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Overview on Oscillating Water Column Devices

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Abstract. Oscillating-water-column (OWC) converters, of fixed structure or floating, are an important class of wave energy devices. A large part of wave energy converter prototypes deployed so far into the sea are of OWC type. The paper presents a review of recent advances in OWC technology, including sea-tested prototypes and plants, new concepts, air turbines, model testing techniques and control.

Introduction

The sea waves are a vast, practically untapped, renewable energy resource. Many concepts and technologies for their utilization have been proposed and developed with varying success. They have been classified with respect to their basic concept and to their location with respect to the shoreline. The oscillating water column (OWC) is widely regarded as the simplest and most frequently adopted type of wave energy converter. More OWC prototypes have been deployed and tested in the real sea than of any other type of wave energy device. The OWC converters may be bottom standing, integrated into a breakwater or floating. They consist of a hollow structure, fixed or floating, open at its submerged part, within which the air trapped above the inner free-surface is alternately compressed and decompressed by wave action. In almost all cases, the air chamber is connected to the atmosphere by a self-rectifying turbine. An extensive review of OWCs can be found in [1].

Resonance plays a central role in almost all wave energy converter concepts if a satisfactory efficiency is to be attained. This involves one or more oscillating bodies or oscillating masses of water (water columns). A single-oscillating-body converter reacts against a fixed frame of reference, in general the sea bottom or a bottom standing structure. This may be avoided in floating devices consisting of two or more bodies that are mechanically inter-connected (hinge or other connection). In OWC devices, the water column acts as an oscillating body without the need of any mechanical connection.

In almost every case, the power take-off system (PTO) of an OWC converter is relatively conventional and reliable: an air turbine (in most cases a self-rectifying version) directly driving an electrical generator, located above sea water level. A dielectric elastomeric membrane generator capable of converting deformation into electrical energy has recently been proposed as an alternative to the air-turbine-generator set [2].

Recent sea-tested OWC prototypes and plants

OWC prototypes have been deployed into the sea since the 1970s, an early case being the Kaimei floating vessel in Japan. Here, only recent realizations are mentioned.

A bottom-standing plant was deployed in 2016 near the coast of Jeju island, South Korea, Fig. 1. It is equipped with two self-rectifying axial-flow impulse turbines of 250 kW rated power each.

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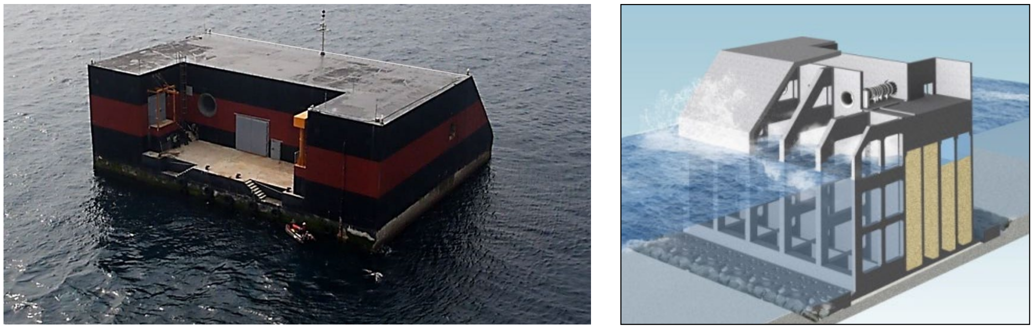

Fig. 1. Bottom-standing OWC in Jeju island, South Korea, completed in 2016. It is equipped with two 250 kW self-rectifying axial-flow impulse air turbines.

The integration of wave energy converters into harbour protection structures has been considered an interesting option since the early times of wave energy development. The costs of the dual-purpose structure are shared, and the access for construction, installation and maintenance are made easier. OWCs are especially appropriate for integration into breakwaters.

A breakwater with 16 OWCs was constructed at Mutriku harbour, in Basque Country, Spain. The plant, completed about 2012, was equipped with 16 bi-plane Wells turbine-generator sets rated 18.5 kW each (Fig. 2).

Fig. 2. Mutriku harbour breakwater with 16 OWCs, completed about 2012.

A much longer breakwater was constructed at the port of Civitavecchia, Italy, integrating 124 OWCs (completed in 2016) (Fig. 3). Only one turbine (bi-planeWells type) was (temporarily) installed. The U-shape of the Civitavecchia OWCs, invented by P. Boccotti [3], allows a longer (and more easily resonant) OWC, while keeping the mouth close to the sea surface, Fig. 4. The U-OWC breakwater concept is planned to be replicated elsewhere in Italy.

Several floating OWC concepts have been proposed and studied so far. Here we mention two that reached the stage of sea tested prototype in the last decade or so.

The backward-bent-ducted-buoy was proposed in the mid-1980s by Yoshio Masuda. A large model, at scale about 1:4th, was tested in Galway Bay, Ireland. It was equipped firstly with a Wells turbine and later with an axial-flow impulse turbine (Fig. 5). A full-scaled prototype was very recently constructed in Portland, Oregon, USA, to be deployed in Hawaii (Fig. 5).

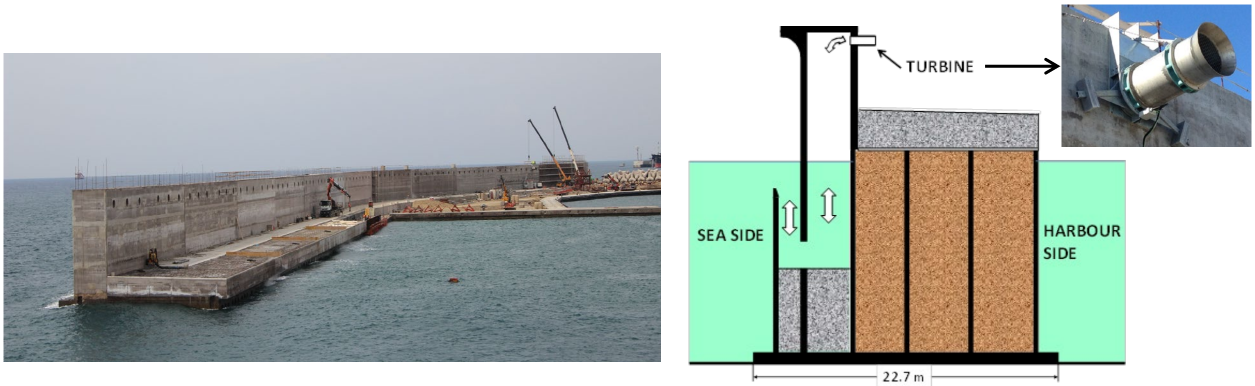

Fig. 3. Breakwater at Civitavecchia with 124 OWCs (2016).

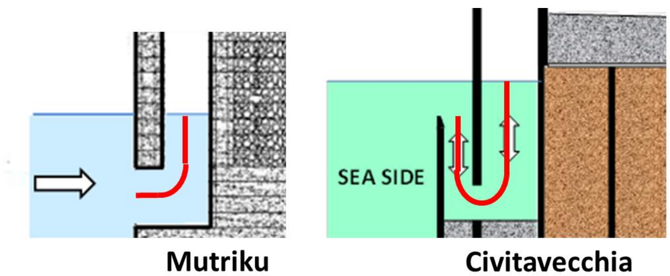

Fig 4. Cross-section comparison of the Mutriku breakwater "conventional" OWC and the U-shaped OWC of Civitavecchia breakwater.

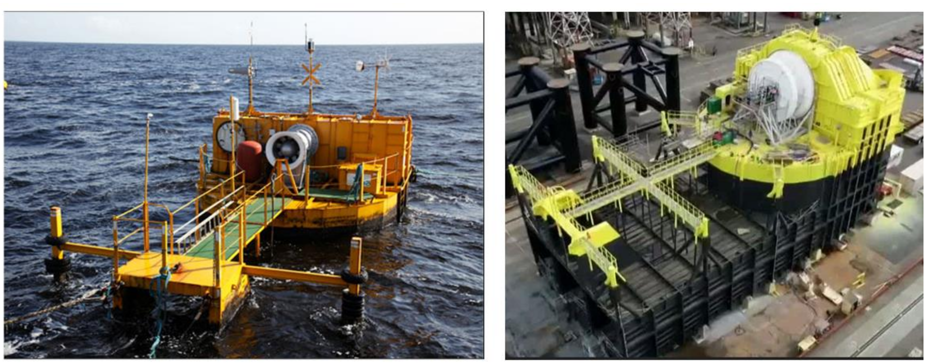

Fig. 5. BBDB prototypes. Left: 1:4th scale being tested in Galway Bay, Ireland, about 2008. Right: full-sized prototype in shipyard, in Portland, Oregon (2019), for deployment in Hawaii.

Another floating OWC concept is the spar-buoy OWC converter, consisting of an axisymmetric floater with a long coaxial vertical tube, open to the sea at its bottom end, within which is located the water column. This concept was extensively studied theoretically, numerically and in wave tank in the last few years. A prototype, scaled about 1:3rd, was built and tested at the BiMAP test site, Basque Country, Spain, in 2018-2019. The converter was equipped with a 30 kW bi-radial self-rectifying air turbine. The turbine-generator set had been previously tested for one year at one of the OWCs of the Mutriku breakwater.

Since the lower opening of the spar-buoy tube is deeply submerged (typically of the order of 30 m below the sea surface), the wave energy is essentially absorbed through the interaction

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between of the oscillating floater and the surrounding waves. A concept in which the opposite situation occurs is the co-axial tube OWC. It may be regarded as a floating axisymmetric version of Boccotti's U-OWC (sea above), Fig. 7. Here, the facing-up opening of the tube is close to the sea surface. Besides, since the water plane area (i.e. the annular cross-sectional area of the inner tube wall at sea water surface level) is very small, the hydrostatic restoring force is also very small, and so is the frequency of the free oscillations of the floating structure that behaves as a semisubmersible structure. For this reason, the heave and pitch oscillations are very weakly excited by sea waves, which makes this kind of wave energy converter appropriate to fit multiuse floating platforms. A rigidly-connected array of five such OWCs was model-tested in 2017 within the framework of the H2020 project WETFEET (Fig. 7).

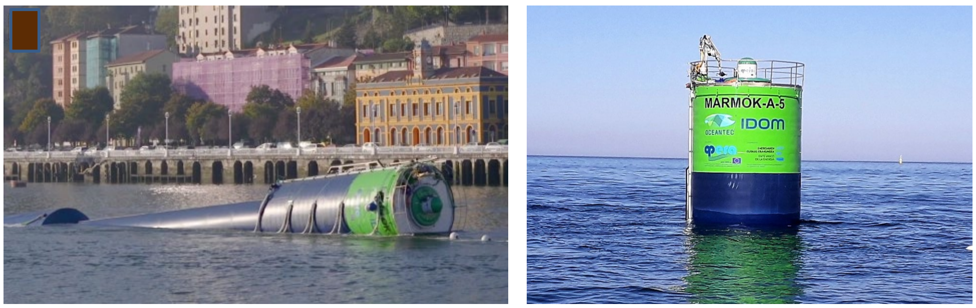

Fig. 6. Marmok-A-5 spar-buoy OWC tested at the BiMEP test site, Basque Country, Spain, 2019. The converter is equipped with a 30 kW bi-radial self-rectifying air turbine (see Fig. 8).

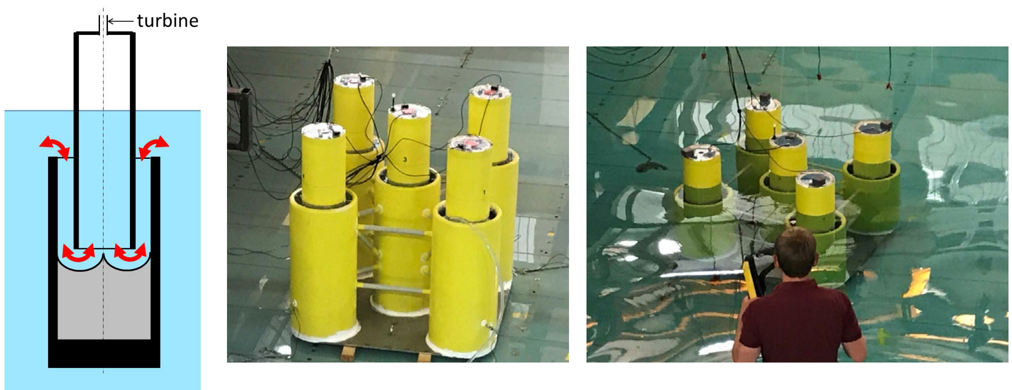

Fig. 7. Co-axial-tube OWC (left); five-OWC rigidly-connected array model (centre); and array being tested in the wave tank of the Coastal Laboratory, University of Plymouth (2017) (right).

Air turbines

An OWC converter is in general equipped with an air turbine coupled to a conventional electrical generator. This may be regarded as a simple and reliable type of power take-off system and is one of the attractive features of the OWC concept. If rectifying valves are to be avoided (which has been the case except in small wave-powered navigation buoys), the turbine must be self-rectifying, i.e., its rotational speed direction remains unchanged when the air flow is reversed by the reciprocating motion of the air column. Two types of such turbines were proposed and patented in the mid-1970s: the Wells turbine and the axial-flow impulse turbine, with variants of both. In spite of their limitations in terms of aerodynamic performance, they remain popular in OWC applications due to their mechanical simplicity and low cost. More sophisticated and efficient self-rectifying air turbines were developed in recent years.

Here, we mention especially the biradial turbine. This is an impulse turbine that is symmetrical with respect to a plane perpendicular to its axis of rotation. The flow into the rotor is radial centripetal and the flow out of the rotor is radial centrifugal. The rotor is surrounded by a pair of radial-flow guide-vane systems, each one connected to the corresponding rotor opening by a duct whose walls are flat discs (Fig. 8). A 30 kW biradial turbine was tested at Mutriku and then installed the Marmok-A-5 spar-buoy OWC in 2018-2019 at the BiMAP test site, Basque Country, Spain (Fig. 6). The turbine was equipped with a fast axially-sliding valve (opening or closing time 0.2 s) capable of achieving phase control by latching (see below).

Fig. 8. Biradial air turbine. Perspective drawing showing the concept (left). Prototype before installion at the Marmok-A-5 spar-buoy OWC (centre), equipped with an axially-sliding high-speed valve (right).

The use of a conventional unidirectional air turbine requires a system of rectifying valves. This has been implemented in early small navigation buoys. Unidirectional turbines with rectifying valves were tested in Japan on the Kaimei floating vessel in 1978-80 and 1985-86, but the results were not encouraging [1]. The Tupperwave is a new concept of spar-buoy OWC equipped with a unidirectional turbine and check valves. The air flows in closed circuit, with low- and high-pressure reservoirs. Model tests were performed in wave tank with an orifice simulating the turbine [5]. The valves seem to remain a major problem.

The spring-like air compressibility effect

The volume of the air chamber of an OWC converter should be large enough to avoid ingestion of green water by the air turbine under rough sea conditions. Typical design values of the air chamber volume divided by the area of the OWC free surface range between 3 and 8m. The spring-like effect of air compressibility in the chamber is related to the pressure-density relationship, and increases with chamber volume. Such effect is important in a full-sized OWC converter. For such effect to be adequately simulated in model testing (Froude linear scale $\varepsilon < 1$ for the submerged parts of the converter), the ratio between the air chamber volume of model and prototype has to be equal to the square ε^2, not the cube ε^3, of the scale [6]. This implies a much larger air volume in the model which in general requires an additional rigid-walled air reservoir connected to the model air chamber. This rule is rarely implemented in model testing of OWCs, which means that most experimental results (published or unpublished) from OWC model testing could be affected by significant errors.

The compressible air in the chamber acts as a spring in series with the damping effect provided by the turbine. This produces a reactive effect that modifies (increases) the resonance frequency and consequently the frequency response of the converter. This effect may be unfavorable or (more rarely) favorable in terms of wave energy absorption (depending on incident wave frequency), but should not be ignored [6].

Control

Most wave energy converters, including especially OWCs, perform more efficiently near resonance conditions. Since real sea waves are irregular (rather than purely sinusoidal) and sea states vary widely along the year, control plays an essential role in converter performance. Generally control is implemented on the power take-off system (PTO), and so control strategies must be adapted to the converter type and especially the mechanical/electrical arrangement of the PTO. A wide range of control methods have been proposed and adopted [7,8].

In OWC converters, the PTO consists of an air turbine driving an electrical generator. The wave-to-wire efficiency of an OWC converter involves three processes: (i) hydrodynamics of wave energy absorption, (ii) aerodynamic performance of the turbine (this may include losses at non-return valves if the turbine is unidirectional), and (iii) performance of the electrical equipment. All three processes are coupled though the rotational speed of the turbine-generator set, and so control of the OWC converter relies largely on rotational speed control.

Phase control by latching was proposed in 1978 by Falnes and Budal to improve the wave energy absorption by oscillating body converters (especially point absorbers). It consists in latching the body in a fixed position during certain intervals of the oscillation cycle. Extending the latching control strategy to OWCs requires to air flow to be stopped during certain intervals of time; this requires a fast acting valve. Because in an OWC air is compressible, latching can be activated at any time without causing large peak forces, which makes it more versatile. For the same reasons why unidirectional air turbines have been unpopular (because valves are needed), also phase control by latching of OWCs has not been seriously considered until recently. The high-speed sliding valve that integrates the new biradial turbine (see above) may be used to successfully implement phase control by latching [9]. The numerical results in Fig. 9 show how latching control may dramatically increase the regular wave energy absorption by a spar-buoy OWC over a significant range of wave periods. Naturally, latching control may be effective only if the device's resonance frequency exceeds the wave frequency.

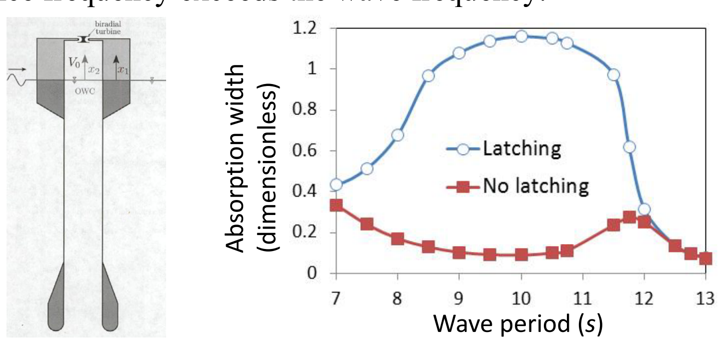

Fig. 9. Dimensionless absorption width of a spar-buoy OWC in regular waves with optimal latching control and without control. Buoy diameter 15 m, draft 38 m. Results from theoretical/numerical modelling [10].

Control of an OWC converter in most cases consists simply in controlling the rotational speed of the turbo-generator set through the electromagnetic torque L_e of the generator. This is mainly because the turbine aerodynamic efficiency depends strongly on its rotational speed. It should also be taken into account that kinetic energy is alternately stored in, and released from, the rotating masses (flywheel effect). An effective control algorithm is $L_e = a\Omega^{b-1}$, where L_e is the electromagnetic of the generator, Ω is rotational speed and the exponent b is (from turbomachinery non-dimensional analysis) approximately $b = 3$. Coefficient a depends on device configuration and size, and on turbine type and size, and must be optimized numerically or experimentally. This algorithm should be complemented to account for constraints related to maximum allowable rotational speed (especially if the turbine is of Wells type) and maximum allowable electrical power (especially in power electronics).

Electrical equipment control

Electrical generators are in general highly efficient machines (about 95%) in the power range above about 2/3 of the rated power. Below that level, the efficiency decreases markedly (see Fig. 10). The power absorbed from the waves varies greatly, depending on the sea state. The highly energetic sea states occur in only a small fraction of the year but their contribution to the total produced energy may be substantial if the rated power of the electrical equipment is large enough to accommodate that. On the other hand, most of the available wave energy concerns the less energetic sea states that occur most of the time. This raises questions: (i) at which level shall the electrical rated power be fixed, and (ii) how to proceed so that it is not to be exceeded (which could endanger the equipment).

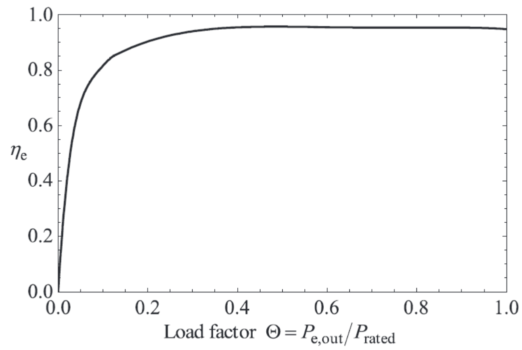

Fig. 10. Electrical efficiency versus electrical load factor for an electrical generator.

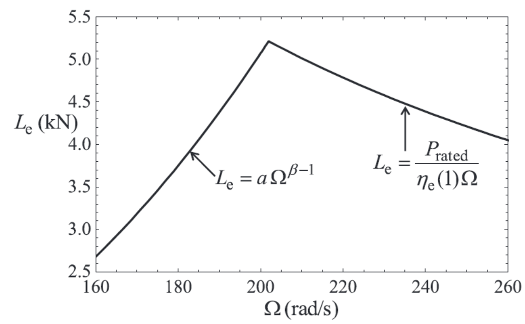

Fig. 11. Control law for OWC converter.

The latter question (ii) is addressed differently depending on the type of wave energy converter. In the case of an OWC device, the power may be constrained by (a) a valve in series or in parallel with the air turbine; or (b) by controlling the electromagnetic torque so that the rated power is not exceeded (Fig. 11), which results in storing the excess energy as kinetic energy of the rotating masses (note that the turbine efficiency drops to very low values at high rotational speeds). Obviously, (b) may be limited by maximum rotational speed constraints (either for the turbine or for the generator). If this is the case, the power available to the turbine has to be reduced. This is done by a mechanical valve to reduce (or simply close) the flow through the turbine. In general, the valve is not fast enough to respond to the power peaks, and its aperture position is changed "from time to time" simply to match the sea state.

The availability of a very fast valve (response time about 0.2 s) in series with the turbine (see Fig. 8) allows what has been called "peak-shaving", i.e. preventing the occurrence of unacceptable power peaks by partially (or if necessary fully) closing the valve, which is left open at the other times. This has been implemented with good results in the biradial turbine tested under real sea conditions while installed at the Mutriku OWC breakwater and later at the Marmok-A-5 spar-buoy OWC, in 2017-19 (European project OPERA), see Fig. 12 [11].

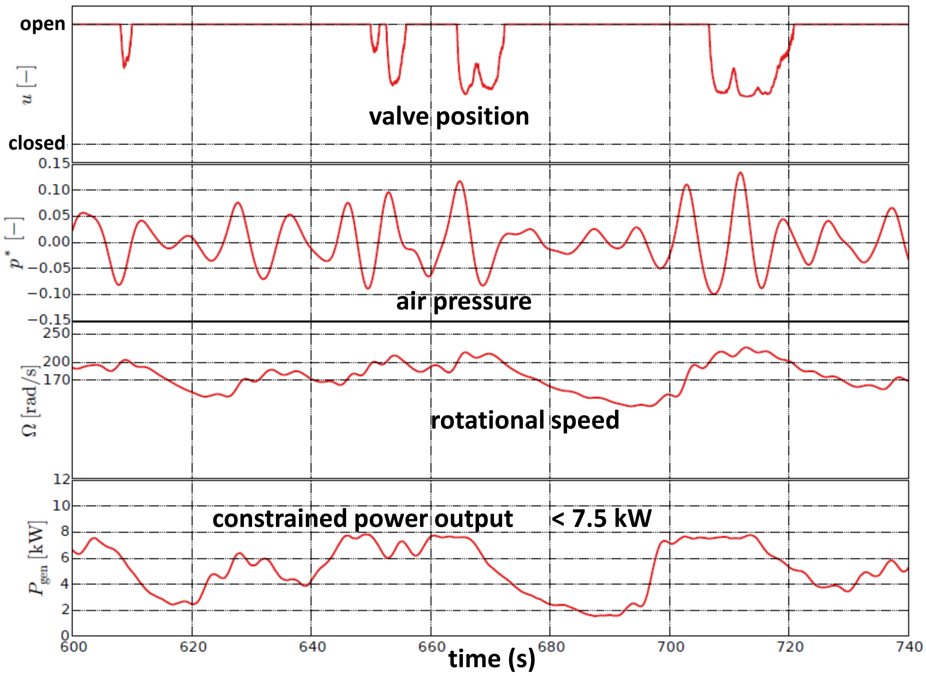

Fig. 12. Measured results of peak-shaving control of one of the OWC converters of the Mutriku breakwater equipped with a biradial turbine and a fast valve [11]. In this test, the electrical generator power was constrained not to exceed 7.5 kW.

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