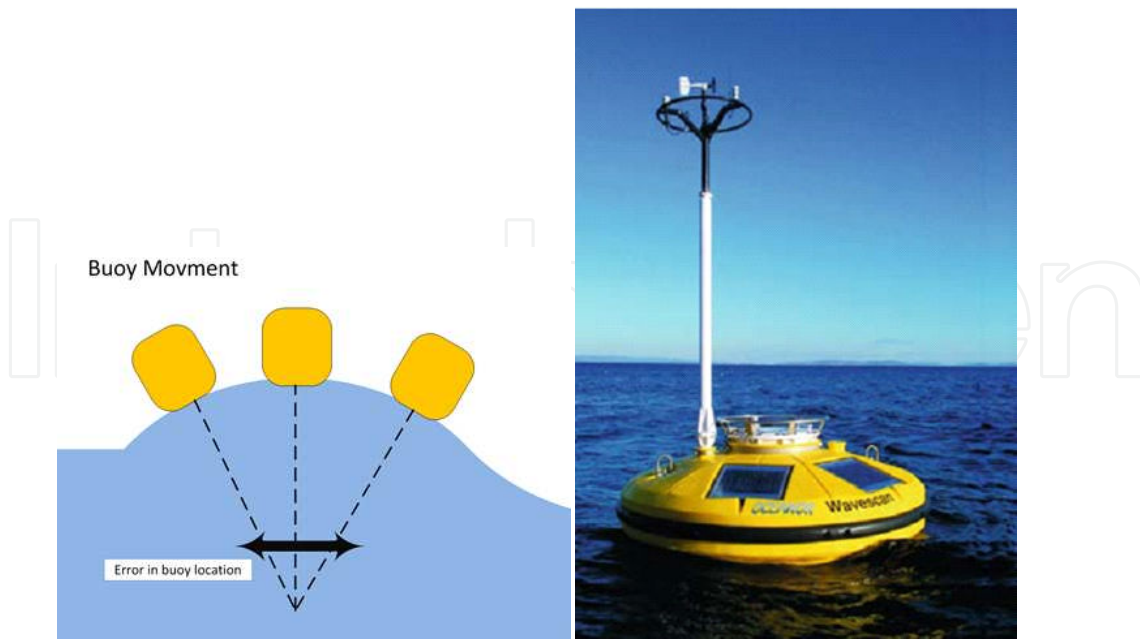
Figure 4. Left side; Error in measurement due to buoy movement. **Right side;** The WaveScan buoy [9].

2. Wave energy convertors

Ocean Waves has been considered as a source of energy since late 18th century and the first patent for capturing wave power was filled in France in 1799 by a father and son named Girard [15]. After World War I when petrol became most important source of energy the interest for harnessing ocean wave power faded. In 1940s, the Japanese wave power pioneer Yoshio Masuda developed an innovative device for absorbing wave power which is known as Oscillating Water Column (OWC) [16]. Oil crisis in 1973 was a great stimulator for governmental funds and researches in wave power extracting but petrol price decline in early 1980s abated interest in wave power [15]. Recently, the Kyoto Protocol on reduction of CO_2 emission, has intensified the interest in this field among researchers. To date, there are various devices which capture power from ocean waves [16, 17]. These devices are distinct in installation location (Off-shore, Near-shore and shoreline) as well as manner of energy harvesting. This section categorise Wave Energy Convertors (WECs) based on manner of interaction with ocean waves.

Excising WECs harvest wave power based on two different principles, Oscillating-WECs and Interface-WECs.

Oscillating-WECs are devices that are in direct contact with ocean waves and oscillate in specific direction related to device design and degree of freedom. J. Falnes, one of the distinguished pioneers in ocean wave power absorption, has been clarified that there are six degree of freedom for a body to oscillate with ocean waves [18]. According to Fig. 5, Oscillation in direction

of 1st, 2ed and 3rd arrows are known as surge, sway and heave respectively. Also rotation around x-axis (mode 4), y-axis(mode 5) and z-axis (mode 6) are named respectively roll, pitch and yaw. Oscillating-WECs are displaced in only these six modes, most of these WECs have oscillation in only one of these modes which are known as single-mode oscillators and some others have oscillation in more than one mode that are regarded as multi-mode oscillators. (Note that in most of Oscillating-WECs there is no variation in y direction, in this case there are only three modes for body oscillation; Surge, Have and Pitch).
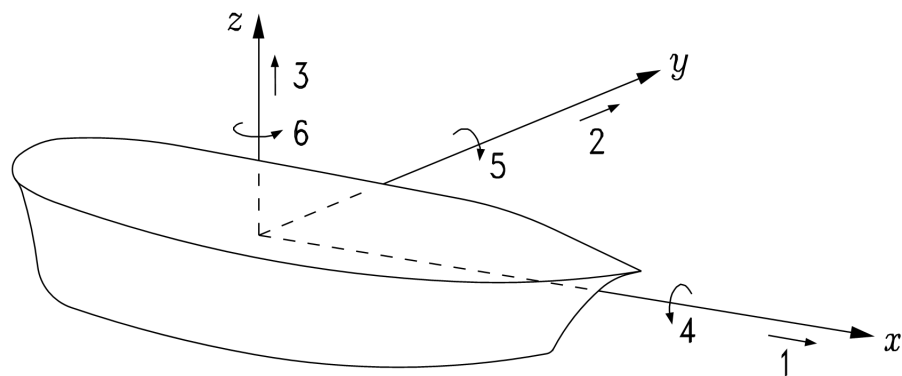

Figure 5. Different oscillation mods of a Wave Energy Convertor: Surge (1), Sway (2), Heave (3), Roll (4), Pitch (5) and Yaw (6) [18].
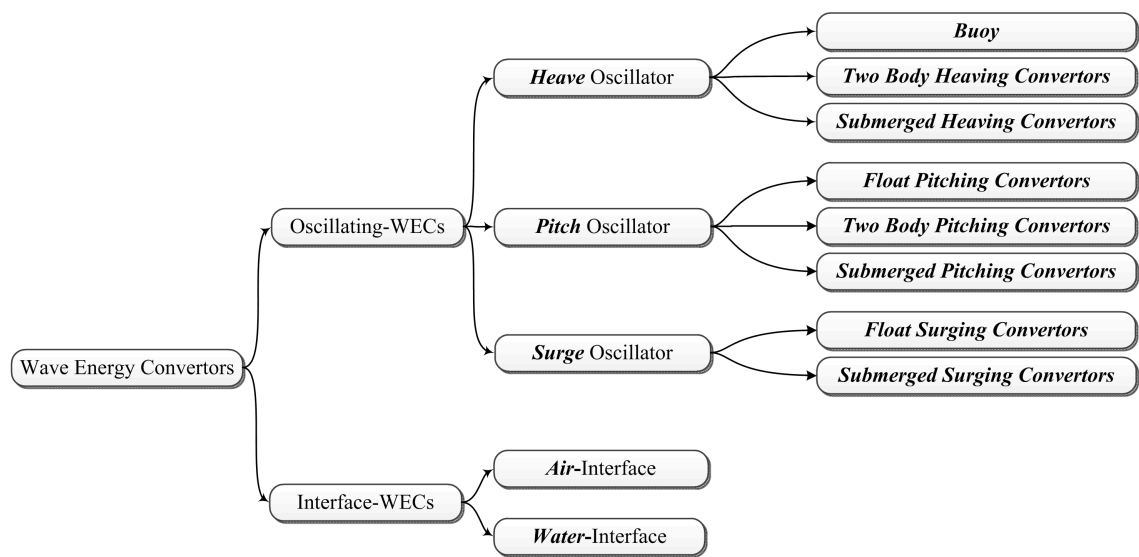

Figure 6. Categories of Wave Energy Convertors.

Interface-WECs are special forms of WECs that are not oscillating in aforementioned modes. In fact these WECs are devices or structures that are fixed in a location and have not interaction with ocean waves. Interface-WECs are used to deliver wave power by an interface (water or air) to the PTO (power take-off). The scheme of classification of WECs is illustrated in Fig. 6.

2.1. Oscillating-WECs

In this subsection, different WECs, which have one or two degrees of freedom, are investigated. Indeed, these WECs are simple in motion due to their restricted motion modes and they can be divided to three distinct categories; Heave Oscillators, Pitch Oscillators and Surge Oscillators.

2.1.1. Heaving oscillators

Heave Oscillators are the simplest oscillators for absorbing wave power. These devices, extract wave power with motion in perpendicular direction to the Sea Water Level and according to the mooring and working principle are divided to three groups; *Buoys*, *Two Body Heaving Convertors* and *Submerged Heaving Convertors* [16].

2.1.1.1. Buoy

Point absorbers or buoys are convertors with one floating body in sea level which is connected to the PTO (Power Take-Off) via a steel structure or a cable (translator). The body fluctuates with ocean waves in earth gravity direction (heave) which cause the steel structure or cable to oscillate with it hence the bidirectional movement of buoy is transferred to the PTO in the other point of translator and PTO generates electricity. To date various buoys have been designed for wave energy harvesting which are same in principal but different in detail. One of these is a buoy that was designed by Budal et al. in Norway [19]. The device was linked to anchor on the sea bed via universal joint (see Fig. 7). An air turbine was implemented on the device for energy converting and it was controlled by latching control.

Figure 7. Norwegian buoy (courtesy of J. Falnes) [16].

Figure 8. Left side; Taut moored heaving buoy with linear electrical machine PTO [16]. **Right side;** Component of tout moored WEC, Sweden [22].

Another buoy type is floating body connected to bottom fixed structure via a cable (taut moored). Due to cable flexibility, this device is not restricted in heave mode and it also has oscillation in surge direction. PTO of device is fixed in ocean bed and cable transfer WEC motion to PTO. There are two different PTO that has been coupled with this type of WEC. Hydraulic PTO was implemented by this WEC in Denmark in 1990s which by piston pump supplies high pressure water to a hydraulic turbine [20] and another is linear electric genera-tor that is housed in inside a steel hull mounted on a concrete ballast structure and converts linear motion of cable (translator) to electric power [21]. This system is developed in Sweden and the scheme of system is represented in Fig.8. Barbarit et al. have investigated different power capture preformation of various WECs by numerical method [22] and capture width of taut-moored WEC is as Fig.9.
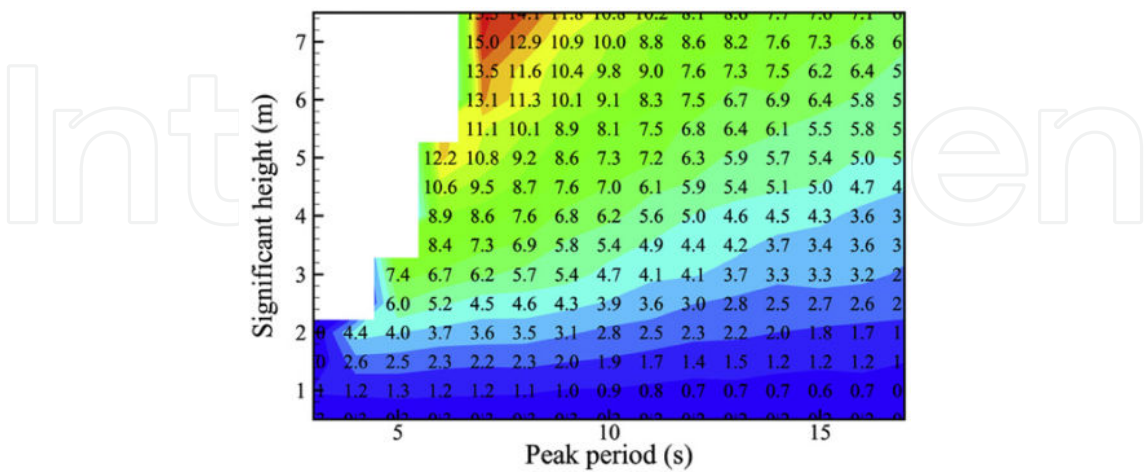

Figure 9. Power capture performance of taut moored WEC for various waves (the vertical axis is wave ampli-tudes in meter and horizontal axis is wave period in second and the annual men absorbed power amount on the table are in kW) [22].

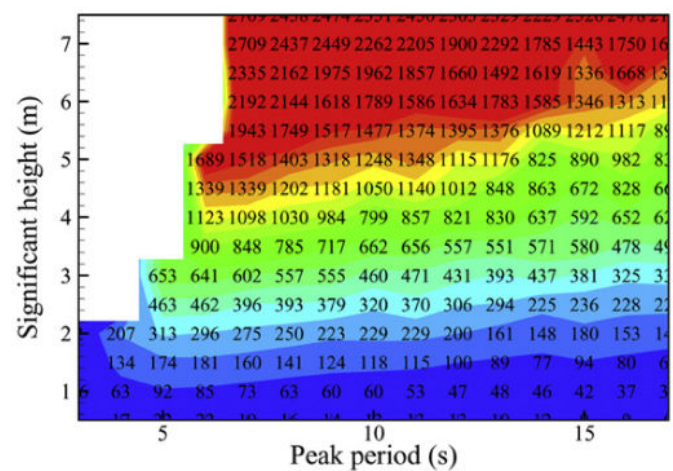**Figure 10.** Wave Star WEC, Denmark [22].

Figure 11. Power capture performance of Wave Star WEC [22].

In the case of heaven buoys, Wave Star Energy company has developed an innovative WEC namely Wave Star WEC. In this device a jack up structure stands on sea bed and provides a reference to the buoys (see Fig. 10). A full sized system is consisting of different buoys in which a hinging arm is utilized to transfer each buoy's motion to the PTO. The buoys have ability to be polled up (survival mode) in case harass ocean condition. Furthermore, hydraulic rams are employed to convert hinging motion of arms. Power capture preformation of 20 buoys Wave Star WEC was investigated by Babarit et el. [22] and the result is as Fig. 11.

2.1.1.2. Two body heaving convertors

Two body heaven convertors are multi-body convertors in which ocean power is extracted from the relevant motion between two bodies. One of these bodies is float on ocean surface and another is completely submerged. Ocean wave interaction with this WEC causes the float body elevates in heave mode as well as it pushes submerged body to the sea bottom due to increase in sea

water inertia. One of the important advantages of this WEC is facility in its installation. Because device does not require any sea-bed connection, it can easily be installed in off-shore. Yet, different devices are developed in this principal one of which is ISP buoy developed in Sweden [23], Irish Wavebob [24] and PowerBuoy inspired by Ocean Power Technologies company.

The schematic of Wavebob is depicted in Fig. 12 left side. According this picture wavebob is consist of an inner buoy, submerged body (body2), and floating buoy (body 1) which are axially connected to each other. Additionally a high Pressure oil hydraulic system is implemented to deliver extracted power to electric generator. Fig. 13 illustrates power capture matrix of Wavebob WEC [22].
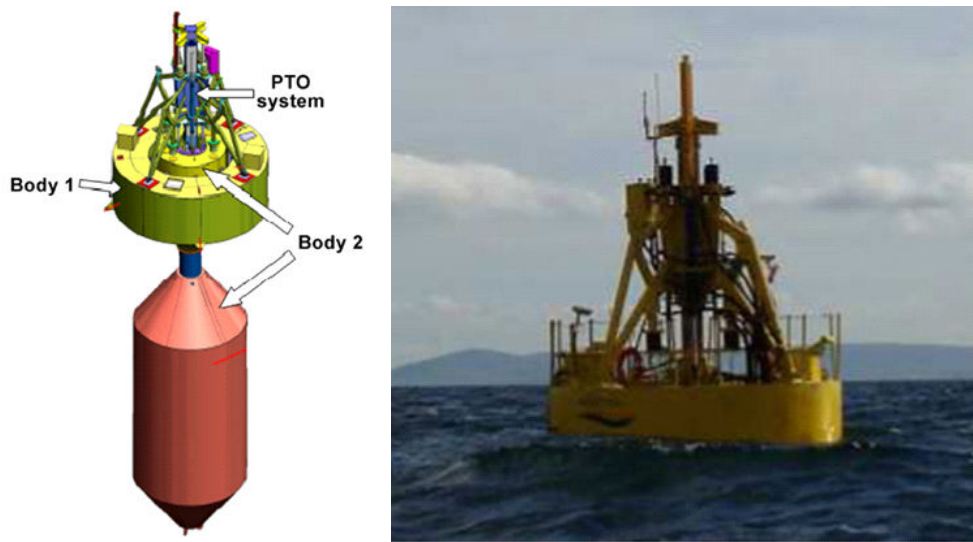

Figure 12. Left side; Principle of Wavebob WEC [16]. **Right side;** ¼ Scale Wavebob WEC, Ireland [22].
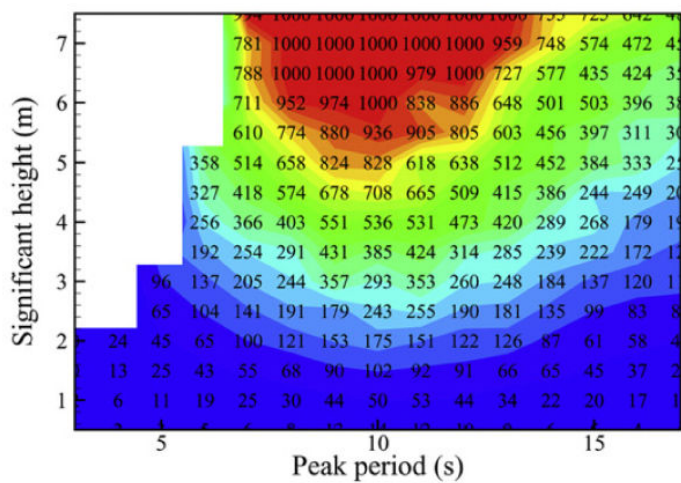

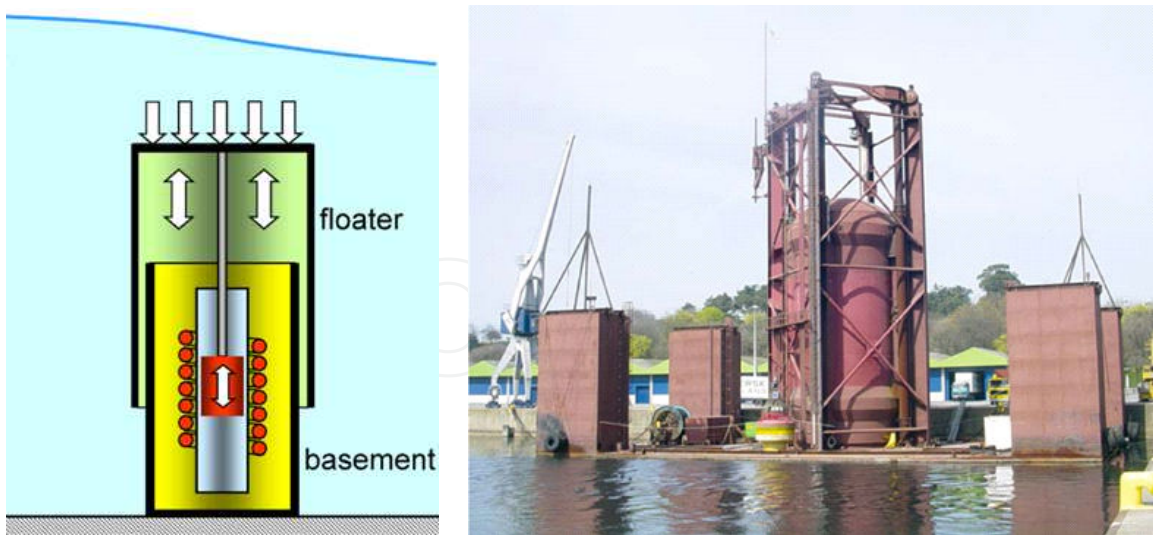**Figure 13.** Power capture performance of Wavebob WEC [22].

Figure 14. Archimedes Wave Swing (**Left side:** Scheme [16]. **Right side:** Prototype [37]).

2.1.1.3. Submerged heaving convertors

The Archimedes Wave Swing (AWS) is a fully submerges off-shore WEC. It is constructed from two main parts, Silo or Basement is an air filled cylindrical chamber which is moored on seabed and floater is oscillating upper part as is illustrated in Fig. 14. Floater oscillates by water pressure variation. By crossing wave crest upon AWS the floater moves down compressing the air inside the chamber and by passage of wave trough upon AWS, the air inside the chamber expands and consequently push the floater up. Beside its unique design, AWS is the first WEC that a linear electric machine is implemented as PTO. One side of linear machine is fixed to the basement and the other side is connected to the floater via a translator, hence oscillation of floater excites linear machine. The AWS was successfully tested in 2004 [25].

Due to their mooring structure and the environment they work in (off-shore), almost all of the heaving oscillators requires highly maintenance. Meanwhile delivering generated electric power to the electric network or consumer is another problem intrinsically related to these off-shore WECs. High cost and Long distance underwater cabling is a commercial problem that heaving oscillators face with.

2.1.2. Pitching oscillators

Pitching oscillators are WECs which extract wave power by hinging motion in wave propagation direction. As it is demonstrated in Fig. 5, the hinging motion of pitching oscillator occurs in the axis in which WEC is installed on. According to device mooring and body design theses WECs are categorized to three types; *Float Pitching Convertors*, *Two Body Pitching Convertors* and *Submerged Pitching Convertors*.

2.1.2.1. Float pitching convertors

Developed in Lancaster University and off-shore WEC, *PS Frog Mk 5* is the best example of Floating Pitching Convertors [26]. As it is illustrated in fig. 15, PS Frog Mk 5 is composed of a large buoyant paddle with an internal ballasted handle below it. It oscillates in pitching mode and is float on sea level. When wave acts on paddle the ballast provides necessary re-action for pitch motion, consequently the wave power is absorbed by partially resisting the sliding of a PTO mass, which moves in guides above sea level. The sliding mass (PTO) con-verts the wave motion into differential mechanical motion within device then the mechani-cal motion is transferred via hydraulic circuit to an electrical generator.

The main advantages of PS Frog Mk 5 is its self-orienting capability with which the device spontaneously adjusts to face incident waves. Meanwhile, by moving ballast in the hall or by controlling sliding mass, it is viable to control PS Frog Mk 5 in resonance frequency in which device has the maximum capture width.
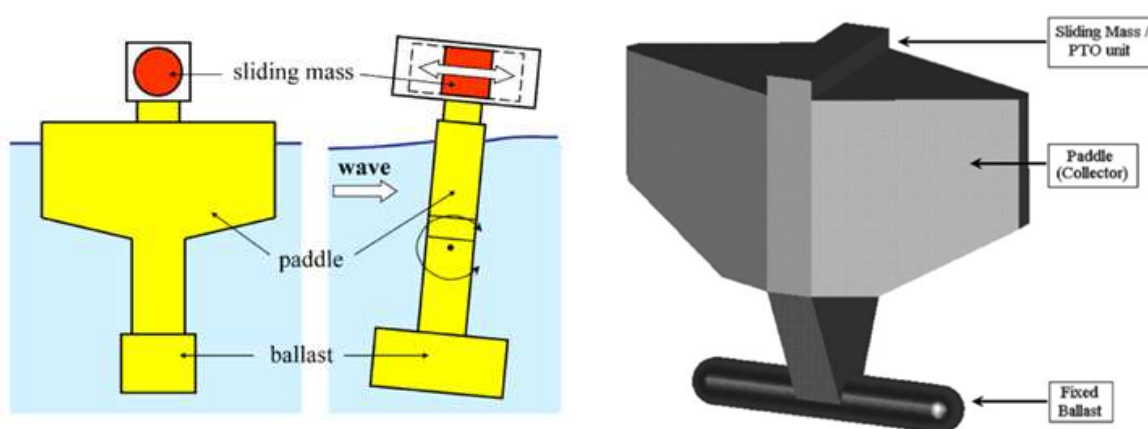

Figure 15. Left side: 2D illustration of PS Frog Mk 5 [16]. **Right side:** Perspective view of PS Frog Mk 5 [26].

2.1.2.2. Two body pitching convertors

Pelamis is a multi-body, floating, off-shore WEC. This device consists of several slender semi-submerged cylinders linked by hinged joins [27, 28]. When wave acts on Pelamis, adja-cent cylinders start to fluctuating by angular motion in the joins in which wave power is ab-sorbed in Pitch and Yaw mods. The scheme of Pelamis is presented in Fig. 16. In this figure, the left side represents the working concept of Pelamis and the right side shows a full scale Pelamis. In Pelamis the motion of cylinders is used to move hydraulic cylinders which pump fluid to high pressure fluid accumulators for short term energy storage. Furthermore, the smooth supply of high pressure fluid in accumulators drives hydraulic motors which are coupled with grid-connected electric generators. About device mooring, because of the self-referencing no rigid connection to the sea-bed is required and a slack mooring is sufficient to hold the device on station.
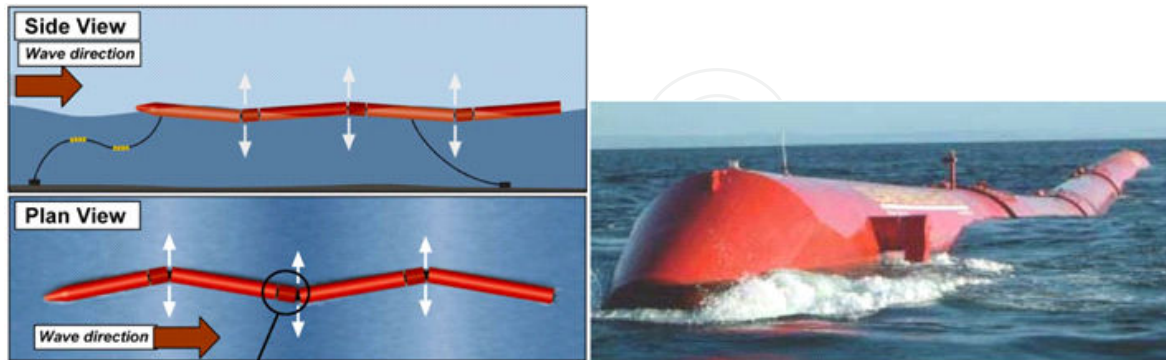
Figure 16. Left side: Scheme of Pelamis and principle of working [27]. **Right side:** Full scale prototype (By Ocean Power Delivery Ltd).

The PTO section of Pelamis is divided to two main parts which are called primary and secondary transmissions. The primary transmission, which stores wave power in hydraulic accumulator, consists of the hydraulic cylinders and their controllers. The secondary transmission, consisting of hydraulic motors coupled to electric generators, converts the energy stored in the hydraulic accumulators into electricity transmitted to shore. The separation provided by high pressure accumulator and controlling of electronically controlled valves, which controls input and output fluid of accumulators, makes it feasible efficient power absorption from ocean waves.

Full scale prototype Pelamis WEC, 120 m long and 3.5 m diameter, has been constructed and has been successfully connected to local electrical power network.

2.1.2.3. Submerged pitching convertors

Yet, there are different devices that fall in this category [29, 30] one of which is Oyster [31], Aquamarine Power Ltd developed near-shore WEC. The Oyster is a bottom hinged rigid flap which completely penetrates the water column from above the surface to the sea bed. When wave attach the Oyster, WEC starts to oscillate in pitch mode, rotational motion around hinging axis, and this motion moves a double acting high pressure sea water pump. A set of non-return valves rectify the flow from the double acting pump consequently the flow is regulated by a gas accumulator. The flow (water) is transferred to the shore through pipeline. In the onshore hydraulic plant, hydraulic pressure is converted into electric power via a Pelton wheel. Finally the water passes back to device in a close lop via a second low pressure return pipeline. The schematic of Oyster is presented in fig. 17. Another WEC that work in the same principle is WaveRoller WEC. In spite of Oyster, the rigid flaps of WaveRoller are short and it harvests wave power only near seabed [30].
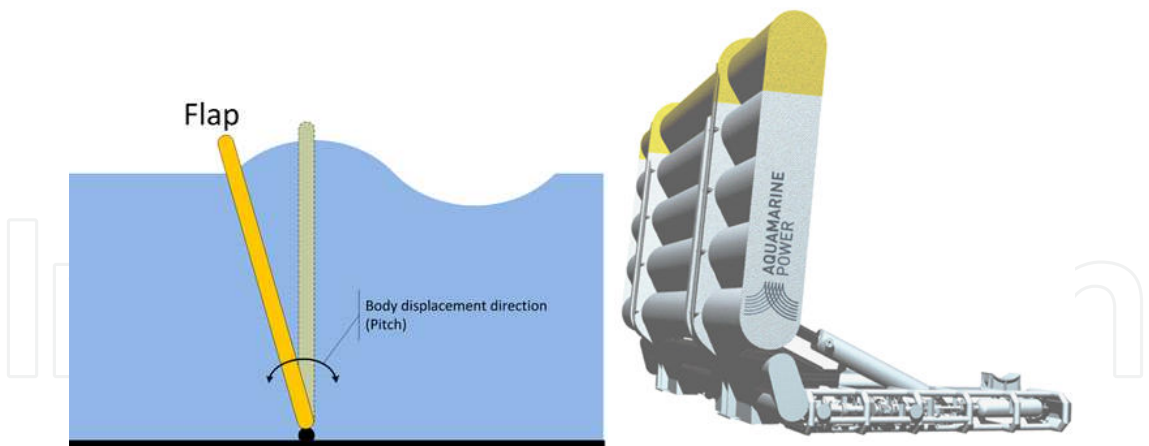
Figure 17. Left Side: Schematic of pitching flap WEC. **Right Side:** The Oyster WEC by Aquamarine Power Ltd [32].
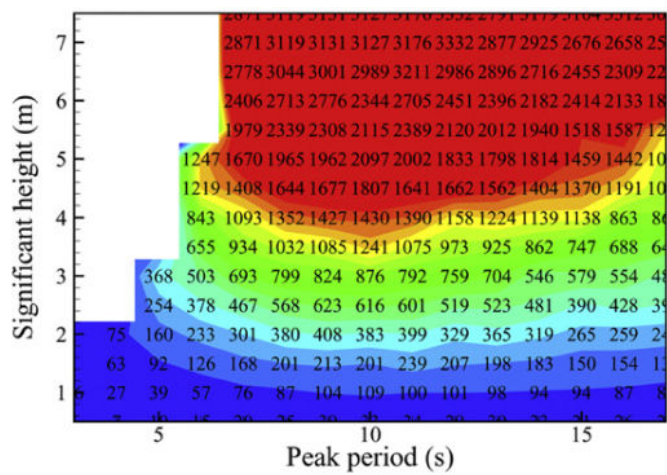

Figure 18. The power matrix of bottom hinged pitching flap [22].

The power capture performance of submerged pitching convertor is presented in Fig. 18.

2.1.3. Surging oscillators

However, waves' force in near-shores is concentrated in surge direction [8], surge wave energy convertors are less developed WECs in comparison to other types.

Developed in Western Ontario University namely "Surfing Wave Energy Convertor" is one of the surge WECs [33]. The Surfing Wave Energy Convertor is comprised of several paddles connected to a common drive train, which mechanically links them to an electric machine. The operating cycle begins with a paddle suspended in the path of the incoming wave. As the waves impact the paddle it is driven horizontally in the direction of wave travel in a 'Surfing' like motion. The horizontal motion of the paddle in-turn drives the electric machine, generating power. Once the paddle reaches the downstream end of the system, the

electric machine is switched to motor operation and drives the system, lifting the first pad‐ dle out of the path of the waves and lowering the next paddle into the wave path.
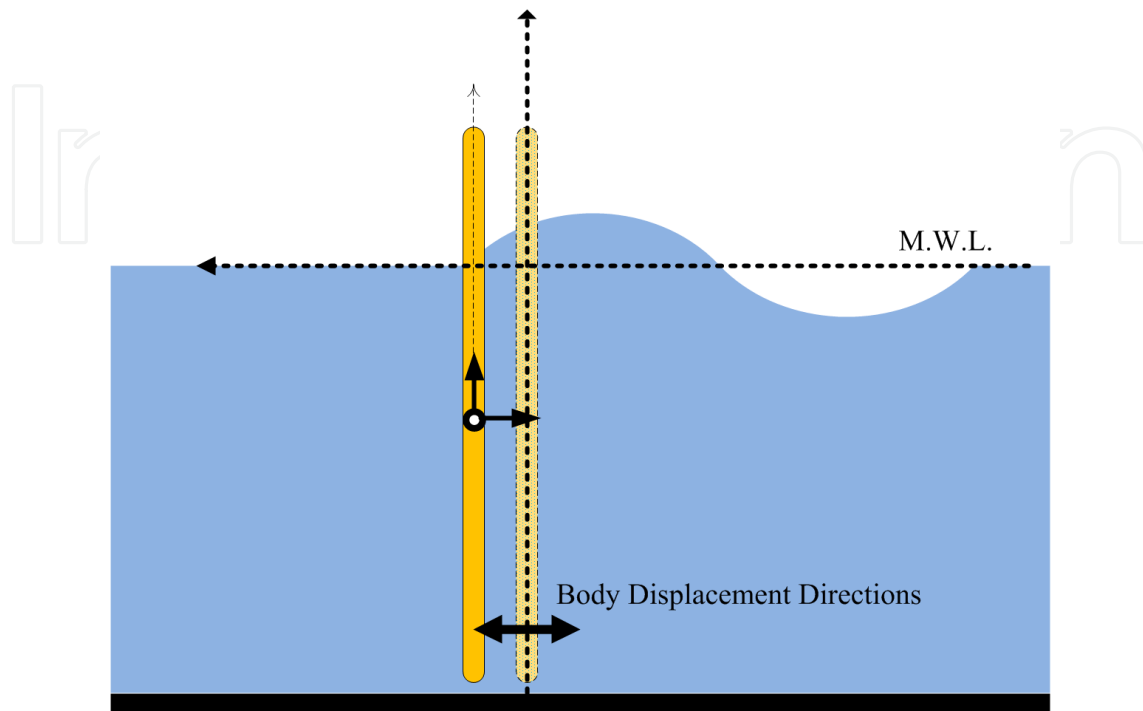

Figure 19. Schematic of Surge WEC.

Another surge WEC is designed by these authors [34, 35]. It consists of a rigid plate which is installed in near-shore vertical to the sea bed. The plate has been connected to a linear gener‐ ator. When waves attack the plate it fluctuate in horizontal direction, parallel to the wave propagation direction (See Fig. 19). Various power electronic instruments has been imple‐ mented to deliver ocean wave power to electric network. The device is still under develop‐ ment in Altin Tara Electric Ltd. in Iran.

2.2. Interface-WECs

Interface-WECs are device that have no oscillation in interacting ocean wave. In fact these devices are designed to deliver wave energy via an interface (Air or Water) to the PTO. In comparison to Oscillation-WECs they require less maintain.

2.2.1. Air-interface

Oscillating water column (OWC) WEC is an Air-interface WEC in which wave power is con‐ verted to the electrical power without direct oscillation of WEC body by water particle. OWC is consists of a floating or bottom fixed structure whose upper part encloses a column of air and whose immersed part is open to the wave action [36]. The scheme of OWC is pre‐ sented in Fig. 20.

When waves attack the OWC, the water pressure below the chamber compresses the trapped air in the chamber and the air is guided to a turbine hence the flow of air to outside of chamber turns the turbine and the coupled generator. Meanwhile, by decline of water pressure below the chamber, the pressure of trapped air reduces and consequently air flows into chamber and drives the turbine again. To date, two type of self-rectifying turbine has been used in OWC; the Well Turbine and Impulse Turbine, both of which have the capacity to rectify air flow that makes it feasible to have unidirectional motion in electrical generator.

The early inventor and developer of OWC is Yoshio Masuda who had commercialized the floating OWC in Japan since 1965 [16]. The OWC has been used for energy converting in both shoreline and near-shore.

Figure 20. Left side: Schematic of OWC. **Right side:** Back view of an OWC [37].

2.2.2. Water-interface

Overtopping wave energy convertors are the main members of water-interface WEC. To date, three overtopping wave energy convertor has been developed; The Tapchan (Tapered Channel Wave Power Device) [38], Wave Dragon [39] and SSG (Seawave Slot-Cone Generator) [40]. One of the well-known overtopping WECs is Wave Dragon. The Wave Dragon is an off-shore WEC, installed in location with depth of 25-40m, which is moored like a ship and consists of three main sections. The main platform, a reservoir with a double curved ramp, is float on the ocean surface and other parts are mounted on it. Two wave reflectors are installed on both sides of platform and intensify wave amplitude approaching to the platform. Finally a Hydro turbine, a set of low head Kaplan turbine, converts the hydraulic head in the reservoir. The Wave Dragon is represented in Fig. 21.

When waves approach to Wave Dragon, the reflectors focus them and guide the water toward the ramp, water overtop the ramp and fill in the reservoir then the turbine generates electricity from water motion inside the device. In Wave Dragon the wave energy convertor has not oscillation with wave, indeed wave power is transferred to PTO by water. In spite of air-interface WECs, water-interface WECs are not capable to be analyzed by Linearized Wave Theories.
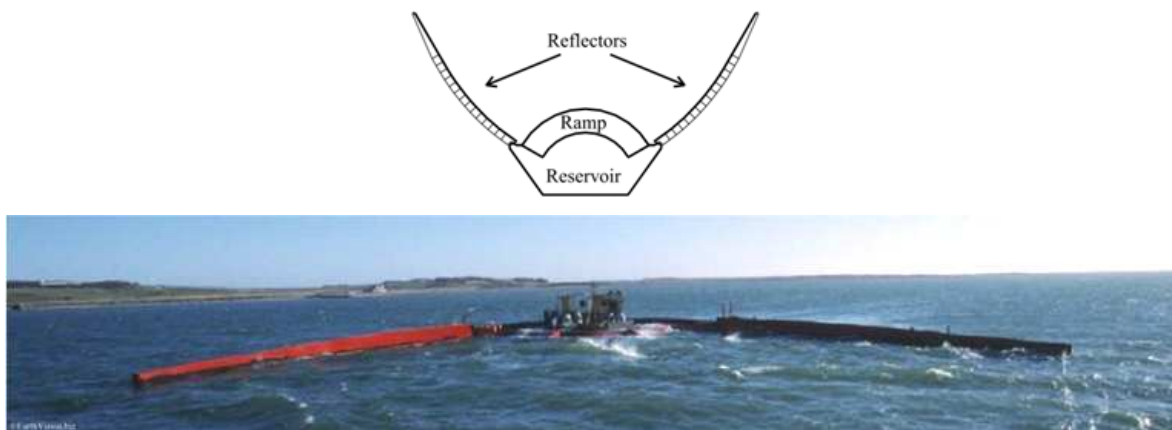
Figure 21. Wave Dragon. (**Above:** Scheme [39] **Below:** Prototype [39])

3. Power take-off

In process of wave energy convertion, after power extraction in WEC, another energy conversion happens in Power Take-Off (PTO). Power take-Off is (mostly mechanical or hydraulic) device in which the absorbed power is transferred to an electric generator. To date, three type of PTO is more commonly used.

- *Air/Water Turbine* forms part of an integral system that consists of a capture device, which also includes an electric generator. This PTO system is used in Interface-WECs (Oscillating wave columns and Overtopping devices). The air turbines which are used in OWC are mostly self-rectifying turbines which convert reciprocating air flow to unidirectional torque. The two implemented turbine in OWC are Well turbine [41] and Impulse turbine [42]. Probably one of the advantages of turbines in PTO is facility of using flywheel for energy storage.

- *Hydraulics PTO* system is consisting of a hydraulic circuit which transfers absorbed power of wave to a hydraulic motor which drives an electrical generator [43]. This kind of PTO is used in Pelamis and bottom hinged pitching flap. Implementation of accumulator is an effective method for energy storing in this PTO.

- *Direct Drive* is consisting of a moving part named translator on which linear generators is mounted. Direct drive is the simplest and probably the most efficient Power Take-Off system. PTO system of heaving oscillators and submerge heaving oscillators are from this kind.

Regard less to the type of PTO, all of the PTOs are connected to an electrical generator which generates useful energy from waves (except especial uses of WEC that is not intended to generate electricity [32]). The two type of electrical generators implemented in WECs are Linear Generators and Rotational Generator.

3.1. Linear generators

Linear generator are the kind of electrical machine in which the rotor (translator) and stator are linear and translator displace in straight path inside stator. Since most of the WECs harness wave power in reciprocating directions, Linear Generators are the most appropriate machines for generating electricity by WECs. It is due to, there is not require for any other interface or other power conversion (e.g. Hydraulic) which decline the transferred power in transmission process. Linear generator is connected to the WEC via translator and displace with it. Yet, three topology of linear generators are considered in wave energy industry.

3.1.1. Linear Permanent Magnet Synchronous Machine (LPMSM)

LPMSAs are constructed in three different configuration; Single-Side, Double–Side and Tubular. In all of these structures the translator (actuator) have moving magnets and primary constitute mover. The core of the primary of a flat LPMSA is made of longitudinal laminations with uniformly distributed slots, which house the windings. Since the windings are located in open slots, the effective air gap is greater than the actual air gap.

In tubular structures the laminations of the shape primary core is longitudinal or disk-shaped. Stacking of the disk laminations increases the effective air gap. The core of the secondary of a tubular LPMSA is generally made of solid magnetic steel. In LPMSM the flux density is supplied by rare earth permanent magnet. Due to ease in assembly, disk shaped laminated tubular LPMSM are preferred to flat types also slitting technique is use on disk lamination to reduce eddy current [44]. The schematic of single side LPMSM is illustrated in Fig. 22.
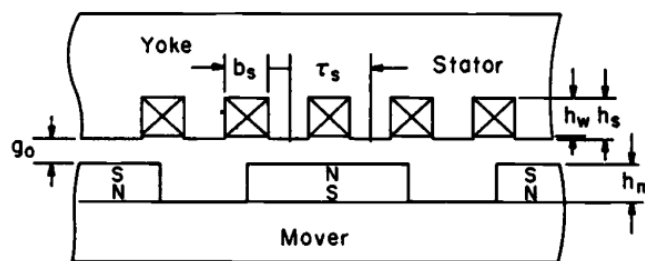

Figure 22. Schematic of single-side LPMSM [44].

3.1.2. Variable Reluctance Permanent Magnet Machine (VRM)

A family of permanent magnet machine, known as variable reluctance permanent magnet machine (VRM), has been developed with high force density. Despite its high force density, low power factor is a characteristic of VRM machines. The machine has a very high inductance, such that the current can be out of phase for almost 90 degree. The variable reluctance permanent magnet family is divided for two subcategory; Transverse Flux Permanent Magnet (TFM) and Vernier Hybrid Machine (VHM).

3.1.2.1. Transverse Flux Permanent Magnet Machine (TFM)

Transverse Flux Permanent Magnet Machines (TFM) has higher shear stresses than other machine topologies, This implies that TFM machines may be more suitable for wave energy application than the synchronous machines. There are two topology of TFM. In the first topology, the coils are in the stator and the magnets are on the translator. The translator is longer than the stator, which means that a part of the (rather expensive) magnets is not used (see Fig. 22. Left). This machine was used in AWS.
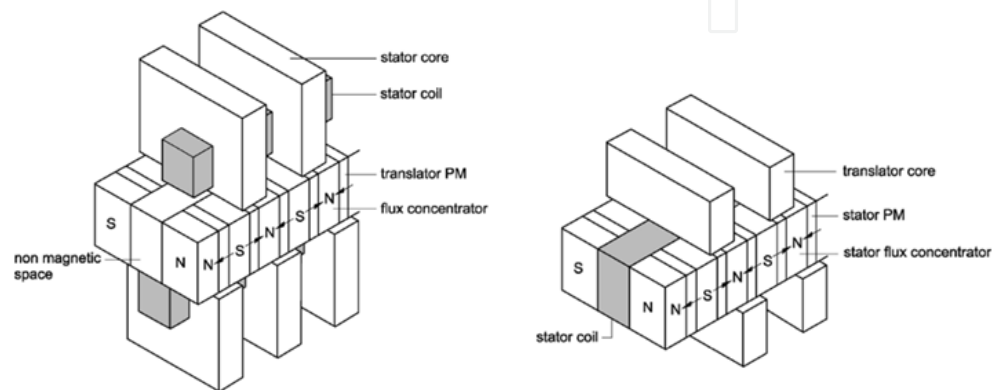

Figure 23. Left side: TFM machine with flux concentration and moving magnets [45]. **Right side:** TFM machine with flux concentration and stationary magnets [45].

As it is illustrated in Fig. 22 Right, the second topology, namely the double-sided moving-iron TFM, is a double-sided machine in which the translator consists only of iron. "In this topology, the stator consists of coils and U-cores on both sides of the translator, which consists of two rows of magnets and flux concentrators with space for construction material in between. Both the conductors and the magnets are kept stationary. The U-cores are now simpler in shape because space for coils is no longer required, and these cores or yokes form the translator."[45]

3.1.2.2. Vernier Hybrid Machine (VHM)

The Vernier Hybrid Machine is constructed from a linear toothed translator constructed from iron laminates which move inside two C-cores. The C-core has coil wounded on each pole also magnets are mounted on pole face. The translator tooth and slots width are similar in dimension to the magnet pitch, hence rapid flus reversal happens over short distance as the translator teeth move from the aligned to the unaligned position. Due to rapid flow change in a short distance, the electric frequency of the flux pulsation is greater than the translator's frequency [46, 47]. The schematic of one pole VHM is presented in Fig. 24. In spite of TFM, the VHM can be constructed from lamination which makes construction easy and small. However power factor of VHM is low, the high shear stress, small sizes and facility of constructing are main advantages of this machine.

3.1.3. Tubular air cored permanent magnet generator (TAPM)

The TAPM machine is proposed for wave application by Baker and Muller [48]. The principle of TAPM is shown in Fig. 25. In this topology, the magnets are magnetized in the axial directions with altering direction of flux [37]. Flux concentrators are placed between the magnets and a varying flux wave is created outside the translator. The large constructional advantage of TAPM is elimination of normal force by removing the steel in stator. Significant support structures are needed to overcome these forces and maintain a constant air gap width. The main problem in this topology is that the magnetic reluctance in the magnetic circuit is increased considerably, since the distance the flux travels in air now is in the range of the pole pitch and not, as in steel stator machines, just over the air gap [37]. The flux of an air cored machine is thus much smaller and the power per air gap area is considerably lower.
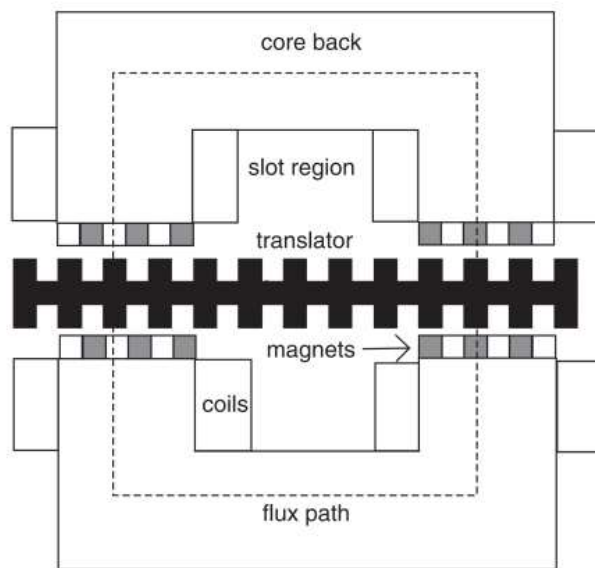

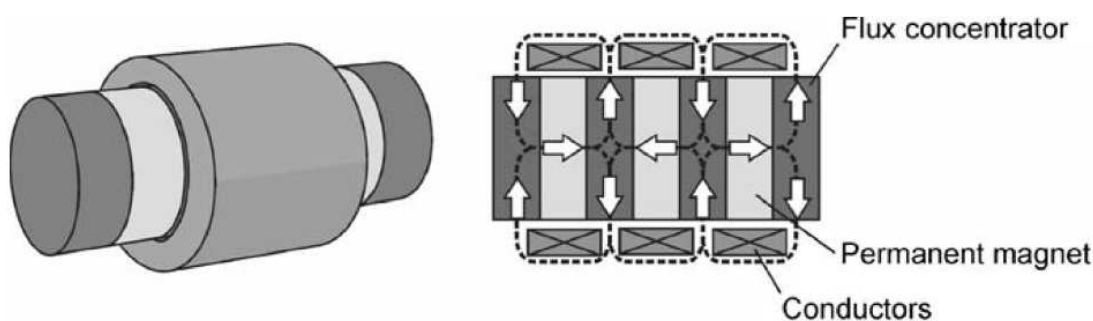**Figure 24.** One phase of Linear Vernier Hybrid Machine [46].

Figure 25. Tubular Air Cored Permanent Magnet Machine [37]. (**Left side:** Three dimensional view. **Right Side:** Cross section view)
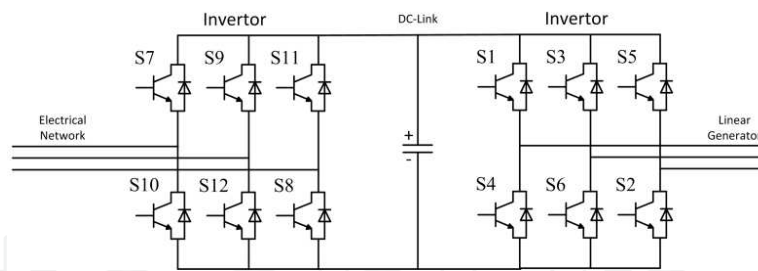
Figure 26. Common used power electronic circuit for connecting linear generator to the electrical network.

Regardless to the type of the linear machine, a linear machine generates fluctuating voltage from reciprocating motion of WEC, which is varying in both amplitude and frequency. Thus, it is not possible to connect linear generator directly to electric grid. For solving this problem, effective power electronic instrument is implemented [49]. One of the common power electronic circuits, implemented with linear generator, has a diode bridge rectifier or invertor rectifier in generator side, in which the generated voltage is delivered to a battery or capacitor after rectifying. Also another invertor is used in grid side to deliver power in DC-Link (battery or capacitor) to the electric. This power electronic circuit is depicted in Fig. 26.

3.2. Rotational generators

However utilization of rotational generator in wave industry is a questionable issue, conventional generators have been used with different wave energy convertors. Pelamis, Oscillating Water Column and overtopping devices are the main WECs which use rotational generator for mechanical electrical conversion. In these cases, the Asynchronous Generator or Induction machine is a preferred machine. It is due to the capacity of this type of machine to act in variable speed condition. Meanwhile, utilization of wound rotor induction machine makes it feasible to control rotor current and frequency which in consequence control the velocity and extracted power by mechanical part (This use of induction machine is so called Double Fed Induction Generator (DFIG)). Amundarain et al. considered the DFIG on OWC for controlling the electrical machine in a proper manner [50]. In comparison to the linear machine, it is much more simple to connect an induction machine to the electrical grid. While, since these machines was designed to act in higher speed, in most of the cases the utilization of rotational machine for convert low speed WEC motion is a low effective manner.

4. Environmental consequences

Renewable sources have been considered as new source of energy to decline our dependence on fossil fuel and be a solution to the global warming and CO_2 emission. Considering, each technology (WEC) beside its advantage might have some side effect and by taking into account the importance of environment in which a wave energy convertor acts (Ocean), finding out and preventing possible negative consequence of WEC carries a huge importance. Thus, before any decision to build a large WEC farm this issue should be considered

accurately to prevent occurring of any other disaster like CO_2 emission and global warming. There are some probable problems that may afflict the ecosystem as a consequence of WEC application, some of which is as follow;

Constructing Wave Farm in a location might cause military importance of location, avoidance of shipping and fishing which not only might change the economy of area but also cause a biological change in the area [51]. The WECs are attractive to the fish and it is due to fish use these devices as protection from predator, availability of food near them, spewing substrates and so on [52]. Hence, restriction for fishing and popularity of WECs by fish may enhance fish population in Wave Farm and this has a negative impact on local species diversity and population density [53].

WECs alter the currents and waves in implemented area and this might change sediment size distribution in area which may favour the accumulation of organic material in area [54].

It was indicated that some species of shark are sensitive to the electromagnetic field of 25-100 uT [55] and also it was shown that migrating European eels can detect the magnetic field of underwater cables [56]. It is worthwhile to find out possible consequence of external electromagnetic field on marine species and reduce the emitted magnetic field from under water cables.

Noises generation during site construction, maintenance and even normal working of WEC can affect dolphin, whales, seals and other fish species, which use underwater sound for communication and finding mat and so on [57, 58]. However little is known about long-term effects of noise on these species, the possible preventing technics should be developed for less interacting of WECs in ocean environment.

5. Conclusion

This chapter presents essential information about generation and potential of ocean wave power. Also the available Wave Energy Convertors has been categorized according to the principle of interaction with ocean waves. The manners of acting and mooring and in some case the average power output of WECs are presented. Meanwhile, the implemented electrical generator by WECs has been described in section three. Finally the possible environmental consequence of WECs has been investigated at the end of this chapter. This chapter reviews the available technologies of harnessing wave power.

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