A REVIEW OF POWER TAKE-OFF SYSTEMS EMPLOYED IN WAVE ENERGY CONVERTERS

Journal of Naval Science and Engineering
2014, Vol.10, No.1, pp.32-44

A REVIEW OF POWER TAKE-OFF SYSTEMS EMPLOYED IN WAVE ENERGY CONVERTERS

İlkay Özer ERSELCAN[1], Abdi KÜKNER[2]

[1]Lieutenant,Turkish Navy,Ph.D.Candidate,İstanbul Technical University, Department of Naval Architecture and Ocean Engineering
[2]Professor, İstanbul Technical University, Department of Naval Architecture and Ocean Engineering

Abstract

The power take-off systems consisted in wave energy converters are studied in this paper. Wave energy converters are systems that are designed to produce electricity by capturing the power of ocean surface waves. Research activities on producing electricity from environmentally friendly and sustainable sources have been in progress since the days of Energy Crisis. Ocean waves are one of such energy sources. Many different types of wave energy converters were designed so far. The power of waves is converted into electricity by the power take-off system of the wave energy converter. High pressure oil hydraulic systems, air turbines, hydraulic turbines and linear generators are frequently used types of power take-off mechanisms. Each type of system has its advantages and disadvantages. The decision on which type of power take-off system to be used in a wave energy converter mainly depends on the method of capturing the power of waves.

DALGA ENERJİSİ JENERATÖRLERİNDE KULLANILAN GÜÇ DÖNÜŞÜM SİSTEMLERİNİN İNCELENMESİ

Özetçe

Bu çalışmada dalga enerjisi dönüştürücülerinde yaygın olarak kullanılan güç dönüşüm sistemleri incelenmiştir. Dalga enerjisi dönüştürücüleri okyanusların serbest sathında oluşan dalgaların gücünü elektrik enerjisine dönüştüren sistemlerdir. Çevre dostu ve sürdürülebilir kaynaklardan elektrik enerjisi üretmek üzere yapılan araştırmalar Enerji Krizi'nin yaşandığı günlerden beri devam etmektedir. Okyanus dalgaları bu tür enerji kaynaklarından bir tanesidir. Bugüne kadar birbirinden farklı, çok sayıda dalga enerjisi dönüştürücüsü dizayn edilmiştir. Dalgaların gücü, dalga enerjisi dönüştürücüsü içinde *bulunan bir güç dönüşüm sistemi vasıtasıyla elektrik enerjisine dönüştürülür. Yüksek basınçlı yağ ile çalışan hidrolik sistemler, hava türbinleri, su türbinleri ve doğrusal jeneratörler dalga enerjisi dönüştürücülerinde sıklıkla güç dönüşüm sistemi olarak kullanılmaktadır. Her sistemin avantajları ve dezavantajları bulunmaktadır. Bir dalga enerjisi dönüştürücüsünde hangi tip güç dönüştürücüsünün kullanılacağı temelde dalgaların gücünün toplanma şekline bağlıdır.*

Keywords: *Wave Energy Converters, Power Take-Off Systems, Hydraulic Power Take-Off, Air Turbine, Water Turbine, Linear Generators*
Anahtar Kelimeler: *Dalga Enerjisi Dönüştürücüleri, Güç Dönüşüm Sistemleri, Hidrolik Güç Dönüştürücüleri, Hava Türbini, Su Türbini, Doğrusal Jeneratörler*

1. INTRODUCTION

The disadvantages of generating the energy needed mainly from fossil fuels were realized during the Energy Crisis in 1970’s. The sudden and great drop in the supply of fossil fuels affected the world negatively in every aspect, from daily life to commercial and industrial activities, including power generation. As a result, the need to generate the energy that the world required from diverse sources attracted the attention of the world and the research activities on this subject started to emerge slowly in the years of crisis. Furthermore, the contribution of increasing fossil fuel consumption in energy generation to the increasing levels of environmental pollution has also attracted the world’s attention. Consequently, the interest in obtaining the energy needed from sustainable and environmentally friendly sources and research activities in the relevant field have continued increasingly until today. The wind, solar power, waves, ocean currents and tides have become leading research areas especially in electricity production since approximately 2/3 of the electricity consumed is generated using fossil fuels worldwide [1].

The electricity production from ocean surface waves is a distinct area of research which has a great potential. It’s reported that the wave power in the oceans was about 2 TW, which could provide more than 10% of the world’s electricity supply [2]. The devices designed for extracting the power of waves and converting it into electricity are called Wave Energy Converters (WECs). A large number of WECs have been designed all over the world over the years. Although they differ in design and size, their principles of extracting the energy are similar, thus they can be classified by several common features such as working principle, location of installation and types of power take-off systems [3,4,5,6]. Most of the wave energy converters are still in R&D stage. Some large scale prototypes were built and tested in real sea conditions, but there is still no device that has reached commercial stage [5].

Wave energy converters capture the power of waves with different methods and they convert the mechanical power into electricity via mechanisms called power take-off (PTO) systems. The electricity is generally produced via rotary generators driven by air turbines, hydraulic turbines and high pressure oil hydraulic systems. Besides these power take-off mechanisms, some wave energy converters consist of direct driven generators called linear generators.

2. TYPES OF WAVE ENERGY CONVERTERS

The random behavior of real sea waves is the primary reason of designing many different types of wave energy converters. However, the wave energy converters can be classified with respect to their methods of capturing the energy of waves or their modes of motions, the locations they are installed and the types of their power take-off systems.

Wave energy converters can be classified with respect to their methods of capturing the energy of waves or their modes of motion as oscillating water column wave energy converters, oscillating body wave energy converters, submerged pressure differential and overtopping devices.

The oscillating water column (OWC) wave energy converters are constructed such that they possess a chamber which is open to the sea allowing the waves to enter. This chamber contains air inside. There is also another opening at the top of this chamber where an air turbine coupled to a generator is installed. When the waves act on the WEC, the surface of the water starts to move up and down. The rising water level inside the chamber compresses the air and forces it to flow out from the opening at the top of the chamber and to drive the turbine, thus generating electricity. When the water level descends, the air flow is reversed. The air flows inside the chamber and drives the turbine again. The oscillating water column wave energy converters are built as floating and onshore systems.[7,8]

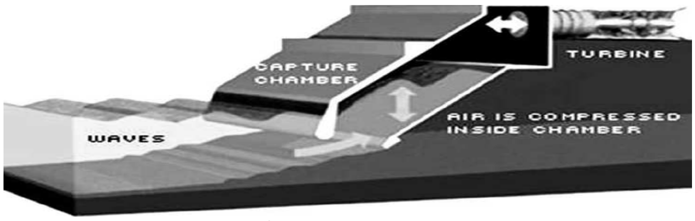

Fig. 1. Schematic view of an on-shore oscillating water column WEC

The oscillating body type wave energy converters are constituted of one or more bodies which oscillate in one or more degrees of freedom against a reference of frame such as the sea bed or each other. This type of wave energy converters generally benefit from heave, surge or pitch motions.

Point absorber type wave energy converters capture the power of waves by a heaving float. The float oscillates in up and down direction due to the force exerted by the waves and delivers the mechanical power to the power take-off system. The power take-off system is generally housed in a secondary body. The secondary body is either bottom mounted or slack/taut moored to the sea bed. The linear motion of the float is then converted to rotary motion via a mechanical interface and electricity is produced by the generator coupled to the mechanical system [9,10].

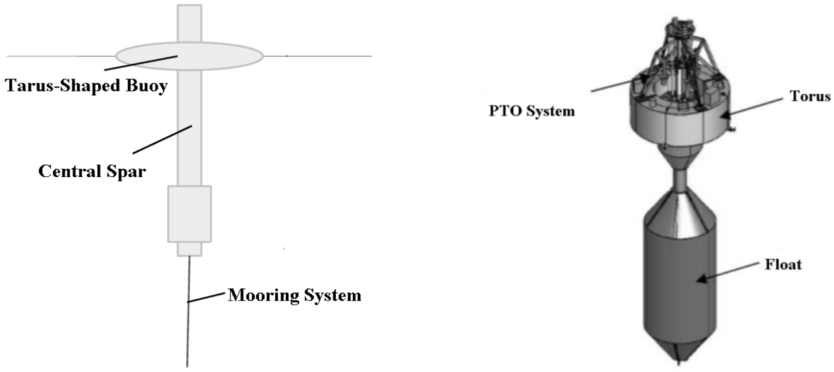

Fig. 2. Single body [8] and double body [9] heaving WECs

Pitching wave energy converters generally have slender bodies aligned with the direction of wave propagation. The oscillating bodies move against each other and activate a power take-off system, thus generating electricity. These devices are slack moored, so that they can align themselves with the wave propagation direction easily [11].

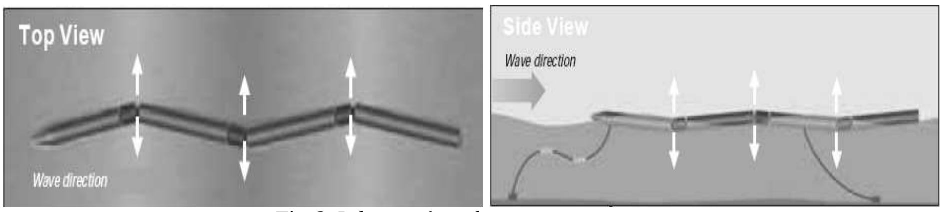

Fig. 3. Pelamis - A pitching wave energy converter

The surging wave energy converters are designed and constructed as flaps which oscillate in back and forth direction. This type of wave energy converters are installed in shallow water near shore line so that they can benefit from the kinetic energy of the entire water column from bottom to the surface. While they can have an installed power take-off system, they are also designed in order to be connected to an onshore facility where energy generation takes place [12].


Fig. 4 LIMPET Wave Energy Converter [12]

Another type of wave energy converter which converts the oscillating motion of its body uses the pressure differential created by waves passing over it. This type of wave energy converter is completely submerged and the pressure exerted by the waves activates the part of the device which interacts with the waves. When the crest of a wave passes over the device, the increasing pressure forces the body to move down. When the wave advances and a crest pass over the device, the body moves up due to decreasing pressure [13].

The overtopping devices capture the power of waves by directing the incoming waves towards a ramp where the waves break and the water is collected in a reservoir. The waves are directed towards the ramp by reflector panels or by a channel narrowing and getting shallower gradually. When the waves are reflected or travel in the channel, they interfere with each other and their heights increase. Eventually, the elevated waves break over the ramp and fill the reservoir. The water collected above the mean sea level flows through low head turbines coupled to generators, thus generating electricity. The overtopping wave energy converters are built as a floating structure (Wave Dragon) as well as on the cliffs in a shoreline (TAPCHAN, Tapered Channel Wave Energy Converter) and the body of a breakwater (SeaWave Slot-Cone Generator, SSG) [6,14,15].

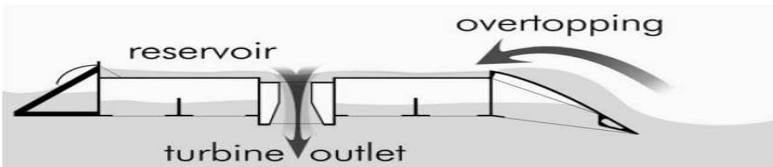

Fig. 5. Schematic view of an overtopping wave energy converter

3. POWER TAKE-OFF SYSTEMS

The power take-off system of a wave energy converter is the section where the mechanical force is converted into electricity. Currently, four types of conversion mechanisms are employed broadly in wave energy converters. These mechanisms are;

- High pressure oil hydraulic power take-offs
- Air turbines
- Low head water turbines
- Linear generators.

The waves exert large forces on floating bodies in low frequencies. This characteristic of the waves makes high pressure oil hydraulic systems suitable for wave energy conversion [16]. Hydraulic power take of systems employed in wave energy converters generally has the following basic structure in most cases.

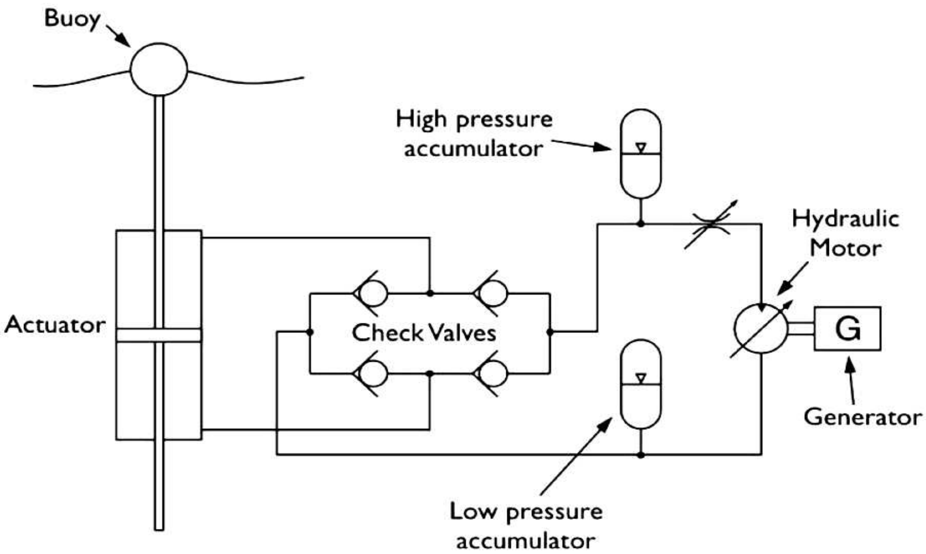

Fig. 6. Schematic of a hydraulic power take-off[4]

The buoy or the body of the wave energy converter subject to waves oscillates due to the forces exerted by the waves and activates a hydraulic ram or a piston which pumps the hydraulic oil at high pressures. The oil pumped into the circuit first passes through check valves which allow fluid flow only in one direction. A group of check valves serve as a rectifier so that the hydraulic fluid always flows in one direction even the motion of the piston is reversed. Then, the hydraulic fluid is gathered in a high pressure accumulator. The high pressure accumulator acts as an energy storage device and also as a dampener which absorbs fluctuations in pressure and smoothes the fluid flow to the hydraulic motor. If an accumulator is not employed in the circuit, the flow rate will be greatly unsteady and the motor output, thus the electrical output of the generator will be irregular. The hydraulic motor coupled with a generator converts the hydraulic energy into mechanical energy, consequently into electrical energy via the generator. The control of the flow into the hydraulic motor is crucial in these systems since it determines the energy output and the overall efficiency of the system. Although the flow is smoothed by the accumulator and a flow control valve in this circuit, more advanced control strategies are employed in power take-off systems to maximize the power output in a broad range of sea states [4]. Finally, the low pressure accumulator supplies a certain level of low pressure in return line in order to prevent cavitation. While the high pressure oil hydraulic power take-off systems are suitable for capturing the intense power of waves, a number of challenges also exist associated with the design and operation of these systems. The containment of hydraulic fluid, the wear of the seals, the efficiency of the power take-off, the maintenance of the system under real sea conditions, the possibility of excess motion of the piston and the need for end-stops and energy storage are among them which are discussed in detail by Drew *et al.*[4].

An air turbine driving a generator is used as a power take-off system in oscillating water column (OWC) wave energy converters. The bidirectional flow of air makes conventional turbines inappropriate for oscillating water column WECs. The shortcoming of conventional turbines is overcome by using self rectifying turbines. Wells turbine, Dennis-Auld turbine and impulse turbines have been used in many applications.

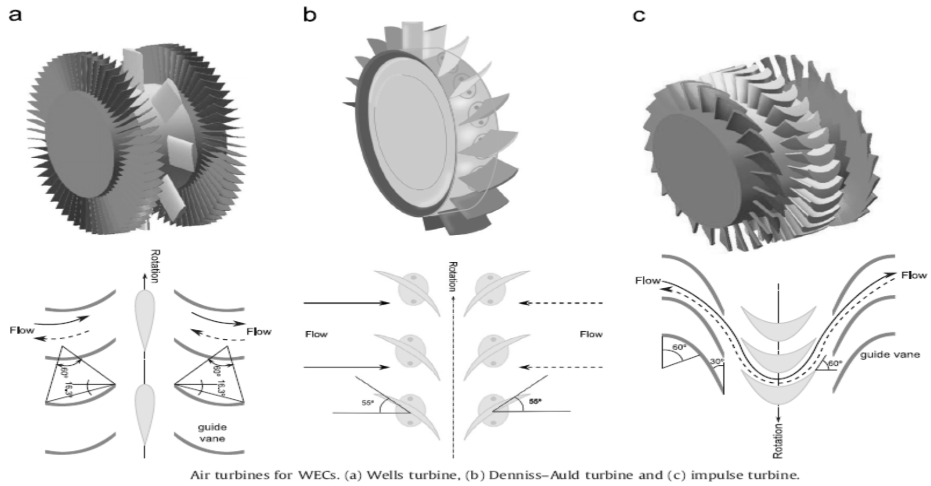

Fig. 7. Air turbines employed in OWCs[5]

Wells turbine is the most frequently used type of turbine among air turbines used in oscillating water columns [17]. The guide vanes in Wells turbines and impulse turbines direct the air towards the rotor blades such that the rotor rotates in one direction without being affected from the change in the direction of air flow. On the other hand, Dennis-Auld turbine which was developed by Oceanlinx uses pitching rotor blades [6]. When the direction of air flow is reversed, the orientations of the blades change. As a result, the rotor continues to rotate in the same direction as shown in Fig. 7.

Hydraulic turbines coupled with generators are another type of power take-off systems used in wave energy converters. The turbines have been in use for many years in electricity generation from hydro power. Hydraulic turbines can be divided into two groups as impulse turbines and reaction turbines. Impulse turbines convert the kinetic energy of water into mechanical energy. The pressure is converted into velocity when the water passes through the nozzles. The high speed water flow is then directed towards the bucket shaped blades. The turbine rotates by the transfer of kinetic energy from water to the turbine. The most common type of impulse turbine is Pelton wheel which is shown in Fig.8-(a).This type of turbine is used in Oyster [18] and in AquaBuoy [19] WECs.

Reaction turbines benefit from the pressure change while the water flows through the rotor blades. The pressure differential created on the rotor blades does work on the rotor blades and eventually the turbine rotates. The most common types of reaction turbines encountered in application are Francis and Kaplan turbines. Francis turbines are generally used in applications in which the water head is high. As a result, they are not very suitable for wave energy converters. Kaplan turbines on the other hand, can extract energy in lower heads, thus are more suitable for wave energy converters [5,20]. The overtopping wave energy converters such as Wave Dragon [21] and Sea Wave Slot-Cone Generator [15] use Kaplan turbines in order to generate electricity.

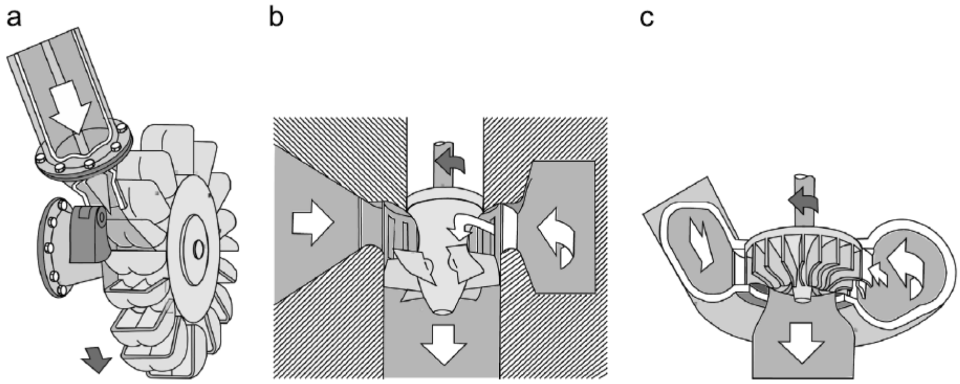

Fig. 8. Hydraulic turbines. (a) Pelton wheel, (b) Kaplan turbine, and (c) Francis turbine [5]

The last type of power take-off system used in wave energy converters is a linear permanent magnet generator. This type of generator has a stator and a translator. It converts translational motion of the wave energy converter into electricity. These generators are directly coupled to the wave energy converter's float without an interface like a turbine or a hydraulic system. This type of generator is installed in a wave energy converter developed by Uppsala University, Sweden [22] wave energy converter and in Archimedes Wave Swing [23].

4. CONCLUSION

The wave energy converters are designed to generate electricity from the low frequency motions of ocean surface waves. Although a great variety of wave energy converters have been designed over years, their principles of capturing the power of waves are similar. The captured power is converted into electricity via a power take-off system. There are four types of power take-off systems commonly employed in wave energy converters. Among them, high pressure oil hydraulic power take-off systems are considered appropriate for capturing the excessive forces exerted by the waves. While each system has its advantages and disadvantages, the decisions on which type of power take-off system is to be employed in a wave energy converter mainly depend on the method of capturing the power of waves. Currently, there is still no system commercially developed and deployed. The research for increasing the power conversion efficiencies of these power take-off systems is continuing.

Table 1. Some advantages and disadvantages of power take-off systems

	Advantages	Disadvantages
High pressure oil hydraulic PTO	• Large forces can be absorbed.	• Fluid containment • Wear of seals • Maintenance • Efficiency
Air turbine-generator	• Low speed of waves is converted into high velocity air flow.	• Low turbine efficiencies. • Reciprocating air flow.
Hydraulic turbine-generator	• No environmental challenge since the working fluid is sea water.	• Sea water is abrasive. It can damage the system components. • The use of hose pumps does not allow high pressure water supply. Turbines can be more suitable for low head applications.
Linear generator	• Direct conversion of mechanical energy • Much simpler structure	• Requires powerful permanent magnets due to slow translational motion. • The machines may be large and heavy in order to convert large wave forces

REFERENCES

[1] International Energy Agency, Key World Energy Statistics, 2012.

[2] Thorpe, T.W., A Brief Review of Wave Energy, Technical Report No.120, Energy Technology Supprt Unit (ETSU), A Report Produced for the UK Department of Trade and Industry, 1999.

[3] Clement, A., McCullen, P., Falcao, A., Fiorentino,A., Gardner, F., Hammarlund, K., Lemonis, G., Lewis, T., Nielsen, K., Petroncini, S., Pontes, M.-T., Schild, P., Sjöström, B.-O., Sorensen, H.C., Thorpe, T., Wave Energy in Europe: current status and perspectives, Renewable & Sustainable Energy Reviews, 2002, 6(5),405-431.

[4] Drew, B., Plummer, A.R., Sahinkaya, M.N., A review of wave energy converter technology, Proc.IMechE Vol.223 Part A: J.Power and Energy, 2009.

[5] Lopez, I., Andreu, J., Ceballos, S., Alegria, I.M., Kortabarria, I., Review of wave energy technologies and the necessary power-equipment, Renewable and Sustainable Energy Reviews 27, 2013, 313-434.

[6] Falcao, A., Wave energy utilization: A review of the technologies, Renewable and Sustainable Energy Reviews 14, 2010, 899-918.

[7] Oceanlinx. Available from www.oceanlinx.com/ (access date: 25 September 2014)

[8] Torre-Enciso, Y., Ortubia, I., Aguileta, L.,I.,L., Marques, J., Mutriku Wave Power Plant: from thinking out to the reality, Proceedings of the 8th European Wave and Tidal Energy Conference, 2009.

[9] D. Elwood, S. Yim, A. Schacher, K. Rhinefrank, J. Prudell, E. Amon, *et al.*, "Numerical Modeling and Ocean Testing of a Direct-Drive Wave Energy Device Utilizing a Permanent Magnet Linear Generator for Power Take-Off," in *ASME 28th International Conference on Ocean,Offshore and Arctic Engineering*, Honolulu,Hawaii,USA, 2009.

[10] M. J. Muliawan, Z. Gao, T. Moan, and A. Babarit, "Analysis of a Two-Body Floating Wave Energy Converter with Particular Focus on the Effects of Power Take-Off and Mooring Systems on Energy Capture," in *ASME 2011 30th International Conference on Ocean,Offshore and Arctic Engineering*, Rotterdam,The Netherlands, 2011.

[11] Yemm, R.W., Henderson, R.,M., Taylor, C., A., E., The OPD Pelamis WEC: Current Status and Onward Programme, Proc. 4th European Wave Energy Conference, Alborg Denmark, 2000.

[12] Aquamarine Power. Available from www.aquamarinepower.com/ (access date: 25 September 2014)
[13] Valerio, D., Beirao, P., Costa, J., S., Optimisation of wave energy extraction with the Archimedes Wave Swing, Ocean Engineering (34), 2007, 2330-2344.
[14] Kofoed, J., P., Frigaard, P., Madsen, E. F., Sorensen, H., C., Prototype Testing of the Wave Energy Converter Wave Dragon, World Renewable Energy Congress VIII, 2004.
[15] Margheritini, L., Vicinanza, D., Frigaard, P., SSG wave energy converter: Design, reliability and hydraulic performance of an innovative overtopping device, Renewable Energy 34, 2009, 1371-1380.
[16] Henderson, R., Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter, Renewable Energy (31), 2006, 271-283.
[17] The Carbon Trust, Oscillating Water Column Wave Energy Converter Evaluation Report, Marine Energy Challenge, 2005.
[18] Cameron, L., Doherty, R., Henry, A., Doherty, K., Van't Hoff, J., Kaye, D., Naylor, D., Bordier, S., Whittaker, T., Design of the Next Generation of the Oyster Wave Energy Converter, 3rd International Conference on Ocean Energy, 2010.
[19] Wacher, A., Nielsen, K.., Mathematical and Numerical Modeling of the AquaBuOY Wave Energy Converter, Mathematics-in-Industry Case Studies Journal, Volume 2, 2010, 16-33.
[20] Davis, V., C., Sorensen, K., E., Handbook of Applied Hydraulics, 1969.
[21] Frigaard, P., Kofoed, J. P., & Rasmussen, M. R. (2004). Overtopping Measurements on the Wave Dragon Nissum Bredning Prototype. In J. S. Chung, K. Izumiyama, M. Sayed, & S. W. Hong (Eds.), The Proceedings of The Fourteenth (2004) International Offshore and Polar Engineering Conference. (14 ed., pp. 210-216). ISOPE.
[22] Eriksson, M., Waters, R., Svensson, O., Isberg, J., Leijon, M., Wave power absorption: Experiments in open sea and simulation, Journal of Applied Physics (102), 2007.
[23] Polinder, H., Damen, M.,E.,C., Gardner, F., Linear PM Generator System for Wave Energy Conversion in the AWS, IEEE Transactions on Energy Conversion, Vol. 19, No.3, 2004.