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Modelling and Control of Hybrid Oscillating Water Column – Floating Offshore Wind Turbines by Means of Intelligent Techniques

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Abstract

The global wind-wave energy sector is experiencing significant growth. This expansion, driven by the growth of businesses and the population, has shifted the attention towards renewable energy sources to alleviate climate change and global warming. Offshore energy technologies, such as Floating Offshore Wind Turbines (FOWTs), offer significant advantages over onshore ones, including higher capacity factors, higher geographic availability, and reduced visual impact. In the last few years, the idea of integrating Wave Energy Converters (WECs) with FOWTs has been proposed and studied within the Automatic Control Group (ACG), yielding satisfactory results. The combination of both systems has emerged as a promising technology in this transition, harnessing both wind and wave energy to produce clean, renewable power and, more importantly, improving the system dynamics.

Nevertheless, there are several challenges in this area need to be addressed, including comprehensive hybrid modeling and advanced control strategies to mitigate platform vibrations, such as top-tower fore-aft displacement and platform pitch. Ensuring the structural integrity and stability of systems subjected to dynamic wind and wave forces is crucial to preventing undesired oscillations. These oscillations can induce mechanical and electrical problems, such as decreased power generation, higher maintenance expenses, and accelerated material fatigue, ultimately reducing the system's operational lifespan. Furthermore, analyzing and comprehending the control performance of aero-hydro-servo-elastic floating structures presents a complex and formidable challenge. The existing time and frequency domain models are complex, computationally demanding, and unsuitable for real-time or feedback control.

In this thesis, the concept of the incorporation of Oscillating Water Columns (OWCs) into FOWT platforms is further developed, presenting a promising solution for hybrid renewable energy production and leveraging shared infrastructure to reduce costs and improve power output. In addition, OWCs are utilized for power generation and serve as active structural control mechanisms, improving the system's efficiency, and stabilizing the platform dynamics. However, this implies addressing two primary challenges in hybrid systems: accurate control-oriented modeling of hybrid FOWT-OWCs systems and effective control of OWCs to stabilize the platform.

Therefore, this thesis explores the computational machine learning approach, which plays a vital role in addressing these challenges from a modeling perspective. This study employs advanced deep dayered Artificial Neural Networks (ANNs), specifically Multilayer Perceptrons (MLPs), to model the complex aero-hydro-servo-elastic behavior of the hybrid system, addressing the non-linear dynamics and computational inefficiencies of traditional models. Several novel deep-layered regressive ANN-based control-oriented models have been developed and benchmarked against the data generated by standard MultiSurf-Wamit-OpenFAST 5MW FOWT output, demonstrating superior performance and accuracy. The simulation results indicate that the proposed ANN-based modeling is a promising alternative to other intricate nonlinear NREL 5MW FOWT dynamical models.

From a control perspective, an ad-hoc Fuzzy Logic Control (FLC) system has been implemented to stabilize the platform, effectively mitigating undesired vibrations and enhancing system stability. The results show that the FLC strategy efficiently reduces the oscillations in the barge-based FOWT-OWC platform, leading to decreased fluctuations in the generated power. Additionally, the FLC improves the platform's dynamic behavior, enhancing stability under a wide range of wind and wave conditions.

Moreover, AI-driven models and control strategies have been implemented. The integration of ANN-driven modeling and tailored PID gain-scheduling control strategies further advances the stability and efficiency of FOWT-OWCs platforms. This research highlights the significance of cutting-edge control methodologies in achieving sustainable energy generation and marks a substantial advancement towards a decarbonized future.

The results have been obtained using a sequence of software tools: MultiSurf, WAMIT, OpenFAST, and MATLAB-Simulink. MultiSurf is used first to create detailed 3D models of the floating structures. These models are then imported into WAMIT for hydrodynamic analysis, evaluating the interaction between water and structures. The WAMIT output is used in OpenFAST to simulate the dynamic response of floating wind turbines and oscillating water columns under various environmental conditions. Finally, MATLAB-Simulink is employed to develop and test the advanced control strategies mentioned above for hybrid systems, enabling the implementation of closed-loop control to stabilize the platform.

Performance comparisons have been made between barges based on controlled OWCs and traditional barge-based platforms. This dual approach combining advanced computational modeling with intelligent control mechanisms offers a robust solution to the challenges faced by offshore renewable energy systems. The findings highlight the potential of hybrid renewable energy systems in addressing global energy challenges, paving the way for future research in feedback control and offshore renewable energy technologies.

This thesis is structured as follows. Chapter 1: Provides an overview of FOWT types and wave energy converters, discussing the advantages and disadvantages of hybrid FOWT-OWCs systems. This chapter also summarizes the current state-of-the-art in FOWT stabilizing methods, followed by the problem statement and thesis goals. Chapter 2: Describes the computational regressive machine learning approach to the Non-linear complex FAST model for hybrid offshore platform. Chapter 3: Develops a comprehensive PID gain-scheduling approach to decrease system oscillations under diverse sea conditions and wind speed scenarios. Chapter 4: Presents the ad-hoc fuzzy control method to reduce oscillations in the hybrid FOWT-OWCs system. Finally, Chapter 5 presents some conclusions and future work directions, including the use of the latest software, such as WEC-Sim, to create a robust non-linear model. This chapter also highlights a case study developed in collaboration with Dr. Nataliia Sergiienko, Senior Lecturer at the School of Electrical and Mechanical Engineering, Faculty of Sciences, Engineering and Technology, University of Adelaide, Australia, where the doctoral stay was performed.