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PERFORMANCE OF A U-OWC – PTO COUPLED SYSTEM USING DIFFERENT CONTROL LAWS

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Abstract. The problem of maximizing the performances of a U-OWC wave energy converter in a variety of environmental conditions is investigated. Specifically, the paper compares two control strategies coupling the U-OWC – PTO system. Two approaches are discussed. The first relies on the tracking of the Maximum Power Points of the system, and empirical relations between the optimal PTO performances and the energy content of the incident sea state are estimated. Secondly, an analytical formulation linking the operational conditions of the turbine to the instantaneous air pressure inside the pneumatic chamber is identified. Results show that a sea state-based controller works better than a wave-to wave fast-acting control.

1 INTRODUCTION

Currently, wave energy is the key actor in the exploitation of energy from oceans. Various harvesting concepts were proposed worldwide, some of them reached the prototype stage, while others are still at the proof of concept stage. Nowadays, Oscillating Water Columns (OWC) are one of the most investigated devices. They can be either floating or fixed structures and have the additional feature of being incorporated into traditional breakwaters. Thus, fostering the development of "Green Ports", that is energy-wise autonomous infrastructures. Recently, an OWC type wave energy converter was proposed by Boccotti [1], later named U-OWC. Its core elements are the same of a classical OWC: it is composed by a pneumatic chamber containing air in the upper part, which is alternatively compressed and decompressed by the fluctuations of the water, located in the lower part of the chamber. An air duct containing a self-rectifying turbine connects the air pocket to the atmosphere. In addition, the U-OWC has a U-shaped duct connecting the water column to the wave-beaten side of the breakwater. This particular configuration induces significant modifications of the hydrodynamic behavior of the plant. Indeed, waves do not propagate inside the plant, and the pressure fluctuations at the outer opening of the vertical duct generate the oscillating water current which forces the air in the chamber to flow through the air duct, thus driving the turbine. From a theoretical modeling perspective, non-linear terms are included into the differential equations describing the oscillating water column dynamics, being the head losses along the U-shaped duct not negligible. Therefore, a time domain analysis is required. The analytical description of the U-OWC was firstly proposed by Boccotti [2], and later validated through small-scale field experiments [3]. Recently, a more consistent representation of the surrounding wave field was proposed by Malara and Arena [4], giving rise to a dynamic model including added mass and hydrodynamic memory effects.

The peculiarity of the U-OWC relates to its capability of reaching naturally the resonance condition, without the need of devices for phase control. Indeed, the geometrical configuration of the system can be properly designed in order to tune the eigenperiod of the plant to a desired wave period. Obviously, the random nature of the wave energy resource implies the inclusion of strategies aimed at maximizing the performances of the system in a variety of wave conditions. In this regard, the optimal performance of the system at different wave conditions could be achieved by appropriately control the rotational speed of the turbine [5]. Indeed, the amount of harvested energy is affected by the aerodynamic efficiency of the PTO mechanism, which depends upon both the speed of the air through the turbine and its rotational speed [6]. Consequently, the implementation of effective control algorithm able to match the speed of the turbine maximizing wave energy converter performance is crucial. For traditional OWCs, this problem was investigated by a number of authors [5, 7-9]. Different approaches were proposed. One methodology [5, 7] relies on the identification of a control algorithm relating the electromagnetic torque applied upon the generator rotor to the instantaneous rotational speed. Amundarain, et al. [8] combined the control on the rotational speed of the turbine with the control on the airflow by the use of air valves. Another methodology [9] proposes a fast-acting control. That is, the instantaneous operating conditions of the PTO components are linked to the actual measured turbine speed and/or the pressure of the air in the pneumatic chamber. An overall comparison reveals that the first kind of control strategy works better for large inertia turbine, while the latter one is more suitable for low inertia turbine.

Regarding the U-OWC, investigations on the behavior of the plant coupled with the PTO mechanism aimed at the identification of a turbine control strategy are still at the first stage of development. The present work proposes a comparison between two different approaches to the problem. For the purpose, the specific case study of the U-OWC prototype under construction in the port of Civitavecchia (Italy) is considered. The first solution relies on a Maximum Power Point Tracking (MPPT) algorithm, aimed to adapt the reference speed of the turbine to the energetic content of the incoming sea state. In this context, the effect of both the significant wave height and the peak period are included. The second solution is a wave-to-wave control algorithm, relating the reference rotational speed of the turbine to the actual aerodynamic conditions inside the plant, by means of measurements of the air pressure and of the water level inside the pneumatic chamber.

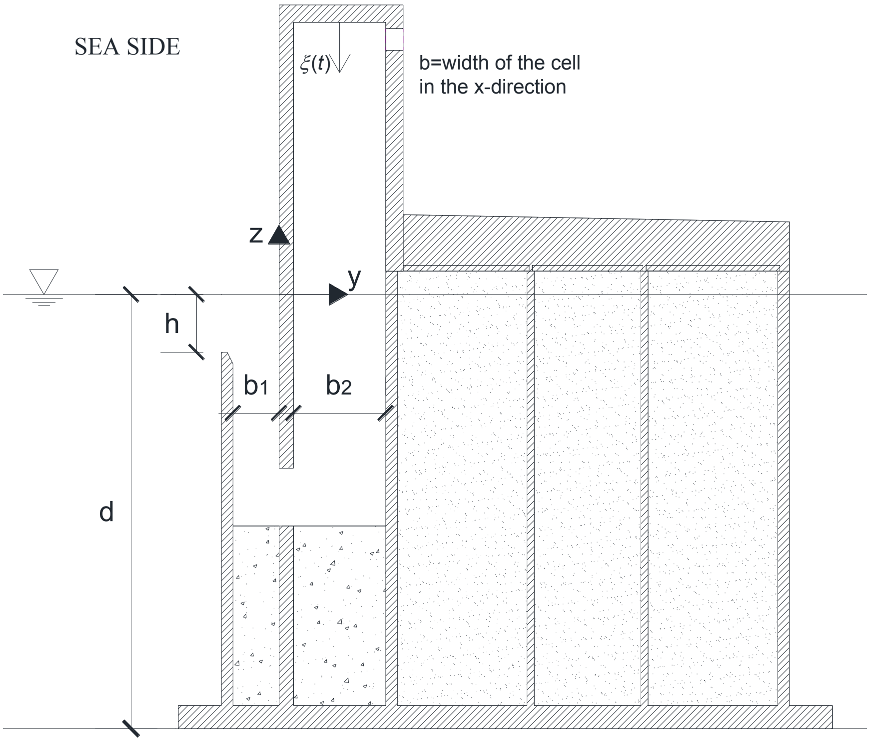

Figure 1: Cross-section of the U-OWC plant in Civitavecchia.

2 U-OWC – PTO COUPLING

In this section the analytical description of the coupled U-OWC – PTO system is illustrated. The joint analysis of these two components is crucial, as the air pressure fluctuations into the pneumatic chamber are deeply affected by the rotational speed of the turbine. Then, the mentioned case study of U-OWC under construction in Civitavecchia is presented.

2.1 Analytical description of the U-OWC – PTO coupled system

The analytical description of the U-OWC – PTO system is pursued by considering the following contributions: U-OWC hydrodynamics; air pocket dynamics; turbine dynamics; and generator influence. The first two elements were investigated by Malara and Arena [4], and their model is here applied. Turbine behavior is described via the equation,

$$T_m - T_g = J\frac{d\omega}{dt} + F\,. \tag{1}$$

where ω is the turbine rotational speed, J is the turbine inertia and F is a frictional torque supposed constant. It is worth noting that a more robust formulation of the problem requires a ω-dependent representation of F. Nevertheless, a constant torque is chosen to simplify the computations. On the left side of the equation appear the applied mechanical torque T_m, and the resistive torque imposed by the generator T_g. The former is computed via the dynamical model [4] describing the oscillations of the column along the U-duct in conjunction with the air pocket fluctuations. Additionally, turbine effect is included as a concentrated head loss characterized by a damping ratio equal to 2.9. In this context, the excitation of the system is the pressure fluctuation acting at the outer opening of the vertical duct $\Delta p(t)$.

Concerning the generator torque, it is constantly calibrated in order to adjust the rotational speed of the turbine $\omega(t)$ to the desired reference value. Thus, its formulation depends on the error between the actual and the requested conditions. The following Proportional Controller is adopted for its estimation:

$$T_g = K_p \, [\omega - \omega_{ref}\,] \, . \tag{2}$$

In this context, the K_p constant is identified through an iterative procedure maximizing the P-Controller efficacy.

Obviously, generator characteristics affects the PTO efficacy. Consequently, limitations to the maximum achievable value of both the generator toque and the generator power must be included in the computations.

2.2 Case study and generation of the input

The case study of interest is the full-scale prototype developed in the context of the enlargement of the port of Civitavecchia, Italy (Fig. 1). The relevant geometric characteristics of the caissons are described in Arena, et al. [10].

In the present work, a Wells turbine characterized by J=0.97 kg•m^2 and F=1 N•m is considered. Additionally, the generator system specifics are the following: nominal power 20 kW, nominal torque 60 N•m.

Typical operational conditions for this specific device are represented via the sequence of 107 sea states utilized for the present analysis (Fig 2). For this purpose, a long wave time history representing the excitation of the system is generated by wave data recorded at the NOEL laboratory of the Mediterranea University of Reggio Calabria. The site allows recording wind-generated sea states whose peculiarity is that they are small-scale models, in Froude similarity, of sea states occurring both in the Mediterranean Sea and in the Oceans. The adopted procedure is the following: firstly, the wave pressure recorded in the undisturbed wave field at NOEL are appropriately transformed, by Froude similarity, in order to be representative of the wave pressure at the Civitavecchia area, denoted as $\Delta p_{CV}(t)$; then, the excitation is computed by taking into account the diffraction problem as $2\bullet\Delta p_{CV}(t)$, thus assuming that the excitation relates to a fully reflective vertical wall. It is worth noting that this approximation is reliable for the purpose of the present analysis, though the specific geometrical configuration is neglected.

3 MPPT CONTROL STRATEGY

The first of the two proposed control strategies is here presented. This approach is based on the idea that the reference rotational speed of the turbine can be related to the energetic content of the incident sea state. A Maximum Power Point Tracking (MPPT) algorithm is implemented, as it is adequate for working with the rapidly changing environmental conditions characterizing sea state sequences. The effect of both the significant wave height and the peak period as reference parameter is evaluated.

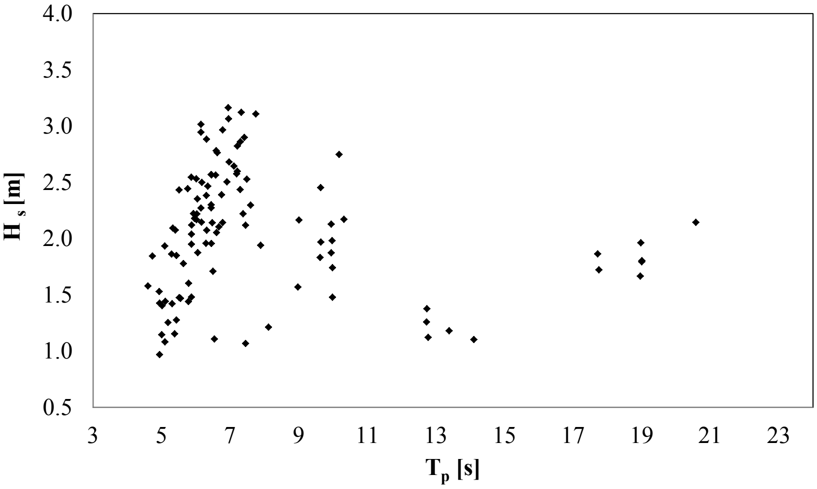

Figure 2: Significant wave height and peak period distribution pertaining to the 107 sea states utilized in the analysis.

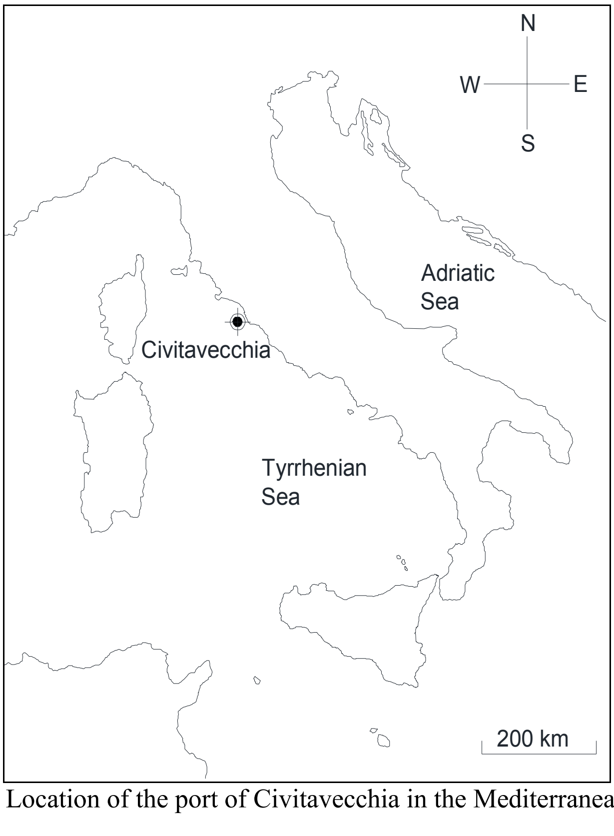

Figure 3: Location of the port of Civitavecchia in the Mediterranean Sea.

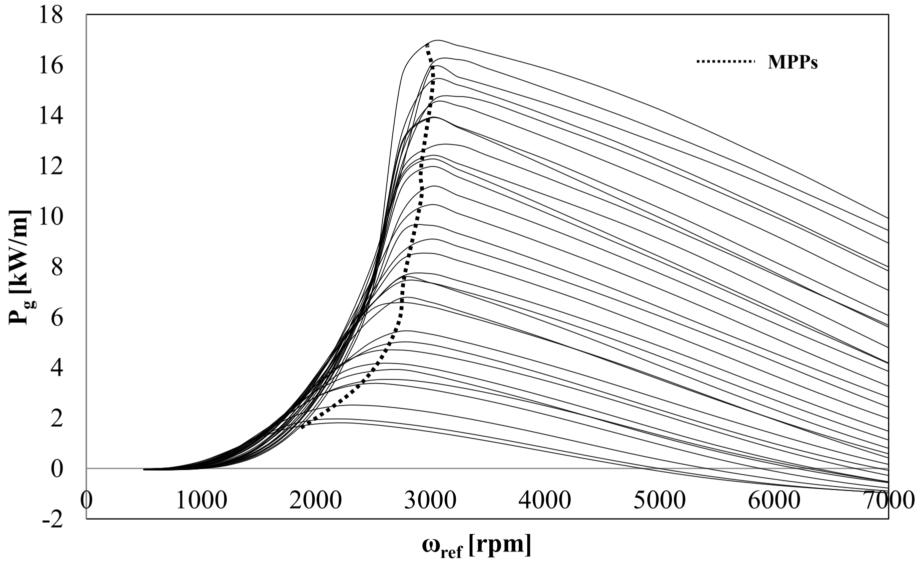

Figure 4: Power Curves for a number of sea states.

Table 1: Ideal case performances, when the system works immediately at the desired MPPs, for each sea state. T denotes the duration of the total simulation, computed as the sum of each sea state's length. E_g denotes the total converted energy by the generator, by one single cell of 3.87 m width.

T [h]	$<E_g>$ [kWh]
16.7	186.6

3.1 Power Curves and identification of the MPPs

The MPPT algorithm requires the identification of the Maximum Power Points (MPPs) of the system, which are representative of the rotational speed of the turbine to which the maximum converted power is associated. The MPP identification procedure assumes the knowledge of the Power Curves of the system (Fig. 4). Each curve shows the average power produced by the generator, when the turbine operates at various reference rotational speed. Power curves are computed for the sequence of sea states derived in section 2.2. The dynamical model described by eq. (1) - (2) is employed by considering a certain fixed value of ω_{ref}. Then, the power curves of the correspondent sea state is obtained. Therefore, the implementation of the MPPT algorithm is aimed to force the system to reproduce the particular operating condition represented by the MPPs, when similar environmental circumstances occurs.

A number of characteristics are eligible as reference parameters to perform the tracking of the MPPs. The present analysis proposes two different approaches: the first involves a relation between the optimal turbine reference rotational speed and the significant wave height of the incident sea state, regardless of its peak period; the second approach relies on a two-parameters relation, where the significant wave height and the peak period are jointly considered.

The effectiveness of the chosen strategy is assessed by comparing the results with an ideal case, pertaining to the condition in which the U-OWC works immediately at the desired MPP.

Thus, each sea state is related to the corresponding optimal reference rotational speed. Results of such simulations are shown in table 1. It is worth mentioning that, in this ideal context, the control strategy does not play any role.

3.2 Performance of the 1-parameter law

The relation between the optimal reference rotational speed and the significant wave height of the incident sea state is here derived. A mean square minimization procedure leads to the identification of a power regression as the best fitting for the data points representative of the MPPs, as illustrated in figure 5. The derived H_s-ω_{ref} is employed in the dynamic model of the U-OWC to perform the tracking of the optimal reference rotational speed of the turbine. The simulation is pursued in realistic conditions, assuming that the significant wave height is calculated from free surface wave data, collected every 10 minutes, in undisturbed field. Thus, the reference rotational speed is computed as a function of the calculated H_s. For this purpose, the long simulation from the sequence of the sea states derived in section 2.2 is considered. The performances of the described control strategy are summarized in table 2. Results show a good approximation of the MPPs tracking method. Indeed, a comparison with the ideal case in which the system works at its MPPs for each sea states denotes only the 16% of difference in terms of mean converted energy during the whole simulation.

Table 2: Performances of relevant parameters when a 1 parameter MPPT control strategy is implemented. It is computed over a simulation of 16.7 hours. ω_{ref} [rpm] denotes the reference rotational speed of the turbine, ω [rpm] the istantaneous speed of the turbine, P_g [kW] the instantaneous generator power, E_g [kWh] the electrical energy converted by the generator, by one single cell of 3.87m width.

$< \omega_{ref} >$ [rpm]	$< \omega >$ [rpm]	$< P_g >$ [kW]	$< E_g >$ [kWh]
2860	3241	9.4	157

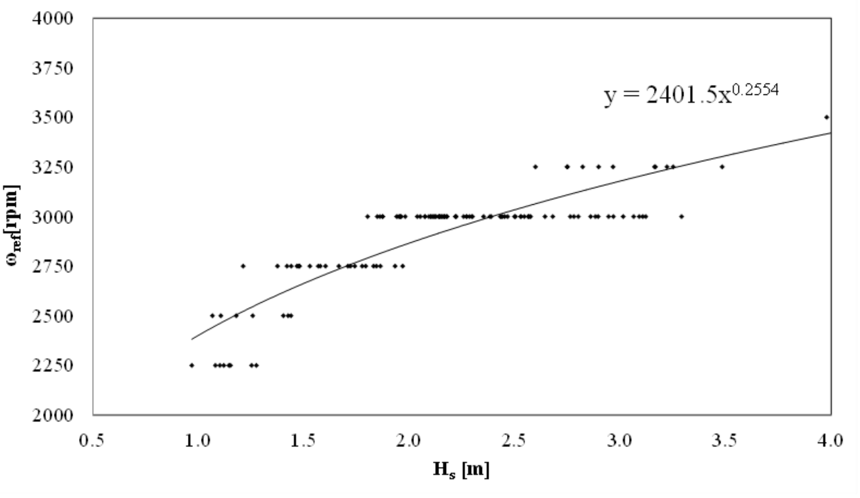

Figure 5: Power regression giving H_s-ω_{ref} relation.

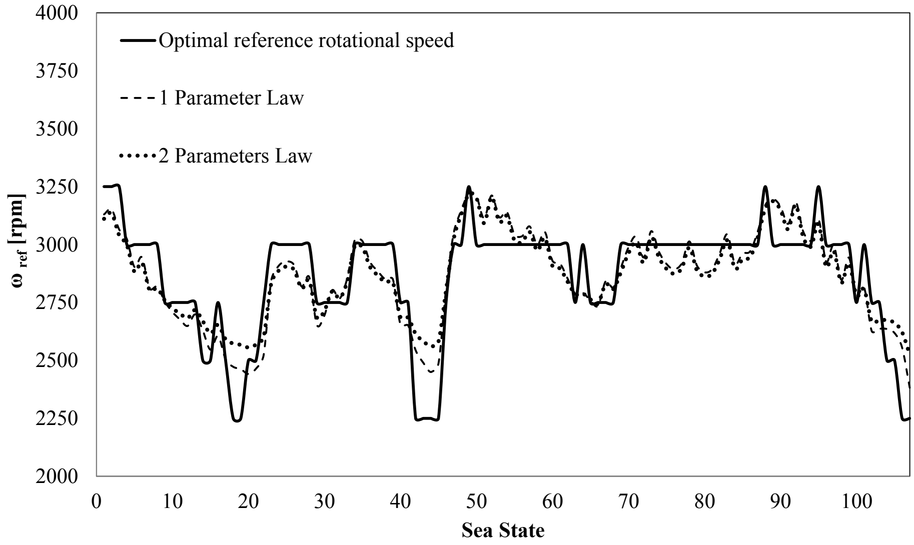

Figure 6: Comparison of the performances of the two control law.

Table 3: Performances of relevant parameters when a 2 parameter MPPT control strategy is implement, computed over a simulation of 16.7 hours long. ω_{ref} [rpm] denotes the reference rotational speed of the turbine, ω [rpm] the istantaneous speed of the turbine, P_g [kW] the instantaneous generator power, E_g [kWh] the electrical energy converted by the generator, by one single cell of 3.87m width.

$< \omega_{ref} >$ [rpm]	$< \omega >$ [rpm]	$< P_g >$ [kW]	$< E_g >$ [kWh]
2865	3242	9.3	156

3.3 Performance of a 2-parameter law

The effect of both the significant wave height and the peck period on the MPPs tracking is evaluated. In this context, a linear two-parameter regression is adopted. Figure 6 compares the performance of this last approach with the ideal one and the 1-parameter approach. It is seen that the 1-parameter approach based on a power-law regression is better able to force the system to work at its optimal reference rotational speed. Thus, the overall performances of the U-OWC – PTO system are not significantly affected by the exclusion of the peak period of the incident sea state, as shown in Table 3. Consequently, a simplified formulation based on one parameter is adequate to the purpose of the MPPT algorithm.

4 PRESSURE CONTROLLED STRATEGY

The second control strategy is here presented. The optimization of the turbine efficiency is pursued by relating its reference speed with the actual dynamic conditions inside the pneumatic chamber.

4.1 Mathematical background

This control strategy is implemented considering that typical Wells turbine experience the stall phenomenon above specific values of the non-dimensional flow coefficient,

$$U^{*} = \frac{u_a}{\omega\, D/2} \tag{3}$$

being u_a and D the average air speed through the turbine and its diameter, respectively. Typical efficiency curves for Wells turbine are described by Curran and Gato [6]. Equation (3) points out that the performances of the PTO mechanics are deeply affected by the instantaneous air flow rate, which is characterized by a large variation over each wave cycle. The turbine rotational speed is controlled by determining the following optimal working condition:

$$U^{*}_{opt} = -\frac{1}{\omega_{opt}\, D/2}\,\frac{1}{A}\,\frac{2}{\rho_{atm} + \rho_{chamber}}\,\frac{dM_a}{dt} \tag{4}$$

In this equation, A is the cross sectional area of the duct hosting the turbine, taking into account for the presence of the hub; ρ_{atm} and $\rho_{chamber}$ denote the air density at atmospheric conditions and the instantaneous air density inside the pneumatic chamber. The latter is related to the atmospheric pressure p_{atm} and to the instantaneous air pressure of the air pocket $p_{chamber}$ through the equation of state for an isentropic process:

$$\rho_{chamber} = \rho_{atm} \left(\frac{p_{chamber}}{p_{atm}} \right)^{\frac{1}{k}} \tag{5}$$

The term dM_a/dt denotes the rate of change of the instantaneous air mass contained in the pneumatic chamber. With reference to figure 1, it is computed as follows:

$$M_a = b\, b_1\, \rho_{chamber} \xi \tag{6}$$

Therefore, the rate of change of M_a with respect to time is:

$$\frac{dM_a}{dt} = b\, b_1\, \rho_{atm} \left(\frac{p_{chamber}}{p_{atm}} \right)^{\frac{1}{k}} \frac{d\xi}{dt} + b\, b_1\, \xi \frac{\rho_{atm}}{p_{atm}^{1/k}} \frac{1}{k}\, p_{chamber}^{\frac{1}{k}-1} \tag{7}$$

Finally, the optimum rotational speed is obtained as a function of the instantaneous water level ξ and air pressure $p_{chamber}$, denoted as G:

$$\omega_{opt} = -\frac{4\; G(p_{chamber}, \xi)}{A\, D\, U^{*}_{opt}} \tag{8}$$

Equation (8) allows calculating the optimum reference speed of the turbine, which is imposed to the system by the generator torque, according to equation (2). The non-dimensional flow coefficient is assumed equal to 0.1, which is the value associated to the peak of the turbine efficiency curve.

4.2 Performance of the pressure - controlled strategy under irregular waves

Performances of the coupled U-OWC – PTO system jointly with the pressure - controlled strategy to drive the reference rotational speed of the turbine are evaluated. The U-OWC is exposed to the data set of sea state shown in Fig. 2. Obviously, the highly pulsating nature of the air pressure in the pneumatic chamber within a wave cycle leads to continuous adjustment in the reference rotational speed of the turbine. Consequently, the quality of electrical power converted by the generator will be strongly affected by this problem. Nevertheless, good performances are achieved, as the electrical energy generated by one single cell when this control strategy is implemented leads to energy losses less than 30%, compared to the ideal case reported in table 1. Table 4 summarizes the performances of the relevant parameters when the described control strategy is implemented.

Table 4: Performances of relevant parameters when a pressure-controlled strategy is implement, computed over a simulation of 16.7hours long. ω_{ref} [rpm] denotes the reference rotational speed of the turbine, ω [rpm] the istantaneous speed of the turbine, P_g [kW] the instantaneous generator power, E_g [kWh] the electrical energy converted by the generator, by one single cell of 3.87m width.

$<\omega_{ref}>$ [rpm]	$<\omega>$ [rpm]	$<P_g>$ [kW]	$<E_g>$ [kWh]
2589	3286	8.08	135

5 CONCLUSION

The paper has proposed a comparison between two different control strategies aimed to maximize the performances of the U-OWC - PTO system in a variety of environmental conditions. The first relies on the definition of empirical formulation connecting the optimal reference rotational speed of the turbine to the energetic content of the incoming sea states. An MPPT algorithm has been implemented, as it is suitable for systems exposed to rapidly changing characteristics of the excitation. In this context, both the effects of the significant wave height and the peak period has been analyzed. Results show that the significant wave height alone is reliable as reference parameter.

The second one involves an analytical law connecting the optimal turbine rotational speed to the instantaneous dynamic conditions inside the plant. Specifically, a control law dependent on the pressure of the air pocket and on the water level inside the pneumatic chamber has been determined. In this regard, attention is focused to the fact that the pressure-based controller relies on a fast-acting strategy, which implies that the reference rotational speed of the turbine is continuously modified upon a wave cycle, performing a wave-to-wave adjustment of the operating condition of the U-OWC - PTO system. This aspect strongly influences the performances of the generator, and the moment of inertia of the turbine plays a significant role.

Despite the fact that the MPPT algorithm assumes that the reference rotational speed of the turbine is kept constant within the sea state duration and that an empirical relation is involved in the determination of the optimal reference speed, the paper shows that is allows converting more energy with respect to the pressure-related control.

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