Optimization and energy maximizing control systems for wave energy converters

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Editorial

Optimization and Energy Maximizing Control Systems for Wave Energy Converters

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In recent years, we have been witnessing great interest and activity in the field of wave energy converters' (WECs) development, striving for competitiveness and economic viability via increasing power conversion while decreasing costs and ensuring survivability. In the community, the consensus is that both optimization and control are sine qua non conditions for success, but many challenges, peculiar to WECs, need to be addressed. Unlike other traditional control applications, the control objective for WECs is to exaggerate the motion, potentially inducing strong nonlinearities in the system and stressing the power-conversion chain and mechanical structure. Therefore, it is crucial to include techno-economical constraints in both the optimization and control objective functions. Furthermore, although often considered as consecutive independent phases, optimization and control are mutually dependent and, ideally, should be considered together.

The book *Optimization and Energy Maximizing Control Systems for Wave Energy Converters* includes eleven contributions [1–11] to this Special Issue published during 2020–2021. The overall objective of this Special Issue is to draw the most updated picture of the heterogeneous challenges that still need to be addressed in the field of wave energy control and optimization, while also to gather novel and cutting-edge techniques and methods to advance the state-of-the-art. The scientific collection presented in this Special Issue will be valuable for both scientists and technology developers, since each paper within is moved by a bundle of theoretical and pragmatic spirits, with the objective of providing advanced and effective solutions to problems that are currently holding back the development of wave energy technologies.

From a critical analysis of the eleven different contributions of this special issue, it is possible to highlight four major connecting threads:

1. Conjunction of both technical and economic considerations to drive decision-making [1,2,8];
2. Inclusion of non-ideal power take-off (PTO) and nonlinear phenomena for the effectiveness of control strategies [4,7,10];
3. Real-time capabilities as a mandatory condition for applicability of estimation, detection, and control algorithms [3–6,10];
4. Various control strategies including all of the above [3,6,7,9–11].

Tan et al. [8] investigate the influence of the size of a heaving point absorber wave energy converter, considering the techno-economic impact of the resulting power take-off. An optimization method is proposed to reduce the Levelized Cost Of Energy (LCOE). The performance of the system is evaluated through a frequency domain model of the device considering three representative sea states for productivity assessment. In order to represent the effect of the PTO size on power production, PTO force constraints have been included in the model. A preliminary economic model is implemented to estimate costs and LCOE at an early development stage. A control-informed optimization is carried out, evaluating the influence of buoy geometry, PTO size, wave resource and control logic for LCOE reduction. The results show that, for this application, the main driver of LCOE is cost rather than productivity. In fact, smaller PTOs have lower productivity, but still

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achieve an LCOE reduction of 24% to 31%. It is also interesting to note that wave resource and PTO size do not influence buoy size since the main techno-economic driver is cost.

Giassi et al. [2] perform an experimental campaign to evaluate the performance of different wave energy farm configurations, considering a bottom-tethered heaving point that can move in 6 DoF. The objective of this work is to evaluate the performance of the array considering different layouts and to compare the experimental results with a numerical frequency domain model. Array configurations were obtained by optimisation with genetic algorithms. The performance of the different configurations was evaluated experimentally under regular and long-crested waves. An important result is the calculation of the interaction factor (q-factor), which lies in the range of 0.77 up to 1.06, while the optimal configuration is the staggered layout. A frequency domain model of the array that predicts the heave motion of each device has been compared with the experimental tests.The numerical results are in agreement with the experimental ones when the test conditions do not involve strongly non-linear phenomena such as parametric resonance, slack line and wave breaking.

Sirigu et al. [1] present a holistic techno-economic optimization of the Pendulum Wave Energy Converter (PeWEC), using an evolutionary-based global optimization genetic algorithm. A strong and validated statement is provided and defended about the need for the inclusion of economic functions already during the first preliminary design. A genetic algorithm is implemented in order to optimize 13 different parameters, comprising shape, dimensions, mass properties and ballast, power take-off control torque and constraints, number and characteristics of the pendula and other subcomponents. Economic estimations are included, based on the mass of the hull and the pendula, as well as the size of the PTOs. Multiple optimization objectives are considered, Capture Width Ratio (CWR) and Capital expenditure over Productivity (CoP), demonstrating that CWR and CoP may be adverse objectives: the most effective device in absorbing and converting the incoming wave energy is not, in general, economically convenient, and vice versa.

Davidson and Kalmár-Nagy [4] propose a real-time detection system to identify when parametric resonance appears in wave energy converters. Parametric resonance is a dynamic instability due to the internal transfer of energy between degrees of freedom, which is known to cause large unstable pitch and/or roll motions, usually with detrimental effects on the power extraction performance and may increase loading on the WEC structure and mooring system. To remedy such negative effects, control systems can be designed to mitigate the onset of parametric resonance. Since real-time detection is key to enabling corrective actions, this paper presents the first application of a real-time detection system for the onset of parametric resonance in WECs. The proposed detection system achieved 95% accuracy across nearly 7000 sea states, producing 0.4% false negatives and 4.6% false positives.

Bonfanti et al. [5] are concerned with the real-time estimation of wave excitation forces, considering the case study of the Inertial Sea Wave Energy Converter (ISWEC). Energy-maximizing control strategies normally require the knowledge of the incoming wave force, which cannot be measured and should be estimated; moreover, since the input (PTO) control action must be provided in real-time, also the estimation should compute faster than real time. This paper investigates the wave excitation force estimation for a non-linear WEC, using both a model-based and a model-free approach. Firstly, a Kalman Filter is implemented considering the WEC linear model with the excitation force modelled as an unknown state to be estimated. Secondly, a feed-forward Neural Network is applied to map the WEC dynamics to the excitation force by training the network through a supervised learning algorithm. Sensitivity and robustness analyses are performed to investigate the estimation error in presence of un-modelled phenomena, model errors and measurement noise.

Garcia-Violiniet al. [3] present a critical comparison of a set of five simple controllers with the common ability to compute in real-time. In fact, it is argued that the computational cost of some complex control algorithms make them inapplicable to real devices; on the other hand, having the objective of actual implementation, a number of energy-maximising wave energy controllers have been recently developed based on relatively simple strategies, stemming from the fundamentals behind impedance-matching. This paper documents this set of five controllers, which have been developed over the period 2010–2020: (i) Suboptimal causal reactive controller; (ii) Simple and effective real-time controller; (iii) Multi resonant feedback controller; (iv) Feedback resonating controller; (v) LiTe-Con. The comparison, carried out both analytically and numerically, encompass their characteristics, in terms of energy-maximising performance, the handling of physical constraints, and computational complexity. In particular, a scoring system is set, explicitly evaluating the following metrics: computational simplicity, stability, constraint handling, and resulting performance.

Mérigaud and Tona [7] propose an energy-maximisation spectral control that is able to include non-ideal PTO systems in the underlying model used to compute the optimal control law. The discontinuous PTO efficiency characteristic is included via a smooth function approximation to ensure computational efficiency. However, the cost function becomes non-quadratic, hence requires a slight generalisation of the derivative-based spectral control approach, initially introduced for quadratic cost functions. This generalisation is derived in the presented paper, providing details on its practical interest. Two application cases are considered, namely a single-body and a two-body heaving point absorbers inspired by real devices. In both cases, the spectral approach calculates WEC trajectory and control force solutions, for which the mean electrical power is shown to lie within a few percent of the true optimal electrical power. Regarding the effect of a non-ideal PTO efficiency upon achievable power production, the power achieved lies within 80–95% of that obtained by simply applying the efficiency factor to the optimal power with ideal PTO. This is a significantly less pessimistic result than the others found in the literature.

Anderlini et al. [6] implement a real-time reinforcement learning control for wave energy converters, to cope with the potential inaccuracies and uncertainties of the underlying mathematical description of model-based controllers. In particular, such uncertainties may be due to both initial limitations of the model (e.g., linear and nonlinear assumptions) and to variations of some parameters during the operative life of the device (e.g., ageing and wear). In this paper, an alternative solution is introduced to address such challenges, applying deep reinforcement learning (DRL) to the control of WECs. A DRL agent is initialised from data collected in multiple sea states under linear model predictive control in a linear simulation environment. The agent outperforms model predictive control for high wave heights and periods, but suffers close to the resonant period of the WEC. The computational cost at the deployment time of DRL is also much lower by diverting the computational effort from deployment time to training. In addition, model-free reinforcement learning can autonomously adapt to changes in the system dynamics, enabling fault-tolerant control.

Previsic et al. [9] tackle the comparison of model predictive control (MPC) and optimal causal control, applied to a heaving point absorber. In recent years, efforts by various researchers have been invested in the design of simple causal control laws, thanks to their simplicity of implementation in a real system. However, it is important to have a fair comparison, under representative conditions, with more complex non-causal controllers, in order to appropriately evaluate the trade-off between power yield and complexity, also including constraint handling ability. In this paper, a linear MPC is compared to a casual controller that incorporates constraint handling. The analysis demonstrates that the MPC provides significant performance advantages compared to an optimized causal controller, particularly if significant constraints on device motion and/or forces are imposed. It is further demonstrated that distinct control performance regions can be established that correlate well with classical point absorber and volumetric limits of the wave energy conversion device.

Haider et al. [10] propose a nonlinear model predictive controller for a wave energy converter with multiple degrees of freedom. The proposed control is computed in real-time and includes non-ideal power take-off and model non linearities. The inclusion of non-linearities in the model leads to a non-quadratic and non-standard cost function, which is challenging to solve in a computationally effective manner. The considered device is the CENTIPOD, simulated in WEC-Sim, while the extracted power is re-written in pseudo-quadratic form and polynomial decomposition. Comparing linear to nonlinear MPC, despite a computational load that is only slightly higher (+35%), an appreciable improvement in power capture is achieved (up to +10.6%).

Demonte Gonzalez et al. [11] consider the application of sliding mode control for a floating heaving wave energy converter, including nonlinear hydrodynamic effects. In fact, the effectiveness of a control strategy is tightly linked to the representativeness of the underlying model, usually related to nonlinearities. Maximising energy extraction normally implies exaggerating the motion of the floater, inducing hydrodynamic nonlinearities: the most remarkable and often impactful are nonlinear static and dynamic Froude–Krylov forces, which are herein included. A sliding mode controller is proposed, which tracks a reference velocity that matches the phase of the excitation force to ensure higher energy absorption. The control algorithm is tested in regular linear waves and is compared to a complex-conjugate control and a nonlinear variation of the complex-conjugate control. Results show that the sliding mode control successfully tracks the reference and keeps the device displacement bounded while absorbing more energy than the other, although simple, control strategies. Furthermore, due to the robustness of the control law, it can also accommodate disturbances and uncertainties in the dynamic model of the wave energy converter.

Conflicts of Interest: The authors declare no conflict of interest.

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