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Editorial

Optimization and Energy Maximizing Control Systems for Wave Energy Converters II

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1. Introduction

Over the past decade, the renewable energy sector has witnessed remarkable growth, which has been attributed to government support [1], financial incentives [2], and technological advancements [3], leading to significant cost reduction opportunities [4] and experience in quantifying cost drivers [5]. In the context of the design of a wave energy converter (WEC), the process involves intricate optimization stages covering each component of the conversion chain, such as the floater, internal mechanics, and energy conversion [6].

The availability of effective control systems for maximal energy harvesting is a critical milestone in the pathway towards the commercialization of WECs, as they have significant potential to reduce the associated levelized cost of energy. Various control methods have been proposed in the literature, encompassing both optimization-based approaches [7] and non-optimization-based strategies [8]. Focusing on the latter, simple controllers based on the impedance-matching (IM) principle uses different architectures [9], encompassing both feedforward structures (which require knowledge of the so-called wave excitation force [10]) and feedback structures, some of which incorporate constraint-handling mechanisms. However, research on energy-maximizing controllers has been mostly restricted to linear time-invariant (LTI) models, lacking systematic and efficient control synthesis for nonlinear systems, which is possible via spectral modelling [11] or appropriate system identification [12]. This is particularly important because nonlinearities are inherently common in most wave energy converters [13], but also because nonlinear mechanisms have the potential to enhance the overall performance of WECs [14].

Moreover, concerning the design and optimization of a WEC, it can be asserted that there exists a lack of comprehensive and systematic research addressing the idea of robustness [15] and stochastic modelling [16]. Precisely, the neighbouring reliability-based design optimization (RBDO) field of research directed its attention to WECs, concerning only structural and maintenance cost uncertainties [17] and the relationship between reliability and hull geometry [18]. Research efforts were directed towards the pervasive shape optimization of single WECs [19] or array layouts [20]. Metaheuristic algorithms became popular options in the field, thanks to their ability to handle the typically high dimensionality of the optimization space [21]. Finally, at the cross-roads between optimization and control, much attention has recently been paid to control co-design [22], based on the awareness that these two aspects (control and design optimization) are intimately intertwined [23].

The book *Optimization and Energy Maximizing Control Systems for Wave Energy Converters II* aims to tackle a wide range of challenges in wave energy control and optimization, while introducing cutting-edge methods and techniques. It serves as a valuable resource for researchers and technology developers alike, offering a blend of theoretical insights and practical solutions aimed at overcoming current obstacles in the field of wave energy technology development.

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2. An Overview of Published Articles

In "Maximum Power Control Algorithm for Power Take-Off System Based on Hydraulic System for Floating Wave Energy Converters" (contribution 1), a hydraulic-based power take-off (PTO) system for floating wave energy converters (FWECs) was investigated, with a focus on achieving maximum power control. The research involved modelling a hydraulic system generator power converter to analyze and optimize the performance of the PTO system under various load control algorithms. Unlike previous studies that primarily focused on input power performance, this study emphasized electrical load control strategies for maximizing power output. The study applied two main algorithms for load control: the perturb and observe (P&O) algorithm for speed control and an optimal torque control algorithm. These algorithms were evaluated to determine their effectiveness in maximizing the power generation performance of the hydraulic-based PTO system. By analyzing the system's characteristics and power generation efficiency under different control variables, the study proposed an optimal torque control algorithm specifically suited for maximizing power output. The key findings included the following: the hydraulic system type is advantageous for FWECs due to its capability to operate efficiently at low speeds and generate high torque; the proposed optimal torque control algorithm demonstrated effectiveness in achieving maximum power control for the hydraulic-based PTO system; and the simulation results were validated against actual sea test data, confirming the feasibility and effectiveness of the proposed load control algorithms. In conclusion, the study contributed to advancing the understanding and application of hydraulic-based PTO systems in wave energy conversion. The findings serve as a basis for optimizing PTO system performance in real-world applications, offering insights for future developments in wave energy technology.

Using MATLAB/Simulink with the Simscape fluids toolbox, a comprehensive model of the wave absorber device with both conventional and improved hydraulic PTO (HPTO) units was developed in "An Improved Hydraulic Power Take-Off Unit Based on Dual Fluid Energy Storage for Reducing the Power Fluctuation Problem in the Wave Energy Conversion System" (contribution 2). The study focused on evaluating the performance of the improved HPTO unit under various irregular wave conditions and investigating the impact of high-pressure accumulator (HPA) pressure constraints on its performance. The key findings from the simulation analysis were as follows: the optimization of control strategy parameters using a genetic algorithm significantly enhanced the performance of the improved HPTO unit, reducing unnecessary fluctuations in generated electrical power; the integration of dual HPA and fluid energy control (FEC) modules improved stability, allowing the HPTO unit to achieve a stable electrical power output up to 87.3% of the time in irregular sea states; compared to conventional HPTO units, the improved model demonstrated superior performance across different sea states, maintaining rated capacity operation during significant portions of wave conditions; and variations in HPA pressure constraints had notable effects on power generation and fluctuation occurrences, with adjustments influencing power output and stability. This study contributed valuable insights for WEC design and optimization, offering a promising solution to mitigate power fluctuation issues through advanced PTO technology.

In "Downsizing the Linear PM Generator in Wave Energy Conversion for Improved Economic Feasibility" (contribution 3), the authors integrated hydrodynamic and generator models into the WEC optimization process to comprehensively assess WEC power production. Three sizing methods for the linear generator were compared, emphasizing their effects on techno-economic metrics. The study incorporated wave resource data from three European sea sites to highlight the influence of PTO sizing on WEC performance under varying environmental conditions. The key findings indicated that PTO sizing significantly affected the power conversion efficiency of linear generators in point-absorber WECs. The study underscored that accurately sizing the generator is critical for optimizing the levelized cost of energy (LCOE). Neglecting to adjust for varying generator efficiencies can lead to substantial errors in estimating annual energy production (AEP) and optimal PTO capacity, with errors reaching up to 10% and 29%, respectively. A comparative analysis revealed that optimizing main machine parameters alongside scaling laws provided a more realistic reflection of WEC techno-economic potential during PTO sizing. Moreover, the study highlighted the pronounced impact of wave resource variability on generator efficiency and LCOE, stressing the need for tailored PTO designs across different sea sites.

The work "Improving Computational Efficiency in WEC Design: Spectral-Domain Modelling in Techno-Economic Optimization" (contribution 4) focused on improving efficiency through spectral-domain modelling (SDM) for the ISWEC (inertial sea wave energy converter), a gyroscopic-type WEC with a hydraulic power take-off (HPTO). Unlike traditional time-domain modelling (TDM), SDM offers both speed and precision, which is crucial for early-stage design in high-energy sea sites. The research evaluated ISWEC performance with HPTO in locations like the Balder site in the North Sea, highlighting the shift to hydraulic transmissions for efficiency. SDM optimizes multi-objective functions: maximizing annual energy production (AEP) and minimizing the cost of energy (CoE). The results revealed trade-offs, where maximizing AEP favours larger, costlier setups, while CoE minimization prefers smaller, economically viable configurations. This study emphasized integrated optimization tools that consider technical feasibility and economic viability, which are essential for accelerating WEC development. Future work includes refining SDM for HPTO dynamics, comparing PTO configurations, and incorporating uncertainty analysis to enhance the design robustness and economic feasibility of ISWEC systems.

The slope-pendulum wave energy conversion (S-PWEC) device was designed and studied in "Design and Research of Slope-Pendulum Wave Energy Conversion Device" (contribution 5). This study focused on the Zhejiang sea area, employing numerical simulations and experimental array testing under 66 different sea conditions to evaluate the S-PWEC's performance. The results demonstrated that incorporating a slope structure at the device's bottom significantly enhances its motion response capability and resilience against extreme sea conditions. In regular and irregular wave tests, the electrical power output efficiency improved by 13.24% and 10.06%, respectively. Array experiments revealed that optimal spacing between floating plates is critical, influencing both diffraction and radiation effects to maximize power output. The key findings included the following: the slope structure effectively enhanced wave energy capture and overall efficiency at a reduced cost; the device demonstrated robustness in handling large wave heights and maintained operational stability with a "self-locking" mechanism; optimal spacing between arrayed floating plates was crucial, with 25 metres identified as maximizing electrical output. Future research will delve into optimizing the bottom oblique plate angle under varying sea conditions and further refining array configurations to enhance overall wave energy absorption capacity through improved design and active control strategies.

The study "Comparison of Offline, Real-Time Models and Hardware-in-the-Loop Test Results of a Power Take-Off for Wave Energy Applications" (contribution 6) focused on comparing different modelling approaches for a power take-off (PTO) system in wave energy converters (WECs), crucial for optimizing energy extraction and reducing costs. Two modelling methods were discussed: an offline detailed model and a simplified real-time (RT) model, both of which were applied to a 250 kW modular electromechanical PTO connected to an oscillating wave surge converter (OWSC). The offline model, implemented in Matlab Simulink (v2018a) with WEC-Sim, accurately captured system dynamics, including wave–flap interaction and PTO mechanics. It served as a benchmark against the RT model, which ran up to 10 times faster and included simplified control algorithms like maximum torque per ampere (MTPA) and field weakening (FW). The study also incorporated hardware-in-the-loop (HIL) tests to validate these models against real-world conditions. The results showed that, while the RT model effectively replicated the dynamics of the offline model, discrepancies existed in force and torque outputs due to control loop discretization and FW algorithm application. The HIL tests demonstrated closer alignment with real-world performance, highlighting the importance of considering real-time dynamics and hardware integration in validating PTO concepts. Understanding these modelling approaches is crucial for WEC design and validation, ensuring accurate performance assessment and technology readiness assessment with appropriate simplifications.

The study "Model Predictive Energy-Maximising Tracking Control for a Wavestar-Prototype Wave Energy Converter" (contribution 7) addressed the challenge of achieving energy-maximizing control to reduce the levelized cost of energy (LCOE) for wave energy converters (WECs). It presented a model predictive velocity tracking control method for a Wavestar-like device in the WEC-SIM benchmark. The control system has a hierarchical structure: the first part estimates the wave excitation moment (WEM) using a Kalman filter (KF) and an extended Kalman filter (EKF) to obtain the amplitude and angular frequency of the WEM. This information is used to compute the reference velocity. The second part was a model predictive control (MPC) method that ensured the WEC tracked the optimal reference velocity for maximum energy extraction from irregular waves. Two Gaussian Process models predicted future WEM and reference velocity, which are crucial for MPC design. The proposed strategy demonstrated excellent tracking performance with minimal errors, pushing the WEC into near-resonance conditions for optimal power extraction. The MPC system also effectively handled input constraints, reducing negative power and protecting the power take-off (PTO) system from large bidirectional energy flows. Future work will focus on enhancing the robustness of the KF and MPC to improve performance under various conditions.

The work entitled "On the Effect of Wave Direction on Control and Performance of a Moored Pitching Wave Energy Conversion System" (contribution 8) examined how wave directionality and mooring dynamics affected the control and performance of a moored pitching wave energy converter (WEC), specifically using the pendulum wave energy converter (PeWEC) as a case study. The research highlighted the importance of incorporating mooring dynamics and wave directionality into the control synthesis and performance evaluation of WECs. It was found that neglecting wave directionality could lead to an overestimation of device performance by up to 50%, even if a predominant wave direction existed at the site. The study used a tailored data-based model to evaluate the PeWEC's performance under different wave directions and site conditions. The results emphasized that, for accurate performance assessment and control synthesis, it is crucial to consider wave directionality, particularly during the initial design stages of wave energy systems. This approach is necessary to advance the commercial viability of wave energy converters.

In "Comparison of Advanced Control Strategies Applied to a Multiple-Degrees-of-Freedom Wave Energy Converter: Nonlinear Model Predictive Controller versus Reinforcement Learning" (contribution 9), the authors compared nonlinear model predictive controller (NMPC) and reinforcement learning (RL) techniques for controlling a multiple-degrees-of-freedom wave energy converter (WEC). Both approaches were tested on a nonlinear WEC–power take-off (PTO) system using the WEC-Sim™ toolbox under various conditions. The results indicated that RL, with optimal agent selection and training, outperformed NMPC, especially under stringent conditions where NMPC struggled. RL also showed better computational efficiency, reducing the task execution time (TET). The case study on Dehlsen Associates' CENTIPOD WEC highlights that RL-DDPG achieves superior power extraction, robust performance, and design flexibility compared to NMPC. This demonstrates RL's potential in enhancing WEC efficiency and operational robustness.

In the work "Measuring the Robustness of Optimal Design Solutions for Wave Energy Converters via a Stochastic Approach" (contribution 10), the author addressed the challenge of ensuring that wave energy converters (WECs) are not only efficient in energy extraction but also robust in the face of uncertain and harsh marine conditions. Unlike traditional approaches, this research employed a stochastic method using Monte Carlo simulations and Gaussian process regression (GPR) to account for uncertainties. The results showed significant deviations in robustness between the nominally optimal designs and those optimized for robustness. For example, applying robustness metrics led to a 20% reduction in performance but improved reliability. A case study comparing two WEC designs (D1 and D2) revealed that D1, although more costly, had better performance and reduced sensitivity to uncertainties. This emphasizes the importance of incorporating robust optimization in WEC design, balancing performance and robustness, and suggests future research should focus on the impact of control logic and environmental uncertainties to optimize techno-economic indices like the levelized cost of energy (LCoE).

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List of Contributions:

1. Roh, C. Maximum Power Control Algorithm for Power Take-Off System Based on Hydraulic System for Floating Wave Energy Converters. *J. Mar. Sci. Eng.* **2022**, *10*, 603. https://doi.org/10.3390/jmse10050603.
2. Jusoh, M.A.; Yusop, Z.M.; Albani, A.; Daud, M.Z.; Ibrahim, M.Z. An Improved Hydraulic Power Take-Off Unit Based on Dual Fluid Energy Storage for Reducing the Power Fluctuation Problem in the Wave Energy Conversion System. *J. Mar. Sci. Eng.* **2022**, *10*, 1160. https://doi.org/10.3390/jmse10081160.
3. Tan, J.; Wang, X.; Polinder, H.; Laguna, A.J.; Miedema, S.A. Downsizing the Linear PM Generator in Wave Energy Conversion for Improved Economic Feasibility. *J. Mar. Sci. Eng.* **2022**, *10*, 1316. https://doi.org/10.3390/jmse10091316.
4. Bonfanti, M.; Giorgi, G. Improving Computational Efficiency in WEC Design: Spectral-Domain Modelling in Techno-Economic Optimization. *J. Mar. Sci. Eng.* **2022**, *10*, 1468. https://doi.org/10.3390/jmse10101468.
5. Wan, Z.; Li, Z.; Zhang, D.; Zheng, H. Design and Research of Slope-Pendulum Wave Energy Conversion Device. *J. Mar. Sci. Eng.* **2022**, *10*, 1572. https://doi.org/10.3390/jmse10111572.
6. Castellini, L.; Gallorini, F.; Alessandri, G.; Alves, E.F.; Montoya, D.; Mudigonda, B.; Tedeschi, E. Comparison of Offline, Real-Time Models and Hardware-in-the-Loop Test Results of a Power Take-Off for Wave Energy Applications. *J. Mar. Sci. Eng.* **2022**, *10*, 1744. https://doi.org/10.3390/jmse10111744.
7. Li, D.; Patton, R. Model Predictive Energy-Maximising Tracking Control for a Wavestar Prototype Wave Energy Converter. *J. Mar. Sci. Eng.* **2023**, *11*, 1289. https://doi.org/10.3390/jmse11071289.
8. Paduano, B.; Faedo, N.; Mattiazzo, G. On the Effect of Wave Direction on Control and Performance of a Moored Pitching Wave Energy Conversion System. *J. Mar. Sci. Eng.* **2023**, *11*, 2001. https://doi.org/10.3390/jmse11102001.
9. Haider, A.S.; Bubbar, K.; McCall, A. Comparison of Advanced Control Strategies Applied to a Multiple-Degrees-of-Freedom Wave Energy Converter: Nonlinear Model Predictive Controller versus Reinforcement Learning. *J. Mar. Sci. Eng.* **2023**, *11*, 2120. https://doi.org/10.3390/jmse11112120.
10. Giorcelli, F.; Sirigu, S.A.; Giorgi, G.; Faedo, N.; Bonfanti, M.; Ramello, J.; Giorcelli, E.; Mattiazzo, G. Measuring the Robustness of Optimal Design Solutions for Wave Energy Converters via a Stochastic Approach. *J. Mar. Sci. Eng.* **2024**, *12*, 482. https://doi.org/10.3390/jmse12030482.

References

1. O'hagan, A.; Huertas, C.; O'callaghan, J.; Greaves, D. Wave energy in Europe: Views on experiences and progress to date. *Int. J. Mar. Energy.* **2016**, *14*, 180–197. [CrossRef]
2. Gonzalez, A.T.; Dunning, P.; Howard, I.; McKee, K.; Wiercigroch, M. Is wave energy untapped potential? *Int. J. Mech. Sci.* **2021**, *205*, 106544. [CrossRef]
3. Paduano, B.; Carapellese, F.; Pasta, E.; Bonfanti, M.; Sirigu, S.A.; Basile, D.; Pizzirusso, D.; Faedo, N.; Mattiazzo, G. Experimental and Numerical Investigation on the Performance of a Moored Pitching Wave Energy Conversion System. *IEEE J. Ocean. Eng.* **2024**, *49*, 802–820. [CrossRef]
4. Ruiz-Minguela, P.; Noble, D.R.; Nava, V.; Pennock, S.; Blanco, J.M.; Jeffrey, H. Estimating future costs of emerging wave energy technologies. *Sustainability* **2022**, *15*, 215. [CrossRef]
5. Giglio, E.; Petracca, E.; Paduano, B.; Moscoloni, C.; Giorgi, G.; Sirigu, S.A. Estimating the cost of wave energy converters at an early design stage: A bottom-up approach. *Sustainability* **2023**, *15*, 6756. [CrossRef]
6. Bonfanti, M.; Faedo, N.; Mattiazzo, G. Towards efficient control synthesis for nonlinear wave energy conversion systems: Impedance-matching meets the spectral-domain. *Nonlinear Dyn.* **2024**, *112*, 11085–11109. [CrossRef]

7. Faedo, N.; Olaya, S.; Ringwood, J.V. Optimal control, MPC and MPC-like algorithms for wave energy systems: An overview. *IFAC J. Syst. Control* **2017**, *1*, 37–56. [CrossRef]
8. Coe, R.G.; Bacelli, G.; Forbush, D. A practical approach to wave energy modelling and control. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110791. [CrossRef]
9. Carapellese, F.; Pasta, E.; Paduano, B.; Faedo, N.; Mattiazzo, G. Intuitive LTI energy-maximising control for multi-degree of freedom wave energy converters: The PeWEC case. *Ocean Eng.* **2022**, *256*, 111444. [CrossRef]
10. Bonfanti, M.; Carapellese, F.; Sirigu, S.A.; Bracco, G.; Mattiazzo, G. Excitation forces estimation for non-linear wave energy converters: A neural network approach. *IFAC-Pap.* **2020**, *53*, 12334–12339. [CrossRef]
11. Bonfanti, M.; Sirigu, S.A. Spectral-domain modelling of a non-linear wave energy converter: Analytical derivation and computational experiments. *Mech. Syst. Signal Process.* **2023**, *198*, 110398. [CrossRef]
12. Faedo, N.; Giorgi, G.; Ringwood, J.V.; Mattiazzo, G. Optimal control of wave energy systems considering nonlinear Froude–Krylov effects: Control-oriented modelling and moment-based control. *Nonlinear Dyn.* **2022**, *109*, 1777–1804. [CrossRef]
13. Davidson, J.; Costello, R. Efficient nonlinear hydrodynamic models for wave energy con-verter design—A scoping study. *J. Mar. Sci. Eng.* **2020**, *8*, 35. [CrossRef]
14. Daqaq, M.F.; Giorgi, G.; Khasawneh, M.A. Deliberate introduction of a nonlinear restoring element to point wave energy absorbers: A review and assessment. *Nonlinear Dyn.* **2024**, *112*, 13695–13731. [CrossRef]
15. Farajvand, M.; Grazioso, V.; García-Violini, D.; Ringwood, J.V. Uncertainty estimation in wave energy systems with applications in robust energy maximising control. *Renew. Energy* **2023**, *203*, 194–204. [CrossRef]
16. Ambühl, S.; Kofoed, J.P.; Sørensen, J.D. Stochastic modeling of long-term and extreme value estimation of wind and sea conditions for probabilistic reliability assessments of wave energy devices. *Ocean Eng.* **2014**, *89*, 243–255. [CrossRef]
17. Ambühl, S.; Kramer, M.; Sørensen, J.D. Reliability-based structural optimization of wave energy converters. *Energies* **2014**, *7*, 8178–8200. [CrossRef]
18. Clark, C.E.; DuPont, B. Reliability-based design optimization in offshore renewable energy systems. *Renew. Sustain. Energy Rev.* **2018**, *97*, 390–400. [CrossRef]
19. Garcia-Teruel, A.; Forehand, D.I. A review of geometry optimisation of wave energy converters. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110593. [CrossRef]
20. Teixeira-Duarte, F.; Clemente, D.; Giannini, G.; Rosa-Santos, P.; Taveira-Pinto, F. Review on layout optimization strategies of offshore parks for wave energy converters. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112513. [CrossRef]
21. Shadmani, A.; Nikoo, M.R.; Gandomi, A.H.; Chen, M.; Nazari, R. Advancements in optimizing wave energy converter geometry utilizing metaheuristic algorithms. *Renew. Sustain. Energy Rev.* **2024**, *197*, 114398. [CrossRef]
22. Grasberger, J.; Yang, L.; Bacelli, G.; Zuo, L. Control co-design and optimization of oscillating-surge wave energy converter. *Renew. Energy* **2024**, *225*, 120234. [CrossRef]
23. Abdulkadir, H.; Abdelkhalik, O. Control co-design optimization of nonlinear wave energy converters. *Ocean Eng.* **2024**, *304*, 117827. [CrossRef]