WEQUAD FRAME

WES Control Systems Stage 1
Public Report

EPF Elettrotecnica Srl

This project has been supported by Wave Energy Scotland

1 Project Introduction

The issues regarding the control of a Wave Energy Converter (WEC) are widely known in the field. Models are approximate and often the hydrodynamic description comes in the form of system of integro-differential non-linear equations, usually coupled together. Moreover, given the nature of the resource to be exploited, the loads are often characterised by very high forces and torques with very low speed. To avoid the installation of expensive overrated electric and hydraulic devices (compared to the mean active adsorbed power), it is common to have the power take-offs (PTOs) working in saturation condition. These issues gave birth to numerous control techniques resulting to the application of as many control theories. Nowadays there is a remarkable gap between the control theory developed and the regulators actually implemented in real WECs. Several motivations can be found, but three are the principal: 1) many control theories involve complex mathematics concepts and numerical methods which are not easily handled by WEC development teams, which are often deprived of control specialists; 2) simple lumped-parameter numerical models are generally considered not advanced enough to ensure the reliability for model based controllers; and, 3) real-time forecasting of incident wave in a real sea environment is an unsolved problem.

In recent years however, the identification of nonlinear hydrodynamic viscous quadratic terms (along with their linearization) and the radiation term convolution integral state space approximation completed the framework for a generalized, simple and reliable lumped parameters WEC hydrodynamic modelling approach. Assuming this modelling method as sufficient, modern control theories can rely on their linearized state space approximation and it is thus possible to synthesise low computational demanding, simple and effective controllers.

The WEQUAD FRAME (Wave Energy converters linear QUADratic control FRAMEwork) project main aim is to apply the linear quadratic modern control synthesis principles to multiple WEC technologies to build a common control development framework for the PTOs power harvesting regulating control laws.

While working on the power harvesting control law, EPF is seeking to develop an overall SCADA (Supervisory Control And Data Acquisition) system, always following the same approach of creating a general framework, a structure, in which several WECs can find their optimal place. Creating a common framework will enable the sharing of short-cuts, standards and best-practices. The project primary aim is thus to create an optimal environment, made of methods and procedures, for the design, implementation and verification/testing of a WEC control system. The focus for the R&D activities will be the feasibility in all its facets and the performance optimization of the primary capture and the secondary conversion. Another fundamental aspect will be the integrability with specific WEC ad-hoc control solutions.

EPF Elettrotecnica Srl (EPF) and INNOSEA UK (INNOSEA) joined in the effort of providing a high-quality control systems developing framework, combining their different know-how in industrial automation, wave and renewable marine technologies. EPF works directly on the controllers' theoretic synthesis and on the design and development of a reliable and complete wave energy SCADA architecture; strong of its longer-term involvement in industrial automation and robotics applications acting as system integrator and enhanced by its wave energy R&D group experience. INNOSEA brings a long-term experience in marine renewables, offshore project management and critical review of project methodologies and outcomes. From a control systems point of view, INNOSEA provides the WECs hydrodynamic modelling environment and databases, fundamental for the synthesis of the model-based controllers and their verification/optimization in a faithful simulated environment.

2 Description of Project Technology

2.1 The SCADA system

Dealing with WECs power harvesting control strategies, the WEQUAD FRAME project applies optimal control theory to the wave power field, building upon a well-known contemporary line of research. The main aim of the project is to extend the current state-of-the-art and bring it to practical applications, possibly testing it in the sea environment. In Figure 1 a functional scheme of the overall control system is proposed. The coding environment and its implementation are orientated to be of easy interface with external sources. Higher level controllers or advanced optimization algorithms could thus further upgrade the WEQUAD FRAME SCADA structure. For Stage 3, when the control architecture is expected to be applied to an existing WEC in sea or at least to some relevant environment scale prototypes, it will be required to have external input regarding the current wave state. This can be managed both by buying a service or interfacing with other WES projects about identification and forecasting sea state conditions.

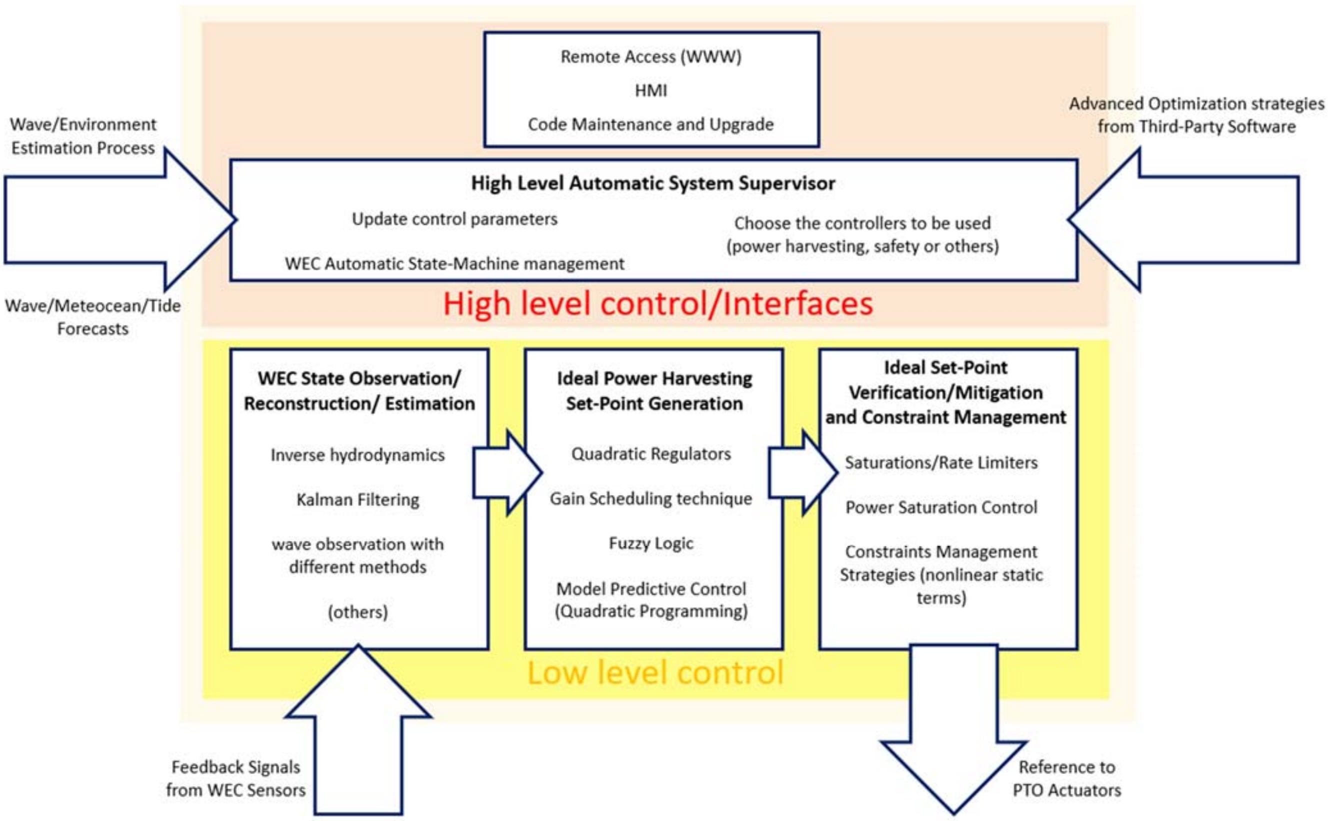

Figure 1 - WEQUAD FRAME project overall control architecture - functional scheme.

Looking at the control architecture scheme, at the top there is the high-level layer, where there are remote access functionalities and the human machine interface (HMI). Another part of the structure that is transversal with the whole control system and dialogues with all the subsystems is the High Level Automatic System Supervisor, the whole part of the code devoted to the automatic management of the device, once live and functioning. This system is responsible for receiving the external parameters and inputs, both from the WEC via sensors and from other remote or physically connected systems, and to change the active control loops according to the state machine operational state. It is the responsibility of this controller to set the control parameters for the lower-level real-time process controller. This lower level controller also receives the measurements from the physical sensors. Its first task is to reconstruct/estimate the overall state of the device, also exchanging information with the higher-level loop. After having estimated the current WEC state, it is possible to compute the ideal power harvesting set-point. Before sending this force/torque reference to the PTO actuators/drives, a verification of the set-point is carried out. Some constraint management strategies, control action smoothing filters and other mitigations are implemented. The last task of the lower level control is to send this information to the PTO system (hydraulic, electric, etc.).

Summarizing, the main functionalities expected by the control system are:

- Computation of the PTO ideal power harvesting control action.
- Verification and mitigation of the computed control action.
- Avoidance of risky conditions, safety procedures.
- Automatic management of the device operations.
- Automatic adaptation of the control parameters to the current sea-state for optimising the power adsorption.
- Condition monitoring enabling preventive maintenance.
- Data acquisition and storage.
- Device real-time status monitoring and alarm system.
- Automatic software fail-safe procedures.
- Remote access and Front-End/Human-Machine Interface.

2.2 Power Harvesting Control Strategies

To build a framework common to all converters, different applications of the main theoretical principles of modern optimal control theory will be developed. A general overview of the expected applications is presented:

- WEC with resistive control/PTO: Linear–Quadratic–Gaussian (LQG) synthetized with the standard hydrodynamic model.
- WEC with reactive control/PTO: LQG synthetized with an augmented model obtained introducing a second order system for modelling the wave incoming force.
- WEC with position/speed controlled PTO (turbine, PTO with rotating mass): LQG synthetized with an augmented model obtained introducing the integral of the speed set-point tracking error.

All these control strategies share the linear quadratic control development framework and the methods for designing the objective cost function to be minimized during the regulators synthesis.

In optimal control theory, the most challenging part is to find the “correct” cost function weighting parameters. The WEQUAD FRAME working method is to link the highest number of parameters to physical constants characterising the system and leave no more than two parameters to be regulated/tuned to obtain the desired performance. In this way, the person in charge of operating/tuning the device has only few parameters with a strong physical meaning to act on.

Constraints management terms are proposed for completing the online PTO set-point computation. These complete the integration with the overall control of the WEC (e.g. development of bump-less transitions with the safety position control). The developed strategies in numerical simulations proved to be robust and reliable with low computational demands. In fact, this solution can be synthetized offline and then implemented in simple look up tables form, without requiring significant computational burden or unexpected online unstable control actions.

3 Scope of Work

The Stage 1 of the project aimed at assessing the feasibility of the proposed power harvesting control strategies and to verify their hardware feasibility. The activities were broken down in three main work packages (WPs):

- “*Technologies Definition and Modelling*”: the EPF-INNOSEA work-team aligned through the modelling environment and a couple of technologies were chosen as test cases for the application of the WEQUAD FRAME control systems. Given the key fundamental of having a linear/linearized model of the WEC, a literary review about PTO modelling capabilities and the possible linearization methods was carried out. The INNOSEA InWave hydrodynamics software modelling hypotheses were discussed and the software potentialities assessed. Lumped parameters time-domain numerical models were setup for the following testing phase.
- “*Feasibility and Demonstration*”: during the activities of this WP the control systems were synthetized and implemented in the two WEC numerical models. Both resistive and reactive resonance controllers were implemented. Their feasibility and a first qualitative evaluation of the controllers’ robustness were assessed. A complete software-in-the-loop architecture communicating in real-time with the industrial hardware that could fit a real WEC installation was tested, for demonstrating the practicability of the proposed solutions.
- “*Synthesis of the Project Outcomes/Organization of Following Steps*”: During the last part of the project a synthesis and evaluation of the activities carried out during the previous activities was carried out. Several contacts with WEC developers were performed, bringing an interesting contribution in terms of requests/specifications that helped to enhance and clarify the structure of the overall SCADA system.

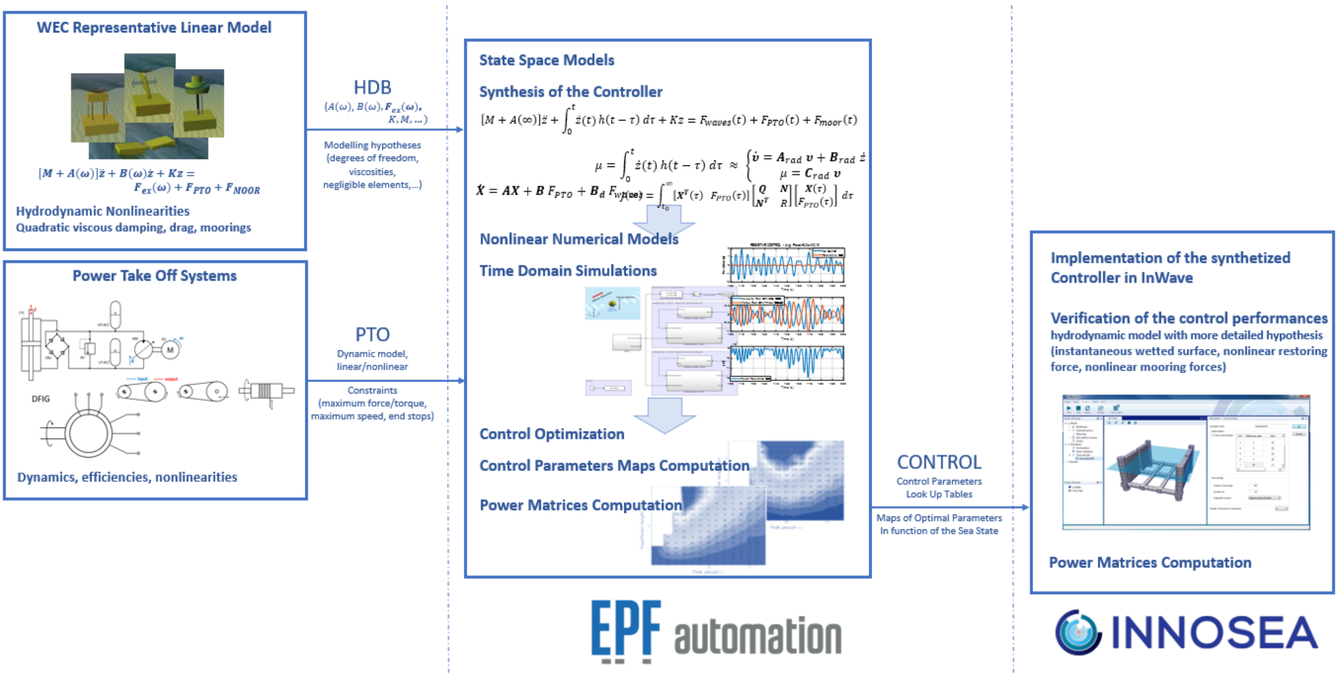

Figure 2 – Schematization of the control synthesis and verification work-flow

4 Project Achievements

The project main achievements are synthetically presented in the following.

- Feasibility verified for a point absorber.
- Feasibility verified for a floating oscillating flap device.
- Development of a control synthesis and verification procedure.
- Identification of automatic system management state machines for the application cases.

- Development of a shared common standard of data exchange (hydrodynamics, control code).
- Feasibility verified for a PLC-PC control hardware architecture.
- Creation of a PTO lumped parameters, time-domain, linearized models archive.
- Creation of a shared synthesis/development/verification methodology among project partners.
- Effective contacts with technology developers (WEC/PTO) for the next Stage 2 project proposal.

Considering the limited time horizon and scope of the project, it is possible to highlight some points that could have improved the project outcomes.

- The presence of WEC developers providing more detailed inputs about constraints, operations and functional requirements of a real device.
- The early involvement of WEC developers could have impacted positively also through the availability of more detailed numerical models for carrying out the feasibility studies.
- There was no availability of a ready-to-use OWC numerical model. This impacted negatively the project, because the application for position/velocity controllers was tested only for a simplified application case.

5 Recommendations for Further Work

Key activities required for continuing the development of the proposed control system toward its commercial applications are all related to the testing and validation of the technology. The numerical feasibility of the proposed oscillating power-harvesting control strategies was verified through the project, the next natural step is to verify it for real WECs and PTOs applications. This will require the synthesis and optimization of the control parameters with time-domain numerical simulations and then to implement the proposed controllers for tank or sea application cases. Concurrently, there will be an effort of design a modular and flexible control hardware/software environment, where it will be possible to integrate different technologies.

6 Communications and Publicity Activity

For this short-term Stage 1 project there was no public communications activities other than a news item on the company's site. A paper coming out from the feasibility studies was submitted to the International Conference on Ocean Energy, that will be hold in Normandy (France) during 2018.

7 Useful References and Additional Data

A deeper knowledge of the contents summarized in this report is contained in the *confidential* reports submitted as deliverables of the WEQUAD FRAME Stage 1 projects.

Deliverable #	1	
Document Name:	WES:	EPF_CS11_D01_[17188 RT_00-A - WEQUAD FRAME]
	EPF:	17188 RT_00-A
Title:	*Technical Report dealing with the Wave Energy Converters to be studied in the project. Technology and Modelling approach is discussed.*	
Date:	06/11/2017	

Deliverable #	2	
Document Name:	WES:	EPF_CS11_D02_[17188 RT_01-A - WEQUAD FRAME]
	EPF:	17188 RT_01-A
Title:	*Technical Report dealing with the Feasibility and Demonstration Studies of the WEQUAD FRAME Project Control Strategies.*	
Date:	06/12/2017	