Adaptive Power Control of Wave Energy Converters for Maximum Power Absorption under Irregular Sea-state Conditions

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Abstract—This paper proposes a novel wave energy converter (WEC) control technique based on an adaptive vector controller for maximum power absorption of the wave energy resource. The proposed controller arises as a suitable solution for a realistic wave energy converter deployment, as it serves from its own wave energy converter velocity to instantaneously determine the required power-take-off force needed for maximizing the power extraction from the waves. The adaptive characteristic of the wave energy controller is achieved thanks to the implementation of advanced signal monitoring and synchronization processes along with vector control algorithms. As a result, maximum power absorption can be instantaneously achieved regardless of the dominant characteristics of the irregular waves.

Keywords—Wave Energy Converters, Adaptive Control

I. INTRODUCTION

The wave energy sector is currently found in a nascent development stage, as ocean wave energy systems are characterized by the presence of highly diversified energy conversion techniques, devices and applications. Hence, a very large number of wave energy converter (WEC) technologies appear to be under research and development processes, making use of very different conversion principles and technologies. As a result, the greatest research effort found in the wave energy sector was focused on understanding and analyzing the main challenges associated with the hydrodynamics and survivability of a widely range of different wave energy converter concepts. [1-2]. However, it has not been until now when the electrical concerns of power generation, including its control for efficient electrical grid integration has become under serious consideration, as several wave energy concepts approach their near-commercial development stages [2].

In the context of wave energy converter control systems, many different proposed solutions appeared in the literature with no sign of a clear agreement in which could be the most suitable control strategy leading to maximum power absorption conditions in a straightforward manner for irregular waves.

Linear damping control appeared in the first instance, and its main implementation was based on providing a resistive force proportional to the wave energy converter velocity. This

controller appears as a non-suitable technology to achieve high efficiency power absorption, as the PTO force is not able to cancel out the intrinsic added mass and spring characteristic of the buoy radiation force, thus leading to non-optimal conditions [3]. Sub-optimal latching and clutching wave energy controllers were also applied where compensation of the inherent added mass and spring terms was achieved by mechanically imposing the buoy velocity to be in phase with the excitation force [4].

Optimal control conditions were reached by applying the so-called reactive control or complex conjugate control [5, 6], in which not only a resistive term proportional to the velocity is applied to the wave energy converter system, but also a reactive term which is proportional to the buoy position or acceleration. The main purpose of this reactive term is to counteract the intrinsic added mass and spring coefficients of the wave energy device, therefore leading to optimal velocity conditions and thus maximum power absorption.

However, under the case of polychromatic real sea conditions, such approaches result in sub-optimum efficient conditions, as the wave energy converter is being tuned for a single frequency component. In this case, the wave energy controller could be tuned to achieve sub-optimal power extraction at the sea state level rather than to a wave to wave scale. Other approaches appeared applying an optimization problem for maximizing the overall power extraction [7]. Several controller methods serving from far positioned measuring buoy stations, which characterize the instantaneous excitation force from the incident waves, appear in the form of model predictive controllers (MPC) [8] or internal model controllers (IMC) [9].

The present paper aims at contributing in the wave energy technology sector by proposing a novel WEC control based on an adaptive vector algorithm for maximum power absorption of the primary resource. The proposed controller arises as a suitable solution for a realistic wave energy converter deployment, as it serves from its own wave energy converter velocity to instantaneously determine the required power-take-off force. Due to the adaptive behavior of the controller, maximum power absorption can be achieved regardless of the dominant characteristics of the irregular wave energy resource.

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II. HYDRODYNAMIC MODELING OF WAVE ENERGY CONVERTERS IN IRREGULAR SEA-STATE CONDITIONS

A. Characterization of the irregular wave energy resource

Since the proposed wave energy converter controller is designed for achieving maximum power extraction under real sea-states, irregular wave conditions need to be accordingly modeled. Most of the approaches found in modeling the performance of realistic ocean waves serve from representative sea state parameters to construct the energy spectrum characteristic of the sea. The Bretschneider spectrum has been considered for this particular case, where the significant wave height H_{wave} and dominant wave period T_{wave} are given as the system input. In this case the EMEC test site has been considered as the study case, for which waves of 7.7s and 1.47m dominant wave periods and significant wave heights respectively appear as the most probable wave characteristics. The Bretschneider wave energy spectrum is depicted in Fig. 1 for the previously mentioned wave parameters.

As it can be observed from (1-2), the wave energy spectrum is used in determining the time domain wave excitation force, which will be set as a system input.

Fig. 1 Bretschneider wave energy spectrum characterization of irregular waves with $T_{wave} = 7.7s$ and $H_{wave} = 1.47m$

$$Ampl_i(\omega_i) = \sqrt{2S(\omega_i)\Delta\omega} \quad (1)$$

$$F_{exc}(t) = \sum_{i=1}^N Ampl_i \Re(\tilde{F}_{exc}(\omega_i) e^{-j\omega_i t + j\phi_i}) \quad (2)$$

Where $Ampl_i(\omega_i)$ are the excitation force amplitudes for each of the wave frequency components, which are obtained from the discretization of the wave spectrum $S(\omega_i)$, $\Delta\omega$ is the discretization step of the spectrum, $\tilde{F}_{exc}(\omega_i)$ are the excitation force coefficients calculated in frequency domain from a fluid dynamic software, and ϕ_i are the random phase angles for each of the frequency components.

B. Modeling of the wave – buoy in

The wave energy converter structure proposed in this paper is presented in Fig. 2 (a) based on a simplified heaving point absorber with a single degree of freedom, which moves with respect to a fixed bottom structure (Fig. 2 (b)). The mathematical model of the wave energy converter and its interaction with the wave energy resource can be obtained by determining the detailed forces acting of the floating buoy

system. From the analysis of such interacting forces, the equation of motion describing the system hydrodynamics can be derived in (3). Due to the fact that real time modeling and control of wave energy converter is pursued for realistic irregular sea applications, the time domain equation of motion has been introduced here, instead of the commonly found frequency domain approach [10].

Fig. 2 (a) Wave energy converter structure proposed on this paper, (b) Simplification of the wave energy converter structure

$$[M + A(\infty)]\ddot{x}(t) + \int_0^t K(t-\tau)\dot{x}(\tau)d\tau + K_s x(t) = f_{exc}(t) + f_{PTO}(t) \quad (3)$$

$$K(t) = \frac{2}{\pi} \int_0^\infty B(\omega) \cos(\omega t) d\omega \quad (4)$$

$$A = \lim_{\omega \rightarrow \infty} A(\omega) = A(\infty) \quad (5)$$

By using (4) and (5) it is possible to model the radiation force term in time domain from the frequency domain hydrodynamic coefficients obtained from the fluid dynamics software. As it can be observed in (3), the term introducing the highest modeling complexity is the convolution term, which represents the radiation force performance on the system. This transfer function has been obtained through a Prony analysis, which derives the radiation transfer function from the impulse response function from (4). For this specific case, an 8 order transfer function was obtained to precisely represent the impulse response function dynamics, which is provided in (6).

$$H_{rad}(s) = \frac{\sum_{i=0}^8 \alpha_i s^i}{\sum_{i=0}^8 \beta_i s^i} \quad (6)$$

$\alpha_8 = 6704$	$\alpha_7 = 2.812 \cdot 10^5$	$\beta_8 = 1$	$\beta_7 = 1.922$
$\alpha_6 = 2.352 \cdot 10^5$	$\alpha_5 = 4.675 \cdot 10^6$	$\beta_6 = 17.79$	$\beta_5 = 26.66$
$\alpha_4 = 7.163 \cdot 10^6$	$\alpha_3 = 1.777 \cdot 10^7$	$\beta_4 = 80.87$	$\beta_3 = 73.39$
$\alpha_2 = 1.393 \cdot 10^7$	$\alpha_1 = 1.119 \cdot 10^7$	$\beta_2 = 96.25$	$\beta_1 = 38.35$
$\alpha_0 = 5.613 \cdot 10^7$		$\beta_0 = 20.12$	

The Laplace domain transformation of the equation of motion is provided in (7), which results in a straightforward expression once the radiation force transfer function of the convolution term from (3) is characterized. Then, the instantaneous control of the device could be achieved by just measuring its velocity $\dot{X}(s)$. From this point in advance, the wave energy converter velocity and position will be

represented by its vectorial notation $v_{WEC}(s)$ and $x_{WEC}(s)$ respectively, for simplicity purposes.

$$[M + A(\infty)]\ddot{X}(s) + H_{rad}(s)\dot{X}(s) + K_s X(s) + H_{PTO}(s)\dot{X}(s) = F_{exc}(s) \quad (7)$$

III. ADAPTIVE CONTROL OF WAVE ENERGY CONVERTERS

The main contribution introduced by this controller structure belongs to the implementation of an adaptive vector controlled WEC able to achieve maximum power absorption for irregular sea conditions. One of the novelties of the proposed control strategy is that a frequency locked loop (FLL) signal monitoring system has been implemented with the purpose of achieving adaptive controller characteristics regardless of the dominant frequency components of the wave energy converter velocity.

According to [5, 6, 11], the wave energy converter model introduced in (7) can be represented by a mass, spring, damper system, from which an electrical analogous model could be derived. Maximum power absorption can be achieved for the case in which the PTO reactance cancels the imaginary components of the intrinsic impedance of the WEC. In this way the system appears at resonance conditions achieving optimum operating performance. Such wave energy converter behavior is achieved by implementing the so called reactive control or complex conjugate control. Therefore the real component of the PTO impedance provides a resistive force equal to the radiation damping component, while the reactive term is in charge of providing instantaneous resonance conditions for the wave energy converter system. In order to achieve such wave energy converter performance, the proposed wave energy converter controller is introduced in Fig. 3.

Fig. 3 Adaptive vector controller of wave energy converters for maximum power absorption

A. Adaptive velocity monitoring and frequency synchronization system (FLL)

One of the novelties of the WEC controller structure is that the control system implements a frequency locked loop (FLL) signal monitoring system. This adaptive signal synchronization method is not considered a novel structure, as it has been widely used and documented in the field of electrical engineering to synchronize power electronic converters with the instantaneous performance of the electrical grid [12]. The specific frequency locked loop system (FLL) implemented in

this paper [12] appears as a two-fold structure. From one side, it has the capability of obtaining the direct and quadrature signals of the WEC velocity, which will be later used by the vector control system for determining the active and reactive power producing components of the radiation force (f_{radP}, f_{radQ}) . Besides that, and keeping the goal in mind of extracting maximum power for any sea state conditions, the wave energy device should resonate with the frequency of the incoming waves. For achieving this, the frequency locked loop system provides the additional functionality of instantaneously estimating the most dominant frequency components of the wave energy converter velocity in real time. Therefore, by measuring the buoy velocity the FLL synchronization system estimates the direct and quadrature components of the buoy velocity along with the dominant frequency component of the velocity

B. Vector control system

In order to have a better understanding on the controller performance, the vector representation of the control system appears depicted in Fig. 4. From this figure, the radiation force $(\vec{F}_{rad})$ and WEC velocity $(\vec{v}_{WEC})$ vectors, along with their respective projections on the orthogonal axes, are clearly identified. This direct and quadrature components of the radiation force are calculated according to (8) by multiplying each of the buoy velocity components with the radiation transfer function. The calculation of the radiation force vector components is possible thanks to the capability of the FLL block for extracting the vector components of the buoy velocity vector.

$$f_{rad,\alpha} = H_{rad}(s)v_{WEC,\alpha} \quad f_{rad,\beta} = H_{rad}(s)v_{WEC,\beta} \quad (8)$$

From the vector representation, the active power-producing term of the radiation force can be determined as the projection of the radiation force vector over the buoy velocity vector, i.e. the component of the radiation force appearing in phase with the velocity of the WEC. Alternatively, the reactive term of the radiation force is the vector component whose projection appears in quadrature with the velocity of the wave energy device. Therefore, the active and reactive components of the radiation force are determined according to (9), resulting in the minimum radiation force coefficients required for achieving maximum instantaneous power absorption. Therefore, the PTO satisfies one of the necessary conditions for extracting maximum power, since it instantaneously provides a force with equal real part as the radiation force, while cancelling out the reactive term introduced by the radiation force transfer function $H_{rad}(s)$.

For the case introduced in (9) maximum instantaneous power absorption will be achieved.

$$\vec{f}_{radP} = \frac{\vec{v}_{WEC,\alpha} \cdot \vec{f}_{rad,\alpha} + \vec{v}_{WEC,\beta} \cdot \vec{f}_{rad,\beta}}{v_{WEC,\alpha}^2 + v_{WEC,\beta}^2} \vec{v}_{WEC} \quad (9)$$

$$\vec{f}_{radQ} = \vec{f}_{rad} - \vec{f}_{radP}$$

Fig. 4 Vector diagram of the proposed wave energy converter controller

C. Virtual PTO spring coefficient system (resonance gain)

Aside from providing the expected real and imaginary components of the radiation force, the PTO should ensure resonance conditions of the wave energy converter with the incoming waves, by considering the dominant frequency characterization of the wave energy field. As it was previously outlined, the instantaneous estimation of the dominant wave frequency components can be achieved thanks to the FLL structure. The additional virtual spring term provided from the PTO (f_0) results from the reactive control requirements, from which the entire wave energy converter system should resonate at the frequency of the incoming waves. This term is the responsible of cancelling out the reactive components of the intrinsic wave energy converter impedance for any of the dominant frequencies of the ocean waves.

The extraction of the equations (10) and (11) is determined from the intrinsic resonator structure of the wave energy device, which can be observed in Fig. 3.

$$H_{res}(s) = \frac{Y(s)}{X(s)} = \frac{s}{Ms^2 + K_s + X_{PTO}} = \frac{s/M}{s^2 + (K_s + X_{PTO})/M} \quad (10)$$

$$s^2 + \omega^2 = s^2 + \frac{K_s + X_{PTO}}{M} \Rightarrow \omega^2 = \frac{K_s + X_{PTO}}{M} \quad (11)$$

$$X_{PTO} = M\omega^2 - K_s$$

Where X_{PTO} is the virtual spring term provided by the PTO, ω is the instantaneous estimated frequency from the FLL structure, M represents the inherent mass of the buoy and K_s the inherent spring coefficient of the buoy.

IV. SIMULATION RESULTS

In order to validate and to obtain a meaningful evaluation of the wave energy converter performance, the proposed adaptive vector controller from Fig. 3 is implemented in simulation. The following results are the ones corresponding to the instantaneous power theory introduced in (9). The entire wave energy converter model and control has been simulated in

MATLAB Simulink. By plotting the average excitation, radiation and absorption powers, it is possible to observe that under maximum power conditions, the average power absorption from the wave energy converter equals the average radiation power, which at the same time is half of the excitation average power. This system behavior was described in [11], from which the maximum power absorption operation principles were described. Therefore, this wave energy converter operating performance is reproduced in Fig. 5, from which maximum power extraction is achieved. In addition, as it was previously outlined for the case in which the WEC operates at resonant conditions, the wave energy converter velocity should appear in phase with the excitation force, being the intrinsic imaginary component of the WEC impedance cancelled due to the instantaneous virtual spring of the PTO. The achievement of such a resonance conditions can be observed in Fig. 6.

With the purpose of observing the adaptive behavior of the proposed wave energy converter controller, Fig. 7 provides the comparison between the average extraction, excitation and radiation powers when a step in significant wave height and period is provided simultaneously at time $t = 2000s$. The significant wave height and period have been changed from

$$H_{wave} = 1.47m \rightarrow 2.16m \text{ and } T_{wave} = 7.7s \rightarrow 9.1s$$

In order to have a meaningful evaluation of the proposed wave energy converter controller, the adaptive vector controller performance is compared with the conventional reactive control strategy introduced in [6].

Fig. 5 Comparison of average absorption, excitation and radiation powers when the instantaneous power controller is applied

Fig. 6 Comparison of WEC velocity and excitation force

Fig. 7 Comparison of average absorption, excitation and radiation powers when a step in significant wave height and period is applied

T_{wave}	Ins. Power Control	Reactive Control [4]
6.3s	$P_{avg} = 73.4 \text{ kW}$ $P_{peak2Avg} = 17.8$	$P_{avg} = 50.1 \text{ kW}$ $P_{peak2Avg} = 23.2$
7.7s	$P_{avg} = 371 \text{ kW}$ $P_{peak2Avg} = 28.9$	$P_{avg} = 281.41 \text{ kW}$ $P_{peak2Avg} = 15.1$
9.1s	$P_{avg} = 1319 \text{ kW}$ $P_{peak2Avg} = 36.1$	$P_{avg} = 701.29 \text{ kW}$ $P_{peak2Avg} = 14$

Table I Average power absorption and peak to average comparison when applying different control strategies under different sea state conditions

As it can be observed in Table I, the proposed power control strategy provides enhanced results for wave periods moving away from the WEC design sea conditions (most probable waves scenario – $T_{wave} = 7.7\text{s}$). For wave periods of 7.7s an increase of approximately 30% output average power is achieved, while for wave periods of 9.1s the adaptive vector control extracts between 70% and 80% increased power absorption when compared with the conventional control. Therefore, the adaptive vector control based on instantaneous power absorption appears as the most suitable solution, since it provides considerably enhanced average power absorption.

V. CONCLUSIONS

This paper proposes a novel WEC control technique based on an adaptive vector controller for maximum power absorption of the wave energy resource. This controller provides a differential contribution in the field of control of wave energy

converters, since it provides an instantaneous adaptive behavior thanks to the implementation of signal monitoring and synchronization systems. In addition, it makes use of the vector control theory, allowing for the implementation of several power strategies. Finally, it was emphasized that the proposed power control strategy allows a larger power extraction for cases where the wave frequency considerably differs its design parameter.

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