Control Strategy of Wave Energy Converters Optimized Under Power Electronics Rating Constraints

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Abstract

The goal of this paper is to show how the control strategy applied to point absorbers in heave can be effectively tuned according to the changes in the incident waves. The aim is to maximize the average power extraction at each given wave, while limiting the value of the instantaneous power. The constraint on the peak power corresponds to the limitation imposed by the rating of the electric and electronic devices, so that the resulting control technique allows improved exploitation of the Wave Energy Converter (WEC). The control strategy optimised under sinusoidal condition is put to test under irregular waves showing a superior power extraction than both purely passive and complex-conjugate control.

Keywords: Point absorber, control strategy, power electronics rating

1. Introduction

Wave Energy can be labelled as a very promising energy source if the contribution it may give to the World Energy portfolio is considered [1]. In spite of this high potential, wave energy technology is still in its infancy. Several different aspects, from the concept design and control to issues related to the Power Take Off system and grid connection are still under investigation in order to find a leading solution being both technically and economically viable.

One of the main challenges in Wave Energy exploitation deals with the maximization of the power extracted from the sea. This results in considerable efforts in exploring several control techniques, mainly developed in the mechanical and hydrodynamic perspective. For the efficient design of Wave Energy Converters (WECs), however, it is also important to consider from the very beginning the rating of the electric and power electronics equipment required to implement the different control strategies. Thus, huge (and costly) over ratings can be avoided. When the selection of the electric generator and power electronics interface has been performed, a constraint on the maximum power that can be handled by the whole system follows. Thus, control strategy tuning becomes fundamental in order to efficiently exploit the device. The impact of control strategies on the sizing of the power electronics equipment has already been analyzed in a systematic way [2], referring to heaving point absorbers and considering a specific sinusoidal design wave. The goal of this paper is to improve the system power performance by tuning control parameters according to the changes in the amplitude and frequency of the incident waves. Thus, the constrained average power maximization is pursued by a sort of "multi-monochromatic" approach.

Irregular waves are finally considered to prove the usefulness of the proposed control technique also under non-ideal conditions.

2. Hydrodynamic model and control basics

The following analysis is developed with reference to a spherical semi-submerged point absorber (also defined as buoy) which is forced into heave motion by incident sea waves [3]. If sinusoidal incident waves are assumed, the interaction between the waves and the device can be well described by the following linear equation:

$$(M + a(\omega))\,\ddot{s} + B(\omega)\,\dot{s} + K\,s = F_E + F_L \qquad (1)$$

In (1) ω is the angular frequency of the incident wave, s indicates the position of the point absorber and " $\dot{}$ " is the time derivation operation. M is the mass of the device and $a(\omega)$ the added mass at the considered frequency. Added mass depends on the radiation force caused by buoy oscillation and it takes into account the mass of water involved in the device movement. F_E is the wave excitation force and F_L represents the force applied by the Power Take-Off (PTO), which can be adapted by suitably modifying B_L and M_L (that are the

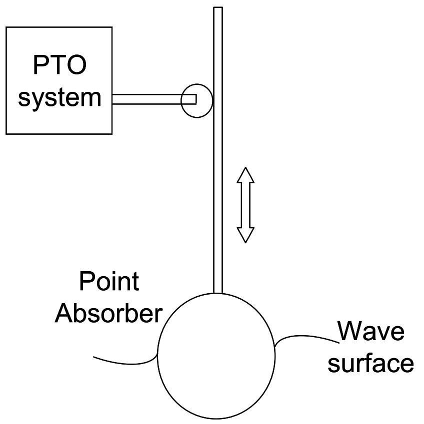

Figure 1: Simplified model of the considered Wave Energy Converter.

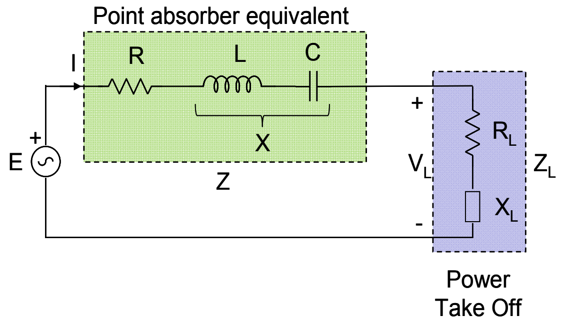

Figure 2: Electrical analogue of the considered WEC, valid under sinusoidal conditions

PTO applied damping and added mass, respectively) as following explained.

Moreover, $B(\omega)$ represents the mechanical damping (comprising the radiation resistance $b(\omega)$, which is frequency dependent, too) and finally K is the hydrodynamic stiffness. Once that the excitation force and the force applied by the Power Take-Off are known, this linear analysis makes it possible to derive the point absorber position s in each instant by solving (1). In the presented case, it can be written, without loss of generality:

$$s = \hat{S}\sin(\omega t + \varphi_s) \qquad (2)$$

where $\hat{S}$ indicates the buoy position maximum value and φ_s the initial position phase angle.

As regards the control of the point absorber, required to optimize the power extraction, it is realized by acting on the force applied by the Power Take-Off, as already hinted. The most widespread control strategies are the linear ones. The simplest, (but ensuring low average power absorption), is passive loading, where the PTO action corresponds to a pure damping (M_L=0, $B_L \neq 0$) of the buoy motion. On the other hand, the maximization of average extractable power is obtained by applying complex-conjugate control, so that a resonance condition is obtained and the buoy velocity finally results in phase with the excitation force. To do this, the Power Take-Off must apply a force having a component which is proportional to the device acceleration by M_L (reactive component), in addition to the one proportional to the device velocity by B_L (damping component).

3. Electric analogue

As long as regular waves are considered the linear model described by (1), corresponding to a mass-spring-damper system, can be equivalently described by a simple electrical analogue [4] as the one depicted in Fig. 2. The voltage generator E, corresponds to the wave excitation force, while the current I is the equivalent of the buoy velocity. The device behaviour is described by the equivalent impedance, Z, comprising a resistance, R (corresponding to the buoy total damping B), an inductance L (corresponding to the total device mass, including the added mass contribution coming from radiation force, $M+a(w)$) and finally a capacitance C (representing the inverse of the spring stiffness, K). The buoy reactance X lumps up the whole reactance of the buoy, being:

$$X = \omega L - \frac{1}{\omega C} \qquad (3)$$

The control action that can be exerted by the PTO, is represented by the load impedance Z_L, modelled as the series between a resistance R_L (corresponding to the damping term B_L) and a reactance X_L (proportional to the term M_L). As a whole, the force applied by the PTO corresponds to the load voltage, V_L and the average extracted power $\overline{P}$ corresponds to the active power dissipated on the load resistance R_L, which can be easily written as:

$$\overline{P} = \frac{E^2 R_L}{(R+R_L)^2 + \left(\omega L - \dfrac{1}{\omega C} \pm \dfrac{R_L\sqrt{1-\cos^2\varphi_L}}{\cos\varphi_L}\right)^2} \qquad (4)$$

where the load power factor $\cos\varphi_L$ is given by:

$$\cos\varphi_L = \cos\left(\tan^{-1}\left(\frac{X_L}{R_L}\right)\right) \qquad (5)$$

It is worth noting that the application of passive loading corresponds to $X_L=0$ ($\cos\varphi_L$=1) and under these conditions the (relative) maximum average power can be extracted when:

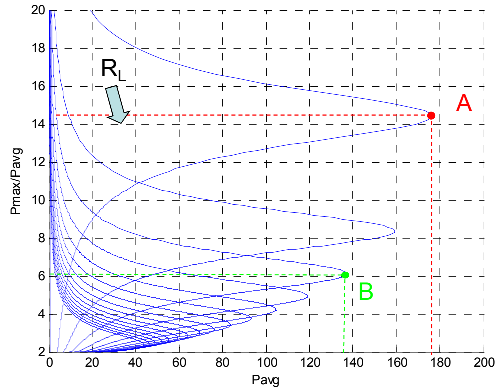

Figure 3: Peak to average extracted power ratio as a function of the average extracted power.

$$R_L = \sqrt{R^2 + X^2} \qquad (6)$$

On the other hand, the complex-conjugate control, leading to the resonance conditions and highest average power absorption, implies [4]:

$$X_L = X \qquad (7.a)$$

$$R_L = R \qquad (7.b)$$

In order to correctly size the electric machine and power electronics converter, it is necessary to consider the peak power that must be handled by the system, which can be expressed, under the considered hypotheses, as a function of the average power as follows:

$$\hat{P} = \overline{P}(1 + \frac{1}{\cos\varphi_L}) \qquad (8)$$

When considering a specific WEC, whose parameters are reported in the simulations section for the selected device, and a given sinusoidal incident wave (having in this case period T=9 s and amplitude A=0.5 m), a graph like the one reported in Fig. 3 can be derived, based on formulas (4) and (8). The first important information that can be obtained from the graph regards the value of the maximum average power that can be extracted from the device if the control parameters are chosen in order to reach the resonance condition, (point A). In the considered case, it is $\overline{P}$ = 175 kW. It can be also noted, however, that to reach such power absorption an over sizing of the electric and electronic equipment by a factor 14.5 is required, resulting in a rather anti-economical choice. From the same figure, however, it can be noted that, if a reduced absorbed power of around 140 kW (point B) is accepted, the power electronics rating can be more than halved (being $\hat{P}$ lower than 840kW). It is then reasonable to wonder how the WEC control strategy should be tuned in order to always respect this constraint on the maximum allowed power (which in the following is supposed to be P_{lim}=840 kW), while maximizing the average power absorption.

4. Mathematical analysis

The goal of this section is to outline, through a mathematical approach, how the control problem can be dealt with and optimally solved in the described perspective, with reference to sinusoidal waves of different amplitude and frequency.

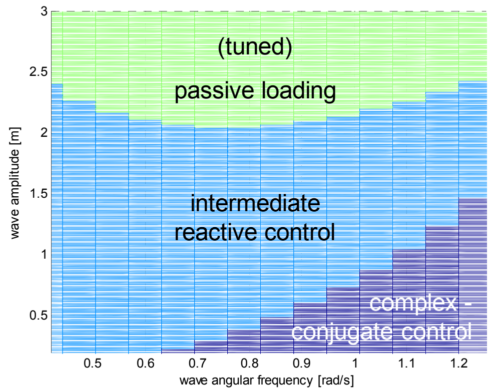

Figure 4: Map of the advisable control strategies according to changes in the sinusoidal incident wave amplitude and frequency.

At first it must be considered that for some values of the period and height of the incident waves (i.e. when they are "small" and having "relatively high frequency") it is possible that, even when applying complex-conjugate control, the maximum allowed value for the peak power is never reached. This corresponds to an unconstrained case and it is well known that, under such circumstances, the maximum extraction of average power is obtained in resonance (7.a-b). After defining the input conditions making complex-conjugate control advisable, the choice of the best control strategy for remaining conditions can be operated.

It is theoretically possible to determine the value of R_L and X_L (or equivalently R_L and $cos\varphi_L$) that maximize the power $\overline{P}$ (e.g. with the Lagrange multipliers approach), while imposing a constraint on $\hat{P}$, but due to the complexity of the analytical expressions, a numerical approach would be required. In the following a simpler, alternative strategy is proposed and adopted.

Once stated the peak power limit P_{lim}, a second order equation in the unknown R_L can be derived from (4) and (8), having $cos\varphi_L$ as a parameter:

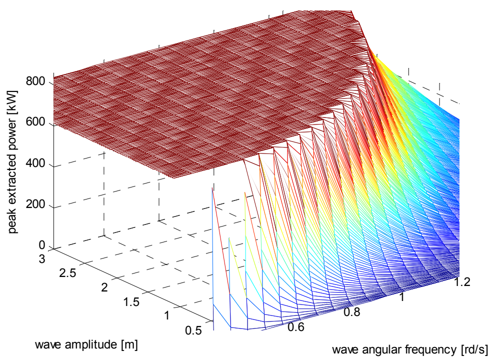

Figure 5: Peak extracted power with the proposed adaptive control technique.

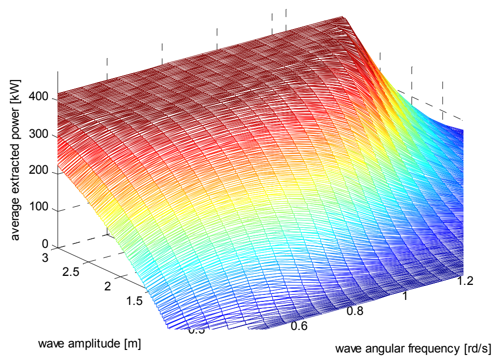

Figure 6: Average extracted power with the proposed adaptive control technique.

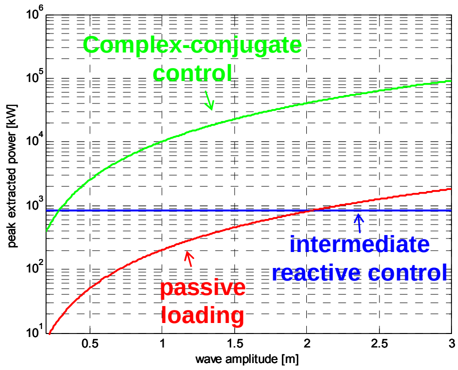

Figure 7: Peak extracted power with three different control techniques, for sinusoidal waves having T =9s.

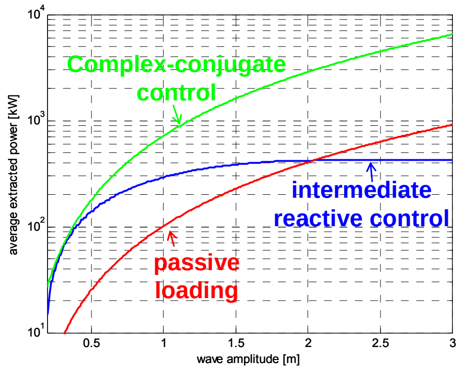

Figure 8: Average extracted power with three different control techniques, for sinusoidal waves having T =9s.

$$R_L^2\left(\frac{\hat{P}}{\cos\varphi_L}\right)+R_L\left[2\hat{P}R+2\hat{P}X\sqrt{\frac{1}{\cos^2\varphi_L}-1}+\right.$$
$$\left.-E^2\left(\frac{1}{\cos\varphi_L}+1\right)\right]+\hat{P}(R^2+X^2)=0 \qquad (9)$$

In order to guarantee that the equation admits at least a positive solution for R_L, it is necessary that there is at least one variation in the signs of the equation coefficients. Since it can be easily seen that, under reasonable operating conditions, both the first and third coefficients are never negative, it is necessary to ensure the negativity of the second one, i.e.:

$$2\hat{P}R+2\hat{P}X\sqrt{\frac{1}{\cos^2\varphi_L}-1}-E^2\left(\frac{1}{\cos\varphi_L}+1\right)<0 \qquad (10)$$

It can be shown, by a proper analytical analysis, that this can be obtained for different values of $\cos\varphi_L$, depending on the input wave and on the buoy parameters. In order to select the best control strategy, once defined the range of possible $\cos\varphi_L$, the highest of them must be selected. This choice can be explained with reference to (8) since, once fixed $\hat{P}=P_{lim}$, the higher is $\cos\varphi_L$, the higher is the average power that can be extracted. It is also worth nothing that, when defining the optimum value of the power factor, it is necessary that it guarantees also that the determinant of the second order equation in R_L (9) is not negative.

Once that the optimal $\cos\varphi_L$ has been identified, (9) is solved to find the optimal value of R_L. Then the corresponding value of X_L can be easily derived from the knowledge of the load power factor (5). Even if mathematically possible, conditions where the proposed method fails in providing the optimal control parameters have not been found for reasonable ranges of the incident waves amplitudes and frequencies, as shown in the following section.

According to this “multi-monochromatic” approach, a sort of map of the optimal control strategies can be drawn, which is reported in Fig. 4 for the considered test case. As expected, when high waves are considered, a pure damping suitably tuned on the incident waves must be preferred in order not to exceed the peak power limit. On the other hand traditional complex-conjugate control is chosen in small and high frequency waves, whose lower energy content can be fully exploited, without risks for the power electronics equipment. In between, intermediate reactive control can be applied, where the ideal control parameters can be derived according to the described method.

5. Simulation results

In order to prove the validity of the presented approach, Matlab/Simulink simulations of the point absorber WEC described in Section 2 were carried out.

The considered systems corresponds to the one discussed in [5-6] and its main parameters are here recalled: buoy mass, M = 268340 kg and buoy radius, r =5 m; the spring stiffness is K = 789740 N/m.

5.1 Regular waves

The first set of simulations was aimed to prove how different sinusoidal incident waves influence the power performance of the point absorber, when it is controlled in order to never exceed the maximum power limit. Such evaluation is made considering sinusoidal incident waves having amplitude, A, in the range 0.2 m - 3 m and period, T, between 5 s and 15 s. Fig. 5 shows the peak power that is obtained when the control parameters R_L and X_L are selected according to the procedure described in Section 4. It can be seen that, in a large part of the considered region, reached peak power corresponds to the stated limitation, meaning that the PTO ensures an equivalent saturation. If Fig. 6 is also considered, it can be seen what the maximum average power extracted by the device is, when applying the proposed optimized control strategy.

It is then useful to analyze the difference in the application of the proposed tunable control strategy with respect to the more traditional complex-conjugate control and passive loading having constant parameters. In order to do this, it is assumed that the sinusoidal incident waves have a fixed period of T = 9 s and the parameters of passive loading and complex-conjugate control are kept constant at their correspondent optimal value (6 and 7a-b, respectively). On the other hand, the proposed intermediate reactive control is tuned as previously described. Under such conditions the effect of the wave amplitude variations on the peak (Fig. 7) and average (Fig. 8) power absorption is considered. From Fig. 7 it can be seen that in case of high waves (A>2 m) both constant passive loading and complex-conjugate control overpass the stated limit for the peak power. Moreover, complex-conjugate control works above such limit for many of the considered wave amplitudes. It can be noted, instead, how the proposed strategy respects the constraint imposed on the peak power.Fig.8 shows how this different behaviour reflects on the average power extraction. It can be clearly seen that the proposed control strategy shows an evident advantage with respect to traditional passive loading for the majority of the operating conditions, while it is still competitive with complex-conjugate control in the low waves part.

Final tests under sinusoidal operations have been carried out in Simulink to evaluate the system performance under dynamic conditions (Figs 9-10). During the first 1000 s, the point absorber is subject to a sinusoidal wave having A= 0.2 m and T = 9 s. Complex-conjugate control is then applied, with R_L = 56.9 kΩ and X_L = 747.3 kΩ and an average power of 28 kW is extracted. In this case the peak power is far below the limit (only 400 kW). At t=1000 s the amplitude of the incident wave is changed to A = 0.5 m (while the period is kept constant). In this case an intermediate reactive control having R_L = 155.6 kΩ and X_L = 762.7 kΩ ($cos\varphi_L$ = 0.2) is applied, leading to exactly respect the constraint on the peak power, while absorbing the maximum possible average power under these conditions, i.e. $\overline{P}$ = 140 kW. Finally, at t = 2000 s, the wave amplitude becomes A= 2 m (the period is still T = 9s). To not to exceed the 840 kW limitation for the peak power, in this case a purely passive control (tuned at R_L = 1152 kΩ) is applied and the consequent average power $\overline{P}$ = 420 kW is extracted. It is also worth noting that when intermediate reactive control or complex-conjugate control are applied, a bidirectional power flow from the WEC to the power grid is detected, while passive loading application guarantees that the power is always positive (injected into the power grid), as expected.

5.2 Irregular waves

It is interesting to investigate if the application of the proposed control strategy leads to some advantages with respect to traditional passive loading and complex-conjugate control, also when applied in irregular waves. In order to do this, a suitable dynamic model of the whole system has been built in Matlab/Simulink and used to perform time domain analyses. Irregular waves are then generated starting from a Bretschneider spectrum having significant wave height H_s = 2.12 m and energy period T_e = 9 s (the same period of the sinusoidal wave used for the analyses of Figs 8-9). At first passive loading is applied under irregular waves, using the R_L= 802.5 kΩ that is optimal (6) for a sinusoidal wave having T =9 s. Under this condition the average power extraction is of $\overline{P}$ = 43 kW and the peak power is $\hat{P}$ = 602 kW (fig. 11). The proposed optimized control strategy is then applied in real time as follows. The peak amplitude of incident waves is measured and R_L and X_L are selected according to the algorithm described in Section 4, based on the measured amplitude of the waves (updated twice per period) and under the simplifying assumption of constant wave period, T = 9 s. This leads to an average extracted power of $\overline{P}$ = 62.7 kW with a peak power of $\hat{P}$ = 719.17 kW. The advantage with respect to traditional passive loading is apparent: the average power extraction is improved by 31%, and the ratio between peak and average extracted power is lower with the proposed control strategy, resulting in a better exploitation of the PTO. From fig. 12 it can be noted that in some parts of the period (corresponding to small waves) a reactive control component is applied and the extracted power is therefore bidirectional, while in the part corresponding to high waves a pure damping is used, leading to unidirectional power.

An additional test was carried out to compare the performance of the proposed control technique with complex-conjugate control. If complex-conjugate control with constant control parameters (R_L = 63 kΩ, X_L = 1145.9 kΩ) is applied, while keeping the power saturation at 840 kW, the average power extraction would be of only $\overline{P}$ = 41.6 kW. A higher average power could be extracted by complex-conjugate control only by increasing the peak power that can be handled

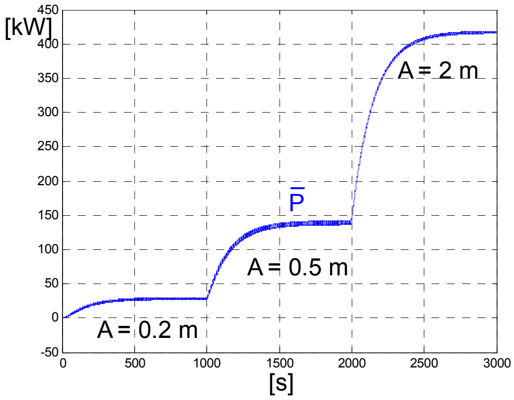

Figure 9: Average extracted power with sinusoidal wave of fixed period (T =9s) and changing amplitude

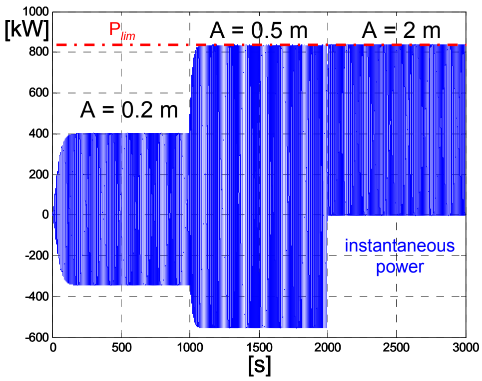

Figure 10: Instantaneous extracted power with sinusoidal wave of fixed period (T =9s) and changing amplitude

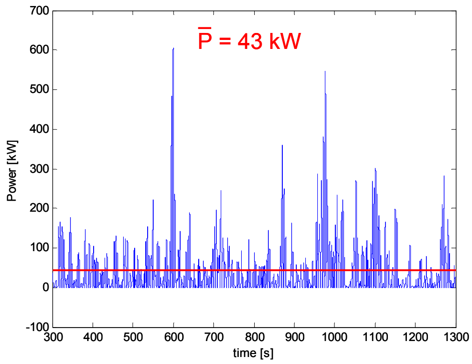

Figure 11: Instantaneous and average extracted power when applying constant passive loading in irregular waves

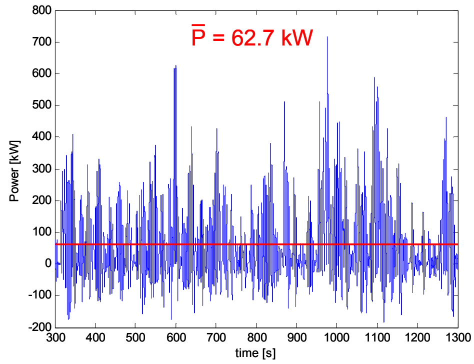

Figure 12: Instantaneous and average extracted power when applying the proposed adaptive control strategy in irregular waves

by the system. The proposed control strategy is therefore highly convenient also with respect to complex-conjugate control.

6. Discussion

It is important to underline that the proposed optimization of the system control strategy under sinusoidal conditions is based on the assumption that a linear approach is to be maintained also when a constraint on the power absorption is introduced. This means that the control parameters that guarantee the maximum average power extraction while respecting the peak power limit, are found by a linear analysis. It should be pointed out, however, that the application of non linear control techniques, which can equivalently ensure that the peak power limit is not exceeded, can potentially allow a higher average power absorption with respect to linear ones. However, the analytical approach to such techniques is much more complicated and generally avoided: numerical and simulative analyses are privileged in that case. It must be also observed that when the considered optimized control parameters are applied in irregular waves, the stated limit on peak power is not automatically respected anymore, but specific power saturation must be imposed by the Power Take-Off. It has been verified that, even when such saturation intervenes in limiting the instantaneous power, the average power extracted by using the proposed optimized technique is still extremely convenient.

7. Conclusions

In the present paper the problem of the optimization of the control strategy for a point absorber in heave is dealt with, taking into specific consideration the power limitations imposed by the rating of the electrical machine and power electronics equipment. It has been shown that the values of the PTO damping and added mass ensuring the maximum average power extraction while respecting a peak power limitation, can be found by a mathematical procedure, whenever a sinusoidal incident wave is assumed. Such linear analysis can be extended to consider sinusoidal incident waves having different amplitudes and frequency in a “multi-monochromatic” approach, so that a map of the best control strategies according to incident wave characteristics can be derived for each specific device. Such approach can be then applied to irregular waves, being the core of an adaptive control strategy that is based on the measure of the amplitude of incident waves. The advantage of the proposed strategy with respect to traditional constant passive loading and complex-conjugate control has been also proved.

Acknowledgements

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