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Reactive control of a wave energy converter using artificial neural networks

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ABSTRACT

A model-free algorithm is developed for the reactive control of a wave energy converter. Artificial neural networks are used to map the significant wave height, wave energy period, and the power take-off damping and stiffness coefficients to the mean absorbed power and maximum displacement. These values are computed during a time horizon spanning multiple wave cycles, with data being collected throughout the lifetime of the device so as to train the networks off-line every 20 time horizons. Initially, random values are selected for the controller coefficients to achieve sufficient exploration. Afterwards, a Multistart optimization is employed, which uses the neural networks within the cost function. The aim of the optimization is to maximise energy absorption, whilst limiting the displacement to prevent failures. Numerical simulations of a heaving point absorber are used to analyse the behaviour of the algorithm in regular and irregular waves. Once training has occurred, the algorithm presents a similar power absorption to state-of-the-art reactive control. Furthermore, not only does dispensing with the model of the point-absorber dynamics remove its associated inaccuracies, but it also enables the controller to adapt to variations in the machine response caused by ageing.
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1. Introduction

With a possible resource of up to 2.1 TW of power worldwide [1], wave energy can become an important future energy resource, thus decreasing society's greenhouse gas emissions. At the moment, the wave energy industry is not mature yet: numerous Wave Energy Converter (WEC) devices have been developed, but none has been established as the best design yet. Reference [2] provides a thorough review of some of the most promising recent technologies. Point absorbers are an established type of offshore WECs [2]. They comprise of a floating body, whose dimensions are small relative to the characteristic wavelength, excited by ocean waves that drive a power take-off (PTO) system, which absorbs energy. WECs are envisioned to be installed in groups, i.e. wave farms, so as to reap the benefits of economies of scale [3]. However, for simplicity we analyse a single, axisymmetric unit subject to motions in heave.

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Over the years, various control schemes have been proposed for the maximization of energy absorption of WECs, with [4,5] presenting comprehensive reviews of the initial and recent studies in the field. In theory, optimal power generation can be obtained through complex-conjugate control, since it regulates the system so as to achieve resonance with the incoming waves [4]. Nevertheless, this is impractical in reality due to the associated large motions of, and loads on, the machine in extreme seas. Thus, alternative control strategies have been implemented, which consider physical constraints on the motions, forces and power rating of the WEC [3].

Latching, model-predictive and simple-but-effective control are real-time techniques for the control of WECs. With latching control, first developed by [6], there is an alternation over a wave cycle of stages when the device is linearly damped and locked in place by the PTO system. Resonance is achieved by regulating the duration of each phase [7]. Model predictive control computes at each time step the force that maximizes energy absorption during a future time horizon [8,9]. Simple-but-effective control applies a force that is calculated by fitting a narrow-banded function to the wave excitation force [10]. While the scaling of latching control to wave farms poses serious problems, [11] have applied model predictive control to multi-body WECs, and [12,13] to an array of three point absorbers. Although these methods include limits on the response and loading of WECs, their behaviour is strongly influenced by the quality of the forecast wave excitation force and of the model of the device dynamics [5]. In addition, model predictive control presents a very high computational cost associated with the real-time optimization. Simple-but-effective control results in similar power generation to model predictive control, but presents a simpler implementation [5].

An alternative type of control strategies relies on time-averaged sea states, thus assuming stationary wave conditions over a prescribed time [3]. With reactive control, simulations are run to calculate the combination of PTO damping and stiffness coefficients that maximise the generated energy in each sea state. Resistive control represents a specific case, where the stiffness term is zero. Force and displacement constraints can be included within the numerical model and cost function, respectively. While this technique may be associated with lower energy extraction than on-line control strategies [13], it is less computationally intensive and presents a simple implementation. Furthermore, the control scheme can be easily extended to the treatment of wave farms, as considered by [3].

All aforementioned methods are strongly affected by the accuracy of the model of the body dynamics they use. For this reason, modelling errors can result in a drop in the generated power. Additionally, the control strategies cannot adapt to changes in the response of the WEC caused by its ageing, with marine biofouling playing a major role. Therefore, in a previous article the authors have developed an algorithm for resistive control based on reinforcement learning that learns the optimal PTO damping coefficient in every sea state directly from experience [14]. This work has been extended to the reactive control of a point absorber in [15]. In contrast to resistive control, reactive control can lead to much higher efficiencies but requires an extension of the search space to two variables, namely the PTO damping and stiffness coefficients. For this reason, learning time in each sea state can become very long depending on the refinement of the discretization of the PTO coefficients. Furthermore, continuous values of the control parameters could result in higher efficiencies. Artificial Neural Networks (ANNs) represent an alternative set of machine learning algorithms which are popular in the computer science industry. They can yield smooth, non-linear function approximations [16] and therefore provide an elegant solution to the above two problems with reinforcement learning. ANNs have been used to provide real-time system identification for WEC dynamics by [17,18]. Furthermore, [17] have successfully applied the ANNs model to the control of the AWS Archimedes Swing WEC.

Here, ANNs will be applied for the first time to the reactive control of a point absorber. Hence, they are employed to map the sea state conditions averaged over a time interval and the applied PTO coefficients to the mean power and maximum displacement that occur over the duration of the time interval. The resulting mapping will be used to select optimal PTO damping and stiffness coefficient at the start of each time interval, once learning has been completed. Numerical simulations are run in both regular and irregular waves to test the efficiency and convergence properties of the proposed control algorithm.

2. Reactive control of a point absorber

2.1. System description

A point-absorber with an electromechanical PTO is considered, as for example analysed by [19] or proposed by [20]. Removing the hydraulic stage in the power conversion process results in an increase in efficiency [20]. Furthermore, as opposed to direct-drive PTO, the use of smaller, cheaper rotating generators is still possible [20].

As shown in Fig. 1, the movement of the float is converted into rotational motion through a mechanical stage. This mechanism drives a generator, which can be of a permanent magnet design as proposed by [20]. A variable-frequency converter delivers the generated power to the electrical grid at the requested frequency. The controller controls the generator through the machine-side converter in order to maximise energy absorption. The grid-side converter keeps a constant DC-link voltage and controls the active and reactive power transmitted to the network [21].

In order to select optimal control actions, the controller requires the heaving body displacement, z, and velocity, $\dot{z}$, as well as the wave elevation, ζ. While the former two variables are inferred from on-board accelerometers, the latter is usually provided by an separate wave buoy for the whole wave farm. Furthermore, the generated power P is obtained from the electric PTO system.

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