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Implementation of an energy extraction control including PTO-losses in a complete WEC model for PTO design procedure

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Abstract—**A wave to wire (W2W) wave energy converter (WEC) model is described. The W2W has been developed to be integrated in a methodology for the selection and optimization of the power take-off (PTO) of a given WEC. This methodology is used as an assessment tool for determining an adequate set of PTO characteristics for a particular prime mover in a particular sea location (with a specific ocean wave climate), and a case study is presented. The W2W has been modified to take into account a power take-off (PTO) losses model and the PTO rated force limitation. These two main modifications allow to properly evaluate the electric power generated by the WEC. In this paper, the PTO model is particularized for an electric linear generator. In addition, the modifications are considered in the definition of the WEC power extraction control. Although the use of reactive mechanical power can increase the extracted mechanical power, the control algorithm must take into account the losses of the PTO in order to avoid an excessive penalization of the electrical power generated by the WEC.**

Index Terms—**Losses model, Power take-off, Wave to wire.**

I. Introduction

IN the context of pursuing a low-carbon production of energy, ocean wave energy is a promising component of the global solution, due to the huge resource available around the world [1], [2]. However, it still poses many challenges, which ultimately represent an obstacle to its economical feasibility. There is a wide variety of WECs, differing in several aspects such as the primary conversion from the waves to the captor, and the PTO equipment [3], [4]. Direct-driven linear generators convert the motion of the captor directly into electricity, without any interface components [5]. This avoids potential failures and energy losses in the intermediate conversion stages. Besides, electric linear generator dynamics present a high controllability of the exerted force, which may enhance the WEC efficiency. This work is carried out in the scope of the SEA-TITAN project [6], with the main goal of designing and developing a new linear generator suited for marine energy. The definition and optimization of its main rated characteristics (force, stroke, velocity) is an essential step in the design process. These main characteristics are obtained by means of an assessment tool, which is based on a W2W in time domain which takes into account the energy production and cost estimation of a PTO integrated in a given WEC.

The implementation of hydrodynamic time domain models goes some decades back with works from [7] and [8], together with other studies published by [9], [10] and [11], among others. As a starting point for this study, the time domain model developed by [12] is selected, which presents a general numerical tool applicable to different WECs. In this work, this model was adapted and extended to include a linear generator PTO, as in [13] (including information about its efficiency by means a losses model, and about its rated characteristics as constraints). This new version of the numerical tool enables the assessment of the generated power, and also to introduce and test some control strategies. The PTO efficiency should be taken into account in the control algorithms in order to maximize electrical power, instead of mechanical power [14], [15]. The optimization of the mechanical energy may lead the system to operate far from the optimum electrical generation. Furthermore, the model also includes constraints to the PTO system, in particular to the force it may exert [16], [17]. This affects the amount of energy extracted by the generator, but also has an effect of the cost of the equipment. Hence, the W2W model may be used to define the main characteristics of the linear generator for a given WEC [18], testing the PTO in different scenarios.

This work presents a study on the effect of the PTO equipment's efficiency on the overall performance of the WEC, as well as the effect of some constraints as the limit on the PTO force on a linear generator [15]–[17], [19], [20]. Although it may be implemented in a wide variety of WECs, the study here presented is applied to a specific WEC: a two heaving bodies device (floater and spar), on which the power extraction is based on the relative velocity between both bodies. Section 2 presents a description of the numerical model in the frequency domain, with particular focus on the identification of the power losses related with the

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PTO. A time domain numerical model is presented in Section 3, which is able to tackle some nonlinearities (e.g. constraints in the motion and on the PTO). Some results for several cases are shown in Section 4. Finally, some conclusions are summarized and discussed in Section 5.

II. Mathematical model of the PTO losses

This work is framed in an R&D project where a linear generator is designed (the linear generator concept has been presented as a patent and, since it is still under analysis of patentability, no further details can be shown). According to this, the PTO model presented in this paper corresponds to an electrical linear generator. Specifically, it is a switched reluctance machine linear generator, but the PTO model is presented in a general way, as a common type of electric linear generator. This kind of PTO is especially adequate for WECs, since the former takes advantage of linear movements and forces of the prime mover and generates electric energy from them [13]. This is the case of a heaving point absorber WEC such as the devices developed by WEDGE GLOBAL, COREPOWER, CENTIPOD, or HYDROFLOAT.

This PTO model is integrated in a previously developed W2W model [21] in order to define the PTO main characteristics, as it is explained in Section IV. This PTO model is necessary both to calculate the extracted electrical energy, and to define the power extraction control in a WEC [22], as it is explained in Section III.

When integrating the PTO model into a mechanical W2W model, the development of a detailed electric PTO model may be discarded due to the faster dynamics of the electric variables with respect to the mechanical variables [23]. Hence, a power losses model is used instead. By way of example, the developed PTO may establish its nominal current at nominal velocity in 10-20 ms, while the ocean wave periods are in the range of a few tens of seconds.

A PTO losses model should take into account mechanical losses, magnetic losses and electric losses [24]:

1) Mechanical friction losses around 1-2% were calculated with a previous linear generator model [23], [25]. The main reason for these values is the relative low velocity regimes at which the generator works. Therefore, this source of losses can be neglected.
2) Magnetic losses encompass both hysteresis losses and Eddie current losses [26]. The magnetic circuit design of an electric generator should take into account the minimization of these losses. However, these sources of losses are strongly dependent on the relative velocity between stator and translator [27]. Therefore, theses losses can be neglected too due the low displacement velocities of the generator and the necessary air gap [23], [28].
3) Finally, electric losses are mainly represented by Joule effect losses [26] in cables and coils. In the aforementioned study, this source of losses represents almost 95% of the losses [23]. This percentage is highly representative in linear electric generators, since high forces and low velocities lead to low efficiencies, specially when compared to conventional rotating generators. The importance of this factor is justified as follows:
   - Low velocity regimes lead to high force regimes.
   - In electric machines, the current is approximately proportional to the current in the coils [29].
   - Joule effect losses are proportional to the square of the current. As a consequence, low velocity regimes lead to high Joule effect losses [14].

The following equation shows a simple expression for the PTO losses model.

$$\begin{aligned}
P_{elec}(t) &= P_{mech}(t) - P_{loss}(t) \\
&= F_{pto}(t) \cdot v_{pto}(t) - P_{cu}(t) \\
&= F_{pto}(t) \cdot v_{pto}(t) - R_{cu} \cdot I_{pto}^2(t) \\
&= F_{pto}(t) \cdot v_{pto}(t) - \dots \\
&\dots R_{cu} \cdot \left(\frac{F_{pto-rated}}{I_{pto-rated}}\right)^2 \cdot F_{pto}^2(t) \\
&= F_{pto}(t) \cdot (v_{pto}(t) - R'_{cu} \cdot F_{pto}(t))
\end{aligned} \quad (1)$$

where P_{elec} is the PTO generated electric power, P_{loss} is the total PTO power losses, P_{cu} refers to Joule effect losses (winding losses), F_{pto} is the PTO force ($F_{pto-rated}$ is the PTO force rated value), v_{pto} is the relative velocity between the two parts of the linear generator PTO, R_{cu} is the electric resistance of one phase of the PTO, I_{pto} is the electric current of one phase of the PTO ($I_{pto-rated}$ is the PTO current rated value), and R'_{cu} is the coefficient to calculate the winding losses of the PTO.

This PTO losses model could be integrated in a WEC analogue electric circuit [30], [31], Fig. 1, in the following way:

1) The heaving dynamics of a one-body point absorber could be modeled as an analogue electric dipole, composed by a voltage source (representing the wave excitation force) and an electric impedance in series (representing the mechanical hydrodynamic impedance). In the case of a two-body point absorber, its dynamics can be simplified to the same dipole circuit applying Thevenin's Theroem [16], [26], [32]. The PTO force can be represented by another voltage source connected to this dipole.
2) The electric power losses calculated with (1), can be integrated in the analog electric circuit (Fig. 1) as a resistance in parallel with the PTO voltage source. The value of this resistance is shown in (2).

$$R'_{pto} = \frac{1}{R'_{cu}} = \left(\frac{F_{pto-rated}}{I_{pto-rated}}\right)^2 \quad (2)$$

The optimal value of the F_{pto} force may be obtain applying Boucherot's theorem or Impedance Matching Condition [26], [32] to the analogue circuit, but considering the PTO losses equivalent resistance R'_{pto}.

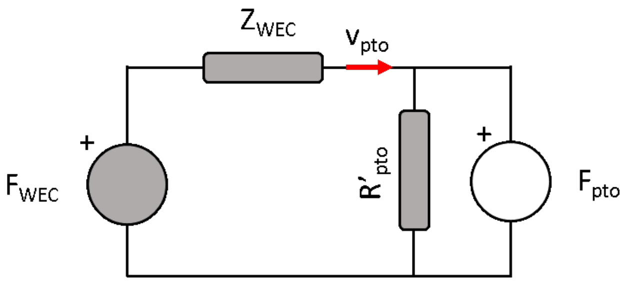

Fig. 1. Analogue electric circuit of a WEC, including a PTO losses model.

The expression of the optimal $Z_{pto-opt}$ in terms of the impedances of the analogue circuit (Fig. 1) is shown in (3). This optimal condition may be expressed in terms of force or velocity (equations (4) and (5) respectively).

$$Z_{pto-opt} = \left(\frac{R'_{pto} \cdot Z_{WEC}}{R'_{pto} + Z_{WEC}} \right)^* \quad (3)$$

$$F_{pto-opt} = \frac{F_{WEC}}{2} \cdot \frac{R'_{pto} \cdot Z^*_{WEC}}{R'_{pto} \cdot R_{WEC} + |Z_{WEC}|^2} \quad (4)$$

$$v_{pto-opt} = F_{WEC} \cdot \frac{1 + 2 \cdot Z^*_{WEC}}{2 \cdot R'_{pto} \cdot R_{WEC} + 2 \cdot |Z_{WEC}|^2} \quad (5)$$

where $\bullet^*$ stands for complex conjugate, $|\bullet|$ stands for absolute value, F_{WEC} is the wave excitation force (in the case of a two-body WEC, it is the equivalent force resultant form the application of the Thevenin's Theorem simplification), Z_{WEC} is the total mechanical impedance, and $F_{pto-opt}$, $v_{pto-opt}$, and $Z_{pto-opt}$ are the values of the respective quantities under optimally controlled conditions.

R'_{pto} may be modified to represent a PTO of a certain efficiency according to (6) and (7).

$$\begin{aligned} \eta &= \frac{P_{elec}}{P_{mech}} = 1 - \frac{P_{loss}}{P_{mech}} \\ &= 1 - \frac{R'_{cu} \cdot F^2_{pto}}{v_{pto} \cdot F_{pto}} = 1 - \frac{F_{pto}}{R'_{pto} \cdot v_{pto}} \end{aligned} \quad (6)$$

$$R'_{pto}(\eta_{rated}) = \frac{1}{1 - \eta_{rated}} \cdot \frac{F_{pto-rated}}{v_{pto-rated}} \quad (7)$$

where η is the efficiency of the PTO in generator mode (η_{rated} is the efficiency at rated force and velocity). This expression is used in Section IV to define the different scenarios of the PTO efficiency and its main characteristics. Besides, (7) is presented in a parametric form in order to modify the PTO rated force and velocity values.

It is worth mentioning that if R'_{pto} tends to an infinite value, the PTO has no losses, and the expressions coincide with those already developed in the wave energy control theory [31]. Then, (3), (4), and (5) take the following optimum control expressions:

$$\begin{aligned} Z_{pto-opt} &= Z^*_{WEC} \\ F_{pto-opt} &= F_{WEC} \cdot \frac{Z^*_{WEC}}{R_{WEC}} \\ v_{pto-opt} &= \frac{F_{WEC}}{2 \cdot R_{WEC}} \end{aligned} \quad (8)$$

In addition, the PTO force should be limited to its rated value, due to its great impact in the energy extraction results [17] [19]. Equation 4 may be modified to take into account this limitation by means of Lagrange Multiplicators Theorem. The expressions of the $F_{pto-opt}$ with its amplitude constraints are presented in [16], [20].

III. Description of the time-domain model

The dynamics of WEC devices may be studied by means of a time-domain numerical model, also called wave-to-wire model, since it represents the whole chain of energy conversion from the waves-device interaction to the final resultant electrical energy. In this section we present a brief description of the wave-to-wire model which is implemented to perform the current work. The WEC under study consists of two bodies, the top floater and the spar below, as illustrated in Fig. 2. The conversion of energy relies on the vertical relative motion between the two bodies. In this analysis only the vertical mode of each body is taken into account.

The model is based on linear wave theory and potential flow, and it is adapted from [12]. In essence, it is the application of Newton's 2nd law, taking into account hydrodynamic and external forces. The hydrodynamic forces include the buoyancy force, due to the variation of the device's submerged volume caused by its oscillatory motions, the excitation force, due to the action of the waves upon the body's surface, and the radiation force, related to the pressure on the device's wetted surface due to the fluid displaced by the motion of the device.

The ordinary differential equations which drive the two vertical degrees of freedom may be written in the following matrix form:

$$M\ddot{z} = F_{WEC}(t) + F_{rad}(t) + F_{hs}(t) + F_{pto}(t) \quad (9)$$

where M is the 2-by-2 mass matrix of the two bodies system, and z is the vertical position of the system, a two-component vector; F_{WEC}, F_{rad} and F_{hs} are, respectively, the two-component vector of excitation force, the radiation force and the hydrostatic restoring force. F_{pto} is the two-component vector of the force imposed by the power take-off equipment. Gravity is not mentioned in (9) since it is cancelled by the buoyancy at equilibrium. Forces induced by a mooring system may be also included in the model, but they have not been taken into account for this work.

In order to compute the excitation and the radiation forces, frequency dependent complex coefficients are obtained using WAMIT [33], a 3-D boundary element method code which solves the radiation-diffraction problem. With regards to the excitation force, besides the frequency dependent coefficients, it is also necessary a profile of the free surface elevation. This profile results from summing a large number of sinusoidal waves, each with a specific frequency and a random phase, and whose amplitude is determined by a predefined spectral model. Concerning the radiation force, it may be expressed as [34]:

$$F_{rad}(t) = -\int_0^t K(t-\tau)\,\dot{z}(\tau)\,d\tau. \qquad (10)$$

where, K is the radiation impulse response function. Amongst other authors, studies on hydrodynamics published by [9], [11] and [35] approximated the convolution integral by a state-space representation, with a set of first order differential equations with constant coefficients. In the present work, the constant coefficients are obtained using Prony's method, by approximating the impulse response function with a combination of exponential functions in the time domain, taking into account the frequency dependent coefficients of the radiation (added mass and hydrodynamic damping), as in [11].

The linearized form of the hydrostatic restoring force is given by:

$$F_{hs}(t) = \rho_w g S_z z(t), \qquad (11)$$

where ρ_w is the water density, g is the acceleration of gravity and S_z is a vector with the horizontal cross-sectional areas of both bodies.

The PTO force term induced by the linear generator is derived from the expression for the optimum PTO force in the frequency domain shown in equation 4. The optimum PTO force is given by the product of the excitation force with a transfer function, K_{pto}, which depends on the impedance, on the hydrodynamic damping, and on the generator losses factor. Note that here the equivalent single body quantities obtained by means of Thevenin Theorem are used, as defined in [16]. In the time domain, the optimum PTO force is written as the following convolution integral:

$$F_{pto}(t) = \int_0^t K_{pto}(t-\tau)\,F_{WEC}(\tau)\,d\tau, \qquad (12)$$

where K_{pto} is now the impulse response function corresponding to the frequency response (4). More sophisticated controls can be implemented, such as predictive controls that optimize the electric power (considering the PTO losses) [36], [37], but they have not been considered in paper since the objectives are selecting and optimizing the PTO main characteristics.

The instantaneous mechanical power available at the generator is given by:

$$P_{mech}(t) = F_{pto}(t)\,v_{rel}(t) \qquad (13)$$

Finally, and taking in consideration the losses in the conversion from mechanical to electrical power, the latter may be written as:

$$P_{elec}(t) = P_{mech}(t) - P_{loss_{elec}}(t) \qquad (14)$$

where $P_{loss_{elec}}$ represents those losses. It is defined by:

$$P_{loss_{elec}}(t) = \frac{1}{R'_{pto}} F^2_{pto}(t) \qquad (15)$$

The model is now fully described. Results for some cases are presented in the following section.

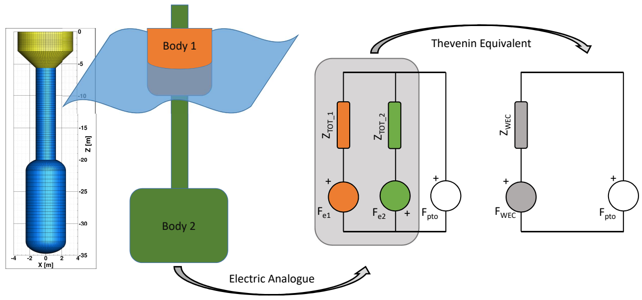

Fig. 2. Two-body point absorber scheme and electric analogue circuit.

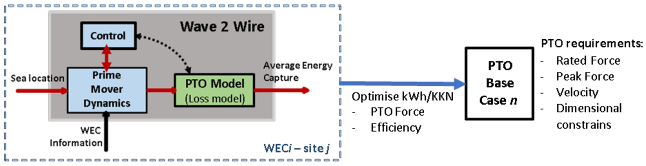

Fig. 3. Scheme to define the PTO modular unit.

IV. Results of PTO Design Methodology

The W2W model, modified with a PTO losses model, can be used to determine the main characteristics of a PTO, according to the necessities of a specific WEC and particular location. Hence, a single PTO module may be defined for several WEC technologies In the R&D project, this analysis tool is used to define the main characteristics of the linear generator to be designed, manufactured, and tested, which are the main objectives of the project. By way of example, in this section we present the results for a two-body generic point absorber, as shown in Fig. 2.

In SEATITAN project, the proposed procedure is based on the analysis of different wave conditions for each WEC device considered in the project (although, as aforementioned, just one case example is presented in this section). With the information of each WEC device, a PTO modular unit is defined based on the different rated forces, velocities and dimensional constrains, according with Fig. 3.

The methodology consists of defining a parameter of the system, namely the limit force ($F_{pto-lim}$ or F_{rated}), to be modified sequentially (including an analysis without force constraints). On the other hand, based on the system force and velocity, the mechanical power and energy are calculated. The criteria to select the force required for each WEC is based on the comparison between the obtained energy reduction and the force and maximum stroke reduction. The latter parameters have the greatest impact in the PTO cost. In addition, several PTO efficiency scenarios are considered in a parametric analysis, in order to evaluate the impact of the deviations from the target PTO efficiency design.

In a first analysis, the W2W tool is used with regular

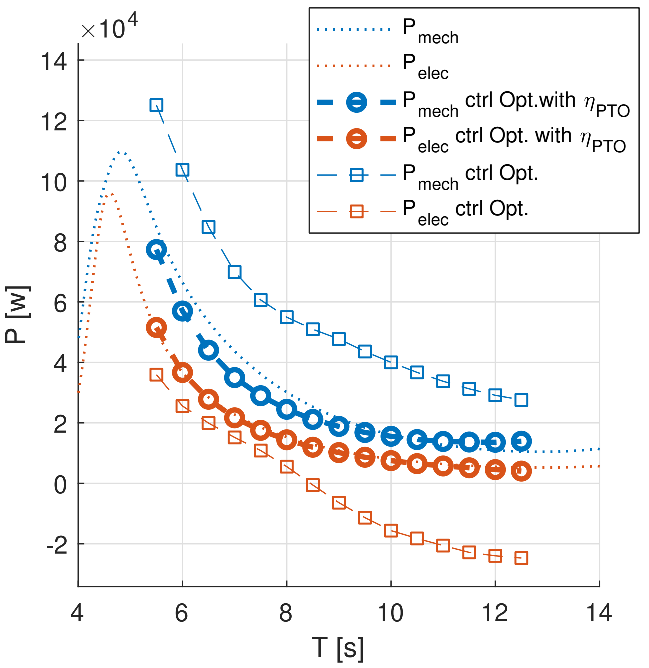

Fig. 4. Electrical and mechanical power profiles for different input wave periods, and with two energy extraction controls.

waves in order to obtain the WEC power output (mechanical and electrical) profile for different input wave periods, which is shown in Fig. 4. The power profiles for 2 cases are shown (solid lines stand for mechanical power and brown lines stand for electrical power):

1) lines marked with squares correspond with the case where the control does not take into account the PTO losses.
2) lines marked with circles correspond with the case where the PTO energy extraction control has been modified to take into account PTO losses.

The PTO efficiency considered is 75%. This figure shows that case 1) is capable of extracting more mechanical power, but the use of excessive reactive mechanical power reduces the electric power generated. In some frequencies, the electric power reaches negative values.

In this section, the methodology is applied taking into account 9 sea states scenarios (9 representative sea states of the target location of the WEC device). In the case example considered, the location is the Wave Energy Devices test site PLOCAN [38]. Fig. 5 and Fig. 6 show the 9 sea states considered over the scatter diagram in PLOCAN location. The sea states of the location are selected from the polynomial expression 16, which relates peak periods and significant height [16]. This expression is obtained applying a least-square approximation for the occurrence data of the sea-states. This approach reduces the number of sea states evaluated and simplifies the graphical representation of the results.

$$H_s = K_{Hs-T_p} \cdot T_p^2 = 0.0146 \cdot T_p^2 \tag{16}$$

where H_s is the significant height and T_p is the peak period.

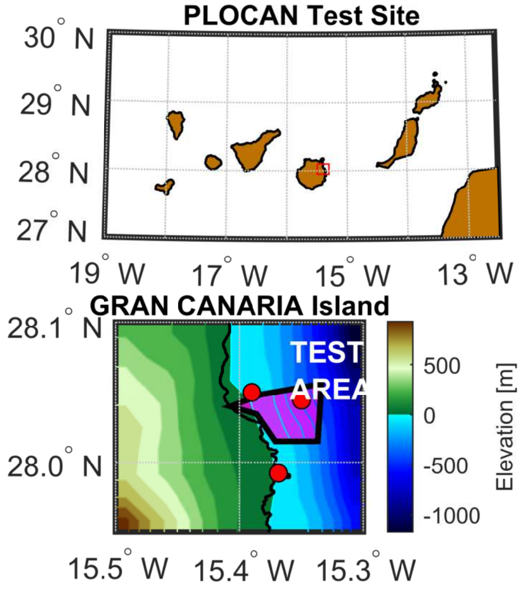

Fig. 5. PLOCAN location and scatter diagram.

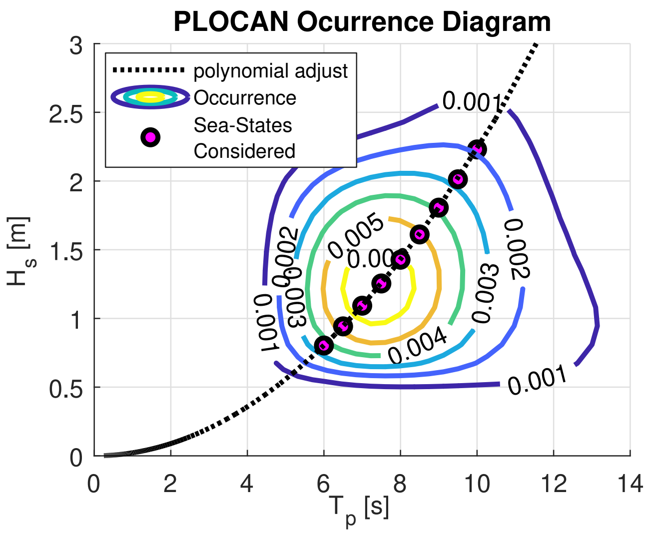

Fig. 6. 8 sea states selected for the PTO characterization methodology.

By way of example, the Fig. 7 shows the results for a specific PTO rated case (140 kN) in the considered sea states. Fig. 7 (a) shows the maximum stroke of the PTO, while in Fig. 7 (b) the extracted average power is represented (solid line represents the mechanical power and dashed lines represents the electrical power). Four efficiency scenarios are analyzed: 70%, 75%, 80%, and 85%. Results show that the maximum stroke has not a clear dependency with the efficiency. The same effect can be noticed in the mechanic power generated, and a light dependence on the electrical power generated may be seen. Hence, the efficiency seems to have more impact in the control strategy than in the PTO rated characteristics selection.

Furthermore, the influence of the rated PTO force and the PTO efficiency is analyzed, and results are shown in Fig. 8. The average power is calculated as an arithmetic average of the power extracted in each sea state, weighted with the sea-state occurrence (Fig.

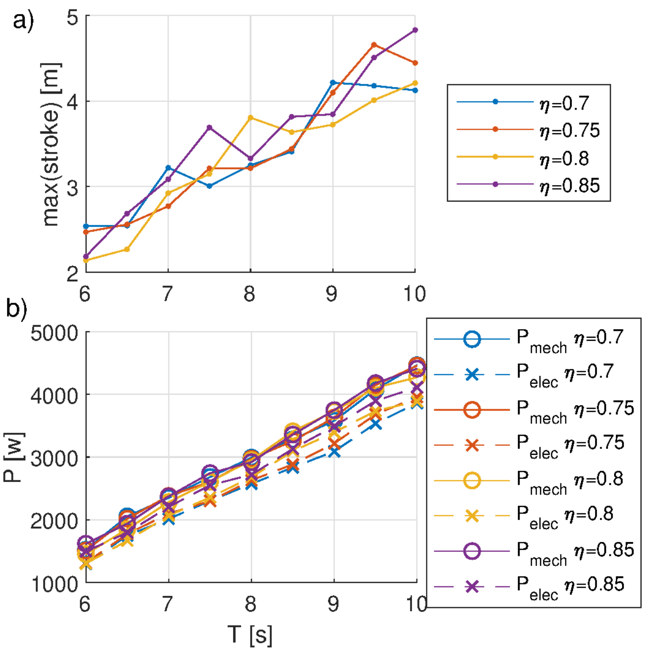

Fig. 7. Example of the results for one PTO rated force case.

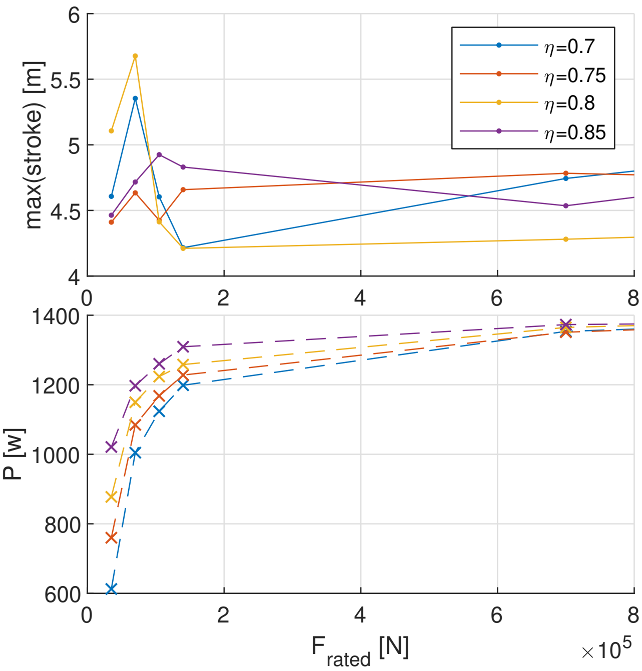

Fig. 8. Summary of the results of the analysis: electric power extracted by the PTO (a) and maximum necessary stroke (b) is presented with respect to the PTO rated force and PTO efficiency.

8 (a)), and the maximum PTO stroke takes into account the whole set of sea states (Fig. 8 (b)).

Fig. 8 (a) shows a light inverse dependence of the maximum stroke necessary in the PTO with the PTO rated force. In addition, a clear direct dependency between rated force and weighted averaged power extracted is shown in Fig. 8 (b). However, in the range 105 kN to 140 KN, a great change in the ratio power extracted vs. PTO rated force is observed. The low ratio observed for rated forces above 140 kN means that the increase of the rated forces (and hence, in PTO cost), has a relative low impact in the total amount of energy harvested from the waves (and hence, the benefits of the WEC power plant). The efficiency has influence in the absolute value of the power generated, but in relative terms, it has less influence in the selection of the PTO rated value (the inflexion point seems to appear at the same value of the rated force, regardless the efficiency value).

V. Conclusion

The analysis tool presented in this paper helps to determine the main characteristics of the PTO. The information provided will be used in the SEATITAN R & D project to determine the minimum PTO module with which the requirements of four technologies may be met. For this purpose, the optimal requirements of each PTO for each technology is first determined.

This analysis tool takes into account the characteristics of a PTO, since they have a great impact in the extracted energy. These characteristics have been integrated in a W2W model by means of a PTO losses model and a modification in the energy extraction algorithm.

On the one hand, the force limitation reduces the ability to extract power from the waves. However, the application of an optimum control in each sea state target demands high values of the force, which leads to low ratio of the extracted power to the rated power of the PTO. The main reason for this is the use of reactive mechanical power in the optimum control, since it leads to increasing the demanded PTO force value in a higher percentage than the power extracted.

On the other hand, the efficiency of the PTO has a great impact in a Direct-Drive Linear generator PTO, because the losses are proportional to the square of the exerted PTO force, and the use of mechanical reactive power should be used taking into account the PTO efficiency.

Therefore, the main rated characteristics of the PTO are needed when defining a power extraction control in a wave energy converter (WEC), and the energy extraction algorithms should be modified accordingly.

In addition, the limitation in the energy extraction introduced by the maximum (rated) PTO force should be analysed carefully, taking into account its direct impact in the PTO costs.

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