Design of an Onshore Wave Energy Converter Device for Electricity Generation

S.Sangar, T.Thiruvaran, V.Aravinthan, B.Thanatheeban

Abstract: Demand for renewable energy is growing faster due to its cleaner nature. Sri Lanka is blessed with renewable energy sources and, currently renewable electricity is mainly produced from hydro power, Solar and Wind. Since, Sri Lank is surrounded by sea; it has huge Sea Wave energy potential and can be harnessed in the future. Wave Energy Converters (WEC) are the devices, which are used to produce electricity using sea wave energy. Wider range of WEC prototypes have been presented worldwide. However, most of the technologies are still at research level because they are expensive and practically challenging. Oscillating Water Column type WEC are matured technology and installed in few places but, they require very high initial investment and big in size because a huge air chamber in the device.

This paper contains description and the laboratory results of a scale model of a new shoreline Wave energy Converter. It has many advantages such easy to build, less maintains is required and moving parts (DC generator) are isolated from sea water. Where the proposed device contains three major parts those are single acting pneumatic pump, Air storage tank and a turbine coupled with DC generator. Sea Wave is used to drive the single acting cylinder which will pump the air into the storage tank. Then the air is used to rotate the turbine. Finally the DC generator will produce electricity.

This prototype device could generate 15W peak power across 25 ohm load when the air storage tank pressure is 3.2 bars. It can produce huge power when we scale up the device. Also, proposed device can be used to harness wave energy by installing at onshore. Future works can be done to analyse the proper mooring system.

Keywords: Renewable Energy, Sea wave energy, Wave Energy Converters, Scale model device Onshore device

1. Introduction

Nowadays demand for renewable energy sources for electricity generation is very high for many industrialized countries to meet increased demand and to reduce CO_2 emission further renewable energy sources are clean, safe and sustainable sources [1]. Ocean has several forms of renewable energy resources such as waves, tides, currents, temperature gradients, and salinity gradients. Especially wave energy is concentrated energy source compared to other renewables [2]. Capacity of wave power is comparable with other major energy sources like nuclear or hydroelectric because estimated available wave power resources globally is more than 1 TW, and possible production of energy annually is 2000 TWh [2].

There are various wave energy conversion concepts, and the research history of wave energy conversion is more than 200 years. More than 1500 wave energy device patents have been registered. The first wave energy patent was registered in 1799 by Girard in France. But the first application of wave energy device was built around 1910 by Bochaux-Praceique to light and power his house in France [3]. The research on wave energy were accelerated between 1970's to 1990 because of oil crisis and environmental consideration. Then again Kyoto protocol on CO_2 and oil crisis 2007 forced the world to move towards the renewable energy sources [3].

This paper illustrates about harnessing wave on shoreline. In section 1.1, background of wave energy and the available wave energy converters are discussed. Working principle of newly developed device and, design parameters are discussed in section 2. Section 3 discusses about results and observations obtained at laboratory.

1.1 Literature Review

There are several advantages of using the wave energy technology. Wave energy shows high power density; solar energy generates wind which drives the wave energy. Solar energy intensity is typically 0.1-0.3 kW/m^2 in horizontal surface at the same time intensity of wave energy is 2 to 3 kw/m^2 in vertical plane which is perpendicular to the direction of propagation of the wave [4]. Only a limited amount of environmental pollution happens, because the emission from these kinds of devices has low potential impact on nature. Waves can move large distance with minimum level of energy loss. Another important aspect is wave devices can produce electricity up to 90% of the time but for solar energy harvesting the time of production is nearly 20 to 30% [4].

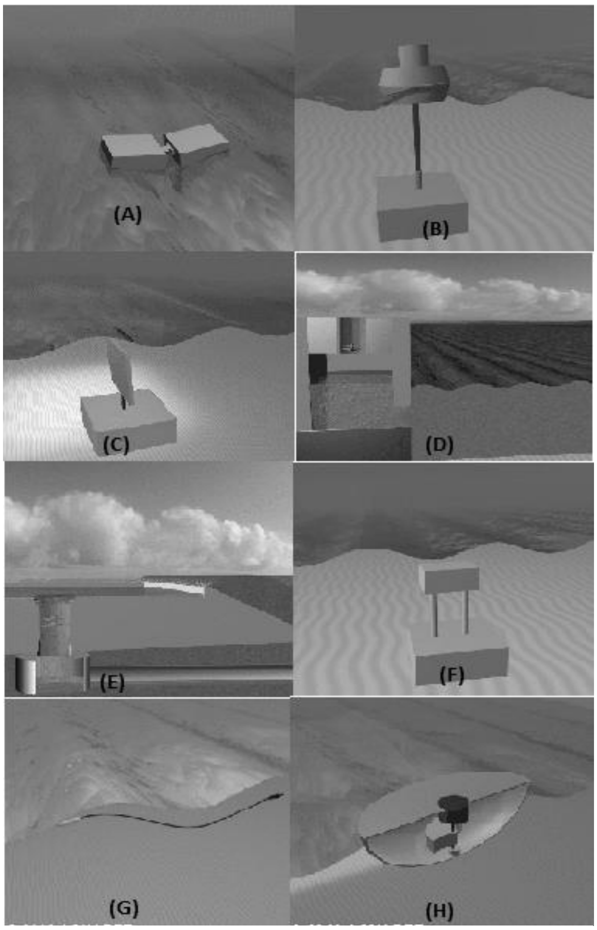

Figure 1 - Types of WEC [6]

Yoshio Masuda is the father of modern wave energy conversion technologies. He developed the first oscillating water column device in 1940s and this was commercialized till 1965 in Japan, then later on in US. After that several wave energy conversion devices were implemented [5]. These wave energy converters are divided mainly into eight types by The European Marine Energy Centre limited (EMEC). EMEC categorizes these devices as attenuator; point absorber; oscillating wave surge converter; Oscillating water column; overtopping device/ terminator device; submerged pressure differential, Bulge wave, rotating mass (Figure 1) [6].

Wave Energy Converters can also be categorized based on their locations as onshore, offshore and near shore devices. Offshore wave energy converter power plants need high installation cost and maintenance cost [7]. On the other hand onshore wave energy converters have many advantages such as easy to maintain and reduced likelihood of damaged by extreme weather conditions [7-8].

Among the several onshore wave energy converters, oscillating water column principle is well proven and most advanced technology among all proposed onshore devices. In oscillating water column (OWC), wave energy is converted into aerodynamic energy and then converted into mechanical energy by rotating a turbine, then this energy is converted as electrical energy via a rotary generator. The OWC functions by air displacement technique as can be seen in figure 2. When water level rises inside the chamber, air inside the chamber will go out. This displacement of air will rotate the turbine which is attached to a rotary generator. When water inside the chamber falls down, a vacuum will be created inside the chamber, so air will come inside through the outlet pipe of the chamber and this air flow also used to rotate the turbine. The OWC uses wells turbine which is a bidirectional turbine [10].

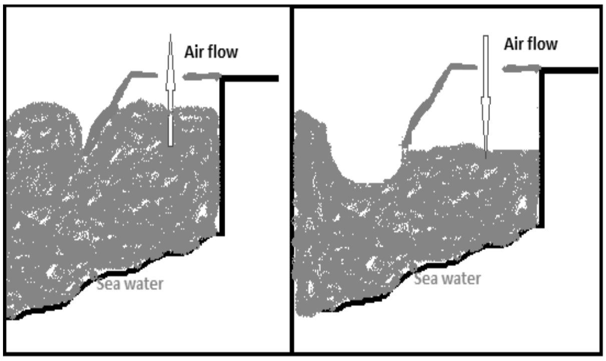

Figure 2 - Working Principle of OWC

However when we go for oscillating water column, it creates some disadvantages such as the requirement of large base structure and high initial investment. Cross sectional areas of most of the OWC pilot power plants are in the range of 100-400 m^2 and height of 10-20m. This is because of the air chamber. Further, the cost of the single OWC device is very high [10]. Another practical issue found was that when we design OWC at micro scale, the outlet air pressure through the OWC is not enough to rotate the turbine which is coupled with a generator. Because the output pressure from the OWC is small. Moreover, continuous electricity production is not feasible since waves are not continuous. Considering above issues a new approach is used to harness the wave energy. Merits of newly developed device are it converts wave energy into compressed air energy and stores in a tank. This stored energy can be utilized when it is required. Moreover energy can be continuously harnessed by releasing stored air at certain flow rate.

2. Wave Energy Converter prototype development

Present study includes the design, implementation and testing a new wave energy converter which is suitable for harnessing wave energy onshore. The device mainly includes a DC generator coupled to a pneumatic turbine, a pneumatic pump and an air storage tank.

2.1 Working Principle of the device

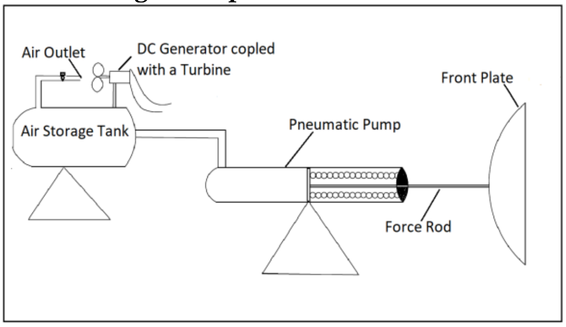

Figure 3 - Schematic Diagram of Developed Device

This sea wave driven compressed air WEC is to be mounted on shoreline. The WEC structure contains a front plate as in above Figure 3. The front plate is attached to the piston rod of the pneumatic pump. When sea wave approaches the shore, momentum of the sea wave moves the front plate and it will drive the piston. Therefore, pneumatic pump will compress the air and store it inside the air storage tank. Back and forth motion of the sea wave on shore will continuously pump and store the air inside the storage tank. This stored air is released, when it reaches a predefined high pressure, to drive a turbine which is coupled with the generator. The generator produces electrical power.

2.1 Design details of the prototype

The prototype was fabricated using locally available materials such as PVC, plastic and stainless steel. Alternatively this can be made using plastic, rubber, synthetic rubber or any composite material. Major consideration is that the material should be corrosion free. Air storage tank in the proposed design is capsule shaped to withstand high pressure. Volume of the storage tank is 18 litres. Outlet air pressure of the storage tank is set according to the required output power from the turbine. An air pump is used to pump the air into the storage tank as mentioned earlier. Diameter of the piston is 5 cm and length is 60 cm of the pneumatic pump in the prototype design. Diameter of the piston is inversely proportional to the required force need to be applied on the front end, further number of strokes required is inversely proportional to the volume of the piston. Force rod of the air pump is spherical segment shaped and named as front end. Effective area of the front end is 1018 cm^2 in the prototype. In this prototype, a permanent magnet DC generator was used. Rated parameters of the generator are as follows; Rated output voltage of the motor is 24 V, rated speed is 1500 rpm, maximum power is 36 W.

2.1 Estimation of the sea wave energy

Sea wave velocity and available wave energy estimation need to be done in order to obtain the device characteristics. Sea wave energy calculations has been done to estimate required minimum speed of the sea wave to operate the device. Sea wave energy estimation has been done by several scholars. For example [11], Sea wave motion is considered to be a triangular wave or similar to it. A wave, traveling at v ms^{-1} velocity with triangular shaped front, contains momentum of mv. Also, the energy of the wave is calculated by

$$E= \tfrac{1}{2}\, mv^2. \qquad (1)$$

where m is the mass of the water in kg in the section of wave being considered. So, Energy of this triangular wave can be given by

$$E=\tfrac{1}{2}.\,(\tfrac{1}{2}.\, b.\, h.\, w.\, p).\, v^2$$
$$=0.25pbhwv^2 \qquad (2)$$

where p is the density of the water in kg/m^3 'b, h and w 'are respectively base, height and width of the triangular wave.

If there are n number of waves for T time period then the total energy for that period is given by

$$E =0.\ 0.25npbhwv^2 \qquad (3)$$

Force exerted by sea wave on a vertical flat surface can be given by

$$F= m.a = m.\, dv/dt$$
$$F= p.A.v^2 \qquad (4)$$

where A is the area of the vertical flat surface.

3. Experimental Results and Discussions

The developed prototype was tested in the laboratory to obtain the characteristics. Stored air pressure in the tank vs output power, air pressure in the tank vs output voltage characteristic graphs were obtained from the tests. Another test was done to measure the required force, to pump the air into the storage tank, at optimum pressure level. Where the optimum pressure is "the pressure inside the tank at which high output power can be generated". These characteristic graphs are obtained to understand the performance of the device and to set the device parameters to get desired output.

parameters highly depend on the characteristic of the turbine, generator and flow rate.

3.1 Air pressure inside the storage tank vs output power characteristic

To obtain the maximum power from the generator optimum load was selected in the test according to the maximum power transfer theorem. Internal resistance of the generator resistance was 25 ohm. Therefore a same value of load is used. Only a resistive load was used by neglecting the effect of small capacitance since the output voltage is less than 20V. An experiment setup was used as in Figure 4 to get a graph of output power variation with air pressure of the tank.

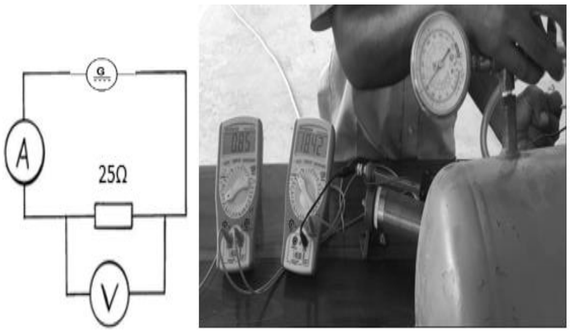

Figure 4 - Experimental Setup Circuit to Obtain Characteristic Curves.

For this experiment the air storage tank was filled with air. Then the output valve was opened in order to rotate the turbogenerator. Measurements were taken for output power for different input pressure from the tank.

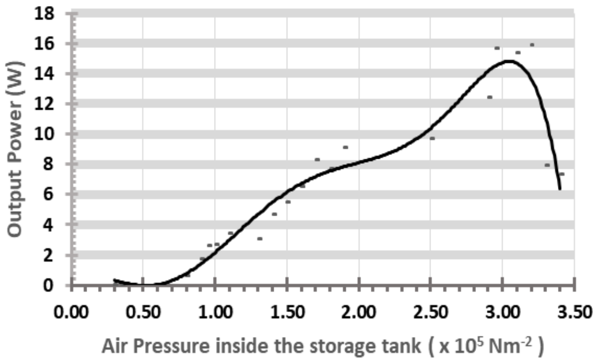

Figure 5 - Variation of Output Power Against Air Pressure Characteristics.

The above results describe that high pressure in the storage tank increases the generated output power up to 3.2 bar but it reduces after that point. In this case, maximum power can be harnessed by the device by setting the air pressure of the tank at outlet to be 3.2 bar. These parameters highly depend on the characteristic of the turbine, generator and flow rate.

3.2 Air pressure inside the storage tank vs output voltage characteristic

Air Pressure inside the storage tank vs output voltage curve was obtained using the same experimental setup explained in section 3.1.

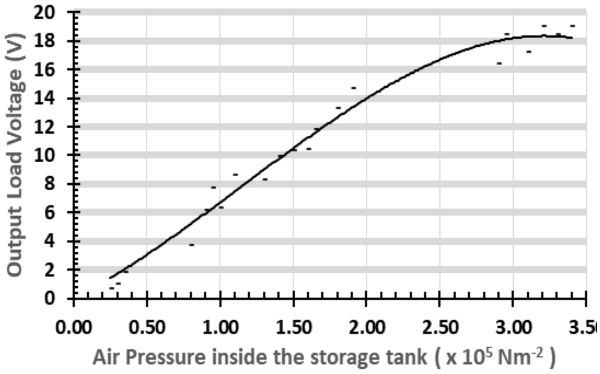

Figure 6 - Influence of Air Pressure in Generated Voltage

The results presented in Figure 6 shows that generated output voltage increases with increase in pressure, however the generated voltage reaches approximately a steady voltage after reaching 3.2 bar pressure. This reduction may be due to the turbulence effect on turbine.

3.3 Air pressure inside the storage tank versus input force to the front end of the device

The porotype was evaluated to obtain the pressure vs force graph. In this experiment, external force was applied on the front plate of the device and observed the developed pressure. Required number of strokes also were recorded.

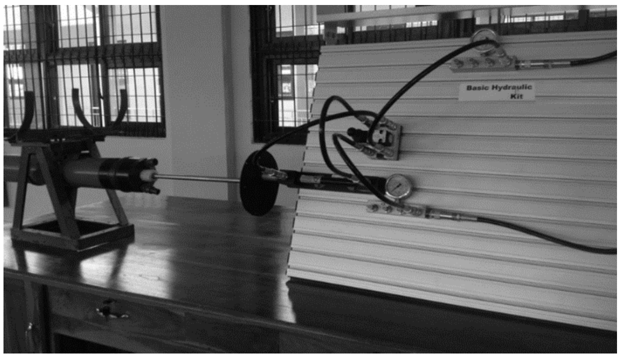

Figure 7 - Experimental Setup to Obtain Applied Force vs Developed Pressure Characteristics.

Table 1 lists the applied force, number of strokes and developed pressure details. As expected, required force increases with the increase in pressure inside the storage tank. About, 65N force has to be experienced in the front plate of the device, repeatedly 115 times (Number of strokes) pushed by the waves in order to reach 3.5 bar pressure at the tank.

Table 1 - Applied Force, Developed Pressure and Required Number of Strokes

Applied force (N)	No of strokes	Developed pressure (x10^5 Nm^{-2})
15	10	0.5
22	22	1.0
33	37	1.5
42	54	2.0
50	72	2.5
60	92	3.0
65	115	3.5

Required force to the front plate is inversely proportional to the area of the piston of pneumatic pump in the device. Total number of strokes can be reduced by increasing the area of the piston, thus it requires increased force to be experienced on the front plate.

Required minimum velocity of the wave, to get 65 N of force on the front plate, can be calculated from equation 4 in section 1.2.

$$v = \sqrt{\frac{p.A}{F}} = \sqrt{\frac{1000*0.1018}{65}} = 1.25 \text{ ms}^{-1} \ldots\ldots\ldots\ldots (5)$$

Therefore any sea wave, with the velocity greater than 1.25 ms^{-1}, can pump and store the air in the storage tank up to 3.5 bar pressure. Also, increasing the area of the front plate will produce more power for same velocity of the wave.

4. Conclusions

Several wave energy prototypes have been proposed however those have some major drawbacks such as high initial investment, requirement of high technical skills in the installation, etc. A prototype was developed with a technique where a pneumatic pump is driven by sea wave force and the air is compressed and stored in a storage tank at high pressure. This stored air is released at certain flow rate to rotate a turbine which is coupled to a generator thus it produces electricity. This device was tested at laboratory. The preliminary experiments showed the proposed wave device is able to harness wave energy. This prototype device could generate 15W peak power across 25 ohm load when the air storage tank pressure is 3.2 bars. Future works need to be done to test the device in the real sea environment. Furthermore, efficiency analysis and improvement study can be conducted.

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