Abstract

Currently, a major focus in global research is on discovering efficient solutions for a carbon-free energy supply technologies. Over recent decades, the world's energy demand has risen considerably, making the production of clean and efficient energy one of the most critical challenges. Within the framework of renewable energy, ocean wave energy stands out as one of the most promising sources. With its vast, yet untapped potential, effectively harnessing wave energy could make a significant contribution to the overall energy supply. Despite the abundance of ocean waves as a resource, the levelised cost of energy for Wave Energy Converter (WEC)s still remains non-competitive compared to other renewable technologies, primarily due to the high costs involved in their energy conversion process. In this scenario, developing control strategies that maximize energy extraction is essential for the economic feasibility of wave energy technology. The objective of Optimal Control (OC) strategies in wave energy, is to maximise the energy absorbed by WEC devices while safeguarding all mechanisms involved in the conversion chain and adapting their operation to the continuously changing characteristics of the wave resource.

At the state of the art, the large part of strategies used to control WECs are designed exploiting a control-oriented models, which is the final result of simplifying assumptions on the systems' dynamical behaviour that could affect the quality, in a optimality sense, of the synthesised control action, or even cause faults in the system. Such faults, can compromise the operability of the systems and nullify the effectiveness of the energy maximising OC. Provided the nature of wave energy control-oriented modelling, the motivation behind this thesis is to contribute to the development of reliable, energy-maximising, and resilient control strategies, by leveraging Fault Diagnosis and Identification (FDI) and Fault-Tolerant Control (FTC) approaches, while enhancing the different actors inside the optimal control chain.

This thesis presents two major contributions. The first concerns the substantial improvement of OC strategies for WECs. In this part, after introducing a new modelling framework for WECs as Linear Parameter-Varying (LPV) systems, strategies are presented that significantly enhance the state of the art in wave excitation force estimation within OC. These strategies contribute to improving the experimental validation of wave estimators, refining the structure of the control strategies themselves by drawing on methods inherited from the field of FDI, and introducing a new estimation framework based on the design of set membership approaches for wave excitation force estimation in the presence of nonlinearities and uncertainty. Subsequently, the problem of improving control strategies is addressed, and a new regularisation methodology of the energy maximising cost function is introduced, together with a novel Model Predictive Control (MPC) that exploits high fidelity numerical simulations to synthesise the control oriented model and incorporate the effects of the mooring system dynamics of wave energy systems. Finally, a new type of energy maximising controller is introduced, developed on the basis of MPC and the previously presented LPV modelling of WEC systems, capable of optimally handling system nonlinearities while maintaining mild computational requirements and consequently being promising for deployment on real time targets.

The second part of the thesis concerns the development of FDI and FTC strategies for WECs. After an initial critical review of the state of the art that identifies possibilities and pitfalls of FDI and FTC in wave energy, a comprehensive FDI framework for WECs is developed, enabling the diagnosis and isolation of faults by generalising the approach to a broad set of wave energy systems, and thus introducing a unified strategy for FDI for wave energy devices. Finally, the integration of FTC systems with the energy maximising MPC strategies is developed and investigated on numerical cases, thereby proposing a framework of FTC OC for WECs. Additionally, it is presented an experimental study of the effectiveness of FTC strategies on the prototype of the Swinging Omnidirectional Wave Energy Converter (SWINGO) device tested in an experimental campaign.

The presented results obtained by enhancing optimal control, and using fault diagnosis and fault-tolerant control architectures applied for wave energy conversion systems demonstrate the potential of the proposed approaches in contributing towards the development of reliable, energy-maximising, fault-tolerant optimal control strategies.