CHAPTER 3
STATE OF THE ART DEVELOPMENTS IN OCEAN WAVE ENERGY CONVERSION

3.1 INTRODUCTION

The known initiatives for harnessing ocean waves started from early 18th century. Due to the improved technological support many different concepts to capture wave energy have been brought to daylight in recent times. But still the technical and conceptual convergence has not yet been obtained to say any one device as best suited for wave energy application. As a result, a proliferation of wave energy technologies is occurring globally. There have been thousands of patents filed around the world on different methodologies to capture the ocean waves and its energy. The first patent was recorded as filed in 1799 by Girard and fills (Mccullen et al 2002). More than thousand different methods had been filed for patent by 1980 around the world (Falcão 2010). The annual report on ocean energy from the International Energy Agency is a source of regularly updated information on the status of developments in wave energy research. Annex 9 of the 2008 report [AEA Energy and Environment and Sustainable Energy Ireland, 2006] showcased around 80 different wave energy concepts under development. However, It is not the main interest of present research to give a detailed review of the different concepts available and proposed till date. Due to the massive number of diverse devices and concepts available it becomes complex even to group them into a simple set of categories. Various authors have proposed different classifications based on the selection criteria.
In 1992 George Hagerman presented an illustrative diagram (Figure 3.1) based on most well-known principles of wave energy conversion. The Hagerman's diagram is represented in figure 3.1 and it is still useful in assessing wave energy converters. The shown classifications are based on the mode of motion of energy absorption (Pitch, heave and surge), fixed or flexible structure, type of force reaction (fixed structure, anchored support and inertial reference) and the type of working fluid (Air, water and hydraulic oil). These classifications are valid today with an additional recent technology with direct energy conversion method.

Figure 3.1 Categorisation of Wave Energy Conversion Principles by Hagerman (Hals 2010)
Figure 3.2 Classification of Wave Energy Converters (Falcão 2010)

(Falcão 2010) reviewed various wave energy conversion devices based on their working principle (Figure 3.2). The devices considered were at prototype stage and with extensive development stage. The review covered all most all the devices tested till the day.

Various wave energy conversion concepts based on their location and operating principle was categorised by (Harris et al. 2004). Authors did not consider the on-shore wave activated body type devices in review (Figure 3.3). There have been significant developmental activities on on-shore devices and its commercialisation in recent times. Author had discussed bout various mooring possibilities and its design constraints for different types of wave energy converters.
Figure 3.3 Schematic Drawings of WEC Devices for Operating Principles and Principal Locations (Harris et al 2004)
3.2  **METHOD OF CLASSIFYING WECS BASED ON PLACE OF WORKING**

WEC's are typically divided into on-shore, near-shore, submerged, and offshore devices. Being close to the electricity grids is a most significant advantage onshore devices possess. Apart from the proximity the on shore devices are easy to maintain, and as waves break during the approach of shallow region, the onshore devices have a reduced possibility of being damaged in rough weather. Once the waves broken, the water particles gets accelerated towards the shore and generates impact stress on device structure, which leads to the requirement of more structural material for device construction. These devices particularly suffer from issues of getting exposed to energy dissipated waves for conversion and requirement of unattractive structures in coastal locations. Near shore devices are located in relatively shallow water region. These devices are often seabed supported, which gives a suitable stationary base against which the device can work. Like onshore devices, a disadvantage is that shallow water leads to waves with reduced power, limiting the harvesting potential. An offshore device can harvest greater amounts of energy because of the higher wave energy content in deep water waves. However, offshore devices are more expensive to construct and maintain. It is also an important factor to consider the higher cost involved in transmitting electricity from the offshore devices. The submerged devices are comparatively less efficient since 95 per cent of the energy in a wave is located between the water surface and one-quarter of a wavelength below it. Another difficulty to these devices is suffering from complex deployment and maintenance procedure.
3.3 **METHOD OF CLASSIFYING WECS BASED ON OPERATING PRINCIPLE**

The wave energy devices are classified based on the wave they work and those are Oscillating water columns (OWC), over-topping devices (OTD), and wave-activated bodies (WAB).

### 3.3.1 Oscillating Water Column

OWC comprises an air chamber bottom opened and partially submerged under the water line (Figure 3.4). This assembly forms an air chamber above the water surface. The chamber consists of an aperture at its upper surface which leads to a self-rectifying turbine. The turbine encompasses an electricity generating unit. As the wave crest passes the chamber, the water level rise inside the chamber and forces the air out. As the wave escapes through the aperture, it rotates the turbine in one direction and hence electricity is produced. During the approach of wave trough, the water column falls down and draws the air in through the turbine and aperture. While the air travels in return to the chamber, the turbine rotates in the same direction due to its self-rectifying ability. The continuous action of waves makes the turbine to rotate and generate electricity with little fluctuation. The thermodynamic losses and noise during the operation are the prominent challenges to the OWC.

An OWC is tested in Indian coast (Figure 3.5) in the year of 1982 with OWC type device and utilised for desalination application (Sharmila et al 2004), (Davies 2005) and (Sundar et al 2010).
Figure 3.4 Example of Shore Mounted Oscillating Waver Column Device (Courtesy International Energy Agency)

Figure 3.5 Wave Energy Conversion Plant at India (Sharmila et al 2004)
3.3.2 Overtopping Devices

An overtopping device works similar to a conventional hydroelectric power generation unit. The device consists of focussing walls and ramps to convert potential energy and kinetic energy of waves into pure kinetic energy, allow the water to flow into an elevated reservoir and store as potential energy (Figure 3.6). Once the water is stored in elevated reservoir, the device works similar to a typical hydroelectric power plant by releasing stored water through low head water turbines back to sea. One of the best example for OTD is Wave Dragon, which is a floating device consists of two large curved focusing walls to focus waves on to a centrally mounted low head turbine. As the water flows through the turbine, the turbine rotates and leaves the water back to the sea. The greatest challenge to the commercial success of the device is its control and stability because of its high dependency on wave direction (Zabihian and Fung 2011).

Figure 3.6 Wave Dragon Operational Principle (Robertson 2010)
Wave dragon (Figure 3.7) is one of the OTD type wave energy converter which floats on the ocean surface. Many researches had been carried out extensively on the concept of wave dragon for improving its overall performance and safety (Peter et al 2006).

3.3.3 Wave Activated Bodies

WABs are devices that work with the relative motion of oscillating bodies resulting from wave motion. WAB type devices encompass small point absorbing devices (Horizontal size negligible when compared to incident wave length), Attenuator - large floating structures aligned with predominant wave direction and oscillated relative to each other (Pelamis and Anaconda), Terminator - Large devices aligned with wave crest (Salter's Duck) and sea floor mounted devices works with pressure differential. These devices require one stable reference with which the wave absorbing body can oscillate and energy is harnessed by power take of systems through resisting or damping the motion of bodies (Figure 3.8). The references can be fixed (Sea floor mounted), can be flexible (Floating devices
with moored to the sea floor), can be by damping plates, can be by another body with different natural frequency and damping coefficient and can be by an adjacent body (in case of large devices like Pelamis). The oscillation of WABs are primarily in translational (Mostly in Heave), rotational (Pitch, sway and roll) or combination of one translational and one or two rotational motion. In general WABs are compact and more effective when compared to other types of WECs.

**Point absorbers**

The devices which are relatively smaller than the incident wave lengths are generally called as point absorbers. Majority of the recent wave energy devices are belonging to this category due to its compactness and effectiveness. As the devices are relatively smaller and mostly work in heave, the wave direction is not considered to be an important factor. Most of the point absorbing devices works with relative motion of buoys or bodies. These devices require a fixed or stable reference to generate relative motion and power a power takeoff system (PTO). The figure illustrates different types of reactions provided for point absorbers.

![Figure 3.8 Various Types of Reaction Mechanisms for Point Absorber](image)

(Courtesy Industrial Research Limited 2004)
These devices are majorly differentiated in their reaction mechanism, the power take-off and the type of energy transmission system, for instance:

Chandrasekaran and Harender (2012) proposed a fully mechanical type WEC with rack and pinion system. The device consists of a floating buoy which is directly connected with a vertically moving rack which drives a unique drive assembly to produce continuous rotation from up and down motion of float (Figure 3.9).

Al-Habaibeh et al (2010) Ocean Navitas proposed a unique simple off-shore floating device called Aegir Dynamo (Figure 3.10). The device consists of a spar with a float moving along the spar. The spar is anchored with the sea floor and a unidirectional gearbox is placed on the float. The up and down motion of float by the wave action is converted into continuous rotation by the help of unidirectional gearbox. A conventional electrical generating unit is further coupled with the device for producing electrical energy.

A unique direct drive ocean energy conversion was proposed by (Agamloh Wallace and Vonjoanne 2008). The device converts up and down motion of floating buoy into continuous unidirectional rotation by using a ball screw arrangement (Figure 3.11). The device was tested in wave flume and the technical feasibility was proved successfully.

A float type WEC was proposed by Hadano et al (2010) which consists of a mechanical PTO system with a floating buoy is connected through a wire rope. The wire rope runs through a unidirectional pulley and a counter mass is mounted on the other end of the rope.
An Australian company Carnegie Wave Energy developed a device named as CETO mounted on the sea floor (Figure 3.12). The device consists of a pump connected with a buoyant float through flexible cable. The heave response of float with respect to the pump is used to pressurise seawater and the collected water from an array of devices further pumped to the shore. A Pelton turbine placed on the shore converts the pumped water into to other usable form of energy preferably electrical energy.

Figure 3.9 Mechanical Type Wave Energy Converter
(Chandrasekaran and Harender 2012)
PowerBuoy developed by Ocean Power Technologies consists of a vertical float using a floating spar with large plate as reference frame. The relative motion between the spar and the float drives a hydraulic PTO that produces electrical energy from the device (Figure 3.13). Arrays of PowerBuoys are electrically linked with each other and the electrical energy is transported to the shore.
Figure 3.12 CETO Wave Energy Converter (Courtesy Carnegie)

Figure 3.13 The PowerBuoy® (Courtesy Ocean Power Technologies)
Figure 3.14 Working Principle of Aquabuoy (Courtesy AquaEnergy Group)

Figure 3.15 Real Sea Test Device (Courtesy AquaEnergy Group)
A Fanavera wave energy's Aquabuoy is similar to the CETO device (Figure 3.14). The Aquabuoy is a floating device consisting of a buoyant float connected with a piston. The piston is inserted into a cylindrical tube and the tube is flexibly moored with the sea floor. When the float bobs up and down, the water is pressurised by the piston cylinder assembly and the pumped water is used to drive a turbine which produces electrical energy.

A shore mounted WEC developed by Israel based SDE Energy (Figure 3.16). The device consists of two or three pontoons connected by a hinge. A hydraulic piston is connected with the pontoon and a cylinder is relatively fixed with the shore line. The up and down motion of pontoons due to the wave action helps the hydraulic piston to pressurise the hydraulic oil for further energy conversion. Number of models in this kind have been tested and demonstrated with successful results.

Figure 3.16 An SDE Installation off the Coast of Jaffa (Courtesy SDE Energy)
Swedish WEC developer with Uppsala University had developed a system named Seabased with a direct energy conversion PTO system (Figure 3.17). It is a two body system with reaction provided from the sea floor. The buoy drives a linear generator and converts up and down motion of waves into electrical energy in single process. The device consists of a possibility of interconnecting several devices together and transmits electrical energy to the ground based grid. The technology was tested from 2006 and obtained several funding support from Swedish government.

Figure 3.17 Seabased's WEC with Direct Drive Energy Conversion (Courtesy Seabased.com)
Ocean Harvesting Technologies developed an offshore WEC named Ocean Harvester (Figure 3.18). The device consists of a wave riding buoy, a counter mass suspended using a metal rope, a mechanical PTO and an anchored foundation. One end of metal rope is fixed with the foundation and run through PTO and holds the counter mass. The device is designed to both generate and store energy during the buoy and counter mass motion by the wave action. The counter mass stored the energy during the upward motion and releases during the next stroke for electrical energy generation. The counter mass also acts as energy smoothening device during the rough waves(Sidenmark et al 2009).

![Figure 3.18 Illustration of Ocean Harvester (courtesy Oceanharvesting.com)](image)

The Danish Wavestar is a seabed mounted near shore wave energy converter belonging to point absorber category (Figure 3.19). The device is placed above the water level using four concrete pillars. The platform can be elevated to the required level through these pillars. The device consists of
multiple floaters with arms and hydraulic PTO. The floaters move along the waves and generate pressurised hydraulic oil for further energy conversion. The device was tested in coastal Nissum Bredning in north Denmark and found robust against storms and rough weather. The company also designed a devise similar to the Wavestar except that the new device consisting of 40 float setups for harnessing waves (Figure 3.20). The device yet to be tested in north sea.

Figure 3.19 Wavestar in Denmark (Courtesy Wavestarenergy.com)

Figure 3.20 Proposed Wavestar to be Installed in North Sea (Courtesy Netpublikationer.dk)
Archimedes Wave Swing (AWS) is an underwater submerged device works with direct energy conversion concept (Figure 3.21). These device extract energy from ocean swells. It consists of two cylinders, out of which one is fixed to the seabed while the upper cylinder moves up and down by the influence of waves. A pressurised gas is filled inside the cylinders to provide stiffness and spring effect. A coil is wound inside the bottom cylinder and magnets are fixed with top cylinder. Electricity is generated directly from the heave response of the upper cylinder due to the cutting of magnetic flex by coils. As a submerged WEC, the device gets an advantage of being less visual impact to the people.

Figure 3.21 Schematic View of AWS (Courtesy Ecomedioambiente.com)
Apart from the heaving buoy type point absorbers, a few devices work in pitching motion of buoyant bodies. One of the suitable examples is Oyster developed by Aquamarine Power Ltd (Figure 3.22). It is a single body bottom hinged inverted pendulum type device mounted on sea bed in shallow region. The device consists of a buoyant flap which swings with respect to its hinged reference. A hydraulic PTO is connected with the flap and pumps sea water to the shore. The flap of Oyster spans the whole water depth and its top portion pierces the water surface. There can be many devices installed in series and the pumped water can be collectively used for electrical energy generation. A pelton turbine is used by oyster to convert hydraulic energy in pumped water into electrical energy. Wave roller (Figure 3.23) and Salter’s mace devices are a few more examples belonging to the Oyster category.

The Pelamis, developed by UK based company is a long cylindrical snake like slack -moored articulated structure consisting of four sections linked together by hinges and hydraulic rams (Figure 3.24). The cylinders experience relative displacement during the wave passing and power the
hydraulic ram. The cylinders are connected such that the heave and sway oscillations are equally utilised by the hydraulic rams. The pressurised hydraulic oil then passed through hydraulic motors driving electrical generators. Gas accumulators are provided in the device to store the excessive energy in the form of hydraulic pressure. A full sized prototype was tested in Scotland in the year 2004 and a set of three Pelamis devices were deployed off the coast off the coast of Portuguese in the year 2008.

![Wave Roller](image)

**Figure 3.23 Wave Roller (Courtesy AW Energy)**

A similar device works with different PTO mechanism is developed by Checkmate Sea Energy Ltd (Figure 3.25). The device consists of a rubber tube filled with water and kept floating on the ocean surface. The device is slack moored with the sea bottom and both the ends of the long tube are sealed. A uniform squeezing or local enlargement to the rube happens during the wave passing. This action creates a pressure difference leads to a local flow of water and which is rectified by using a pair of duck-bill valves. This rectified flow is then passed through a turbine between high and low pressure reservoirs.
Another device which works with pure pitching action (rotation) is the most famous WEC named nodding Duck (designed by Stephan Salter - University of Edinburgh). This device consists of a cam like floater which oscillates in pitch during the wave motion (Figure 3.26). A string of these
floaters are connected and kept floating on the ocean surface parallel to the wave front. A hydraulic PTO is attached with the device which works with an inertial reference inside the duck.

![Image of the Duck wave energy converter](image)

**Figure 3.26 The Duck Version of 1979 (Courtesy of University of Edinburgh)**

### 3.4 FUNDAMENTAL REQUIREMENTS OF A SUCCESSFUL WEC

Though there have been many devices tested in real sea application to produce electrical energy, most of the device fail in commercial viability and safety. Many findings and lessons have been learnt in past about effectively utilising the waves and its potential. Many devices failed in drawing board and many in laboratory testing, a very few went on to the real sea environment and struggling to impress the public and scientific community. Each experience gives us a valuable lesson to make us understand the requirements for a good wave energy converter. Some of the most important findings are pointed are (Hals 2010):

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✓ WEC should have its primary wave absorbing unit at the proximity of ocean surface where the wave energy is concentrated at most.

✓ Unlike other ocean applications, a wave energy absorbing body should be designed to endure a combination of relative large motion and forces. The total energy harnessed is proportional to the velocity and force in phase.

✓ Energy absorbing corresponds to energy removing from incident wave. The energy removing from any incoming wave can only be done by generating a wave which destructively interacts with the incoming wave. Hence, an efficient wave energy converter should be a best wave generator.

✓ A device should be safely working or surviving in repetitive extreme wave climates and be able to produce enough electricity during mostly occurring wave conditions.

✓ Small units of many WECs is much efficient than deploying a few large devices at a particular site.

✓ To be a successful WEC the device must exploit more than one mode of motion.

✓ To be economically competitive, the device should be sophisticated to withdraw itself from the wave interaction whenever there is a requirement.

✓ The working principle, components and deployment procedure must be as simple as possible. Because working in the ocean environment is an expensive process, having complicated engineering installed inside the ocean will lead to high maintenance cost.
The device should be safeguarded from extreme waves without mechanically limiting the heave response. Stress by extreme waves on the mechanical structure will be extremely high that the limiting response would damage the entire device. It is not economical to make a structure heavy to withstand against a 100 year wave as it occurs very rarely and the structure lies redundant most of the time.

The station keeping of device should not affect the overall conversion efficiency.

The device should work efficiently over the range of most commonly occurring incident wave frequencies it is subjected to. Smaller devices are in resonance at narrower wave frequency range which is not economical for highly varying wave nature. Hence, the device should have control and adjusting mechanism to work effectively in wider frequency range.

The device should have its highest efficiency level at low energetic seas.

The device should not be location specific, it should be capable of mass produced.

On the above listed findings basis, the focus has been given to design, develop, experiment and analyse a device which addresses most of the listings and be efficient and economical to the Indian shore.

Majority of above listed requirements can only be addressed by point absorbing devices due to their technical and economical compactness. These are the devices offers relatively low capital investment and high power capture to mass ratio wave energy conversion solution. Hence, a point absorber is chosen as suitable for Indian economical and wave energy conditions and researched further for improvement.
3.5 STATE OF THE ART DEVELOPMENT IN POINT ABSORBING WAPS

Numerous investigations have been made to find out various methodologies to improve the overall economics of point absorbing WEC by making modifications to its working principle and control of various parameters. Figure 3.27 explains a typical wave energy conversion system and its various energy transfer stages. The first stage is a front end interfacing stage which interacts with ocean waves directly and produces translational, rotational or combined motion of a body. A power take-off system captures the motion and converter into more convertible form of energy by offering resistance to the motion of primary front end interface. PTO then transfers captured energy to a conventional electrical generator or other methods of electricity generating unit and electrical energy is generated.

Figure 3.27 Simplified Representation of a Wave Energy Conversion System (Bhuyan 2007)
Various schemes of wave energy conversion process and its energy conversion mechanisms are represented in Figure 3.28. Almost all the existing WEC's falls under the criteria and can be used for easy reference. The first scheme represents the OWC systems, the second scheme represents the WABs with direct energy conversion systems, the third scheme represents the point absorbers with sea water pumping PTO systems, the fourth scheme represents the OTDs and the final scheme represents the devices with hydraulic rams. Investigations are being carried out around the world on each of the conversion stage and potential improvements are recorded. The following are a few attempts made by researchers to find the possibility of improving the system.

Figure 3.28  Various Wave Energy Conversion Schemes (Khan et al 2009)
3.5.1 Front End Interface

All of the point absorbing WECs use a buoyant member or called as buoy to oscillate along with the wave and provide hydrodynamic interaction to extract energy. The fig illustrates the 2D representation of how energy is absorbed by a buoy from wave. As stated already, absorbing a wave means generating a wave which can destructively interface with the incoming wave. Hence, a good wave energy absorber must be a good wave generator. As the front end interfaces (buoys) are the only portion of a WEC which interact with the primary energy resource (wave), the entire device efficiency depends on the buoy geometry and design. A special focus is given in the present research to design a front end interface with maximum conversion efficiency as possible.

The parameters that are connected to the ability to absorb energy are excitation force, radiation impedance and damping. The first two parameters are dependent on the buoy geometry. The lase parameter, the damping, has to do with the generator characteristics and how energy is extracted from the generator. A detailed study is carried out in the present research on various improvements and suggestions made my researchers around the world. A few of those points are discussed here. Majority of these researches are talking about the various buoy geometries and their impact on energy conversion.

Stallard et al (2009) investigated the impact of change of shape of upper portion of a heaving buoy and recorded the impact (Figure 3.29). It was observed that the change of upper surface of a heaving buoy provides an advantage of limiting the upper limit of buoy’s heave response during the extreme waves without providing any mechanical limiters or end stoppers. The achievement is done by immersing the buoy further down and increasing the hydrodynamic damping which prevents the buoy from having excessive
heave acceleration. The author also claimed that the hydrodynamic damping and natural frequency of the device can be easily varied with very little change in float mass.

Orazov et al (2010) proposed a novel excitation scheme of producing a mechanical amplification of motion by using inner and outer floats with ballasting chamber within (Figure 3.30). The ballasting tank in each floats help the device to vary their mass by in taking and draining sea water depending on the incident wave frequency. The variation of mass is so instantaneous that the water flow in and out happens twice in one motion cycle. A 25 – 65 % improvement in overall conversion rate was claimed by the authors due to their novel excitation scheme.

![Diagram of buoy configuration](image)

**Figure 3.29 Buoy Configuration Tested by Stallard et al (2009)**
Folley et al (2007) made an investigation of finding the impact of water depth in performance of small surging type WEC. The author concluded that the device performance is higher in terms of conversion efficiency in shallow water than deep sea environment.

Flocard and Finnigan (2010) presents the result of experimental investigation carried out on a bottom pivoted pitching cylinder. The investigation showed that the damping and inertia modifications (Ballast) of the float were the significant factor which influences the performance of pitching cylinder.

Backer et al (2010) performed a numerical simulation to find analyse importance of buoy geometry and slamming effects in overall
performance of a heaving point absorber (Figure 3.31). The author concluded that the buoy geometry and draft are important factors to be considered while designing a wave energy converter to prevent it experiencing losses due to bottom slamming. Author also found that the peak impact load on the hemisphere and that on the 45° cone is approximately 2, whereas the power absorption is only 4 – 8% higher for the 45° cone.

![Figure 3.31 Bottom Shapes Tested for Finding out the Impact of slamming (Backer et al 2010)](image)

Weller et al (2010) reported the performance of heaving absorbers when placed in close arrays. Authors found that under certain conditions positive interactions (where the average power output of the array exceeds the same number of isolated devices.) are measured. Experiments were conducted in both regular and irregular waves and found that the overall efficiency of the array is affected by draft of individual buoy member.

Vantorre et al (2004) investigated the impact of variation of buoy geometry, the external damping and a supplementary inertia in overall performance of a heaving point absorber. The results showed that the power absorption performance was dependent on wave height. For regular waves of relatively small amplitude the absorption length significantly exceeded the absorber diameter and diminished with larger wave heights. An estimation of absorption length of 60% of buoy geometry was made in irregular waves.
Agamloh et al (2008) employed a Computational Fluid Dynamic (CFD) code to simulate a coupled fluid structure interaction for a wave energy device and assesses the power output in 3D numerical wave flume.

Gilloteaux and Ringwood (2009) investigated the impact of variation in wave direction on performance of a generic point absorber. Author investigated five different models and highlighted the influence of the directional spread and of simultaneous wind sea and swell systems. The result showed that the excitation of sway, roll and yaw motions significantly affected the behaviour of a generic point absorber. The result also showed that mooring system plays an important role regarding the dynamic behaviour of a point absorber.

A detailed experimental investigation was made by (McCormick et al 1982) on heaving, vertical, circular cylinder and the relationship between buoy size, draft and various hydrodynamic parameters on cylinder performance was established.

### 3.5.2 Power Take-off Mechanisms

 Though the concepts of energy capture from waves vary from device to device, conversion of harnessed energy to electrical energy is done only by conventional high-speed rotary electrical generators. A few devices use a linear electrical generator to directly convert the oscillation of a body into electrical energy. A power Take-off (PTO) mechanism converts the motion of a wave activated body into a form of energy which is acceptable by electricity generating unit. There are various forms of PTO mechanisms experimented at various WEC technologies and each contained their unique advantages and challenges. A brief review of different PTO mechanisms are done here
a) Hydraulic Power Takeoff (PTO)

A WEC experiences low frequency high intensity energy source, which need to be converted as high speed mechanical rotation to feed a conventional electricity generating unit. A hydraulic system of energy transfer and conversion is well known to engineering community. Early wave energy researchers got convinced by the potential applications of a hydraulic system to use it in the applications of wave energy conversion. A typical hydraulic system is shown in Figure 3.32. The hydraulic piston is activated by the forces of wave through a floating buoy, which forces the fluid to flow in and out by creating pressure difference. This pressurised oil flows through check valves, gets rectified the flow direction and rotates a hydraulic motor. A variable capacity hydraulic motor can be used to obtain a uniform rotation from variable flow of hydraulic oil. However, an accumulator is used in wave energy conversion application to store the excess energy in the form of pneumatic pressure and release whenever is needed. Inclusion of an accumulator enables any wave energy device to store and restore the excess energy and produce a quality power.

Falcão (2007) performed a detailed numerical study on impact of hydraulic accumulator on hydrodynamics of buoy and performance of electrical equipment. A generic modelling of power take-off and its control was also presented in the article.

Schlemmer et al (2011) proposed a novel hydraulic PTO design for heaving buoy type WEC. The author had analysed two different hydraulic concepts: one uses a serial power flow path (Hydraulic Transformer Circuit) and another using a parallel power flow path (Hydraulic Parallel Circuit (HPC)). The author concluded that the HPC was superior when compared to its counterpart due to its fewer conversion steps and compact size.
Figure 3.32  A Typical Hydraulic Circuit used in a WEC with Hydraulic PTO (Drew et al 2009)

A detailed design, simulation, performance evaluation on 1/7th scale model and a full scale testing of a hydraulic PTO (Figure 3.33) was demonstrated by Henderson (2006) for Pelamis WEC. An expected performance was obtained from the experimental investigation and a combined efficiency of 80% was obtained.

Figure 3.33  A Simplified Model of Hydraulic PTO Proposed by Henderson (2006)
b) Limitations of Hydraulic PTO

There are numerous challenges faced by Hydraulic PTO system when it is applied in off shore. The off shore is a highly harsh, corrosive and expensive environment. Frequent visits and maintenance will be an extremely expensive affair that any WEC would not want to encage with. The following are a few challenges mentioned in literature.

c) Containment of Working Fluid

Any hydraulic system operates by having a fluid as their working medium and transfer energy in the form of pressure. Using sea water as such fluid medium challenges the WEC due to its corrosive nature, possibility of biological growth, mineral deposit and effects of temperature variation. Hence, the developers go for hydraulic oil which would not challenge them in above aspects. However, there are many environmental regulations which restrict the utilisation of hydraulic oil in off shore environment. Going for environmentally friendly hydraulic oil adds additional burden to the economic viability of any device.

d) Hydraulic Sealing

Most of the land based hydraulic systems are developed for low velocity applications and correspondingly the various accessories are designed and made. Hydraulic sealing is an important part of any hydraulic system to prevent oil from leaking due to wear and repetitive sliding of close tolerant components. The sealing is done by special rubbers and composite materials; life of those depends on the number of working hours, sliding velocity and temperature generated. A typical WEC will have to experience huge velocity and stress which adversely affects the life of a sealing system.
Thus a hydraulic PTO requires repetitive maintenance and inspection which is highly expensive.

e) Efficiency of a Hydraulic PTO

The hydraulic PTO consists of hydraulic motors (Figure 3.34) and turbines which converts mechanical energy into hydraulic energy and hydraulic into mechanical energy respectively. The maximum efficiency that can be attained by a hydraulic device is around 80% at peak load and it exponentially reduces for part loads. The other transmission systems and valve systems contribute to the loss of energy by the way of generating heat. A WEC will work mostly in part load which significantly affects the overall efficiency of the device. There have been many electronics designed to improve the part load efficiency of a hydraulic actuator and being investigated for WEC application.

Figure 3.34 Variable Displacement Hydraulic Motor used for Wave Energy Application - Courtesy International Energy Agency
3.5.3 Turbine Energy Conversion

A device which converts energy in a fluid flow into a mechanical rotation is called turbine. There have been many different turbines used for various applications for ages. The conventional hydroelectric power plants use turbines for generating mechanical rotation from flowing water. The wind energy generators use wind turbine for extracting energy from blowing wind. There are lot more applications for a conventional turbine which is known to common man. A typical turbine will have symmetric curved blades around its axis which deflects the flowing fluid through it. When the fluid gets deflected, it applies an equal and opposite reaction on each blades and makes it rotated. This conversion of energy happens due to the change of momentum in the fluid flow. WEC’s use this principle for producing mechanical rotation from energy generated by ocean waves.

a) Low head turbine

OTDs use a low head turbine to produce mechanical rotation by focussing sea waves into it. The turbine is directly coupled with an electricity generating unit to produce electrical energy. Major challenges to these devices are solid particles and biological growth on the turbine. As the turbine is exposed on the surface and sunlight the marine growth will be significant and efforts need to avoid it. Apart from the challenges from surrounding, the turbine efficiency is affected by continuous variation in flow intensity which challenges the economic viability of the device.

b) Wells Turbine

OWC devices use a pneumatic turbine called wells turbine which is specially designed to rotate in one direction for both directional air flow (Figure 3.35). The significant advantage if these turbines are, they don’t cause
any environmental issues due to leakage of fluid. The turbine use air and sea water for creating pressure difference which is highly environmental friendly. The thermodynamic losses and noise generation are primary challenges to the device.

![Diagram of Wells Turbine](image)

**Figure 3.35 Wells Turbine (Takao and Setoguchi 2012)**

### 3.5.4 Sea Water Pumping

A few devices use piston pumps to pump sea water to an elevated reservoir and generate electricity by draining the stored water through a conventional turbine. Again solid particles and marine growth affects the performance of these devices.

### 3.5.5 Direct Energy Conversion

Reducing the number of components and conversion stages are key factors for any WEC to be successful in commercial energy generation. The recent wind turbines are eliminated from conventional heavy gearboxes and
improved electricity generating systems are directly coupled with turbine shaft. A similar principle of eliminating PTO mechanisms are proposed in early stages of wave energy research and concluded that the heavy structural requirement, requirement of improved magnetic property and variability of waves will not make the proposal to be an economical alternative. Recently, due to the development of new magnetic materials and improved power electronics made the direct energy conversion competitive.

![Diagram of various configurations of Direct Drive WEC Systems](Vermaak 2012)

**Figure 3.36 Various Configurations of Direct Drive WEC Systems (Vermaak 2012)**

A conventional generator contains a stator with coil and a rotor with permanent magnets. The generators require a drive to rotate the rotor and stator produces electrical current due to the cut in magnetic flux. A linear generator works with the same principle whereas the rotor is replaced by a translator with magnets. The translator is surrounded by stator windings with sufficient gap in between. The translator is spring loaded that it can relatively reciprocate inside the stator. The translator is coupled with a heaving buoy in a typical WEC. As the heaving buoy oscillates, an electrical energy is induced on the stator winding and electricity is produced. The produced electrical energy will be highly variable in frequency, voltage and current. Conversion
of this poor quality electrical potential into a power acceptable by electrical grid involves lot of electronics and it is not economically viable at the moment. There are various methods (Figure 3.36) in which the concept of direct energy conversion is used in wave energy technology.

Archimedes Wave Swing (AWS) was the first wave energy device of direct energy conversion kind, tested in real sea environment in the year 2004. It is a submerged device filled with inert gas. It consists of an upper part which moves against a bottom part fixed to the seafloor. The floater is coupled with translator consisting of permanent magnets. During the wave passage, the floater reciprocates up and down due to the variation in pressure above it generated by passing waves. This oscillating helps stator to cut the magnetic flex and produce electrical energy. The gas filled inside the chamber acts as spring and provides the floater a restoring force, the variation of pressure inside the chamber varies the spring constant of the device thus the device can be tuned.

An attempt to smoothing the power output from a single direct elect generator for ocean wave energy conversion is presented in (Brooking and Mueller 2005). A hydrodynamic modelling was performed in (Eriksson et al 2005) and various methods of performance improvements as analysed on direct drive wave energy conversion. It was concluded that controlling generator damping becomes critical in improving the overall conversion efficiency.

3.5.6 Mechanical Power Takeoff

The most primitive method of converting oscillator motion of a buoy into continuous rotation is using mechanical gearboxes with ratchet assemblies. Similar to wells turbine, unidirectional gearboxes were developed and patented for many applications to convert alternative rotational input into
continuous rotation. The basic configuration of this method is connecting a buoy with one such unidirectional gear system through some means and producing continuous unidirectional rotation from oscillatory/reciprocating motion of buoys. The critical issue of the mechanical system is extracting energy in both the strokes of the wave. Hadano et al (2007) made a study on using a float and counter mass connected by a rope and passed through a pulley system. The results showed that the counter mass decreases the performance of the system as it works against falling motion of float. Hence, the author decided to make the down stroke as a free fall condition.

Agamloh et al (2008) proposes an innovative model of using contactless force transmission system by adopting a ball screw and clutch arrangement to convert up and down motion of buoy into a mechanical rotation. Al-Habaibeh et al (2010) proposed an innovative technology of using a unidirectional gearbox and generator system called Aegir Dynamo to convert bi-directional motion of float into unidirectional rotation and produce electrical energy.

3.6 OPTIMUM OSCILLATION OF WAVE ENERGY CONVERTER

Most of the WECs are oscillating bodies oscillating in one or more than one mode. Any oscillating body performs extremely well when the forced oscillation is in phase with its natural frequency. This phenomenon is called as resonance. At resonance, the velocity of oscillating body is naturally in phase with the excited force which gives greater energy transfer. It is quite obvious that any oscillating WEC works more efficiently when the incident wave is in phase with the natural oscillation of the device. The optimum condition approximately satisfied also for wave frequencies close to the actual natural frequency of the oscillator. This range of frequency is called as resonant bandwidth of a device. To be efficient, resonant bandwidth of a
device should be designed such that most occurring waves should be lying in this band. Real ocean waves rarely exhibit regular conditions. Instead, the waves are continuously changing in amplitude, frequency and direction. Hence, a wider band with is required for a wave energy device. In practice, highly expensive larger devices will have more bandwidths compared to the economical point absorbers. As the point absorbers are very small in their horizontal extension, the resonant bandwidth is too narrow that a mechanism to vary or tune the natural frequency is imperative to make the device commercially viable.

The Figure 3.37 shows latching control of an oscillating system in heave. The curve a shows the free surface elevation of water particles during the wave motion or the heave response of a small object with negligible mass. The curve b shows the heave response of a large object which is in resonance with incident wave. The curve c shows the heave response of a small device with natural period away from the incident wave period. Control of phase of oscillation is obtained by locking the motion of buoy in a particular position for a while and releasing it. This method is called as latching control (Falnes 2004)

![Figure 3.37 Resonance and Phase Control (Falnes 2004)](image_url)
3.6.1 Unconstrained Continuous Control

During the initial studies, phase control was done with regular waves with off resonance phase and improved results were obtained. Subsequently, when optimum phase control was studied with real, irregular waves, the need for predicting the waves became important. It was found that mass of the system, stiffness, damping of oscillating body and PTO damping can be adjusted to vary the natural frequency of the device and hence the resonance band can be tuned. Hence, it was proposed to obtain optimum condition for each wave by tuning the device by predicting upcoming wave and its excited force. With predicted excited force, the controller has to provide appropriate optimum oscillating velocity. Another way of optimising the oscillation is by reactive control. In this case, the velocity of oscillating device is measured or predicted and given to the controller; the controller controls the applied force by varying the stiffness or PTO damping and makes the oscillation optimum. These controls are called as continuous control because it can act at any instant of time during the oscillation.

3.6.2 Discrete Control

An alternative strategy is latching control. In the present case, the controller acts only finite number of instants during each wave cycle. In practice, the natural period of a buoy will be shorter than the predominant wave period of a site. Hence, even the wave period outside the resonance band, approximate optimum phase can be obtained by latching the buoy at an instant when the velocity becomes zero, and releasing it at an instant when the phase velocity can be in phase with the passing wave. The adjustment of PTO damping should be appropriate to maintain the device amplitude optimum. The PTO damping should always be matching with the radiated damping so that the energy conversion of the device can be optimum. The latching may be achieved by mechanisms, such as friction clutches and mechanical stoppers.
In the case of hydraulic PTOs, the latching can be done by closing the fluid flow valves. The latching requires some amount of predicting the waves in future, this makes the strategy challenging for its development.

Another method of control is just opposite to the latching control, called unlatching or declutching technique. In the present case, the PTO is disengaged from the primary moving body and engaged only when optimum velocity is obtained.

3.6.3 Development of an Improved Wave Energy Conversion Device

From a detailed analysis of various designs of WECs and its control methods, a few conclusions are made on requirements of a WEC to be most successful. These conclusions are necessary for carrying out the further research in order to obtain a best device for Indian wave climate.

The following are a few concluding remarks obtained from the detailed review of state of the art in the field of wave energy conversion.

- The device should be a small portable point absorber to be economically viable and mass produce.
- Utilisation of hydraulic PTO is not preferable due to its demand to frequent maintenance and monitoring.
- The device should be a near shore device for economical energy transport system and accessibility.
- The device should not be affected by its mooring system
- The device should not be a wave direction dependent.
✓ The floating structures with turbines are not suitable for wave energy application due to the potential for marine growth.

✓ The technology of direct energy conversion system is highly immature and expensive, hence not advised for the moment.

✓ The proposed device should be capable of adapting to various control strategies for its performance improvement.

✓ The device should be simple in construction and operation so that it should not require frequent maintenance.

All these inferences suggest potential advantage to a near-shore, heaving buoy type, platform mounted point absorber with mechanical power take-off system. The research is designed in this background and a new improved design of a novel wave energy converter is proposed, fabricated and experimentally investigated for technical feasibility.