A Study on Energy Conversion from Ocean Wave for OWEC Prototype

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Abstract: Ocean wave energy, ocean tidal energy as well as ocean thermal energy is an immense source of renewable energy. Oceans water cover approximately 71 % of volume of earth. Waves carry enormous quantity of energy among them. Wave energy is obvious source for renewable energy harvesting in oceans. The aim of this research is to develop an innovative approach for electric power conversion of the vast ocean wave energy. An oscillating-buoy wave energy converter (WEC) using air to hydraulic pressure has been proposed to enhance the wave energy generation from wave fluctuations. In the device, the an electric generator is implemented to convert the mechanical energy generated by wave energy into electrical energy. Design concept and working principle of the OWEC circuit is discussed alongwith mathematical model.

Keywords: Wave energy converter; Energy harvesting system; Wave turbine; OWEC.

Introduction

Sustainable and renewable energy is becoming increasingly important due to the expected exhaustion in current energy resources and the reduction of environment pollution. Sun provides more than 99.99% of energy and earth contributes about 0.01% [1]. Fossil fuels are a form of antediluvian eon solar energy. All sources of energies, except geothermal and nuclear, are ultimately powered by the sun [2]. Earth radiates heat and its thermal energy come from radioactive decay (80%) and planetary accretion (20%) [3]. Oceans encompass over 70% of the earth's mass. Ocean tides are caused by earth's gravitational interaction with the moon (68%) and sun (32%). Ocean waves are caused by friction of winds with the water surface. Oceans are a great form of renewable energy which is stored in the form of thermal energy (heat), kinetic energy (tides and waves), chemical energy (chemicals) and biological energies (biomass). Tidal current or wave generators harvest kinetic energies, and osmotic power plants and thermo-electric generators reap salinity and thermal gradients [3]. Wave power density distribution all over the earth is shown in figure 1.

Wave energy comes from the winds as they blow across the oceans, and this energy transfer provides a convenient and natural concentration of wind energy within the waves. Wave energy generation refers to the energy of ocean surface waves and the utilization of that energy to generate electricity. The energy within a wave is dependent on the following factors; wind speed, duration of the wind blowing, the distance of open water that the wind has blown over (fetch), and water depth [1]. Wave power could be determined by wave height, wavelength, and water density. This mathematically could be described as in [4]:

$$P = \frac{\rho g}{64\pi} H^2 T \approx \frac{1}{2} H^2 T \ kW/m$$

Where, P is the wave energy flux per unit wave crest length (kW/m); q the mass density of the water (kg/m^3); g the gravitational gravity (m/s^2); H the wave height (m) and T is the wave time cycle (s).

For example: for a 1.6 m wave and 10 s period, the power produced is approximately 12.8 kW/m.

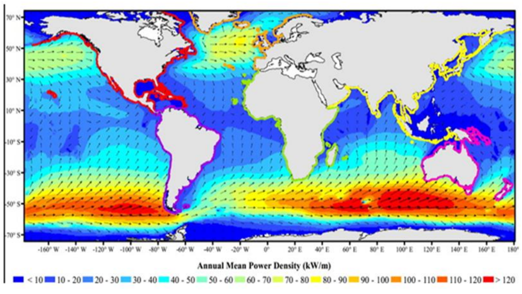

Figure 1: Annual Mean Power Density over Earth

The development of wave energy generation (WEG) has been taking place for about 35 years. In most devices developed or considered so far, the final product is electrical energy to be supplied to a grid. In practice, three main methods of energy storage have been adopted in WEG. An effective WEG way is storage as potential energy in a water reservoir, which is achieved in some overtopping devices, like the Wave Dragon [5] and the Tapchan [6]. The working principle of these devices is shown in Fig. 2 (a). The overtopping wave energy converter works in much the same way as a hydroelectric dam [7].
The second WEG method is based on the oscillating water column. This WEC type depends on the air column and the difference in pressure generated by waves as in Fig. 2(b). In this device, the size and rotational speed of the air turbine rotor make it possible to store a substantial amount of energy as kinetic energy (flywheel effect - the Wells turbine) [8].
The third energy conversion way which is paid more attention to in recent years is floating buoy wave energy converters as shown in Fig. 2(c). In a large class of these devices, the oscillating (rectilinear or angular) motion of a floating body (or the relative motion between two moving bodies) is converted into the flow of a liquid (water or oil) at high-pressure by using hydraulic systems.

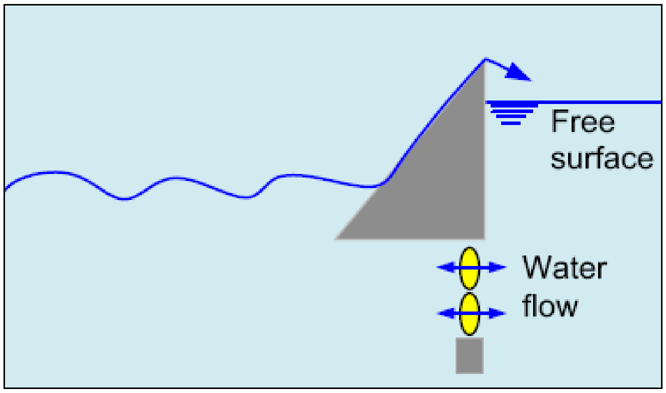

Figure 2(a): Overtopping WEC

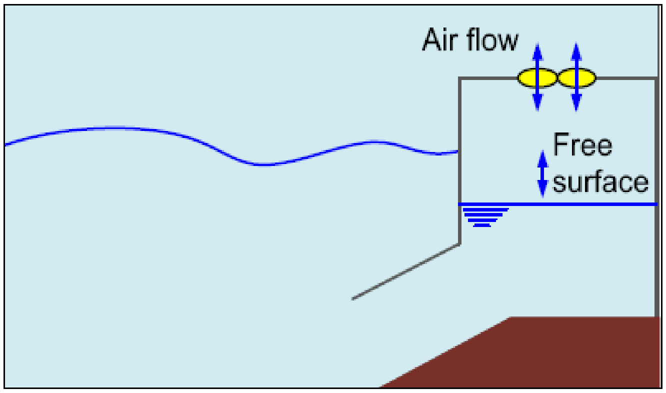

Figure 2(b): Oscillating water column WEC

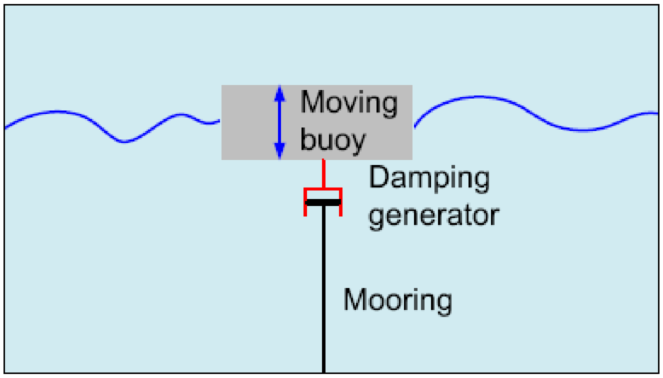

Figure 2(c): Floating-buoy WEC

Figure 3 gives the general diagram for power generation using ocean energy.

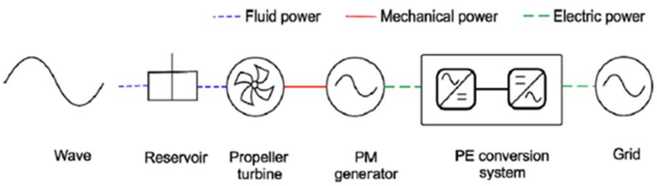

Figure 3: Technology used in Power Generation from Wave Energy

Related Work

Falcão [9] focused on a study of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator. The author carried out a general modeling analysis, system performance and design as well as a simple control method. Yang et al. [10] studied on a heaving-buoy wave energy converter equipped with high pressure hydraulic power take-off machine. The mathematical model was derived in order to investigate the wear damage in the hydraulic machine. Although some valuable investigations were obtained by adopting these floating devices, their working efficiencies were not so high.

Falcão [11] compared to traditional wave-energy-converting technologies such as the oscillating water column and overtopping devices, the oscillating body type wave energy converter(WEC) and classified as a 3rd generation device. Its advantage is the ability to work in the deep sea to capture more wave power. A heaving buoy was proposed as an oscillating-body wave energy device, which is also called a point absorber. Astariz and Iglesias [12] Furthermore, a two-body heaving buoy was suggested to operate against the tide oscillations. Shi et al. [13] highlights the work of Ocean University of China (OUC) which developed a 10 kW buoys-array pilot WEC as the phased achievement of the final aim, which is a 100 kW prototype device. It comprises four normal-sized buoys instead of one large floater, in order to capture more wave energy under low-density conditions. In order to convert the energy captured by the heaving buoy, two direct-driving technologies, namely, a rack & pinion system and a linear generator have been proposed and used. In the rack & pinion system, the ratchet wheels are used to cause the unidirectional rotation of the generator. Hong et al [14] proposed another method to convert the wave energy transmitted by the heaving buoy is to employ a hydraulic pressure system (HPS). A HPS can adapt better to the slow motion of WECs and smoothen the irregular fluctuations in the random-wave energy using an oil/gas accumulator. Therefore, the HPS were applied in different kinds of WECs,
such as Pelamis, Pendulum, Wavestar, and Duck [1]. The feasibility and reliability of HPSs and accumulators have been proven through in-house experiments and actual sea trials. The motions of the oscillating bodies of a WEC are strongly affected by the variation in the pressure of the HPS. The interactions between the wave-driven bodies and the power take-off (PTO) modules of the HPS have significant effects on the energy-conversion efficiency of the WEC. As the desktop tool, a mathematical model based on a simplified mass-spring-damper system was employed to simulate the interaction of the HPS and an oscillating buoy [9].

It should be noted that most of these numerical models focused on the hydrodynamics of the heaving buoys under effects of the HPS. On the other hand, there have been few reports on the operating performance of the HPS and accumulators with respect to buoys.

Based on the validation of experimental data, Josset et al. [15] designed a numerical model called "wave-to-wire" that can realize the prediction from the incident wave energy to the output electrical power directly under specific devices, including SEAREV, the hyperbaric converter [16], the oscillating water column device [17] and the array of WEC [18] The energy transmission, loss, and related dynamic interactions between each two energy converting stages can be all considered during these calculations. Compared to the former numerical models which only can deal with an individual energy converting stage, the wave-to-wire model is a promising desktop method for fully understanding of the performance of the wave energy converter.

Oscillating BUOYS Array WEC

A pilot WEC rated to 10 Kw and developed by OUC was deployed at the test site, which is located at the south of Zhaitang Island, on January 10, 2014. As shown in Fig. 4, a cubic frame was employed to support the four oscillating buoys [19] . A submerged floating body was fixed to the frame bottom to provide buoyancy and keep the frame motionless. The frame was also connected to concrete ballast using steel wires and ultrahigh-molecular-weight polyethylene ropes. A 500-ton crane boat, used in conjunction with a semi submerged barge, deployed the device and the ballast together. This technology is also available for future salvage operations.

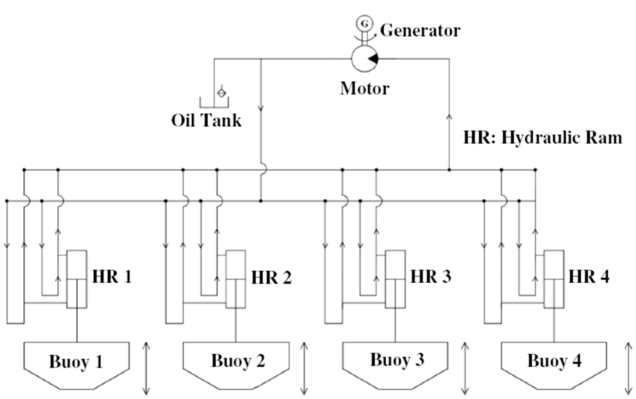

Figure 4: WEC on-Site Figure 5: WEC on-Site

As shown in Fig. 5, a hydraulic ram was installed on the top of each buoy. During the oscillation of the buoys, the hydraulic rams could operate such that they exhibited both up and down motions. The high-pressure oil from four buoys was collected directly to drive the hydraulic motor on the platform without using any accumulator.
An electricity control & management system presented on the platform was used to consume all the generated electricity on-site. Four heaving buoys were originally expected to oscillate in different phases under incident wave conditions to generate relatively constant oil flows to drive the generator.

Mathematical Model of OWEC

Most of the invented WECs convert the energy from ocean wave to usable energy directly without energy storage. Those systems totally depends on real time ocean wave conversion result, if the wave is strong enough then the energy converted will be high. On the other hand, if the ocean wave is weak then the converted energy will be weak or no energy will be converted at all. The most promising and reached commercialized stage and widely used WEC is the oscillating wave column (OWC). OWC becomes a part of Air Hydraulic (AH) Presto 1 system in extracting the sea wave energy. AH Presto 1 is a short form of Air-to-Hydraulic Pressure Storage version 1.
The ocean incident waves forced the ocean water into the column of OWC through the submerged opening. This will cause the water free surface inside the column to lift upward. When the incident wave force is zero, the free water surface will stop raising and starts to fall down due to gravity. This creates an oscillation inside the column. The trapped air will be occupied on the upper part of the free water surface inside the column. The oscillation of free water surface inside the column due to the incident wave action displaces a volume flow rate of air and produces an oscillating air pressure which causes turbine to rotate for generation of electricity.
The energy from a single incident wave entering the OWC is taken as the beginning point. The ocean wave consists of potential energy (PE) and kinetic energy (KE). Assume a particle on one point of the wave line. This particle will follow the wave motion up and down results in vibration. The vibrating particles produce a Simple Harmonic Motion (SHM) and the equation of an SHM is given by equation (i):

$$y = Asin\frac{2\pi}{\lambda}(vt - x) \qquad \text{(i)}$$

Where:
A= Sea Wave Amplitude (in m)
v: Wave propagation velocity (in m/s)
λ: Wave length (in m)
t: Wave cycle time (in s)
The particle velocity vp, can be determined by differentiating equation (ii) with respect to time:

$$v_p = \frac{dy}{dt} = \frac{2\pi Av}{\lambda}cos\frac{2\pi}{\lambda}(vt - x) \qquad \text{(ii)}$$

Potential Energy PE, per unit volume can be determined as in equation (iii):

$$PE = \frac{2\pi^2\rho v^2}{\lambda^2}A^2 sin^2(\frac{2\pi}{\lambda}(vt - x)) \qquad \text{(iii)}$$

The kinetic energy KE, per unit volume can be derived as in equation (iv):

$$KE = \frac{1}{2}\rho {v_p}^2 = \frac{2\pi^2\rho v^2}{\lambda^2}A^2 cos^2(\frac{2\pi}{\lambda}(vt - x)) \qquad \text{(iv)}$$

The total energy, generated per unit volume as resulted in equation (v),

$$E_t = PE + KE = \frac{2\pi^2\rho v^2}{\lambda^2}A^2 \qquad \text{(iv)}$$

The energy developed in the OWC can be represented from the water flow in Figure 6 When a volume of ocean water enters the OWC through the submerged opened end, the upward force generated and caused free water surface to rise in the opposite direction of the gravity:
The rising up of the free water surface developed an energy termed as E_{owc-ow}, resulted from the product of the propagating wave and the volume of the ocean water inside the OWC. The volume of free water surface is the volume being displaced. The energy developed inside the OWC due to the rising up of free surface ocean water can be determined as follows in equation (v):

$$E_{owc-ow} = E_t V \qquad \text{(v)}$$

Where, $V = \pi r^2 h$
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V: volume of displaced sea water (in m^3)
r: internal radius of OWC (in m)

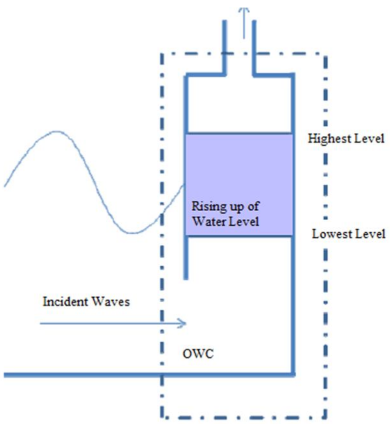

Figure 6: Developed energy in OWC

h: distance of water free water surface travels from lowest level to highest level (in m)
Assuming that the lowest level of free water surface and the highest level is equal to ocean wave peak to peak, (that is twice the amplitude), therefore, h=2A.
The law of energy conservation states that energy can be neither created nor be destroyed. If we assume that the air inside the OWC is incompressible and by ignoring the energy loss, the energy due the rising water free surface $_{Eowc-ow}$, is equal to the energy due to the air motion. That means the volume displaced by the water free surface is equal to the volume displaced by the air, $E_{owc-air}$. as stated in equation (vi):

$$E_{owc-ow} = E_{owc-air} = \frac{4\pi^3 \rho \square^2 A^3 r^2}{\lambda^2} \quad \text{(vi)}$$

Where,
ρ: density of sea water (in kg/m3)
r: internal radius of OWC (in m)
The power generator requires high pressure and rotary torque in ensuring that the mechanisms to function accordingly. The characteristics of the ocean wave and the developed air pressure from the trapped air on the upper side of the water free surface inside the column will be considered. It is known that the upward force, also called as the lifting force of the free water surface is greater as compared to the downward force. By differentiating equation (vii), the force generated due to the rising up of the free water surface can be given by:

$$Force = \frac{dE_{owc-air}}{dr} = \frac{8\pi^3 \rho v^2 A^3 r}{\lambda^2} \quad \text{(vii)}$$

The pressure developed that may act on the surface of turbine is written as in equation (viii):

$$P_{air} = \frac{Force}{Area} = \frac{8\pi^3 \rho v^2 A^3 r}{\lambda^2 Area} \quad \text{(viii)}$$

Ocean Energy in India

An assessment made by Ministry of New and Renewable Energy indicates around 8000 MW potential of tidal energy in India. This includes 7000 MW in Gulf of Khambhat, 1200MW in Gulf of Kutch in Gujarat and 100MW in Sunderban delta. Southern tip of India (near Kanyakumari, southern Nagercoil and around) have prominent potential for wave power. Presence of strong winds without hindrance makes it a favorable site for off shore wind and wave power generation. Considering sites offering more than 10 kW/ m only, the wave power assessment [20] comes around 40 MW. However this entire power cannot be harnessed fully due to constraints such as availability of resources and natural conditions. The report on Study on Tidal and wave energy in India: Survey on potential and proposition of a roadmap, by IREDA, AFD and IIT, Madras submitted in December 2014 estimated the tidal power potential in India to be around 12500 MW for the tidal stream technology at Kutch and Khambhat and tidal barrage technology in the parts of India at some sites with large amount of back waters.

Environmental Impacts of Ocean Energy

Offshore and onshore wind farms create a noise so nobody wants to have them in their backyard (NIMBY). Ocean transport, tidal and wave power generation activities affect marine organisms [21]. Offshore wind turbines create risks of collisions, disturbance and bird migration. Electromagnetic fields and underwater noise disturb marine life [22]. When fishes pass through the turbine blades, they are injured in tidal and wave power plants. The tidal power plants change and modify wave and tide patterns at remote locations affecting the nearby environment [23]. Ship and generator noise upsets underwater creatures. Power generation equipments interfere with the navigational systems. Many marine creatures like turtles detect direction by the intensity of magnetic fields which can fail due to local magnetic fields [24]. Marine reproduction is badly affected by exposure to electromagnetic fields and noise bursts [25]. Marine animals migrate from high noise areas causing the environmental crisis. Ocean energy is clean in nature, but can affect the local ecosystem. Reversible osmotic power plants can provide both water and clean water. Pakistan has installed these plants in Thar Desert. These plants supply 25 MW electricity and 22 million gallons of clean water.

Conclusion

Ocean energy is clean and renewable in nature, yet has minor environmental reservations. Major ocean energy research activities include wave technologies (45%), tidal stations (23%), economic or policy studies (15%) and environmental concerns (17%). In this paper, a complete mathematical wave-to-wire model of the ocean wave energy converter is presented. The main subsystems of the converter were described, and the dynamic models were integrated to evaluate the energy storage of the system. Then, the hydrodynamic, mechanical, and electrical characteristics of the main subsystems were discussed and the dynamics of the entire process is evaluated. Integration of ocean energy to the electric grid is another constraint yet to be addressed more realistically. Interconnection of ocean energy sources by running cables through salty waters and then to offshore grid poses serious challenges. Choice of AC/DC transmission of ocean power also needs economic and technical evaluations.

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