Control Requirements for Wave Energy Converters Landscaping Study

Final Report

WES_LS04_ER_Controls

Revision	Date	Purpose of issue
1	18/07/2016	WES External Issue

PROJECT PARTNERS:

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Glossary of Abbreviations

CAPEX	Capital Expenditure
CE	Conformité Européene
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
DDPM	Digital Displacement hydraulic Pump-Motor
dof	Degree of freedom
EMEC	European Marine Energy Centre (Orkney)
EMI	Electro-Magnetic Interference
FIR	Finite Impulse Response
FMEA	Failure Modes and Effects Analyisis
GCC	Grid Code Compliance
GW	GigaWatt
HMI	Human-Machine-Interface
HP	High Pass filter (in control signals) OR High Pressure (relating to fluid power)
I/O	Input/Output
IEC	International Electrotechnical Comission
IR	Impulse Response
IRR	Infinite Impulse Response
kW	kiloWatt
LCoE	Levelised Cost of Energy
LP	Low Pass filter
MATLAB	MATrix LABoratory - a commerical numerical computing environment
MIMO	Multi-Input, multI-Output
MTBF	Mean Time Between Failure
MW	MegaWatt
NWEC	Novel Wave Energy Converter', as in WES's second competitive call

O&M	Operations & Maintenance
OPEX	Operating Expenditure
OWC	Oscillating Water Column
PI	Proportional Integral (controller)
PID	Proportional Integral Derivative (controller)
PM	Pierson Moskowitz - a particular idealised parametric description of sea-state
POC	Point Of Common (connection in electrical networks)
PTO	Power Take Off
R&D	Research & Development
STATCOM	STATic synchronous COMpensator
TPL	Technology Performance Level
TRL	Technology Readiness Level
UPS	Uninterruptable Power Supply
USDoE	United States Department of Energy
WEC	Wave Energy Converter
WECsim	open source Wave Energy Converter simulation suite in MATLAB
WES	Wave Energy Scotland
WMI	Wave Measurement Instrument

1 Executive Summary

The Scottish Government through Wave Energy Scotland (WES) is delivering a programme of carefully structured and staged R&D designed to help direct the nascent wave energy industry onto a road to affordability.

The control of forces, motions, power transmission, and auxiliary systems is a fundamental requirement of any wave energy converter (WEC) system and is should be considered integral to the entire concept and design development.

WEC control has a number of very specific challenges and functional requirements. The aim of this landscaping report is to describe these requirements in both generalised and control-centric terms so as to engage strongly with the wider control engineering community. It is the first major report to take this approach.

The report provides a wide-ranging foundation upon which WES can formulate a programme of R&D. The report is also intended to offer direct knowledge and insights to researchers who are developing WEC primary converters and/or power-take-off (PTO) systems, particularly those working in the WES programme.

WES's strategy is to focus efforts on system and sub-system aspects that have a clear mapping to the core metric areas of performance, reliability, survivability, cost-base and practicality, each of which has a strong influence on levelised cost of energy (LCoE) i.e. affordability. Control has a direct influence on all of these and is thus a core consideration in system development. Most of the important control functional requirements can be deduced from and mapped to one of more of these core metrics. Control of structural, hydrodynamic and power train loads for instance has a clear influence on survivability (and thus capital cost) and on system performance. It is possible to design WECs that can absorb over a broad range of wave frequencies with very little need for fine control. However, such WECs may be bulky and thus expensive. Other forms may have a narrowband response and poor production unless controlled in a more complex manner. There is thus a strong conceptual trade-off between control and structural/hydrodynamic design and an acceptable balance must be stuck between viable control and device bulk and cost.

As yet there has been little design convergence in the industry and, although there are a number of different families, each device tends to have its own unique combination of sub-systems. In developing control functional requirements, it is appropriate to take a generic, high-level approach, suitable for interpretation with respect to the wide range of WEC concepts and designs, rather than attempt to develop a different set of requirements for pre-defined sets of WEC type, size, machinery, etc.

A WEC will typically comprise a primary converter interacting with the wave field, a power-take-off (PTO) providing a working load path to the primary converter while passing power to an electrical system, potentially via smoothing storage. A station keeping system and electrical collection systems for multiple units will also be present.

Although embodied in integrated hardware, the control system will include high level supervisory/diagnostic functions and low level, real time dynamic control processes handling the wave-by-wave forces, responses and power flows. It is the latter which form a unique challenge.

The vast majority of WECs function on (hydro)dynamic response principles, with the stiffness, damping and inertial characteristics reflecting the unique geometry and dynamics of the particular design. The WEC geometry and mass properties define the intrinsic hydrodynamic interactions with the waves, while the control system may act through the power-take-off system (and potentially by directly altering the WEC hydrodynamic properties) to influence the overall system dynamics, and hence the power capture, loads, and motions, in response to the wave conditions.

In most WEC systems, the plant under control is the WEC primary converter and control is exercised by the PTO. Analogous to power transfer in electrical circuits, the external impedance is associated with the primary converter geometry and mass properties, defining the hydrodynamics. The internal impedance is associated with the PTO under control. Such a general arrangement crops up in many braches of mechanical and electrical engineering and a control solution for maximum power transfer based on complex conjugate matching of the controlled impedance to the source is familiar. However, the implications of finite load and motion constraints make such a solution generally impractical for most WEC designs and conditions. The control optimisation problem is therefore subtle and highly interactive with other design features.

At present, few proposed WECs are controlled through changes to the external impedance terms – i.e. it is unusual to alter the physical attributes of the primary converter. This is quite unlike wind turbines where power regulation is now almost universally based on changing geometry by pitching the blades. There is much promise however in exploring such front-end control for WECs.

While many other systems must be controlled under stochastic and spectral excitation, WEC operation and control is distinct from most other dynamic systems because the hydrodynamic coefficients are frequency dependent. The importance of this to the control optimisation problem depends on the WEC characteristics.

Any response control requires an accurate system model. Transforming the system equations of motion from the frequency to the time domain introduces convolution integrals which represent a significant calculation overhead in any real time control implementation and which would pose major challenges in the application of standard control methodologies. It is possible to create an approximate state space representation suitable for the industry standard development tools and real time implementation.

The ability of the PTO to apply loads under control define the capability of the control system to influence the WEC response and hence power capture. A particular PTO system may be constrained or inhibited in its ability to apply loads independently of the direction of travel, with severe implications for the WEC control. While PTOs have been demonstrated offering four-quadrant operation (forces applied independently of motion, and able to apply resistive and reactive control terms) other non-linear control strategies have been proposed to achieve acceptable performance despite the constrained performance of other simpler PTO systems and WEC concepts, including coulombic damping from passive pumping systems, and ‘latching’ to shift phase of response without reactive power..

There are significant practical and analysis challenges in implementing effective control. Although some fixed reference WECs such as breakwater Oscillating Water Columns (OWC) and pitching flap devices have a single degree-of-freedom, most proposed devices are multi-degree of freedom with many also being multi-body with multiple controlled degrees of freedom. As we move from one to multiple degrees-of-freedom, system (hydro)dynamic coefficients are replaced by coefficient matrices with non-zero, off-diagonal terms, representing coupling effects.

In terms of the physics, linearity breaks down as waves become steeper whilst hydrodynamic coefficients also exhibit non-linearity as response excursions increase.

More practically, there are typically constraints on WEC or PTO motions and forces that mean idealised targets cannot be met. WEC control is inherently high gain due to the high force, low speed environment, meaning that effective control can be susceptible both to signal noise and to structural flexibility in the load paths which for control sensors can mask underlying velocities and accelerations.

Taken together, such issues can erode significantly the theoretically attainable performance to more modest practical levels.

The complexity and highly variable environment of the wave energy real time control challenge makes it a compelling potential candidate for machine learning/neural control methods.

Wave energy capture may be described in terms of the forces and motions at the WEC (the impedance model), or equivalently in terms of the far field interaction of waves incident on the WEC and the waves radiated and diffracted by the WEC (the far field model). The optimisation of power capture may be framed as either the matching of the internal and external impedance across all frequencies, or as the maximised cancelation of the incident, diffracted and reflected waves with the waves radiated away from the WEC as a result of the WEC motion. The impedance model lends itself to practical control implementation, while the far field approach offers fundamental insights into the theoretical limits of power capture of different WEC types, and the relationship between the ‘wave making’ capability of the WEC and its ability to absorb waves

Some WECs have PTOs that tightly couple the primary converter to the electrical generator. Examples are direct drive linear generator PTOs and some OWC systems with fixed geometry pneumatic turbines. In these cases, control of the WEC can be exercised entirely through the generator. However it is more typical and more desirable to adopt slack coupling by including storage in the PTO power train - a common feature in hydraulic PTOs. The energy storage accumulator decouples the generation system from the absorption process, allowing rapidly fluctuating and reactive power transfer associated with the wave energy absorption process, while providing the averaged smooth power to the generation system. This enables efficient wave energy absorption including reactive control (including mass and spring terms) while allowing smooth power to be supplied to the generation system, in turn allowing reduced electrical rating and cost. The energy storage and smoothing process can usefully be modelled as a low pass filter, with a smoothing time constant being a function of the size of energy storage, again emphasising the interactive nature of control system development and overall design development. Idealised storage and generation control would be non-causal as knowledge of future waves would allow stored energy to be run down or built up in anticipation of the energy capture over the future few minutes. Storage design and control is driven more by the wave groupiness than by the short-term peak powers, which drives required storage capacity to low minutes rather than a few seconds. Smoothing action and short-term energy storage help greatly in allowing WECs to meet typical grid code requirements.

A well-managed approach to control system architecture and development is essential to successful deployment and integration. Unless designed to be modular, expandable and maintainable, the control system will be difficult to manage during development and deployment. A balance must be struck between centralised and decentralised functions. The system must handle with suitable robustness and redundancy all necessary real time and supervisory functions, both being supplemented with diagnostics. Basing the system upon commercially available, proven, suitably specified elements is highly recommended, as too is fulsome adherence to established control communication standards.

Adopting an integrated approach to control system development, linking simulation, potentially tank testing and implementation directly to one another is also recommended and helps greatly in modular upgrading and ongoing improvement.

Sensors, whether directed at the wave field, the primary converter or the power train, deserve particular attention. Modularity and compatibility are, as far as possible, required to minimise problems. System diagnostics should extend to the sensors with redundancy being a useful starting point for system reliability and improved measurements. Development of new generations of sensors and communications technology bring with them the prospect of much more comprehensive, real-time data than hitherto, such as in defining the hydrodynamic WEC surface pressure field.

Functional requirements must extend to meet the needs of assembly, commissioning, dockside maintenance, deployment, and recovery. The human-machine-interface (HMI) system should also be considered very carefully for the full range of end users. Development stage WECs are prone to failures and require careful and intensive monitoring. To ease the burden of data overload, the HMI and its alarms, data streaming and presentation systems should be designed with the operator in mind.

There is already significant practical experience in the industry in the development and roll-out of control systems for WECs covering both real-time algorithms based on complex control theory and the practical aspects of implementing both high and low level systems. The industry should not ignore lessons already learned.

However, there is also much still to be learned and no shortage of promising control avenues to be explored in the ongoing quest for wave energy affordability.

2 Introduction

2.1 Wave Energy Scotland's R&D programme

Despite many years of technical development, there is still insufficient evidence that wave energy will achieve commercial affordability. The sector continues to search for the most promising direction, witnessed by a plethora of device ideas and a lack of technology convergence. A number of concepts have been taken to large scale demonstration, but lack of a clear pathway to cost-effectiveness and competitiveness has inhibited follow-through investment.

WES is a Scottish Government initiative designed to address these failures by establishing a technology development programme that addresses 'technology performance levels, TPL' (effectively a measure of likelihood of achieving affordability) as well as 'technology readiness levels' (TRL) through a structured R&D programme.

Two major open competitive calls have been held for development of power-take-off systems and for early stage development of novel wave energy converter (WEC) ideas. These are areas of high relevance to long term affordability.

Other areas of high significance to affordability include materials, structural loads, control, and technology transfer from other sectors. Rather than launch further open R&D calls in these areas, WES has commissioned landscaping studies to help inform status, needs and R&D strategy. In terms of control, a two stage process is being followed with the first stage defining and clarifying the sector's functional requirements for control and the second stage identifying promising control solution R&D directions, potentially drawing upon other sectors.

The present report is the outcome from the first stage of the control study.

2.2 Readership

The report aims to meet the needs of three stakeholder groups.

Firstly, the Stage 1 'functional requirements' landscaping is intended to form a foundation for the subsequent Stage 2 'control solutions' exercise, which will reach out beyond the wave community. The present report therefore tries to define sector requirements in a form that can be understood throughout the wider world of control engineering.

Secondly, since WEC control determines how a power-take-off system's dynamics interact and influence the hydrodynamic performance of the primary converter, it follows that researchers working in either discipline (specifically WES's existing family of contractors) have a good knowledge of the functional requirements of controlling that interaction.

Thirdly, the report aims to help steer WES's initial thoughts on control system R&D needs.

2.3 Scope

The report addresses the broad topic of control of wave energy converters. The aim is to convey a comprehensive statement and explanation of the functional requirements and scientific targets that need to be satisfied for a WEC control system to be effective.

WEC control is a challenging topic but is more readily assimilated if the context for control is understood. Chapter 3 provides that foundation, developing the theme of control functional requirements in a number of ways.

Firstly in Section 3.2, it is shown that all of the main control requirements for WECs are closely mapped to the metrics that influence cost of energy, these being performance, availability/reliability, survivability, cost base and practicality. The metrics are central to the way in which Wave Energy Scotland assesses the merits of all R&D proposals across all aspects.

In Section 3.3, control functionality is discussed at a high level in terms of the sub-system that control is seeking to influence (the primary converter) and the sub-systems that control is generally expected to be exercised upon (the power-take-off). This provides a platform for more in-depth discussion of control later in the report. Significantly, the separate concepts of high level, supervisory and low level, real time control are introduced. Both are important and relevant to the control requirements landscaping study, but the latter is what sets wave energy apart from other renewables such as wind in both opportunity and challenge.

In Section 3.4, it is argued that control requirements may be generalised but not given specifically for all possible WEC types. Within the high level WEC families lie design choices which can greatly influence both the detail of the functional requirement and the ability of that requirement to be met.

Notwithstanding this, it is shown in Chapter 4 that a generalised mathematical approach is both possible and insightful when developing an understanding of the control functional requirements and how they relate to economic related outcomes such as energy absorption and costs of equipment. The chapter presents some of the fundamental system physics of wave energy, including showing how the governing equations, which due to frequency dependant coefficients can otherwise be rather cumbersome to work with computationally, can be re-expressed and approximated in the time domain in a form that is control friendly. It is shown how energy yield may be maximised by controlling the impedance of the power-take-off dynamics to match the intrinsic hydrodynamics, and how this approach must be adapted in practice to take account of uncertainties in the inputs, approximations in the system model, and constraints in response excursions or loads. Chapter 4 is presented in a form that is targeted at the control engineer rather than the hydrodynamicist and is possibly one of the first major wave energy reports to do so. This emphasis leads to practical insights of importance to the development of control systems for implementation on real systems.

Although for most WECs, the central control challenge relates to the low level control that the PTO exercises over the primary converter, there are other elements in the power chain that require a real time rather than supervisory approach. Chapter 5 deals with power conditioning, specifically an examination of drive train energy storage, presenting the functional requirement and the mathematical model in the control familiar form of a low pass filter.

Those wave energy technology developers who have deployed devices at larger scale in the real sea have demonstrated that the low level, real-time control functional requirements, although rightly forming a strong TPL focus, are not the only challenges that WEC control must meet. Practical considerations and high level, supervisory functional requirements are also essential to successful deployment and operation.

Chapter 6 looks at the practical requirements and processes that must be met in an effective implementation of real time control. Topology strategies are covered as are sensing systems and communications.

Chapter 7 focusses on high level control requirements and touches upon information gathering, interpretation and presentation. Key aspects are diagnostics and effective human-machine-interfacing. Monitoring and interpretation of prevailing sea state and real time wave conditions seen by the WEC are clearly inputs of fundamental importance to the WEC system. The challenges of estimating these inputs are described.

Chapter 8 provides some guidance on how the control system should be developed in parallel with the wider system and develops the theme of control system and overall system design being strongly inter-related.

Chapter 9 draws together various aspects of the report with some overall conclusions.

3 Context

3.1 The Control Challenges of Wave Energy

Technically, even the simplest form of WEC (such as an inshore OWC or surge flap device) is a complex, inherently highly non-linear system displaying strongly coupled interactions between the wave climate, the hydrodynamic prime mover and the power-take-off. Effective control requires a full understanding of input conditions, expected response characteristics and of target states. Inputs can be difficult to measure and interpret in real time, hydrodynamics are inherently more complex than fixed body dynamics, and there are complex interactions in response. Comparisons with wind energy quickly show the relative importance of control in achieving economic outcomes, and the level of challenge.

WECs are proposed with many different operating principles with numerous ways of classifying them: fixed/floating, inshore/offshore, terminators/attenuators/point-absorbers relying upon pitching/reciprocating/bulging/blowing/ articulating prime movers having single/multiple degrees-of-freedom and single/multiple bodies. The classifications are generally unhelpful in a control context where the generalised system dynamics and control strategy are of greater importance than particular physical manifestation.

As a broad generalisation, devices with better long term potential for affordability pose greatest control challenges in terms of meeting performance, reliability and survival requirements. Control orchestrates the wider system to work in concert as a successful operational platform, with particularly demanding control being required for WEC concepts with higher potential absorption capability per unit mass. As in many familiar applications, control must have absolute robustness and fault tolerance otherwise the system can quickly be taken out of its design envelope and put in danger. The fact that WECs are designed to operate unattended in remote and hostile environments compounds the control challenge. Compared to other renewables such as solar, wind and tidal, control of WECs has a far more critical function and has greater affinity with the space and aviation sectors.

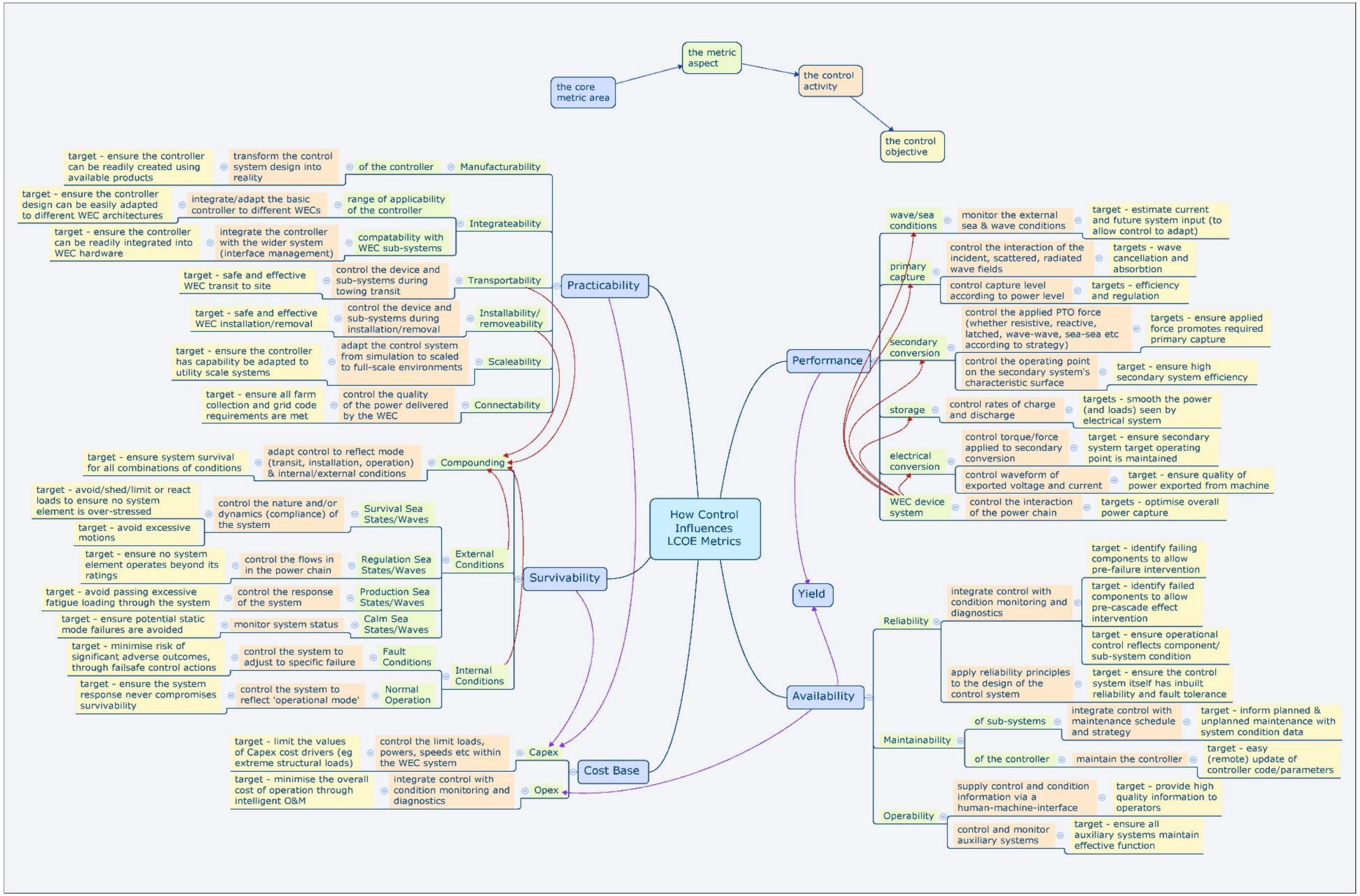
3.2 WEC Control and Influences on Levelised Cost of Energy

In setting priorities, designing programmes, assessing proposals and evaluating project outcomes, Wave Energy Scotland has developed a framework that focusses on potential impact on medium-term affordability. It has been concluded that for levelised cost of energy (LCoE) targets to be met, prospectively £150/MWh in a market that is several GW's mature, contributory technologies must have a positive profile across a range of sub-metrics. These cover performance (the ability of the technology to enable high system power capture and delivery), availability (the ability of the technology to contribute through reliability and otherwise to high production uptime), survivability (the ability of the technology to help the system endure the harsh marine environment), cost base (the ability of the system to contribute to capex and opex costs that are similar to competing renewables) and practicality (the ability of the technology to contribute to making the overall system viable and safe at all stages in the lifecycle).

Control is fundamental to realising a system that has a positive profile across all of these metrics and thus must be a central consideration in the drive to affordability.

In terms of setting high level, generic functional requirements for wave energy, it is possible to take each of the five metric requirements and to identify necessary control activities that must be undertaken and control targets that must be met to ensure the required positive profile.

This is done in the map given as Figure 1. For simplicity, the map shows the metric with which the control requirement has strongest affinity but there are also major interactions between many of the control requirements that offer secondary, positive economic outcomes. For example, power smoothing in the power train is a direct requirement for grid compliance but also influences the system's capex balance including the ability to reduce the rating and costs and improve the capacity factor of the entire electrical system.



- Figure 1 Control and its Influence on Levelised Cost of Energy

3.3 WEC Control - Engineering and Control Systems and Sub-Systems

3.3.1 Introduction

This section provides a descriptive overview of the system context for control for wave energy conversion systems ahead of the more generalised and mathematical treatment of Chapter 4.

3.3.2 A high level view of the context for control

An overall schematic map of the physical elements of a WEC system is provided as Figure 2 showing also the core high level supervisory and low level real time control processes. These will already be familiar from the LCoE contextual discussion of Section 3.2. The schematic provides the basis for more detailed control schematics in Chapter 4.

A generalised control system for individual wave energy converters operating within an array may be described with respect to the separately definable sub-systems that are under control, and also the different processes and sub-systems that make up the control system itself. This modular approach allows the function and hence the functional requirements to be described, along with important interactions. The sub-system level functional requirements may also be related to the operational and economic outcomes.

In the figure, ‘plant’ is grouped together on the right in the green boxes, split by the generalised stages of conversion, these being the:

- Primary converter: the hydrodynamics of the WEC structure and the radiation/absorption interface where energy is exchanged with the sea.
- Secondary converter: the power-take-off system resisting and reacting to the wave induced motion, absorbing the power into the WEC for conversion to electricity.
- Tertiary Converter: Generation and conditioning systems converting the energy to electricity and exporting it to the grid.

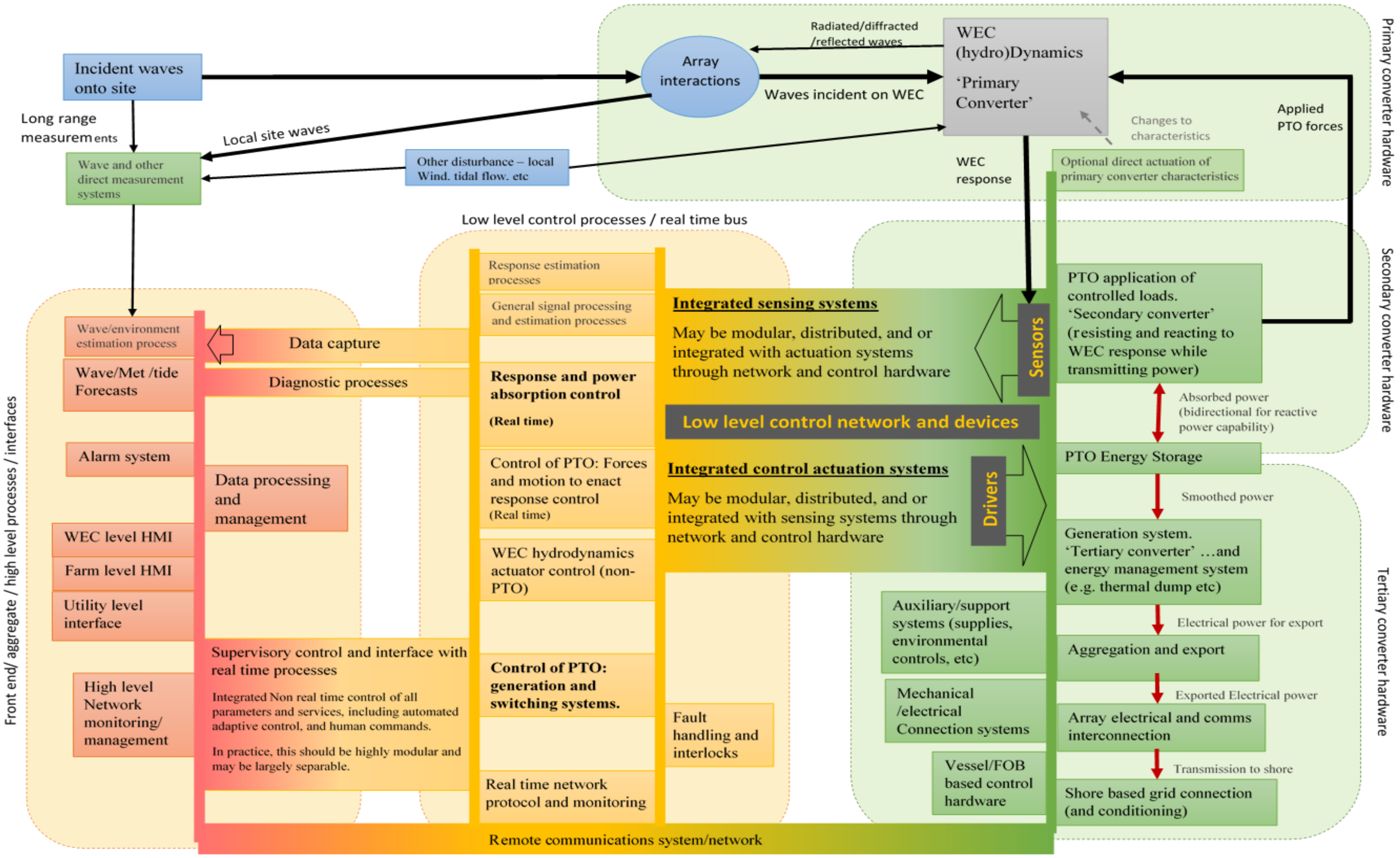
The flow of power from absorption to export is shown with red arrows.

The control system is loosely distinguished from left to right (and from red to green) into high level and low level processes and interfaces with the levels being distinguished as:

- High level: Supervisory control and human interfaces, non-real-time processes (although still including rapidly updating ‘live’ processes, directly interacting with real time control), alarm system, data handling and post-processing.
- Lower level: Real time processes and input-output, measurement and real time signal estimation, response and generation control algorithms, real-time signal processing, data capture.

The highly interconnected nature of the control systems is illustrated with lines showing busses of communication and I/O. This schematic therefore does not show explicit control signal paths but rather the framework required for them to operate. However, signal paths and more detailed models are described for the response and generation control processes in other sections (Chapter 4 for dynamic control and Chapter 5 for storage control).

In the low level control hardware, an integrated system of sensors and drivers and real-time communications links the control system processes to the WEC hardware. These control processes may run on a combination of hardware/firmware and software, and potentially be implemented with distributed devices running processes in parallel while in real-time communication. For example sampling of transducers and signal conditioning may be implemented on local control hardware and firmware, making the inputs available to the control algorithms running on a central processor via a real time control network. Similarly a mixed control topology with centralised and localised elements can be used for interpretation and driving of the resulting control outputs to the WEC machinery. In a physically small and/or centralised WEC (e.g. a heaving buoy), conducive to short cable runs, the I/O control devices may be housed alongside the central processor to avoid the need for local communication network cabling.



- Figure 2 A Structure for Control of Wave Energy Converters

3.3.3 Hardware under control

3.3.3.1 Introduction

The WEC hardware is loosely described in terms of sub-systems along the energy train from the waves through to export of electricity. While this description is generally applicable, not all subsystems exist or have the same role in all WEC types.

3.3.3.2 Primary converter

This term is used to describe the WEC structure and mechanisms in direct interaction with the waves, acting in concert with the secondary Converter (the power-take-off) to absorb power.

WEC hydrodynamics

A primary function of the control system is to influence the response of the WEC(s), generally to maximise power absorption dynamically within a number of constraints on motion, loads, wear, fatigue, etc to meet the overall economic requirements of the system. However, the dynamics of the WEC are expected to be primarily a function of the WEC's physical characteristics.

The control functional requirement for a specific WEC is therefore intrinsically linked to its design and operating principles. However, the general mathematical framework for modelling WEC dynamics may apply along with a number of general principles as discussed in Chapter 4.

WECs able to achieve a broad frequency response through their intrinsic hydrodynamics may have less requirement for the PTO to tune the frequency response actively than do narrow band devices with natural frequencies away from the wave resource.

Inertia driven concepts (for example, submerged surging flaps) may generally be expected to rely on high excitation forces rather than a resonant phased response, reducing the requirement for reactive mechanical power to correct the phase of the response.

Direct actuation of WEC hydrodynamics

The WEC response and interaction with the waves may be influenced directly by systems able to alter the external hydrodynamic properties. For example, changes in the external geometry or mass properties may be enacted. These could be controlled either between discrete states in adaptation to changing conditions (for example, in moving from a good power capture to a survival strategy) or potentially in real time as in, for example, moving the centre of gravity or continuously varying the geometry.

WEC response may be altered by sub-systems that apply internal forces not associated with power transmission, for example dedicated mechanical negative spring actuators or dynamically adjusted coupling of effective rotational inertia. These may be under varying levels of control sophistication and may be real time or slowly adaptive. The distinction is lack of direct energy exchange with the PTO train.

3.3.3.3 Secondary converter

This describes the primary transmission of the power-take-off i.e. the actuation system resisting and reacting to the wave induced motion of the primary converter and transmitting energy from (and to) the waves via the primary converter and the energy storage and electricity generating system.

The control system is expected to play a very important role here as it is through control of the loads applied through the PTO system that the WEC response and absorption may be controlled and optimised.

Depending upon the overall WEC design and control philosophy, it is possible and may be appropriate for this system to operate without or with limited active control of the loads, for example by using fixed mechanical systems with fixed impedance characteristics such as a Wells turbine (for low pressure, air pumping devices) or simple non-return valves. However, without mechanical wizardry of considerable complexity, such systems can be sub-optimal and not able to realise fully the potential of the rest of the WEC structure and systems. In contrast, fully active and continuously variable load control allows optimal absorption to be achieved within the engineering constraints of the WEC (e.g. load limits, motion limits, gain limits). Systems have been proposed that offer a degree of active control as a compromise between engineering and control complexity and performance.

The background to the response control topic is very briefly summarised in Section 3.3.4.2.

3.3.3.4 Energy storage

The instantaneous wave power incident on the WEC, and absorbed by the power-take-off, fluctuates wildly between waves and between wave groups. Ratios of peak to average power of well over fifteen to one are normal, with the variations occurring over seconds.

Generally the power absorbed through hydrodynamic interaction is passed through an energy store prior to conversion to electricity and export to:

- avoid excessive rating of the electricity generating and transmission system,
- enable reactive power to be returned to the absorption system, and
- allow smooth output.

In the case of direct electrical production in the secondary converter (primary PTO transmission) such as through a directly driven linear generator, energy storage could be placed downstream of the electricity generating system, alternative to the illustration of Figure 2. However, the role of energy storage is the same and has similar control requirements.

Control functionality is required for managing the energy storage system, monitoring the hardware elements to provide diagnostic and process inputs and controlling the attached systems to use the energy storage to best effect in maximising absorption and conversion efficiency whilst smoothing output.

3.3.3.5 Tertiary converter

This describes the generation and energy management systems as well as the aggregation and export systems required to deliver electricity to the grid.

Electricity generation hardware

The electricity generation system may be quite conventional if fed via a smoothing energy storage system or, alternatively, generation could be an integral part of the initial conversion process as in an electrical direct drive. In the latter case, energy storage and smoothing would still be required downstream for cost effective aggregation and export to the grid.

The control requirements for this system relate to continuous power smoothing (management of energy storage), start/stop/switching systems, maintaining optimal efficiency, and meeting grid code compliance. Diagnostics also play an important role in maintaining availability.

Auxiliary systems

Auxiliaries include power supplies and controllers, back-up systems, thermal management, diagnostic and monitoring sensing systems, maintenance/tooling systems, etc. These systems are likely to evolve substantially during development of new WECs and the control system requires sufficient headroom, I/O capacity, and flexibility for integration and adaptation.

Robust heat rejection systems are required for conditions of excess power absorption or in fault conditions where absorbed power may not be exported. These may be passive in nature but are likely to involve some form of active control depending on the type of power-take-off system.

Aggregation and export (transformers and switchgear)

Although topologies will vary, the transmission of electricity from individual WECs to a central substation will require connection to inter-array cables and is likely to involve step-up transformation and isolation switchgear. The mains circuit connecting the WECS together in the farm requires monitoring and protection systems, and isolation capability for handling individual WEC removals/intervention. Array electrical networks might comprise subsea transformer hubs, with or without integrated switchgear.

Remotely operated and subsea systems rely on the control system for monitoring and control, and the application of robust interlocks.

Grid connection and conditioning

The shore substation is the final delivery point for electricity to the grid, and is likely to include step up transformers and fault protection & isolation switchgear with a well-defined minimal set of functional requirements for monitoring and control to meet ‘grid code compliance’ requirements.

Any power conditioning (STATCOM) included at this stage of power transmission must also be controlled and monitored according to its specific requirements.

Grid code compliance is covered in Section 5.3.

3.3.4 WEC Control

3.3.4.1 Introduction

As shown in Figure 2 A Structure for Control of Wave Energy Converters Figure 2, control duties can be separated into high level supervisory functions and low level real time control of WEC response, power capture and general loading.

3.3.4.2 Real time response control

This primary function of the control system uses measurements of the response and loading of the WEC, and potentially direct measurements of the incident waves, to derive control actions to influences that response, generally to maximise power absorption dynamically within a number of constraints on motion, loads, wear, fatigue, etc to meet the overall economic requirements of the system.

The control action is generally through the forces exerted by the PTO system (‘secondary converter’ above) and potentially though less commonly through direct external actuation of dynamic characteristics of the WEC (as described above under ‘primary converter’).

This process is usually real time and must be applied with a sufficiently low latency (time lag) to remain stable at the desired open loop gains. As is the case with control in other applications, the latency that is sufficient in turn depends on the physical characteristics of the plant (the WEC and the PTO system) under control.

Real time response control is treated in depth in Chapter 4.

<u>Control of the PTO system to meet demands of response control process</u>

To achieve the target loading to be applied by the PTO to the primary converter, there must be a process controlling that PTO system. The somewhat unusual load, power, and efficiency demands required for wave energy applications tends to lead to novel PTO technologies with integrated control functions. Depending on PTO solutions, control may faithfully produce any demanded load within acceptable limits and operate with well-defined and understood characteristics. Alternatively, control may be a complex process introducing major distortions to any demand load signal.

There is a subtle but important distinction between actual and estimated force output and a well-integrated control process can take full account of the characteristics of the PTO to make this distinction moot. The PTO control process may use a local force feedback mechanism (as familiar from wave tank paddle control) or it may be able to operate open loop, depending on the characteristics of the PTO system.

Direct control of WEC hydrodynamics

If the WEC is equipped with controllable dynamics outside the PTO system, a concept introduced in Section 3.3.3.2, then the controllable features will be actuated in response to measured inputs and commands. These features may include an adaptable external geometry or an alterable mass (e.g by pumping water ballast) or inertia (e.g. by moving the radius of gyration or centre of gravity). The control process may be real time, actuating in tandem with the PTO system in response to individual waves, or it may be adaptive, operating more slowly in non-real-time in response to changes in underlying sea state conditions.

3.3.4.3 Control of PTO generation and switching systems

The electrical generation systems may generally involve multiple generators, and involve a combination of switching and protection systems, power conditioning & electrical phase correction and real time control of power transmission, typically from an energy storage system (see Section 3.3.3.4) buffering the absorption process from the generation. There may be exceptions according to system design, for instance with Oscillating Water Column devices which have been constructed with single generators and no active storage.

The requirements for control of power conditioning and meeting grid code compliance are covered in Section 5.3.

The real time generation control process may be somewhat separable from the absorption and response control process, if the power captured, or energy stored, or a proxy thereof, is treated as an input to the generation process in its own right. (For systems without storage, separation is not possible and control over the hydrodynamics is exercised more directly by the generator). Measurements of power inputs (and potentially predicted absorption) may be usefully applied if available as a direct input in a feedforward control term. The control background and requirements for electricity generation systems are covered in Chapter 5.

3.3.4.4 High level supervisory control and diagnostics

As Figure 2 shows, WEC control is not confined to the highly specific and challenging topic of real time response, power capture and load limiting. There are also the more common supervisory, condition monitoring and diagnostic requirements that are found in all plant control applications.

These essential but less unique aspects are covered in Chapters 6 and 7 which deal with real time monitoring/diagnostics and on further functional requirements.

3.4 Tailoring Control to Specific WEC Families

3.4.1 Introduction

The purpose of this section is to examine the proposition that it is possible and useful to develop separate functional specifications for each of the common WEC families that are commonly used to group devices. It is concluded that this is an aspiration of limited value since the detailed functional requirements and the controllability are largely determined by the detailed design choices within the primary converter and the power-take-off system, choices which have numerous permutations.

Wave energy technology has experienced little if any consensus on convergence over its forty years of modern development and the concept or combination of concepts likely to offer best prospects for long term affordability is still unclear.

EMEC maintains an ever-growing list of 256 developers and has adopted the eight family classification system (nine, if we include ‘other’) originally proposed by the Aquaret project[1]. This proposes a taxonomy of attenuators, point absorbers, oscillating surge absorbers, oscillating water columns, overtopping devices, submerged pressure differential, bulge wave and rotating mass devices. The classification has found widespread use including in the EU’s ocean energy strategy project, SI Ocean[2].

The classification scheme, although useful in grouping proposed devices according to visual similarity, lacks consistency. Two of the families relate to orientation, five to primary capture method and one to secondary conversion. From a control perspective, the groupings provide little insight and are of no practical use. Different proposed designs within each family have radically different control capabilities and requirements.

Each distinct device has its own characteristics and control capabilities and control requires to be tailored accordingly. Elsewhere in this report, generalised descriptions of control requirements are nevertheless provided both in terms of high-level supervisory and low-level real time control of response and generation. The generalised approach provides a common starting point for tailoring to specific devices. Indeed, the description and process of the most challenging control functions may be successfully applied to practically all proposed WEC concepts.

In practice, control should not be regarded as an aspect that is applied retrospectively – each device requires a strategy for achieving high performance and surviving extreme seas (the two main functional requirements of wave energy) and this tends to be a design trade-off between engineering and control solutions. Control must therefore be considered part of the conceptual design and included in the iterative process of design development.

3.4.2 Primary Conversion

Decisions on a range of features must be made when developing a primary conversion strategy. Each of these has a control implication as indicated in Table 1.

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[1] www.aquaret.com
[2] www.si-ocean.eu

Aspect	Design Options	Control Implications
primary absorber type	oscillating water column	The principle of primary capture is the normal means of classifying a WEC family. The general model of absorption control in Chapter 4 applies to most absorber types but is tailored by detailed design choices. Different absorber types have different levels of controllability – OWCs have the complexity of an air spring between primary absorber and the PTO; the flexible tube lacks discrete degrees-of-freedom etc.
	float	
	flap	
	articulating	
	flexible tube	
	rotor	
	overtopping	
target location	coastal	Decreasing water depth and shoaling results in: • circular particle orbits becoming more elliptical & surging, • wave speeds and wave lengths decreasing, • wave steepnesses and breaking increasing, • sinusoidal wave profiles becoming trochoidal, • seabed friction causing power loss, • refraction of waves aligning the waves to the shore, • refraction of waves reducing directional spreading. From a control perspective, the nature of the overall system input thus depends strongly on depth and may make control response more demanding.
	inshore	
	offshore	
orientation	terminator	Orientation has an influence on the maximum theoretical hydrodynamic capture width of the device and influences the complexity of the system model required in any control system. Lightly damped point absorbers are likely to require motion constraints and tend to lack broadband response - there is significant headroom for control benefits. Terminators tend to have simpler, 2-dimensional characteristics and are readily designed to have broadband response - there is less headroom benefit to be derived from control. Line absorbers can require multiple power-take-off units, increasing the co-ordination complexity.
	line absorber	
	point absorber	
	hybrid	
restraint	bottom fixed	Buoyant, moored devices generally have more degrees-of-freedom than rigidly fixed devices to derive reaction forces for power absorption. Defining and meeting hydrodynamic response and performance targets can thus be a more complex control challenge. The lack of compliance in fixed devices can lead to the system having to react to more extreme loading.
	buoyant moored	
force reaction	self-reacting	The system model for a device which reacts against a fixed structure is generally simpler than for one where different bodies within the device react against one another.
	external reacting	
position	submerged	For surface piercing devices, heave and, depending on design, pitch and roll exhibit hydrostatic stiffness. Once submerged hydrostatic stiffness falls to zero, albeit buoyancy continues to exert a fixed force. For pitch and roll this can be manifest as a rotational stiffness related to the centre-of-mass/centre-of-buoyancy lever arm. Overall, the

Aspect	Design Options	Control Implications
	floating	stiffness of submerged devices is generally significantly lower than for surface-piercing devices[3]. Submerged devices also generally exhibit reduced wave excitation and altered radiation forces. This leads to modified response, reduced power absorption and additional motion constraint considerations. The controller's system model needs to adapt to these should submergence be used as a power and loading regulation control strategy. The ability to change system hydrodynamics by submergence may be an attractive option for WEC control in long period or extreme seas[4].
	adjustable	
geometry	fixed	Shape influences the values of all of the hydrodynamic parameters in the system model and thus the system transfer function. In principle, being able to change shape or size provides a route to controlling loading, response and power capture[5].
	controllable	
absorption mode	resonant	For resonant wave energy converters, a core design/control requirement is to ensure velocity of response is broadly in phase with wave excitation. Other devices do not rely on dynamic response effects and will seek to harness either a wave's potential energy (e.g. low head, overtopping devices) or its kinetic energy (e.g. propeller or rotor devices)
	non-resonant	
passive spectral response	broad band	Inherently broad band devices are designed to exhibit desired performance passively over a wide range of frequencies[6] using only resistive damping control, which implies non-resonant or multi resonant response. Narrow band devices exhibit good performance over a narrow range of frequencies and require more complex control (four-quadrant reactive or latched) to achieve broad band capture[7].
	narrow band	
physical properties	fixed	A WEC's unrestrained response depends on its dynamic as well as its hydrodynamic properties. In principle, being able to adjust the dynamic parameters provides a route to controlling response and power capture[8].
	adjustable	

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[3] this can be a positive design consideration, allowing devices of lower bulk to be tuned to typical wave spectra

[4] although submergence is as yet a rarely used WEC strategy

[5] although this as yet is a highly unusual feature of WEC technology in sharp contrast to wind and tidal stream energy where adjusting geometry (through blade pitch control) is the accepted means of power regulation

[6] passive broad band performance can be attained through design by increasing device scale or by creating resonances at different frequencies using different modes

[7] notwithstanding the challenges of more complex control, narrow band devices generally have the advantage of being smaller and less costly

[8] radius of gyration, ballast mass and inter-body stiffness all offer promising opportunities for control but as yet such strategies are highly unusual

Aspect	Design Options	Control Implications
primary energy transfer path[9]	pneumatic	The primary energy transfer path is used to convey resistance/reactance and control actions from the power-take-off back to the primary absorber.
	mechanical	
	hydraulic	
	hydrostatic	
capture mode	surge	A fully unrestrained rigid body WEC has six degrees-of-freedom, three translational and three rotational. It is normal for some of these motions to be fully restrained or fully unrestrained and for others to be resisted by the power-take-off. For multi-body devices, body connections such as hinges will couple motions thus reducing the overall number of independent degrees-of-freedom. For effective power capture, the central functional control requirement for a slender WEC is to ensure for the far wave field that wave radiation maximises cancelation of the incident wave.[10] For non-slender, terminator devices, cancellation by the radiated waves of far field reflected and transmitted waves is the analogous target. For many devices, carefully coupled, multi-mode capture is required to achieve good hydrodynamic performance.
	heave	
	pitch	
	yaw	
	sway	
	roll	
	combined	

- Table 1 Classification of WEC Primary Conversion and Control Implications

The table identifies that numerous design decisions on the primary converter affect the system transfer function and its complexity. The footnotes to the table also identify that direct control of the primary converter is unusual in the sector - control to date has generally been exerted indirectly via the secondary converter.

Table 2 indicates the classification profiles for a range of well-known WECs. The equivalent tables for tidal stream and wind energy devices would be considerably simpler and more uniform. Comparing the Table 2 profiles of the Wavegen OWC and Pelamis to the control implication notes of Table 1 indicates that:

The Wavegen Breakwater OWC:

- sees highly non-linear waves but predominantly from a single direction
- in long breakwater, terminator mode, operates on 2-dimensional wave effects
- operates with a simple, single degree-of-freedom
- is resonant and with simple resistive control is capable of high broadband efficiency
- reacts structural forces externally
- due to rigidity, in high seas has to deal with very large forces.

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[9] in terms of what the moving converter directly acts upon rather than the form of energy that drives the power-take-off; e.g. many hydraulic PTOs will be driven by a mechanical ram

[10] Wave energy capture and far field wave effects are described by way of example in Section 4.6

Aspect	**Wavegen BreakWater OWC**	**Carnegie Ceto-5**	**Pelamis**	**APL Oyster**
primary absorber type	OWC	float	articulating	flap
target location	coastal	inshore	offshore	inshore
orientation	terminator	point absorber	attenuator	terminator
restraint	bottom fixed	moored	moored	bottom fixed
force reaction	external	external	self-reacting	external
position	floating	submerged	floating	floating
geometry	fixed	fixed	fixed	controllable
absorption mode	resonant	resonant	resonant	resonant
passive spectral response	broad band	narrow band	narrow band	broad band
physical properties	fixed	fixed	fixed	fixed
primary energy transfer path	pneumatic	mechanical	mechanical	mechanical
capture mode	surge	heave-surge	pitch-yaw	pitch

- Table 2 Primary Conversion Classification for a Range of WECs

In total contrast, the Pelamis line absorber:

- sees largely linear waves but with directional spread
- operates on 3-dimensional wave effects
- operates with coupled, multiple degrees-of-freedom
- is resonant but requires complex control to achieve high, broadband efficiency
- reacts structural forces internally
- due to compliance, in high seas can partially avoid very large forces.

Given that the core functional requirements for wave energy converters are to capture power efficiently in normal seas and to survive the ravages of extreme seas, it is clear from the comparison that there is a device-specific balance between to what extent objectives are met by passive design and by complexity of control.

3.4.3 Power-Take-Off

As for the primary converter, it is inappropriate to adopt a strict family approach to define control requirements with respect to power-take-off systems. Guided by generic needs, it is more productive to generate requirements based upon the characteristics of the primary converter and the control capabilities of the selected PTO, which may apply in different combinations in a proposed WEC design. A system design approach should ideally be taken to ensure that the overall WEC configuration is cogent and viable.

Various WEC power-take-off systems are proposed according to system design strategy but generally comprise a secondary converter (the front-end power transmission interacting directly with the WEC response), storage, a tertiary converter (the transmission driving the electric generator), and an electrical generator. The storage, if included, serves to decouple the processes of power capture from the waves by the secondary converter and the generation of electricity by the secondary converter, allowing the secondary converter to be rated and controlled separately to achieve the best overall economics.

There are many design decisions to be taken in configuring a PTO which affect the level of control that can be exercised over the WEC and hence the potential performance. These choices are also driven by reliability, cost, and other economic drivers. While some PTO design features options may be independent, there are a number of established topologies, particularly for hydraulic and pneumatic conversion systems.

Low pressure pneumatic systems (in particular air turbines) are suited to Oscillating Water Column and diaphragm type primary converters. They are attractive for their ability to provide cheap, effective and passive gearing between the slow wave speed and the high generator shaft speed through funnelling, and for their ability to avoid transient loads through air compressibility, although the latter phenomenon can diminish controllability of wave power capture depending on the complexity of the turbine. The main challenge of OWC technology is achieving acceptable efficiency as airflow changes direction and speed with the wave cycle, which is highly unusual for air turbine applications.

Selection and control of a pneumatic turbine is influenced primarily by the damping characteristics that are required to be applied to the primary converter to achieve best power absorption, as explained mathematically in Section 4.4. Pneumatic systems lend themselves better to purely resistive ‘turbine mode’ (damping) control than to fuller reactive control (again explained in Section 4.4) which would require power to flow in both directions during the oscillatory cycle and hence need variable pitch blades, reversing variable speed, high flow control louvres, or some combination to allow the aerodynamic machine to operate as a pump for parts of the oscillatory cycle. The turbine damping level that maximises power absorption at the WEC’s resonant frequency is one which is equivalent to the hydrodynamic damping associated with the device at that frequency. It is normally desirable however to apply a damping that is higher than this, perhaps many times greater, as this will raise capture efficiency at higher and lower frequencies in the sea spectrum, thus improving bandwidth and overall capture. Such overdamping also reduces the size of the turbine and the extent of the device motions, both of which can be desirable.

The fundamental design decisions that have to be taken for low pressure pneumatic power-take-off turbines and their implications for control are outlined in Table 3.

Oil hydraulic systems are extremely common in wave energy applications and if anything are becoming more prevalent. High pressure oil hydraulics systems (also known as Fluid Power systems) are particularly suited to pitching flap, heaving float, and articulating primary converters, and in principle could even be applied in an OWC via a piston mechanism. The challenge of power transmission at low speeds and high forces are well met by this technology and energy storage is also available in the form of high pressure gas accumulators.

From a control perspective the hardware lends itself very well to reactive power transmission with highly dynamic and responsive load control. In a pneumatic system, the generator control plays a strong role in the initial power capture through speed control of the turbine whereas in most hydraulic systems the generator control has very little direct effect on the behaviour of the primary converter because of the buffering provided by energy storage accumulators. Reactive control and storage control are dealt with in detail in Sections 4.4 and 5.2.

Control action for a typical hydraulic PTO topology applies both to the loads imparted by the PTO actuators to influence the response of the WEC and its interaction with the incident waves and also to the generation system to regulate the energy stored and the smoothing of output power. As for other PTO's, high level supervisory monitoring and control must also be applied to auxiliary functions such as heat rejection systems, electrical power supplies and diagnostics. The PTO mechanisms require substantial low level controls to allow the chosen equipment to provide a controllable force and/or motion suitable for the real time demands outlined in Chapter 4.

The main design decisions that require to be made for an oil hydraulic based system and their implications for control are listed in Table 4.

Aspect	**Design Options**	**Control Implications**
Turbine Type	Axial	Radial machines tend to have slightly higher efficiency in low head flows but are bulkier than axial turbines. In radial machines, the head-flow-speed-efficiency characteristic is generally controlled by adjusting stator guide vane settings. In axial machines, control of rotor blade pitch is more common. In selecting a specific turbine, high efficiency is achieved through design choices and control choices.
	Radial	
Rectification	External	Aerodynamically or mechanically self-rectifying turbines such as the Wells, Denniss-Auld and Dresser-Rand machines achieve rectification of torque in reversing flows by design whereas conventional turbines require external rectification of airflow through a system of ducts and valves. These valves, depending on type may require active switching control at the point of reversal of the pumping action. The valves can also be used for 'latching phase control', a means of retarding the response of the primary device to bring wave excitation and device velocity into phase alignment.
	Self-Rectifying	

Aspect	Design Options	Control Implications
Manifolding	Yes	Manifolding involves feeding flows from adjacent primary converters into a common PTO turbine. Were all devices working in synchronisation then no control of the individual flows would be needed. However phase mismatch means that an actively or passively controlled valve system is required to avoid devices driving against one another rather than against the turbine. Manifolded systems introduce rather different control considerations for the turbine as manifold pressure (essentially a mini-accumulator) becomes an intermediate control target rather than the responses of the individual primary converters.
	No	
Speed	Fixed	Whether the turbine is controlled against a fixed or variable speed characteristic is determined by the type and sophistication of the generator system which is assumed to be hard-coupled via a common shaft or through a low ratio gearbox. The situation is directly analogous to wind turbines where power electronics and high slip technologies has enabled cost-effective variable speed operation for increased power capture. Like variable pitch control, variable speed control allows the turbine to operate at peak efficiency for a wide variety of flows. High speed turbines have useful inertia which can help smooth load and power transients. Variable speed control can harness that ability more fully than fixed speed control.
	Variable	

- Table 3 Pneumatic Power-Take-Off Design Options and Control Implications

Aspect	Design Options	Control Implications
Actuator Type	Rotational	Hydraulic actuation of forces and torques may be applied through 'cylinders' over a finite range of stroke (avoiding end-stop shock). The coupling of forces applied by cylinders to the moving WEC structure depends on the particular kinematic arrangement, allowing for gearing of the forces and motions. Cylinders are highly cost effective in generating high forces and remain efficient over the speed range. Rotational actuators such as a ring cam or winch-type arrangement may provide control of torque on a suitably coupled axis of the WEC structure, or on a winch line. These have the benefit of no end-stops but are generally high cost for a given load capacity and life.
	Linear	
Flow and Pressure Control	Passive	A simple pumping system may use passive non-return valves for e.g. rectification and pressure containment duties. However, this leaves control limited to the pumping pressure, is highly coarse and non-linear, and does not allow any reactive control. Control of loads and flows may be actively and sensitively controlled through digitally controlled valves and/or specialised rotating machinery. Discrete, quantised control of net loads applied to the WEC structure may be achieved using multiple piston areas (in linear or rotational systems) with banks of digital valves operating against a single pressure, allowing highly efficient power transfer at low cost but with the introduction of some control distortion due to the quantisation process. The use of coupled rotational machines to provide continuously variable pressure and flow to the actuators involves greater part load losses and requires rotational machines of a much higher rating than required for average generation. Independent control of flow and pressure enables reactive interfacing with the primary converter and high system energy capture. Hybrid systems are under development to overcome these challenges[11].
	Active stepped	
	Active continuous	

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[11] including a project commissioned by WES to develop a continuously variable PTO based in digital displacement hydraulic pump-motor (DDPM) technology designed to control loads in reaction to the wave forces.

Aspect	Design Options	Control Implications
Pump/Motor and Generator	Variable Speed	Power may be extracted from the energy storage accumulators over a relatively tight range and with low frequency fluctuation compared with the input wave power. Power output must still vary between wave groups and seas states to accommodate low frequency fluctuations and as pressure builds and falls in the accumulators.
	Fixed Speed	Power may be extracted at a fixed generator shaft speed using variable displacement motors and a fixed speed generator synchronised to the grid or with fixed displacement motors using variable speed generators and associated power electronics to convert to grid frequency. Control of power extraction is driven in both cases by electrically induced torque.

- Table 4 Hydraulic Power-Take-Off Design Options and Control Implications

Further families of PTO exist, each of which includes sub-sets and design attributes that affect control capabilities.

Various mechanical PTO solutions have been proposed ranging from reciprocating direct drive systems with a variety of gearing and rectification technologies through to inertial systems based on gyroscopic precession or eccentric rotating mass.

Equally, various direct electrical solutions are under development ranging from several forms of linear generator through to dielectric and piezo-electric generation technologies that can be directly integrated into the skin of flexible primary absorbers.

Although these systems may all have similar high level control objectives based on enabling high primary capture and extreme load smoothing, detailed control implementation is radically different, reflecting detailed topologies and controllable elements.

In conclusion, although there is a de-facto classification system in place that allows wave energy devices to be placed in families, it is not sufficiently consistent or applicable to allow the development of particular control functional specifications. Depending upon specific design decisions that are made, it may well be the case that certain of the generic functional specifications are either not relevant (e.g. for an inherently broad band converter there may be limited advantage from reactive control) or that they cannot be delivered (e.g. not all PTOs are capable of developing reactive control forces). It is far better to be aware of the high level and generalised functional requirements outlined in Sections 2.1 and 2.2 and, in terms of real-time control, in Chapter 4.

4 WEC Control – The Dynamic System

4.1 Introduction

This Chapter is devoted to control of WEC response to incident waves and of associated power absorption.

Response Control refers to the control process and actions influencing the motion and power absorption of the WEC. Response control acts through forces applied by the power-take-off (PTO) system and power is captured through the net work done against those PTO forces.

As outlined in Sections 3.3.3 and 3.4.2, response control may also be effected through direct actuation of the WEC hydrodynamic characteristics, either to enable greater power capture through the PTO indirectly (e.g. by adjustment of the WEC's geometry or mass properties), or as the result of the same PTO actuation mechanism both altering the WEC hydrodynamics and capturing power into the conversion system (e.g. in a pulsating geometry directly coupled to the PTO).

Figure 3 shows a generalised response control process, with the WEC structure and dynamics undergoing wave excitation, the resulting motions being sensed by the control system (potentially along with direct force measurements, and direct wave measurements), and the PTO force and any other actuation mechanisms being controlled as a function of those inputs.

4.2 A Mathematical Representation of the Generalised WEC and its Control

There are many standard texts on waves and their hydrodynamic theory to which the reader is referred [Lamb, 1932].

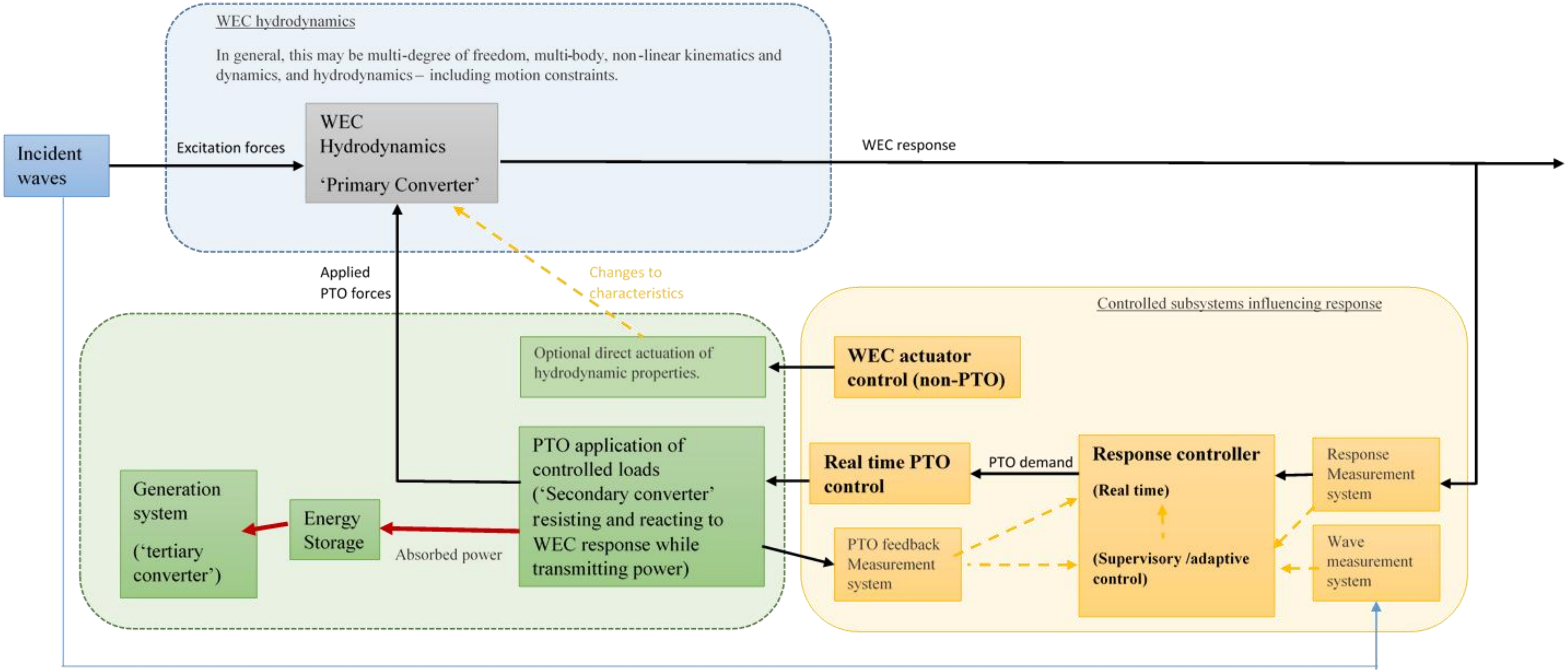
In common with all types of wave encountered in physics, ocean waves are energy transmission phenomena. They initially gain their energy through viscous interaction with wind flows over a spatial fetch. Once of appreciable size, waves can travel for ocean scale distances and can move well out of the weather systems that initially produced them. Such remotely brewed seas are referred to as swell and tend to have long periods (and thus wavelengths). There is very little mass transport associated with the transmission of ocean waves. Energy associated with the wave manifests itself as orbital motions of the water particles, with the orbital motion decaying with depth. For shallow water, the otherwise circular motions are distorted into an elliptical pattern. A wave contains a perfect balance between potential and kinetic energies. Ocean waves exhibit all the usual properties of other types of wave, viz reflection, refraction, diffraction and, highly relevantly to wave energy device behaviour, can interfere with one another either constructively or destructively – two waves of equal amplitude travelling in the same sense but in antiphase will fully cancel. Wave speed (celerity) and wavelength both depend upon wave period and in a real sea with mixed periods, the fact that different waves travel with differing celerity makes it very challenging to predict an exact wave history at a specific location even in the short term and even in a stable sea state. The spectral aspects of waves are touched upon in Section 4.8.1.

The general linear potential theory of wave power absorption has been well established since the late 1970s, including a range of important results and insights with major implications for control requirements. This theoretical framework has been used to define the optimal WEC control problem and define ultimate absorption limits of different WEC types (e.g. the point-absorber limit) and the engineering specifications required to approach this limit (e.g. volume, motion, and load ranges). It also provides the starting point for efficient and accurate computational models, the basis of control development and optimisation activities. The classical linear theory however is not appropriate for assessing survivability in extreme wave conditions.

A body of literature has expanded (and often repeats) to the present day. This section will highlight some of the most important, well-established results and implications and will place them in the context of the functional requirements for practical control systems. Notably, these results include the analytical solutions for optimal control using linear models, the corresponding wave interactions in the far field, and the corresponding ultimate capture limits. Some important implications for practical design and control implementation are discussed.

A selection of useful references is provided where more derivations and examples may be found, along with examples of development activity targeting different control approaches.

The literature is not typically focussed on control implementation challenges beyond the highest level constraints and principles. In contracts, this report highlights issues where control functional requirements can strongly influence the limitations and potential of response control.



- Figure 3 Response Control and System Interaction for a Wave Energy Converter

4.3 WEC Hydrodynamics and Absorption Model

4.3.1 Introduction

Prior to proving an essential mathematical understanding of the generalised WEC (hydro)dynamic system, from which it is possible to derive a mathematical statement of the most effective control strategies, it is probably helpful to provide a more descriptive overview.

The majority of wave energy converters are dynamically active and operate on the principle of wave action exciting a dynamic response which can then be harnessed to drive a power-take-off system. The overall system comprises elements that relate to the WEC body, to the power-take-off and to the wave hydrodynamic environment. The WEC body introduces mass or inertial terms (and in some designs, mechanical stiffness). The power-take-off, as a dissipative element, can be characterised by a damping term (this resistive term being supplemented in certain designs by reactive capability).

In terms of the ocean environment, like any other floating body, a surface-piercing WEC experiences hydrostatic stiffness, which is the basis of resonant response in most designs. However, hydrodynamic elements define wave energy's uniqueness. That the wave environment dictates the system excitation is intuitive but, less obviously, it also gives rise to further hydrodynamic terms. To understand their origin, it is useful to imagine the overall hydrodynamic system as two superposable force regimes. The first relates to the case in which the WEC body is held fixed so that it forms a reflective barrier, at least partially, to incident waves. The wetted pressure field experienced on the surface of the body in this wave scattering situation creates an excitation force. In the second regime, the WEC body is oscillated in an otherwise calm environment. In this regime the WEC works against the surrounding water and imparts energy to it, that energy being carried away from the device by radiated waves. The pressure field experienced by the device as it is oscillated gives rise to a force which can be resolved into two components, one in phase with body velocity and one in phase with body acceleration – from these radiation force components, effective ‘added damping’ and ‘added mass’ coefficients can be extracted. The combined hydrodynamic force regime is a weighted sum of the scattering and radiation forces, duly weighted by the magnitude of the incoming wave and by the magnitude of the response respectively. The latter is a function not only of the hydrodynamics but of the full combined dynamic system.

Mathematically, the system model can be rather complicated due to the hydrodynamic terms being frequency dependent, WECs generally having multiple rather than single degrees-of-freedom and wave inputs, hydrodynamics and power-take-off elements having various non-linearities. Notwithstanding these issues, control engineers will recognise the basic system as one involving a source impedance (the hydrodynamic and hydrostatic terms) and a load impedance (the body and power-take-off terms). Such systems crop up in many branches of electrical, structural and mechanical engineering and technical analogies such as maximum power transfer in electrical circuits through complex conjugate control, if familiar, are certainly relevant and useful in aiding understanding.

Turning now to a more formalised treatment, the framework of analysis has historically centred on classical hydrodynamic descriptions with the WEC dynamics and wave excitation represented by linear frequency dependent coefficients derived from linear potential theory [Newman 1977 and Falnes 2005].

Well-established numerical panel methods (implemented in commercially available software such as WAMIT) are generally used to derive hydrodynamic coefficients in multiple degrees-of-freedom as a function of wetted geometry and for a selected coordinate system. These multi-degree-of-freedom and frequency dependent coefficients generally include cross terms representing the hydrodynamic interactions between the motions and forces in different degrees-of-freedom. It is typical and convenient to align the degrees-of-freedom with those under control, although not all degrees-of-freedom would typically be expected to be under control.

This allows the linear equations of motion to be generally written in the frequency-domain:

$$\left(\boldsymbol{M} + \boldsymbol{M_a}(\boldsymbol{\omega})\right) i\omega U(\omega) + \boldsymbol{B}(\boldsymbol{\omega}) U(\omega) + \boldsymbol{K} \frac{U(\omega)}{i\omega} = -a(\omega) W(\omega) - F_{control}(\omega)$$

Where:

- $U(\omega)$ is a complex vector of response velocity (representing the phase and amplitude of the sinusoidal response velocity in each degree-of-freedom)
- $a(\omega)$ is the scaler complex amplitude of a sinusoidal incident wave component. In this linear formulation, an amplitude spectra representing a realistic sea state can be created from multiple components with the results for each component being superposed to give the overall spectral response.
- $\mathbf{M_a}(\boldsymbol{\omega})$ and $\mathbf{B}(\boldsymbol{\omega})$ are the real matrices of frequency dependent added mass and radiation damping. These dictate how waves are radiated due to motion of the WEC and define the associated forces, $\mathbf{B}(\boldsymbol{\omega})$ determines how waves and energy are radiated out from the WEC, while $\mathbf{M_a}(\boldsymbol{\omega})$ is associated with evanescent waves entrained with the WEC motion and not radiating net energy over the wave cycle. These terms together make up the complex radiation impedance and they are part of the same physical process intrinsically linked through the Kramers-Kronig relationship, a general theorem connecting real and imaginary parts in response functions with relevance in wave hydrodynamics [Kotik 1962].
- $\boldsymbol{M}$ is the non-frequency dependent mass matrix of the WEC dynamic system, incorporating the free body inertia tensor and the effective mass of each degree-of-freedom. This generally depends on the mass and mass distribution.
- $\boldsymbol{K}$ is the non-frequency-dependent stiffness matrix representing the buoyancy of the WEC (and/or pressure stiffness for a fixed OWC). For floating systems this depends on the wetted geometry and is therefore also intrinsically linked to the radiation and excitation coefficients.
- $W(\omega)$ is a complex excitation vector relating the complex wave amplitude to the resulting complex excitation force on the WEC, the result of pressure applied by the wave over the

acting surface of the WEC. Note that the linearity assumption allows the hydrodynamic terms (excitation and radiation) to be defined separately.

- $F_{control}(\omega)$ is the controlled force applied through the power-take-off system which is generally defined in the analysis below, the focus of this report. Different constraints imply different control functions, also as discussed below. Representation in the frequency domain may be highly approximate for some types of PTO.

For directional WECs and realistic directional spectra, these coefficients and the wave components must also be defined as a function of incident wave direction allowing directional wave spectra (defining the amplitude and direction of wave components) to be applied to solve for the WEC response.

Moorings and other external forces (e.g. dedicated spring mechanisms) are not included explicitly above but may be introduced with linear approximation or explicitly in a time domain representation (see below).

Note that the Laplace operator generally familiar in control engineering descriptions is not used in the expressions above because the definition of the frequency dependent diffraction term, $W(\omega)$, (and potentially the controlled force term) is non-causal (i.e. the impulse response functions may extend backwards as well as forwards in time) and is therefore not representable by a Laplace transform. This issue may be circumvented in models by using causal approximations as described in Section 4.3.3.

For floating, rigid-body systems, the model generally includes six free degrees-of-freedom plus additional degrees-of-freedom for any relative motion between multiple bodies. WEC design for kinematically restricted motion may allow reduced order systems, all the way down to a single degree-of-freedom for single bodies rigidly coupled to a fixed reference (for example, a seabed mounted surging flap or a narrow oscillating water column).

To absorb power and influence the WEC response, the control system must have some degree of control of the loads acting through some of these degrees-of-freedom. Depending on the WEC type, the PTO may act on multiple degrees-of-freedom, and further degrees-of-freedom may not be directly observable or controllable. The controllability of the WEC is determined largely by the interaction of the controlled degree(s)-of-freedom and the intrinsic WEC hydrodynamics, in turn a function of the wider WEC operating principles.

This controllability also depends very strongly on nonlinear effects such as the relative range of loads available for application by the control system (and the PTO) compared to those induced by the waves. The range of forces is likely to be limited by the PTO, particularly in larger waves. This load saturation is an important nonlinearity and design parameter.

Rearranging and leaving the control force general, the response due to combined force of wave excitation and control can be written:

$$U(\omega) = -\left[\left(M + M_a(\omega) - \frac{K}{\omega^2}\right) i\omega + B(\omega)\right]^{-1} [aW(\omega) + F_{control}(\omega)] = -Z_{hyd}(\omega)^{-1} F_{total}(\omega)$$

Where the intrinsic hydrodynamic coefficient matrices on the left hand side have been lumped together into a single complex impedance matrix – a ‘transfer function’ between the total applied force and the response. Complex impedance is a familiar concept in other dynamic systems, notably electrical networks.

In developing practical models, a number of important identities are useful. Firstly, the values of $Z_{hyd}(\omega)$ and $W(\omega)$ are intrinsically linked (they are a function of the same WEC geometry and hydrodynamics) through the Haskind relations and secondly, the imaginary and real parts of the radiation impedance $M_a(\omega)$ and $B(\omega)$ are linked through the Kramers-Kronig relationship [Falnes, 2005].

It is apparent that a suitable frequency domain representation of the control force function allows the general WEC control problem to be framed as transfer functions in a manner familiar to classical control engineering, albeit with all the limitations of representation and application inherent in the linear model. The hydrodynamic terms do throw up some more unusual phenomena with direct implications for the response and absorption control problem, as discussed further below.

4.3.2 Direct control of the WEC hydrodynamic impedance

For some WEC types, the intrinsic impedance term $Z_{hyd}(\omega)$ may also include mechanical systems not absorbing power such as mechanical springs that may be useful in overall dynamic design and response. Also, in general, control could be applied to alter the hydrodynamic matrices directly, making them non-static or at least adaptive over time, either with actuation systems not directly transmitting any net power (for example, systems that adjust the volume or inertia/mass properties of the WEC), or coupled directly to the control forces and PTO system (for example, in a directly coupled pulsating absorption mechanism). Almost by definition, power can only be absorbed and converted through the power-take-off system and its controlled application of force.

4.3.3 Time domain representation

The frequency domain representation outlined above uses complex variables to represent force and motion, with the matrix operators defining phase and amplitude relationships on an assumed sinusoidal input at each frequency. For a linear model, this is reducible to a transfer function for WEC motion as a function of the incident wave defined as a complex amplitude at each frequency component and direction, and hence for the associated forces and the power absorption. The WEC response to a mixed spectra is the superposition from the components of that complex amplitude spectra.

In the time domain, the frequency dependent hydrodynamic terms may be represented by corresponding impulse response functions following the method of Cummins [Cummins, 1962], removing the infinite frequency asymptote of the added mass as a constant coefficient, leaving a convolution kernel for the radiation terms. Similarly, the wave excitation also forms a convolution. In principle, suitably windowed impulse response functions (from the inverse Fourier transform of the frequency domain functions) allow for time-stepping numerical solutions for the WEC response. Note that in n degrees-of-freedom, n by n convolution integrations are required for each coefficient matrix (corresponding to the matrix operations of the frequency domain expression).

$$-\int_{\infty}^{\infty} k_{exc}(\tau)u(t-\tau)d\tau - f_{control}(t) = (m + m_{a\infty})a(t) + \int_{0}^{\infty} k_{rad}(\tau)u(t-\tau)d\tau + kx(t)$$

If they are small for a given application (e.g. small volume, or slender device in long waves) the wave diffraction terms may be neglected and Morison's equation [Morison, 1950], or slender body theory, used for the excitation forces. Similarly, computation may be greatly simplified if the radiation terms may be approximated as constants in the frequency domain if the response and incident spectrum is sufficiently narrow banded. [Newman, 1977]. Caution should be exercised in applying such simplifications commensurate with the sensitivity of the results to errors. For example, yield projection may require a greater degree of accuracy than generalised power-take-off design models.

The major advantage of a time domain representation is that generalised non-linear functions may be applied arbitrarily at each time step, in particular for control terms allowing for more realistic models of power-take-off characteristics. This is especially important where non-linear effects such as load saturation or discontinuities (e.g. latching or coulombic damping[12]) dominate the behaviour of particular power-take-off mechanisms, but also potentially important for testing the impact of more subtle but potentially important non-linearities in the PTO plant such as backlash in mechanical connections.

Mooring systems and viscous effects may also be represented more realistically and some important, leading order, non-linearity in the hydrodynamics may also be introduced. This provides for a more realistic simulation environment.

State-space representation

A useful state-space representation can be formed by approximating the computationally demanding convolution integrals with rational functions (a set of ordinary differential equations), as first described by Jefferys [Jefferys, 1984]. Yu and Falnes [Yu & Falnes, 1995] have reported a method of direct synthesis of an approximate state-space model from the exact hydrodynamic impulse response functions (and hence the frequency domain equivalents) by deriving a canonical form of the state-space representation and then numerically solving for coefficients that minimise the error in representation of the hydrodynamic impulse response functions. Due to the elimination of non-causal impulse response, this method is more accurate for smaller volume and slender WECs with relatively insignificant memory terms in the excitation response kernels.

The state-space model may offer more familiarity and accessibility to modern control engineering practice and existing implementations of numerical control optimisation techniques applicable in state-space representations (for example, in MATLAB) may be adapted for direct application to the WEC response problem.

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[12] latching in its various forms is discussed in Section 4.9.3; Coulomb damping, as described in Section 4.9.2 refers to application of a fixed force from the PTO, meaning that until the WEC can overcome that force, it will be unable to move

The tools for generating a state-space representation are now built into the open source WECsim suite running in the MATLAB environment [Tom, Lawson & Yu, 2015].

In any of these models, care must be taken not to ignore the potential impact of more subtle and uncertain aspects of the plant model such as the power-take-off and load path dynamics, as discussed further below. These may determine ultimate performance and should be considered important design drivers.

4.3.4 Numerical modelling issues

The analytical approaches afforded by frequency domain analysis offer important insights into the control problem and routes to formulations useful for the derivation of control functions. More accurate models require time-domain simulations with more direct representation of terms including non-linearities.

Ultimately, the particular models and associated control functions require numerical solutions of response and power. In the development of control functions it is useful to have fast running models with sufficient accuracy to capture the requirements of the control algorithms and parameter optimisation process while allowing iterative optimisation methods. More accurate and detailed models may then be used for finer optimisation and detailed performance assessment once the development is in its latter stages.

Validation of the applicable limits of models is required at each stage, with respect to physical tank testing and more sophisticated simulations. A control algorithm is only as valid as the model is was developed on. It is likely that development of control algorithms and parameters will continue to be informed and refined into full scale trials and beyond as important effects are recognised and included in the modelling and development process.

For certain circumstances (e.g. small bodies or a slender body approximation, in narrow band spectra) radiation and diffraction coefficients may be usefully approximated at a single frequency (i.e. without memory effects or hydrodynamic interactions) to avoid calculating convolution integrals at each time step, without the loss of too much accuracy in the results. Furthermore, if the approximations are valid for the size and shape of WEC under study, changes to coefficients with depth of submergence may be applied according to the relative motion hypothesis [Newman, 1977] which shows the approximate equivalence of strip and diffraction theory.

Non-linear drag terms may also be incorporated relatively easily in time-stepping models.

Great care must be taken in the range over which such simplifications may be made, taken in the context of the model’s purpose. Any approach towards modelling the ultimate performance limits of a WEC would be likely to inherently invalidate out these simplifications in all but the smallest waves. Simulation tools should be chosen appropriately for the geometry of the specific converter. A smaller body will exhibit less wave diffraction and greater non-linearity and so a small body assumption similar to strip theory methods are appropriate. A larger converter with stronger wave diffraction and weaker non-linearity will benefit from 3D wave diffraction methods. Many WECs require both diffraction and nonlinearity as the act of absorbing wave energy can bring an otherwise small absorber into the diffraction regime. Wave energy conversion also requires detailed modelling of the power-take-off systems and control, which are not accommodated for in general offshore engineering simulation packages.

Developments continue in fundamental hydrodynamic modelling techniques and the computational power required to make use of them in the development of WEC and control system design. These may open new and powerful approaches to the development of control algorithms and optimisations.

4.3.5 PTO effects

It is important that models used for control development properly represent any aspects of the PTO which influence the implementation of the response control process. The most obvious of these are load constraints, but other very important effects include any discretisation of loads, delays and filters on input signals, and local dynamic effects in the load path (for example structural flexibility).

On the other hand, the dynamics of the WEC system under control may not be affected by transient and intra-component effects in the PTO, potentially allowing much complexity to be left out of PTO models for faster development and much faster run time in whole machine simulations.

While tank models may be used to validate the hydrodynamics simulations, these generally do not help with validating models of the power-take-off systems that are enacting the response control. Dedicated laboratory test rigs may provide a useful stepping stone to characterise aspects of the control process through to physical application of forces. However, the lack of WEC dynamics (particularly inertia) in many such test rigs generally makes direct representation of the control process impossible, so a combination of element-validation with integrated simulation is generally required.

It is particularly important that control and PTO characteristics relating to control stability are properly represented in any integrated machine simulations. In physically realisable systems, even open loop application of control forces by the PTO still results in a dynamic system with finite stability margins. Analytical approaches to these stability issues are discussed in more detail in Section 4.4.

4.4 Impedance Control

4.4.1 Introduction

The transfer function of force per velocity is generally described as an impedance, in common with similar mathematical descriptions of electrical circuits and acoustics. Using the same coordinate system, response control dynamics may be usefully described in the same way as an ‘internal impedance’ to the WEC response that may combine in the equations of motion with the ‘external impedance’. For this reason, it is generally convenient to model the WEC hydrodynamic with a coordinate system including the controlled degrees-of-freedom directly.

For response control based on the response of the WEC only, i.e. by outputting a force from the PTO as a function of the position, velocity, and potentially acceleration of the WEC's controlled degrees-of-freedom, a compact description is possible, compatible with a robust and practical control implementation.

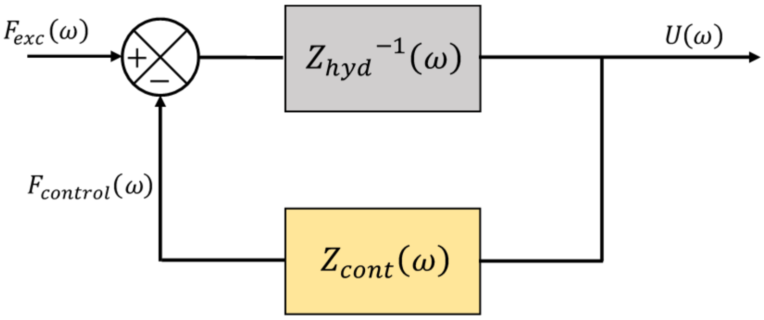
$$-F_{control}(\omega) = Z_{cont}(\omega)U(\omega)$$

The controlled impedance $Z_{cont}(\omega)$ is expected to be a function of mass, damping, and spring terms (with some caveats on the practical application of virtual mass). The sign convention above is stable for positive coefficients. These coefficients may in theory be frequency dependent if the function is allowed to be non-causal (able to use information on predicted future response). $Z_{cont}(\omega)$ could also be defined and implemented as a generalised transfer function and corresponding difference equation (and impulse response), provided it satisfies stability and available information requirements.

With the dynamics of the WEC similarly lumped together in a single, complex, multi degree-of-freedom and frequency dependent matrix representing the WECs response to incident waves $Z_{hyd}(\omega)$, and a vector representing the excitation forces, $W(\omega)$, as described above. We can write the equation of motion as:

$$\left(Z_{hyd}(\omega) + Z_{cont}(\omega)\right)U(\omega) = -aW(\omega) = F_{exc}(\omega)$$

In block diagram form, the may be represented as a familiar feedback control loop as in Figure 4.



- Figure 4 Block Diagram of Controlled Impedance Feedback on Hydrodynamic Response

The transfer function for the WEC dynamics with controlled impedance can therefore be expressed:

$$\frac{U(\omega)}{F_{exc}(\omega)} = \frac{Z_{hyd}(\omega)^{-1}}{1 + \left(Z_{hyd}(\omega)^{-1}Z_{cont}(\omega)\right)}$$

with characteristic equation (sensitivity function):

$$1 + \left(Z_{hyd}(\omega)^{-1}Z_{cont}(\omega)\right) = 0$$

the roots of which determine the stability of the system.

Provided both the impedance terms are positive definite (negative real eigenvalues, corresponding, in a single degree-of-freedom, to having negative damping), and the sensitivity function is proper (no more poles than zeros), then this system is stable.

The potential for instability arises in practical systems from additional and unavoidable features such as delays in the control loop and the dynamics of the control plant. Strong nonlinearities can also make robust stability analysis challenging, particularly for multi degree-of-freedom systems where stability criteria including non-linearities such as load saturation are generally not well defined.

4.4.2 Linear stability analysis with delay and local PTO dynamics

A fixed delay may be introduced in the linear formulation (as a linear frequency dependent phase shift) to examine the impact on stability and the 'delay margin' defined for a given set of assumed coefficients. The linearity assumption means that delays in input, process, and actuation may be lumped together into a single latency, t_d, on the control signal path.

$$\frac{U(\omega)}{F_{exc}(\omega)} = \frac{Z_{hyd}(\omega)^{-1}}{1 + \left(Z_{hyd}(\omega)^{-1} e^{-i\omega t_d} Z_{cont}(\omega)\right)}$$

The effect of delay is to limit the impedance terms applied by the control system to lie within a bound of stability. The delay can be very small relative to the response period, but still induce instability. For example, any delay at all (e.g. control latency) is associated with the instability of mass terms in the control at the delay period and therefore targeted compensation must be implemented.

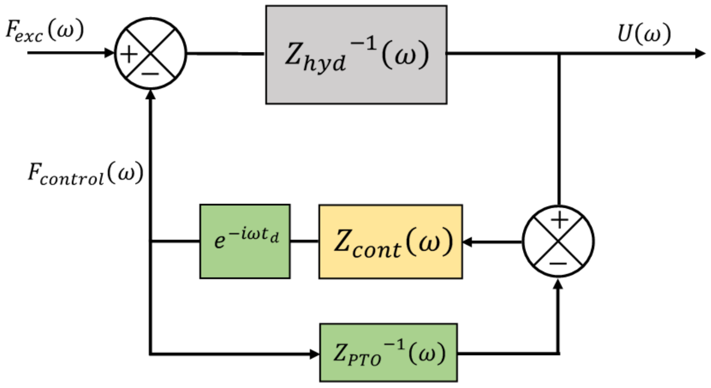
The wave periods and WEC dynamics may be expected to be well below any sampling frequency and therefore easily separated from stability issues due to the control latency. However, local PTO and structural load path dynamics typically introduce natural frequency(ies) of response far closer to the sampling/latency period of the control system. Instabilities are therefore likely to emerge around high frequency structural/PTO/delay resonances that may not have been considered of primary importance in the WEC design process.

Local disturbance in the input response measurements due to local PTO and load path dynamics may be included in the model formulation, either implicitly in $Z_{hyd}(\omega)$ as additional degrees-of-freedom coupled (e.g. in-line) with the controlled degrees-of-freedom, or more qualitatively as a separate approximate term for control analysis.

For example, lumping actuation and local structural stiffness and mass into an effective second order transfer function (an inverse impedance) for the PTO to act through $Z_{PTO}(\omega)$ when applying force to the WEC, we could write:

$$\frac{U(\omega)}{F_{exc}(\omega)} = \frac{Z_{hyd}(\omega)^{-1}}{1 + \left(\frac{Z_{hyd}(\omega)^{-1} e^{-i\omega t_d} Z_{cont}(\omega)}{1 + e^{-i\omega t_d} Z_{cont}(\omega) Z_{PTO}(\omega)^{-1}}\right)}$$

which can be represented in block diagram form as



- Figure 5 Controlled Impedance Feedback with Control Delay due to Local PTO Dynamics

It may be advantageous to design the input measurement system to implicitly avoid such local disturbance in the feedback loop while measuring the spatially averaged wave frequency motion of the intended WEC hydrodynamic degrees-of-freedom. This suggests mounting motion sensors carefully and perhaps distributing multiple sensors across the structure to derive estimates with disturbance rejection.

4.4.3 Power capture

Using time domain expressions for a given frequency component, the real hydrodynamic power absorbed over the cycle can be determined from the excitation force as:

$$u(t) = \mathcal{R}e\{U(\omega)e^{-i\omega t}\} = \frac{1}{2}\left[U(\omega)e^{-i\omega t} + U(\omega)^* e^{i\omega t}\right]$$

$$f_{exc}(t) = \mathcal{R}e\{aW(\omega)e^{-i\omega t}\} = \frac{1}{2}a\left[W(\omega)e^{-i\omega t} + W(\omega)^* e^{i\omega t}\right]$$

$$p_{abs}(t) = f_{exc}(t)u(t) = \mathcal{R}e\{aW(\omega)e^{-i\omega t}\}\frac{1}{2}\left[U(\omega)e^{-i\omega t} + U(\omega)^* e^{i\omega t}\right]$$

$$\Rightarrow p_{abs}(t) = \frac{1}{2}a \cdot \mathcal{R}e\{W(\omega)U(\omega)e^{-2i\omega t} + W(\omega)U(\omega)^*\}$$

where the asterisk superscript denotes taking the conjugate transpose. Note that in this form the power is complex and represents real and reactive power transfer. So the instantaneous power at each frequency consists of a double frequency oscillation about a steady value (the average absorbed ‘active’ power over the cycle). As is familiar from other second order systems, only the resistive, dissipative, terms can contribute to the active power with the others (mass and spring terms) contributing to the oscillating reactive power.

So the average absorption over the wave cycle is:

$$P_{abs}(U(\omega)) = \frac{1}{2}a \cdot \mathcal{R}e\{W(\omega)U(\omega)^*\} = \frac{1}{4}a\left(W(\omega)U(\omega)^* + W(\omega)^* U(\omega)\right)$$

Following a similar approach, the average power radiated out over the wave cycle due to the response can be expressed with respect to the hydrodynamic impedance:

$$P_{rad}\big(U(\omega)\big) = \frac{1}{2}U(\omega)^{*}Z_{hyd}(\omega)U(\omega)$$

And if $U(\omega)$ is defined then the power capture may also be expressed directly in terms of the controlled impedance:

$$P_{capture}\big(U(\omega)\big) = \frac{1}{2}U(\omega)^{*}Z_{cont}(\omega)U(\omega)$$

The real and imaginary parts (using only $\mathcal{Re}\{Z_{cont}(\omega)\}$ and $\mathcal{Im}\{Z_{cont}(\omega)\}$ respectively) are the active and reactive powers, and the magnitude is the apparent power.

Without defining $Z_{cont}(\omega)$, net power captured by the WEC can also be defined as what power is absorbed but not radiated back out. Also, noting that only the real damping term of the hydrodynamic impedance can transfer net power over the cycle (the 'added mass' term is associated with evanescent waves entrained with the WEC motion, and the hydrostatic stiffness term is also purely reactive):

$$P_{capture}(\omega) = P_{abs}\big(U(\omega)\big) - P_{rad}\big(U(\omega)\big)$$

$$= \frac{1}{4}a\big(W(\omega)U(\omega)^{*} + W(\omega)^{*}U(\omega)\big) - \frac{1}{2}U(\omega)^{*}\mathcal{Re}\big\{Z_{hyd}(\omega)\big\}U(\omega)$$

For a given input wave amplitude spectrum, we can linearly superpose the power from the individual wave components. Algebraic manipulation leads to some well-established theoretical results and implications in the linear regime (discussed below), and this remains a useful model for control development through extension to include non-linear functions and practical constraints.

Solving the above expression for the response $U(\omega)$ that maximises $P_{capture}(\omega)$ gives:

$$U_o(\omega) = \frac{a}{2}\mathcal{Re}\big\{Z_{hyd}(\omega)\big\}^{-1}W(\omega) = a\big[Z_{hyd}(\omega) + Z_{hyd}(\omega)^{*}\big]^{-1}W(\omega)$$

This derivation from the power expression may be found very compactly in Pizer [Pizer, 1995].

4.4.4 Impedance matching

By solving for the controlled impedance at maximum absorbed power, the well-known optimal solution of complex conjugate control is derived. Substituting the result for optimal response above into the equation of motion:

$$\Big(Z_{hyd}(\omega) + Z_{cont}(\omega)\Big)U_o(\omega) = -aW(\omega)$$

$$\Big(Z_{hyd}(\omega) + Z_{cont}(\omega)\Big)\big[Z_{hyd}(\omega) + Z_{hyd}(\omega)^{*}\big]^{-1} = -I$$

So power capture is maximised when:

$$Z_{cont}(\omega) = Z_{hyd}(\omega)^*$$

This ‘impedance matching’ result is familiar from electrical circuits but here applies with respect to frequency dependent hydrodynamic coefficients across multiple degrees-of-freedom.

Importantly, this result also implies that, for maximum power capture, the power radiated as waves away from the WEC due to the action of the PTO is the same as that absorbed by the WEC as it responds. This observation may be intuitively understood with reference to the far field wave interactions discussed in Section 4.6.

In practice this impedance matched control is not generally realisable for a number of reasons:

- For most WEC types in the wave sizes of interest the response is incompatible with the assumed linearity and with any motion and load constraints, invalidating the result.
- For self-reacting, multi-body devices, a non-fixed source of reaction also makes likely the appearance of degenerate modes of response with associated extreme and physically unrealistic combinations of reaction loads through the PTO and WEC structure.
- The complex conjugate of the hydrodynamic impedance is anti-causal. That is to say, while the hydrodynamic impedance has an impulse response function decaying in time, the complex conjugate has an impulse response decaying into the future – so prediction would be required to apply it through a real control system.

Notwithstanding the above caveats, for WEC types with sufficient volume, motion ranges, and sources of reaction this impedance matching model and the insight it provides may usefully inform locally near-optimal control solutions for small wave conditions where linearity is applicable and relative motions are not excessive.

A good example here is the successful paddle control of an absorbing wavemaker in a wave test tank, where the hydrodynamic impedance may be accurately determined and a causal approximation (e.g. fixed coefficients) applied to match this with a controlled impedance, cancelling out the added mass and hydrostatic terms and maximising absorption over as broad a band as possible, while simultaneously radiating the desired waves for testing.

4.4.5 Including constraints

More generally and more practically, the linear optimal control problem may be framed as the $Z_{cont}(\omega)$ that maximises absorption while meeting any constraints (as discussed below) on loads, motions, coefficients, matrix properties (e.g. positive definite impedance), causality, etc.

A number of approaches may be taken to derive solutions for constrained optimisation in the frequency domain, ranging from elegant analytical methods in the linear regime to brute force numerical methods wrapped around time-domain simulations.

Given the multiple, nested non-linearities likely to be present in a given WEC application, it is likely that detailed time-domain models are required to derive robust control optimisation suitable for practical application. However, frequency domain and analytical methods are likely to offer the wider ranging insights required for whole-system level design.

4.4.6 The inverse problem and potential for reduced parameterisations

In the linearised, frequency domain description above, the absorbed power in a given wave spectrum can be expressed as a function of the controlled impedance. Changes in response and absorption can then be expressed as a function of changes in controlled impedance. However, because the total impedance matrix is inverted in the power expression, changes to individual components of the controlled impedance generally affect all of the components of that inverted matrix in the power expression. Therefore the response and absorption changes due to individual changes in the control matrix are not orthogonal and cannot be superposed in this form to provide simple parameterised relationships between adjustments to the control matrix and the resulting WEC response.

While canonical, state-space representations may make effective use of complex modal representation, modal coordinates do not directly provide a solution for such an orthogonal control parameterisation for multi degree-of-freedom systems because the damping may not generally be uncoupled (as in classical structural vibration approaches) and heavily damped complex modes are generally heavily influenced by changes in the controlled coefficients as they combine with the intrinsic impedance to change the nature of the response. Indeed, for some WEC concepts, the altered modes of response may be associated with increased absorption (for example, by using damping in multiple degrees-of-freedom to induce a coupled response with lower natural frequency).

Perhaps investigation of this issue from a new perspective and knowledge base could result in a method of deriving quasi-orthogonal control parametrisations. The potential to create reduced parameter controls designed to adjust (as orthogonally as possible) for the size and shape of the power, motion, and force operators would be highly desirable for the development of robust adaptive control.

For example, we could envisage reducing an N by N control matrix to just two parameters controlling (as far as is possible given the WEC characteristics and controllability) for the peak and central frequency of the WEC power operator while maximising bandwidth and minimising unnecessary fatigue loading on a cost-benefit basis. Such a simplification at the live control level would allow for automated adaptive control to then be applied simply and robustly to these reduced parameters to maximise yield safely in changing sea conditions.

Structured approaches using stochastic optimisation and/or machine learning techniques could also be brought to bear on this challenge, and such methods may ultimately be more powerful in dealing with non-linearities, extending across the whole range of sea states, and implicitly incorporating potential wave by wave adaptation. Nevertheless, any insights or additional tools provided by the classical theory is likely to assist these endeavours.

4.4.7 Array interactions

The overall hydrodynamics of an array of devices may be described as a single multi-degree-of-freedom impedance function, much like any other multi-body dynamic system. However, defining fixed cross-terms to represent the diffraction and radiation interactions of free floating bodies does not take account of potential drifting of relative positions in the wave field (due to absorption, reflection, wind and tidal stream).

4.5 Generalising to Include Practical Effects and Non-Linear Functions

The frequency domain representation may be generalised to provide a useful description of the control problem including additional linear effects such as constant delays and additional plant dynamics. Some non-linearities may also be treated in the frequency domain with well-established techniques (for example, ‘describing functions’ to model amplitude and frequency dependence in terms of the fundamental harmonic only).

An effective linear impedance may be described, from an arbitrary force and motion history, as that which would pass the same average real and reactive power over the same motion cycle.

These can be used as a windowed measure in real systems of what impedance is effectively being applied after load saturation and actuation delays.

The most challenging non-linearities to characterise and model include memory effects. Notably backlash in bearings, and any hysteretic effects in materials or in PTO control implementations. Along with other potential sources of uncertainty in measurement and force application, these should be minimised by design but must still be carefully considered in the modelling process where they can severely constrain the achievable performance.

Numerical simulation tools and techniques allow for detailed nonlinear models to be run directly, leaving only the developer’s choice of assumptions and omissions to introduce errors to the results.

The WEC control problem typically involves relatively large output force as a function of relatively low velocity when compared to other real time control applications (such as temperature controllers, autopilots, etc). On one level this is compensated by the correspondingly high inertia of the WEC, but lack of stiffness or mechanical play (backlash) in the actuator load path may result in a local stability challenge.

4.6 The Far Field Model and Ultimate Limits of Power Capture

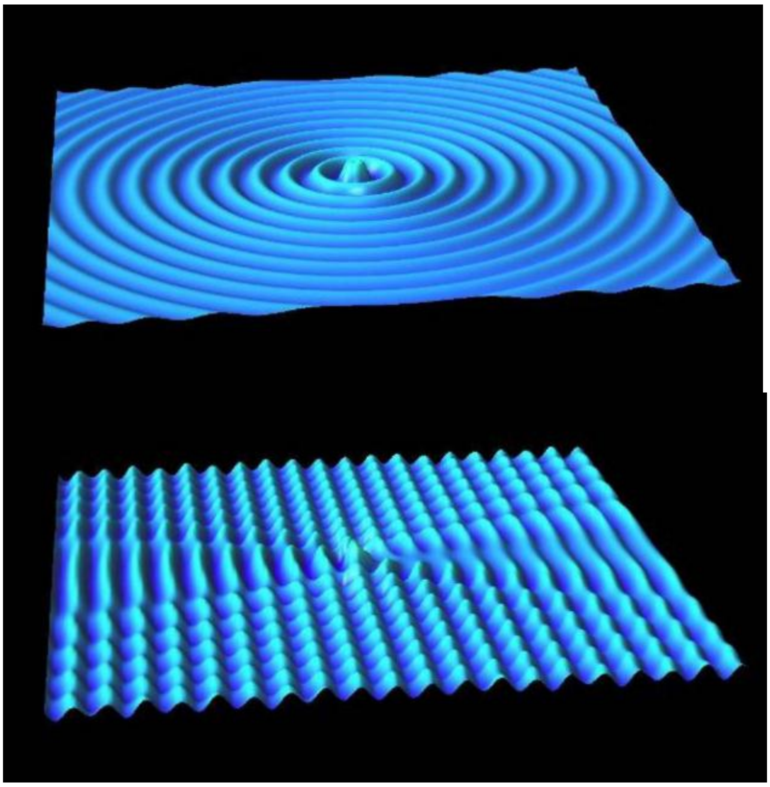
It was shown in Section 4.4, for the impedance matched condition, that the optimal radiated energy matches that absorbed. Analysing wave interactions into the far field, including those radiated as a function of assumed WEC response, can also be used to derive the optimal phase and amplitude of the radiated waves, and hence the optimum WEC response amplitudes and phases, for maximum absorption at each frequency. For a slender device with little wave scattering, this analysis shows quite intuitively that the maximum power capture condition is associated with maximum cancelation of the undisturbed, transmitted, incident waves through destructive interference, effectively maximising the wave ‘shadow’ behind the WEC, as shown for a single degree-of-freedom, symmetrical body in Figure 6. This optimal response and radiation corresponds to a perfectly matched impedance at one frequency. The spectral optimal would consist of multiple components in superposition. Realistically achievable controls may be far from such an optimum but the concept of far field wave cancellation remains valid and useful.

For devices with greater back-scatter, the radiation challenge is simultaneously to cancel these waves.

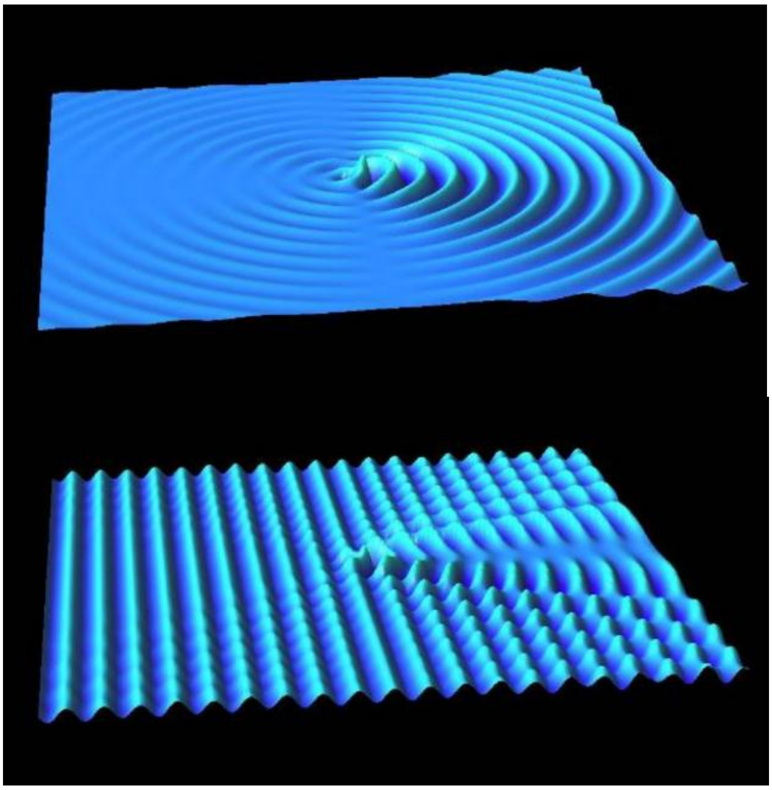
This far-field approach frames the control and wider design problem as how the WEC can be designed to practically radiate waves of the required amplitude and frequency to cancel out those prevalent on the site [Falnes, 2005].

The result already given above for optimal controlled impedance corresponds to this response derived from maximising the far field cancelation, as it must using the same physical assumptions of linearity and potential fields to represent the hydrodynamics. However, applying the far field analysis in 3d gives rise to the less intuitive but highly insightful results of ultimate normalised capture widths for individual WEC types according to their fundamental response modes and hence radiation patterns.

A WEC can absorb far more energy from the waves around it than is projected in front of its cross-section because the machine interacts with the entire wave field around it not just with the waves that pass directly through the system. The theoretical limit for wave energy absorption is commonly expressed in terms of the capture width: the width of wave front that contains the same incident power as that being absorbed.



- Figure 6 Monopole Radiation Pattern from a Heave Only Response (above) and the Interference with an incident wave for the Optimal Phase and Amplitude (below)[13].



- Figure 7 Radiation Pattern from an Optimally Phased Array of 5 Heave Only Responses Spaced Downwave (above) and the Interference at Optimal Phase and Amplitude (below)[14].

The role of multiple bodies and spatially distributed modes of response in generating higher capture widths may also be understood in this far field context, as shown in Figure 7 and this highlights the potential importance of array interactions for single degree-of-freedom WECs like heaving buoys. A line absorber can also be described in this manner as a linearly distributed phased-array of monopoles – a concept familiar from ultrasonic and radar applications where the relative phasing of emitters dictates the focus and direction of a radiated beam. [Stansell, P. & Pizer, D.J. (2013)]. Radiation patterns can also reveal the potential inherent in asymmetric bodies and in multiple degrees-of-freedom, which produce multi-pole, directionally focussed patterns. Combining WEC shape and response motions therefore opens up the opportunity to radiate strongly in one direction whilst radiating little in other directions.

How realisable the linear ultimate power capture limits are should be considered more of a conceptual WEC design issue than just a control problem for a given WEC concept. The practically achievable limits depend on the WEC dynamics, volume, and geometry, and sources of reaction for the PTO system, plus force and motion limits and other physically manifested constraints. The subject and implications of ultimate limits is therefore largely outside the scope of this report.

However, it is important to grasp the significance of the WEC characteristics on setting the boundaries and requirements of the control system, and also the role of controllability in

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[13] Pictures from Pelamis Wave Power courtesy of Wave Energy Scotland

[14] Pictures from Pelamis Wave Power courtesy of Wave Energy Scotland

approaching limits, and the importance of treating the interaction of the WEC dynamics with the control and power-take-off properly at the conceptual and design stage.

In the modelling and design of control systems it is important to understand where limits in the forces, motions, and control gains impact on these ultimate limits. It is typical for the ultimate limits implied by the linear modelling of a given WEC to be very far from practical and for the associated loads and motions to grossly invalidate the linear model from which the ultimate power capture is derived.

Of course, the whole system design, and the resulting control requirements, must ultimately be an economic trade-off depending on many other factors.

4.7 Practical Application of Impedance Control

4.7.1 Introduction

The non-frequency dependent terms of the hydrodynamic impedance, the physical mass and the buoyancy, may in theory be compensated out using a causal control implementation within the confines of constraints and linearity. The frequency dependent terms may be approximated by fixed terms that best maximise power capture over the spectrum, avoiding the need for prediction provided the remaining performance gap is relatively small.

The impedance control paradigm for wave energy is similar to that for human-machine, tactile feedback, haptic interfaces, where a desired mechanical impedance (typically including ‘virtual mass’) is generated through control of forces applied by an actuation system. Research and successful approaches to this problem may be a fruitful ground for cross fertilisation with WEC control.

The requirement for force feedback control of the actuators depends on the type of PTO. This may be treated as an inner loop with its own transfer function, and stability and performance issues interacting with the wider system.

4.7.2 Measurement issues

Implementation of a controlled impedance requires control of the force applied by the PTO as a function of measured position, speed, and acceleration. As with any control application, avoiding disturbance, noise, and error in these input measurements is critical to performance.

Compared with other control applications, the velocity and acceleration range being measured is quite low compared with the resulting forces to be applied as a function of those inputs (i.e. the system gain is very high). Therefore care must be taken over the effective sensitivity of the sensing system, accounting for sampling rates, resolution, noise, and disturbance.

Care should be taken to avoid disturbance from structural flexibility in the load path. In particular, while it is convenient to house position and/or velocity transducers directly in or in-line with PTO actuators, this may result in local dynamics effectively disturbing the desired estimation of the WEC position, especially if the PTO induces discontinuous loads that translate to spikes in signals measured on that load path.

4.7.3 Spring

Position measurement of the controlled degree-of-freedom may generally expected to be straightforward with relatively low disturbance and noise due to the smoothing effect of the system inertia.

It can be advantageous to lower the WEC natural response frequency to improve matching with the hydrodynamic impedance through a negative spring term, whether through mechanical techniques or through a virtual negative spring force generated by the controller. A negative spring is inherently statically unstable meaning it can only be applied such that it combines with the external buoyancy terms to retain a net positive spring overall (i.e. the virtual negative spring must be less than the physical positive spring in every degree-of-freedom, thus the combined spring matrix must be positive definite).

4.7.4 Damping

Velocity measurement may be taken in the controlled degrees-of-freedom directly using a variety of available transducers. The high duty and environment generally demands non-contact transducers. The output from encoders or timing based position sensors may be differentiated but care must then be taken to ensure the position resolution sampling rate is compatible with the required resolution of the velocity signal.

For rotating degrees-of-freedom, inertial measurement systems are available including combined gyroscopic measurement of 3d rotation rate. These may be combined with a kinematic estimation process to provide velocity measurements in desired controlled degrees-of-freedom. This approach offers the possibility of using redundant and distributed sensors to reject disturbance and noise while maintaining higher overall reliability if error detection systems (e.g. voting) are also employed.

4.7.5 Mass

Including virtual mass in the controlled force introduces different challenges. Since the virtual mass term makes the control impedance the same order as the external impedance, the transfer function is not strictly proper so for virtual mass greater than the physical mass the closed loop gain remains greater than one as frequency tends to infinity. Therefore, any delays in the feedback terms can result in instability at double the delay period.

Delays are unavoidable in practical digital control systems (and in explicit numerical solvers such as Euler’s method), and they are a major limiting factor to the achievable control gains generally. However, this impact is particularly acute for virtual mass.

The mass term may be stabilised by introducing a low pass filter with time constant targeted at rolling off the frequency response above the wave response periods of interest but below the effective delay frequency. Provided delays remain small, the impact on performance can also be small.

Mass terms are far more sensitive to local dynamics of the PTO system and disturbance on sensing systems. The acceleration at the wave response frequencies may be low relative to local disturbances due to structural vibration and other sources.

Deriving acceleration from velocity or position measurements introduces further processing delays and phase shift due to noise issues associated with the differentiation. Inertial sensors (accelerometers, now available in low cost chips that are driving the Internet of Things) offer direct linear acceleration measurement but to measure the relative acceleration of the controlled degrees-of-freedom requires multiple sensors with a kinematic estimation process. However, an estimation approach using multiple distributed inertial sensors may also offer improved disturbance rejection.

4.7.6 Cross terms in multiple degree-of-freedom systems

The whole WEC design and the associated control design for multiple controlled degrees-of-freedom and hence Multi-Input-Multi-Output (MIMO) control is an inherently complex and interactive one. The optimisation of control parameters in MIMO systems (e.g. the coefficients of damping, spring, and mass matrices) must be treated along with the wider system dynamics and governing models. There are some particular insights with practical implications that are worth highlighting however.

The cross terms in the controlled MIMO impedance (in the damping, spring, and mass matrices) effectively pass phase information from response elsewhere (spatially in the wave field and/or in pure phase according to the mode of response) to the other degrees-of-freedom. This implies the effective impedance applied at each degree-of-freedom (based on local force vs velocity over the cycle) is a function of these cross terms and machine wide response, in turn a function of the wave frequency and direction components (and hence wave number via the dispersion relation).

In effect this means that a single, real-valued control matrix can apply complex reactive control through the action of cross terms, coupling the forces applied at each degree-of-freedom with the responses at all others. The PTO requirements and the control constraints must be defined in terms of reactive power requirements even where only a damping matrix (i.e. with terms only multiplying with velocities) is controlled.

Used properly, this complexity is a strength of MIMO control allowing maximum use of available measurements to provide additional response bandwidth and hence greater absorption across the frequency range. For example, degrees-of-freedom spatially separated (e.g. in an array) can allow multiple, low-noise, position measurements to provide implicit frequency (and wave length) dependent reactive control (i.e. like that provided directly by mass and damping terms) at other degrees-of-freedom. In combination, with directly applied damping and mass matrices similarly reinforcing or negating each other for different wave components, the fully cross-coupled solution has the opportunity to make the best use of available signals of varying quality and to maximise the use of available information.

As another example, cross-coupling down length in a line absorber allows for the response down the whole length to be tailored to provide the necessary reaction forces for maximum absorption overall, accounting for non-linearities. Due to the travelling nature of waves there is also an implicit predictive element in measuring from specially separated degrees-of-freedom that are responding to different parts of the wave field.

As discussed in Section 4.4.6, achieving optimal control, and potentially more useful control parametrisations, with multiple degree-of-freedom system requires a control and dynamics model with controllable terms intrinsically coupled across all degrees-of-freedom. This problem lends itself to stochastic optimisation techniques such as simulated annealing and genetic algorithms.

Modern machine learning techniques could allow for generalised definitions of control functions rather than fixed linear coefficients, including implicitly adaptive control to take advantage of any available predictive inputs in meeting response constraints.

4.7.7 Generalised linear function (frequency dependent coefficients)

Fixed controlled impedances may provide robust and high performance control if the WEC design is compatible with a practical control implementation, and if that system is properly implemented. However, further performance gains remain possible from alternative formulations of the controlled impedance and from adaptive control of the impedance parameters.

4.7.8 Causal impulse response synthesis

The controlled impedance may be implemented as a generalised transfer function, or synthesised directly in the time-domain as a generalised, finite impulse response (FIR) function(s).

The purpose of this approach is to create a better overall match for the total hydrodynamic impedance while retaining a practical implementation requiring only present and past measurements (i.e. casual) [Clement and Maisondieu, 1993]. Numerical methods familiar from existing control applications may be applied with whole system models to solve numerically for the filter coefficients that provide the best overall performance. Of course, load and motion constraints may still introduce major non-linearity before application. Furthermore, smoothly adapting FIR implementations is more complicated than transfer function coefficients.

This may offer some benefits in performance over fixed mass, damper, spring impedance models particularly in optimising for specific sea conditions, but the issues of signal measurement and stability with respect to delays and effective gains remain, albeit somewhat less intuitive to analyse.

4.7.9 Predictive impedance matching

The hydrodynamic impedance includes frequency dependent terms, and while the corresponding impulse response functions of these physical properties are causal, the corresponding optimally matched controlled impedance is not. The excitation function is inherently non causal, that is to say, the future wave elevation is generally required to evaluate the current excitation force. Although the period of time involved may be insignificant for small volume WECs, this may not be the case for larger volumes.

A non-causal transfer function implies the corresponding impulse response functions extend into the future as well as the past. This implies that any controlled impedance seeking to fully match the hydrodynamic impedance across all frequencies would need to act in response to events that have not yet transpired.

Such a controller could be realised if the incident waves were known with sufficient accuracy a few waves in advance and optimal impedance could then effectively be applied to all frequencies at once by changing continuously over time. The period of prediction required broadly corresponds to the decay time of the WEC hydrodynamic impulse response functions [Falnes, 1995].

While much is made in the literature of the academically interesting causality issue and the corresponding prediction requirement, there remains little practical evidence of major overall power capture benefits that wave by wave frequency prediction could offer over fixed impedance control with reactive terms well-matched to the local sea statistics (adapting over time). Importantly, the relative benefits or otherwise depend on the bandwidth of the WEC response, in turn a function of the volume and degree of over-damping [Price, 2009].

However, for very different reasons, short term wave envelope prediction (with residual errors in exact phasing) could be very valuable for increasing the overall power capture in the majority of sea states where the WEC response is not maximised due to constraints, as discussed in Section 4.8.

Any potential also depends on the wave by wave accuracy of short term wave prediction systems. The requirement for accurate phase information could potentially be dramatically lessened by adopting a windowed Hilbert transform approach to predicting envelope and frequency time series, for corresponding adaptation of the impedance.

4.7.10 A note on tank wave maker control

Wave tanks rely on force feedback and impedance control to both radiate the waves desired in the tank for testing, and to absorb undesirable waves resulting from reflections. The absorption control process consists of applying a velocity measurement to a best match impedance function to that exhibited by the paddle hydrodynamics, then applying the resulting force through the paddle actuator in superposition to the force required to radiate the desired waves, in an attempt to absorb all waves incident on the paddle.

A wavemaker paddle has the advantage of a fixed source of reaction for the actuator, operation in a single degree-of-freedom, and for open backed paddles no radiation in the down wave direction. These characteristics make it a great wave absorber, but subject to impracticalities as a full scale WEC. However, the close analogy is likely to be the source of useful experience in practical application of controls for devices with fixed sources of reaction and tight force control capability.

4.7.11 Constraints

Constrained optimal control problems are familiar from most other applications involving the control of forces and motion. WEC response control is limited by the ranges of motion that the PTO mechanisms are allowed to move through, and the ranges of load they can apply.

Constraints in load and motion are generally expected to be dominant in defining the optimal response control function. It is possible for load and motion constraints to be applied in the linear formulation to give constrained optimal controlled impedance solutions, for example by using the method of Lagrange multipliers. Evans described such a global constraint formulation [Evans, 1981] later expanded on by Pizer [Pizer, 1993].

However other less obvious constraints on the gain that may be applied through the PTO can dominate the performance limits of the controller, particularly in small waves. As is also familiar with control problems in general, the closed loop transfer functions that may be applied are a function of the dynamics of the plant including the actuation system and any finite stiffness, inertia, mechanical play, delays etc. that may be included.

As briefly described above in Section 4.4.2, delays and phase shifts in the control process (for example, associated with sampling rates and noise rejection filters on transducer inputs) may also be included in the linear formulation along with additional dynamics of the PTO and other mechanical systems interacting with the WEC response control.

These issues may be key to specifying the design of the PTO system and structural attachments to enable maximum WEC control gain and to avoiding simplified models giving unrealistic expectations for the performance of the real machine. Thus, understanding these interactions is a key requirement for both control and the wider PTO and WEC structure design.

The role of constraints is also important in adapting the control parameters to changing sea conditions where control optimisation problem becomes one of balancing risk of breaching constraints against maximising the power captured in moderate seas.

4.7.12 Alternative approaches to impedance control implementation

Mathematically, a desired response can be achieved by controlling either the WEC motion directly or the impedances - the output control forces are the same in each case. Despite the mathematical equivalence of the two approaches and the identical loads and motions implied, there are practical differences with respect to measurements and sensitivity to errors.

A control process may achieve a demanded impedance accurately with reference to easily measured and reliable inputs of the WEC’s motion. Errors in short term adjustments made to this demand impedance (resulting from errors from the wave force measurement systems, and any prediction systems) would be relatively benign on the performance. Under impedance control, the phase of the response is dictated by the excitation, with the impedance controller only adjusting phase of the response relative to the waves rather than directly dictating response motion. Thus any errors in the impedance applied have only a second order effect on the power capture performance. Even with a predictive system, errors in the predicted phase of the incoming waves would have a relatively minor impact on the demand impedance error (dictated mostly by fixed terms) and even less impact on the resulting response.

Controlling directly for WEC response (velocity and position over time) as a function of measured excitation force is an alternative method of implementing PTO control. The impedance controller relies on the accuracy of the assumed hydrodynamic impedance. A direct response controller would similarly rely on the accuracy of the radiation model used to estimate the exciting wave forces. This is only possible where a fixed source of reference is available to allow the PTO force to determine the WEC response in absolute terms relative to the wave excitation. Additional and challenging sensing systems would be required to measure the forces applied by the waves directly and independently of the PTO forces, for example, using distributed pressure sensors on the outer structure. A system operating ideally would recreate the same control forces as an equivalently set impedance controller.

Direct measurement of the exciting forces could be expected to offer significant advantages in a generalised control system using multiple overlapping sources of information on the WEC excitation and response. For example, a machine learning approach could use such inputs to refine models of the WEC dynamics implicit in control policies trained over time.

4.7.13 Maximising absorption with respect to wave conditions

For now, continuing to treat the control and hydrodynamic impedances as fixed for a given sea state and from the expressions above, we may define linear power, response, and force operators as a complex function of the frequency of the incident wave components. The WEC power absorption in a spectrum may be defined and visualised as the summation of product of the power operator at each frequency and the corresponding component of the incident wave spectrum (it is generally convenient and practical to work with discrete components).

Maximising power capture from a given amplitude spectrum (sea-state) can be visualised as maximising the total from each component through spectrum. This implies that a wider (higher bandwidth) of response is generally preferable. A higher bandwidth, less peaky response is also more robust to variations in frequency within the wave train.

The bandwidth is largely a function of the inherent hydrodynamic characteristics of the machine and also the related extent to which it may be overdamped under control. Larger volumes (or larger areas for inertia driven/dominant concepts), allow for higher damping to be applied to a given response and for larger longer waves to be radiated at finite amplitudes, corresponding to an ability to absorb such waves.

Extending the describing function approach, the whole WEC response control may be defined as a function of frequency and amplitude of the incident wave. While these do not linearly superpose, the approach provides useful insight into the onset of the non-linearities as the power operator diverges with increasing amplitude from the corresponding idealised linear operator.

4.8 Adaptive Control

4.8.1 Introduction

Technical challenges in adapting control on a wave-by-wave basis, which requires short-term predictive ability, are considerable and remain a research topic. Far more realisable and practical is to adapt control settings to reflect slowly varying factors such as the prevailing spectral description of the host sea.

Within any sea state, which conventionally is measured over a period of 15 to 30 minutes, there will be a mix of wave frequencies, amplitudes and directions.

For resource assessment and general oceanographic purposes, it is conventional to parameterise the sea states by reducing their time histories to height and period descriptors. Historically, the most common parameters have been significant wave height, H_S, and zero up-crossing period, T_Z. Traditionally, in the days of strip chart recording and visual observation by mariners, H_S was taken as the mean of the highest third of the wave heights in the record, with wave height being defined as the difference between adjacent troughs and crests. T_Z was defined as the average time between successive upward crossings relative to the mean elevation. With greater digital and computing capability, these definitions have been supplanted by approximate equivalents based upon spectral moment analysis.

Given a time history of sea elevation at a specific point, the corresponding frequency spectrum, $\epsilon(f)$, can be found by Fourier transformation. Defining the n'th spectral moment as:

$$m_n = \int_0^{\infty} f^n \, \epsilon(f) df$$

significant wave height is expressed as:

$$H_s = 4\sqrt{m_0}$$

whilst zero up-crossing period is defined as:

$$T_Z = \sqrt{\frac{m_0}{m_2}}$$

For wave energy purposes, an alternative period parameter, energy period, T_E, is common. This, relative to the wave record, is the period of the regular wave that, for a height equivalent to the significant wave height, would have the same power density.

$$T_E = \left(\frac{m_{-1}}{m_0}\right)$$

T_E is the period parameter generally used to categorise sea states independently of the spectral shape, as it quantifies the incident wave power (in kW, this is $0.49\ T_E {H_S}^2$) regardless of the exact shape of the spectra.

Some in the industry prefer the use of spectral peak period, T_P. This measure does not have an equivalent, moment based definition. The peak period, T_P, is of very limited use for describing real seas, which can have multiple peaks as in the example illustrated in Figure 8.

For oceanographic climatic purposes, long term records of sea states are normally presented as dual probability scatter diagrams.

Spectral parameters do not provide any insight into spectral shape. A number of standard shapes have been developed and are used for design and analysis purposes and as the basis for time series synthesis. Common spectral shapes are Pierson-Moskovitz, Bretschneider and Jonswap. A failing of all of these is that they describe locally brewed seas but fail to provide for distantly created swell which typically introduces a second spectral peak at a longer period. Such factors are relevant in design and tuning of a WEC for a specific location.

Aside from period and height parameterisation, measured wave spectra are also usefully parameterised by direction and directional spreading. Measurements of waves are most commonly conducted by wave rider buoys fitted with accelerometer arrays. Whereas wave height and period are adequately estimated by heave activity, directional information relies upon pitch and roll response.

The relevance of spectral parameters to slow, adaptive control of WECs, as discussed in Section 4.8.2, is that PTO damping and potentially reactance can be tailored to optimise overall performance for the prevailing wave period and wave height ranges.

In passing, it is worth noting that the US Department of Energy as part of its wave energy programme is engaged in a major investigation into Advanced WEC Dynamics and Controls. The thrust of the work at the time of writing is to investigate whether it is possible to determine experimentally to a high degree of accuracy the dynamic and hydrodynamic coefficients of the WEC system model, including at full scale, and to use these techniques to slowly adapt that model should these coefficients change over time[15].

4.8.2 Adapting response control with wave measurements as input

Real-time control of WEC response and power absorption uses real-time measurement of the WEC response as input. For optimal power capture in changing conditions, the control parameters defining how the response inputs map to the actuated outputs may be adapted with respect to knowledge of the local wave conditions and other environmental loading and disturbance.

Regularly updated measurement and estimation of the local wave spectrum (without phase information) can be used to adapt control parameters. This may be based on prior knowledge of the ‘best fit’ control settings for application in that sea state (for example in a look-up table, fuzzy rule-base, or similar scheme) or through self-learning, adaptive control techniques (machine learning, pre-trained or otherwise).

A typical wave measurement system consists of a commercially available wave buoy transmitting acceleration signals from its on-board motion sensors. The time-series may be processed in a number of ways to derive estimates of the spectra over a given time window. While such spectral measurement systems are available and well understood, the measured

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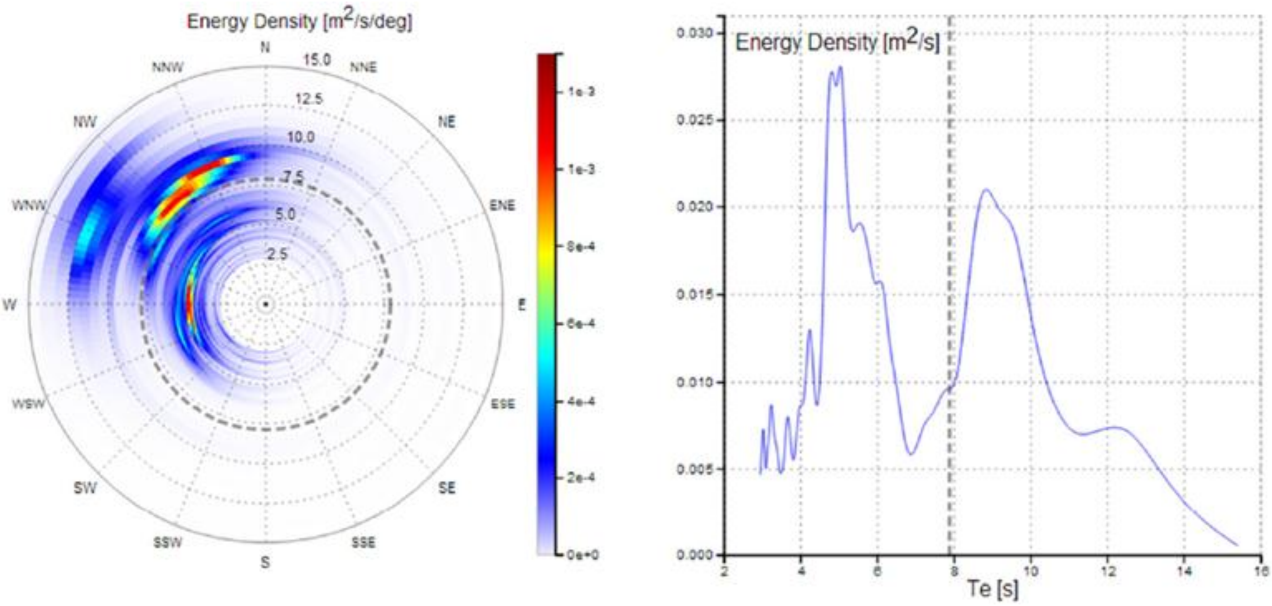
[15] at time of writing, informative webinar material was available at: http://energy.sandia.gov/webinar-recording-available-advanced-wave-energy-converters-wec-dynamics-and-controls/

spectrum does not include the phase information required to recover the water surface elevation at the WEC(s) but represents only the statistics of the wave field over a given time-window. Directional information may be recovered successfully from a suitably instrumented buoy by using probabilistic estimation algorithms [Cruz J., Mackay E., Martins T. (2007)].

Experience has shown that a 30 minute window, as indicated by Figure 8, provides sufficient resolution for reliable and consistent directional spectra. In this case, most of the available energy is contributed by a combination of a swell from the NW, centred around 9 seconds period, and a local wind chop from the east centred around 5 seconds. Spectral estimates may be improved in resolution, or a similar resolution achieved in shorter time windows, by combining multiple spatially separated buoys in ensemble.

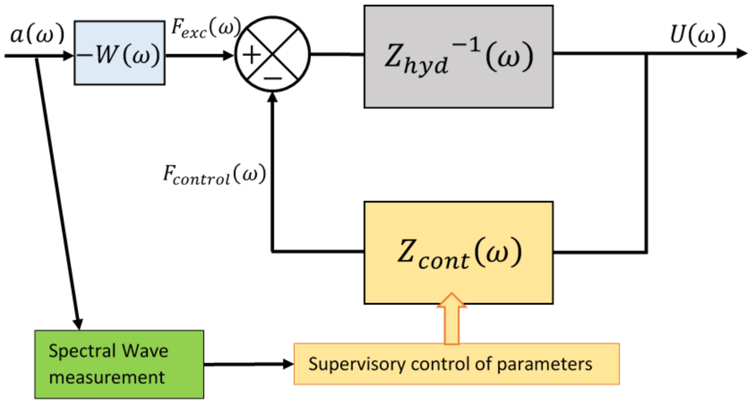


- Figure 8 Example Plot of a 30 Minute Directional Wave Spectrum Derived from Accelerometer Measurements from a Single Buoy.

4.8.3 Statically defined seas

With the ability to progressively 'turn up' or 'turn down' the WEC response (and absorption) in a given sea condition, and hence to remain optimal within a set of constraints as conditions change, the adaptive control problem can be framed in familiar terms as 'gain scheduling'. The response control parameters selected for a given, pseudo-static sea condition are defined with respect to any constraints and extremes events expected for that condition.

Gain scheduling of control parameters is determined according to measured sea conditions and response history. As indicated by the block diagram of Figure 9, the supervisory control process may involve look-up tables derived from model optimisations (open loop), and may be responsive to measured WEC response using parameterisations to apply settings depending on the motion and/or force history (closed loop).



- Figure 9 ‘Gain Scheduling’ Adaptive Control

4.8.4 Predictive control for constraints

The ultimate adaptive system can control the WEC in an ‘animalistic’ fashion for optimal motion and absorption within constraints in immediate response to any changes in wave conditions and even any wave by wave inputs that might be available.

This complex challenge could be broken down into smaller steps through parameterisations of the response control algorithm as discussed in Section 4.4.6.

4.8.5 Deterministic short term wave prediction for response control

While the technology is not yet proven or as familiar as it is for spectral wave measurement systems, the potential to include wave by wave prediction of the incident wave field in the WEC’s response control offers the ability to adapt control settings wave by wave. This includes frequency adaptation and the application of non-causal impulse response functions in the controller.

While much attention has been paid in the literature to the potential role of prediction in frequency dependent response control, short term wave prediction may be more valuable for increasing the overall power capture in the majority of sea states where the WEC response is not maximised due to motion and load constraints. In these conditions, where the majority of energy may be captured over the year, a fixed parameter controller optimised for the sea state with respect to motion constraints would be limited according to the biggest wave groups expected, leaving the response over-constrained the rest of the time. In lulls in particular this represents a lost opportunity.

Adapting the controller to meet the constraints as the wave envelope oscillates, through groups and lulls, could offer major advantages. Since waves come in groups and lulls, if the machine response could be ‘turned up’ and ‘turned down’ adaptively between groups then dramatic improvements in yield would accrue on average. The detection of such changes in excitation would be required to be robust in proportion to any increased exposure to risk taken. Any adjustments could only be made safely within the error bounds of the prediction system.

4.8.6 General machine learning approach

Instead of defining real-time response control algorithms and their parameters explicitly and separately according to theoretical models, as described above (for example, in fixed impedance control) they both may be embedded implicitly in a single adaptive control policy using machine learning techniques, allowing for continuous learning and optimisation. Optimisation may be conducted through using training sets in numerical models and, in theory, continuously in the field.

Adaptive and generalised machine learning is now reaching many real world applications but these are still dominated by pre-trained systems. Training may be subject to regular upgrade with continuously collected additional information but achieving robustness appears to require a pragmatic and somewhat brute force approach to succeed for the time-being.

Any application of machine learning in WEC control is likely to benefit greatly from the many insights gained over the past decades, as touched on above, perhaps from reduced parameterisations and hierarchical information and process structures derived through more classical techniques and optimisation methods. For example, it may be that an underlying impedance control mechanism is inherently robust against measurement, estimation, and prediction errors because of the sensitivity issues while machine learning may be effective at fine tuning this with respect to constraints and all available information.

4.9 Approximations/Alternatives to Optimal Control

4.9.1 Introduction

Not all PTO systems are able to provide the continuous, fully independent, four quadrant control of velocity and force that is needed for high-bandwidth, optimal impedance control, even within a restricted load and motion range. More generally, the challenge of transmitting the forces and power associated with wave power capture is beyond conventional and industrially available systems and is therefore part of the wider wave energy technology development challenge and the subject of ongoing research and development. Some PTO concepts have limited capability whilst others are simply not suited to impedance control – for instance, low-head pneumatic machines with appreciable inertia do not lend themselves readily to alternating between pumping and turbine mode.

In tackling the ongoing control development challenge of wave energy, it is important to appreciate the limitations of today’s PTO systems and their associated control strategies.

A number of control strategies have been proposed to maximise power capture despite limitations in the capabilities of PTOs. Although sub-optimal compared with ideal impedance control, they represent potential improvement on simple, continuous resistive control. The strategies have been proposed either as a cost reduction measure or as an approximation strategy in the absence of technology available to provide fully reactive and/or continuous control of forces.

4.9.2 Coulombic damping

Perhaps the most technologically simple control function to implement with a PTO system is for force to be applied passively as work is done over a yielding actuator at roughly constant load. Below the yield point, the WEC will be fully restrained; once yield is exceeded, the WEC will be resisted by a constant force. This is the case for a hydraulic cylinder pumping through a non-return valve. This is a highly non-linear function but is purely resistive and over the wave cycle may be considered a rough approximation to a linear damping coefficient dissipating the same energy over the same motion. In a hydraulic system, the fluid pressure may be a controlled variable allowing some control over the effective damping applied. The main drawback of this system is relatively poor performance in irregular waves when the force is too low for the bigger waves and too high for the smaller ones (e.g. not yielding at all in the smallest waves of the sea state). The major attraction to developers is the great simplicity of the PTO hardware and the option to remove control and control actuation requirements from the primary transmission altogether to give a mechanically passive system.

For WEC types of low stiffness designed to contour the wave excitation rather than respond in resonance with it (e.g. inertia driven surge concepts), there may limited benefit from reactive control due to the restricted design range of PTO loads. Coulombic damping may be a suitable, simple, alternative strategy.

4.9.3 Latching (a.k.a. non-linear, phase control)

Another non-linear control concept often studied in the literature and in tank tests over the past three decades involves, by whatever means are suitable, holding the WEC response fixed or partially restrained over part of the wave cycle to achieve optimal phase alignment with the forces applied during the working stroke of the wave cycle [Budal, 1981].

The strategy is applied for wave periods that are longer than the WEC’s natural period. At these periods, the system is stiffness dominated and thus the wave exciting force and response velocity are mismatched in phase leading to periods of negative product and poor power absorption. The idea of latching is to retard the response at the extremities of travel to hold back the response temporarily and hence introduce a phase correction that induces response velocity and exciting force to peak roughly together and to remain of the same sign at all times. The motion of the device between successive release-catch actions is dominated by a rapidly decaying impulse response at the natural period, resulting in bursts of high power delivery.

This type of control is non-causal since timing of release requires knowledge of force behaviour in the short-term future. This has been the subject of a number of studies to develop probabilistic predictive schemes for instance based on Kalman filtering. Alternative approaches are possible involving, for instance using force levels to trigger release, similar to yield in Coulombic damping.

The latching concept faces practical difficulties of differing severity depending upon the type of WEC and PTO. Generally however, the reaction forces required to hold the primary converter fixed are no smaller than would apply in a moving controlled system, and the motions required are greater to achieve similar power. A mechanical system to achieve latching is also not straightforward, especially on large floating WECs.

A latching system may be more practical on OWCs where the waves act on a gas pressure which might be checked and released using a valve arrangement based on, say, an iris mechanism, an inflating annular diaphragm/membrane or, in the case of an externally rectified turbine, the use of the existing rectifying (potentially louvre) valves. For an OWC, latched phase control is a credible approach – isolation is triggered at the no-flow extremities of travel and the danger of high transients is ameliorated by compressibility of the air volume that transmits pressure and flow from the water column to the turbine. Compressibility also means that the column, unlike the flow, is not fully arrested during latched phases which, if suitably accounted for in the controller, can be positive in improving power capture. Many OWC designs are broadband and have little to gain directly from phase control, however effective latching strategies open up the possibility of reducing the size and cost of the OWC structure and to recover any associated loss of bandwidth through control. Reducing the capture quality of the converter, whether OWC based or otherwise, however tends to reduce the scale of the hydrodynamic damping which in turn leads to high resonant amplitudes of response. In a phase controlled system, large undesirable amplitudes can therefore be expected at all controlled frequencies. A balance must therefore be struck in optimising the design and control strategy.

4.9.4 Critique of control alternatives relative to optimal impedance control

Generally in the motion control industry, for instance in motor/generator control, the ability to apply force in either direction, while moving in either direction is referred to as 4-quadrant control. This term has been adopted in the wave energy industry to describe the interaction of the PTO with the primary WEC. The quadrants refer to the force vs velocity plot. 4-quadrant implies the capability to transmit power in both directions, thus in the context of wave energy take power from the sea and also put it back over different parts of the cycle. Depending upon design, this capability is not always present, but as is clear from the description of impedance control in Section 4.4, the ability is necessary for unimpeded application of loads throughout the wave cycle, particularly for the application of mass and spring terms in the control function. 4-quadrant control is often referred to in the wave industry as ‘reactive’ control due to the ability to transmit reactive as well as resistive force and power.

A purely resistive PTO may only apply force opposing the direction of travel (i.e. by definition is in phase with velocity) and hence may only absorb power and cannot apply mass or spring terms to adjust the phase relationships between the exciting force and the response. An air turbine may be controlled to provide a range of pressure-flow-speed characteristics, but in all cases, whether linear, quadratic or otherwise, the relationship will always be resistive.

Coulombic damping described above is a highly non-linear form of purely resistive control, as indeed is latching control.

Parametric control of the damping, which is possible with an air turbine, to provide hysteretic response may allow for some effective spring or mass to be applied while moving (by creating asymmetries in the load and power cycle) but this is of limited use while power transfer must remain unidirectional. Also, the responsiveness to applied loads required to implement this strategy would typically be associated with a reactive power capability anyway.

Clearly, full reactive power capability offers the greatest potential for maximising absorption as it allows generalised control of forces from the PTO systems and for ‘tuning’ of the frequency response in addition to damping, as in impedance matching. The optimal phase condition and amplitude condition may be optimised for thorough control of both resistive and reactive terms in the controlled impedance.

Ultimately, the mutual loading, performance and cost base trades-off between WEC design, PTO capability and control complexity need to be understood before the overall solution that minimises LCoE can be identified.

4.10 General Design Optimisation

The problem of control optimisation is intrinsically linked to optimisation of the WEC itself. A change in the external geometry of the WEC may offer a cost effective and powerful route to reduced LCoE, provided the optimal controls are available to use it.

While this completely general approach to optimisation is very ambitious and is ultimately tantamount to automating the entire design process, the problem may be modularised and reduced to minimal parameters at the development stage. For example, having an optimal control process included inside the process of geometry optimisation (perhaps just involving a few driving parameters) ensures that the latter is able to take full advantage of the former and vice versa.

A brute force, generalised optimisation approach using modularised optimisation processes in a single numerical model is increasingly approachable. However and as ever, the constraints and modelling details benefit from real-world experience and learning to avoid ‘garbage-in-garbage-out’.

4.11 Real Time Response Control Conclusions

Drawing together the foregoing, the following key points are important:

- Linear theory of absorption and corresponding theory of optimal control is well established but does not generally extend to practical requirements for implementation.
- WEC control may be described in terms of mechanical impedance, using the PTO to control force as a function of WEC response.
- Depending on the specific WEC, both the causality and the frequency dependence of the hydrodynamics may be approximated with causal and/or fixed frequency functions with limited error. However, caution must be used in any such simplifications.

- The WEC hydrodynamics may be represented by a 2nd order transfer function, but the coefficients are frequency dependent in general, and the excitation term is non-causal.
- The PTO acts in combination with the inherent hydrodynamic impedance to allow the PTO to absorb power and manage constraints.
- Control may also be applied to adjust directly the WEC physical characteristics and hence wave response and absorption. While this can increase absorption and/or manage response goals such as motion constraints, power absorption can only be achieved through the working force of the PTO, however controlled.
- Depending on the WEC type, the PTO may act on multiple degrees-of-freedom, and further degrees-of-freedom may not be directly observable or controllable.
- The linear formulation of the WEC response, wave interaction, and absorption leads to well-known optimal impedance control solutions and ultimate power capture limits.
- These ultimate limits involve frequency dependent and non-causal functions, due to the nature of the hydrodynamic coefficients with which the controller is interacting.
- Sub-optimal causal, and fixed frequency controls may be defined for a given incident sea state. The degree of compromise in this depends on the WEC hydrodynamic characteristics.
- Linear modelling may be valid for the bulk of incident wave power but the assumption of linearity is typically breached for unconstrained optimal control solutions in the wave heights of interest. However, this depends very heavily on the characteristics of the specific WEC.
- Time domain modelling is required to properly represent general application of control forces including non-linear idiosyncrasies of PTO and wider WEC designs. This may be achieved using linear formulations for the hydrodynamics and different modelling assumptions and approximations are possible for different WEC characteristics.
- A state-space time domain model may also be adopted with some further approximation of the hydrodynamics. This is now included in the MATLAB WECsim suite.
- The range of forces that the PTO can apply is likely to be limited, particularly in larger waves. This load saturation is an important nonlinearity and design parameter that also tends to invalidate linear unconstrained optimisations.
- Motion range limitations, again depending upon design, may also be an important constraint, with implications for the validity of models and their associated optimal control solutions.
- The response control system may be represented as a classical closed loop transfer function with corresponding sensitivity function for the purposes of high level stability analysis. This allows the stability impact of delays in the control signal path and local PTO dynamics to be examined.

- Power captured by the WEC is the net of what is absorbed and what is radiated back into the sea. Solving the linear formulation for the maximum absorption gives a theoretical ultimate power capture and corresponding control function – a mechanical (internal) impedance matched to the hydrodynamic (external) impedance of the WEC.
- For a slender WEC, solving for the response which radiates waves for maximum cancellation of the incident waves also gives this optimal absorption response but with insight into the relationship of the WEC response type (and radiation pattern) to the ultimate power capture potential (within the confines of linear theory). For WECs with greater backscatter, similar far-field wave cancellation objectives apply.
- Arrays of individual WECs may absorb substantially more energy through wave interactions if controlled under a single process, effectively treated as a single multi-body WEC.
- These linear optimal power capture results are generally severely affected by realistic non-linearities including motion and load constraints.
- Such solutions for systems without fixed sources of reaction for the PTO (e.g. free floating multi body systems) may also involve unlimited and physically non-realisable reaction forces.
- Constraints on force and motion may be applied in the frequency domain using analytical methods to account for physically realistic limits and to gain insight into the performance impact.
- The multi degree-of-freedom solution for power capture inverts the combined impedance matrices, and therefore prevents simple linear superposition of responses due to individual coefficient changes. Modal coordinates are not a straightforward solution due to the role of the control terms themselves in determining the modes.
- A general approach to developing control parameterisations for a reduced number of quasi-orthogonal variables would offer a major advantages for adaptive control of multi-degree-of-freedom systems.
- Important non-linearities in the power-take-off system may be loosely represented in frequency domain through linearized and amplitude dependent functions. These measures may also be applied in real time to quantify the effective impedances provided by non-linear or highly delayed functions.
- The practical implementation of impedance control implies requirements for position, velocity, and acceleration measurement in the controlled degrees-of-freedom.
- The avoidance of signal latency, disturbance, and excessive phase shift (e.g. due to badly set low pass filters) may be important for stability of high gain systems.
- Care must be taken over the effective sensitivity of the sensing system, accounting for sampling rates, resolution, noise, and the local dynamics of the PTO.

- Where appropriate compact and cost effective inertial measurement systems may offer a good solution for distributed estimation of the WEC response for use as control inputs, with relative motion derived from a kinematic estimation process.
- Compensation terms are generally required to stabilise the application of virtual mass in particular.
- Force feedback mechanism required to deliver a demand force from the PTO introduce their own performance and stability issues interacting with the wider system. This must be understood to design for expected overall performance.
- The control impedance may be implemented directly as a generalised impulse response (IR) function (implemented as explicit, finite IR or rational function, infinite IR), an approach that may lend itself to different optimisation processes.
- Prediction of the incident waves over a timescale similar to the length of the hydrodynamic response memory could potentially allow implementation of effectively non-causal control functions (applied to predicted inputs) to provide optimal control across multiple frequencies simultaneously. This is considered practically very difficult however. The value of meeting such challenge depends on the characteristics of the WEC and should be considered important only if substantial improvements are possible relative to the performance attainable using fixed impedance control matched statistically to the incident sea conditions.
- Short term adjustments in control parameters to maximise absorption over wave groups and lulls may offer a less demanding but more rewarding application of wave prediction.
- While controlling for WEC response directly (i.e. position control) is possible as a function of measured or predicted wave excitation force and is an alternative form of control implementation, it presents a number of additional challenges over a force control approach.
- Direct measurement of the exciting wave forces (for example through distributed pressure measurements on the WEC structure) could potentially offer some advantage in a generalised control system using multiple overlapping sources of information on the WEC excitation and response.
- Adapting control parameters for changes in sea conditions is generally an important feature for maximising power capture safely over the year. The WEC power capture response with respect to amplitude and frequency may be shaped (as far as is possible) by the control system to best capture the specific incident spectra.
- In general, the frequency response may be less important for some WEC types than others, depending on the bandwidth. Similarly, amplitude response and the need to apply motion constraints is WEC dependent.
- As an alternative to full reactive control, especially for PTOs that lack four-quadrant capability, latching control may offer substantial improvement over purely resistive control,

but force and motions constraints, as well as the same non-causal force issues that arise for reactive control, may limit practicality.

- Control optimisation is intrinsically linked to optimisation of the whole WEC design. Features of the WEC (e.g. geometry and mass properties) may only be properly understood with respect to the practically achievable control solutions to make best use of them. It is therefore important to include control and PTO systems properly, with sufficiently representative detail, in the wider design process and any modelling or assessments undertaken.

5 Functional Requirements for Power Conditioning

5.1 Introduction

Chapter 4 focussed on the interface between the PTO and the WEC primary converter. These elements form only the initial links in the power chain and control of course must consider the full chain, all the way through to supply to the grid. The present chapter deals with two important additional links in the chain. Firstly, Section 5.2 looks at control of energy storage in the power train. Not all WECs include energy storage between the front end PTO and the generator, but it is a highly desirable feature in removing excessive variability in the delivered power. Section 5.3 deals with electrical power quality and grid code requirements that WECs, as distributed generators, typically need to meet, based upon regulations in force in the UK.

5.2 Control of Power Smoothing with Energy Storage

5.2.1 Smoothing

One of the essential functions of the generation control process is to use any energy storage facility in the PTO system to smooth the absorbed power, making the output power some sort of windowed running average of the absorbed power. An important design objective of power smoothing, including control, is to balance the ratings and hence cost of the power generation and transmission system against the cost of the energy storage. The levels and nature of smoothing action achievable by the control system is limited by the relative and absolute energy storage volume and the ratings of the generation and export equipment.

The precise definition of smoothness depends on the constraints being met. It may be defined in terms of windowed averaging or a frequency response filter as described below for a simple linear control process, or in terms of maximum range of power fluctuation suitable for minimising storage requirements using a non-linear and potentially predictive control process. Even for a non-linear, range defined controller, the requirements may be well understood and quantified in terms of a linear smoothing model.

Economic matching of the output power range to the energy storage for the accepted input power range of the WEC is necessary to allow the smoothing control function without shedding excessive power over the year and without over-rating or under-rating the generation system. This means that the control functionality has to be considered as part of the wider PTO design processes.

5.2.2 Linear first order energy smoothing model

The smoothing problem may be simply understood in terms of a first order filter applied to the instantaneous absorbed power. The required size of energy store can be directly related to the required smoothness of power output in terms of a filter defined to give a desired attenuation of the statistically expected input power range, and that filter may be expressed as a closed loop control process with respect to stored energy.

The statistical distribution of input power may be directly measured in service, or estimated in models as a function of the input wave statistics. The amount of stored energy required to enable a linear smoothing process is a direct function of the wave group statistics. If modelling is applied then care should be taken with the statistics of synthesised wave inputs, as the long period wave group statistics may be challenging to properly represent accurately and may not be present in wave spectra synthesised with finite components according to common models such as Pierson-Moskowitz or Bretschneider.

The energy stored is the net of power out and power in, integrated over time, represented in the Laplace domain by:

$$sE(s) = P_{in}(s) - P_{out}(s)$$

If we assume a power smoothing control approximating a 1st order low pass filter, effectively averaging the instantaneous absorption, i.e.:

$$P_{out}(s) = P_{in}(s)\frac{1}{\tau s + 1}$$

so

$$sE(s) = P_{in}(s)\left(1 - \frac{1}{\tau s + 1}\right)$$

Rearranging gives the stored energy as:

$$E(s) = P_{in}(s)\frac{\tau}{\tau s + 1}$$

and net power taken into store as:

$$sE(s) = P_{in}(s)\frac{\tau s}{\tau s + 1}$$

The stored energy is the input power scaled (from watts to joules) and low pass filtered according to the level of smoothing applied – less smoothing (lower τ) means less storage required. Under this process the net power taken into the energy store is a high pass filter of the power input as expected – the energy store has to accept the rapid fluctuations as the smoothed power output is delivered.

We can quantify this relationship between the required stored energy range and the output power range by substituting

$$P_{in}(s) = P_{out}(s)(\tau s + 1)$$

to give:

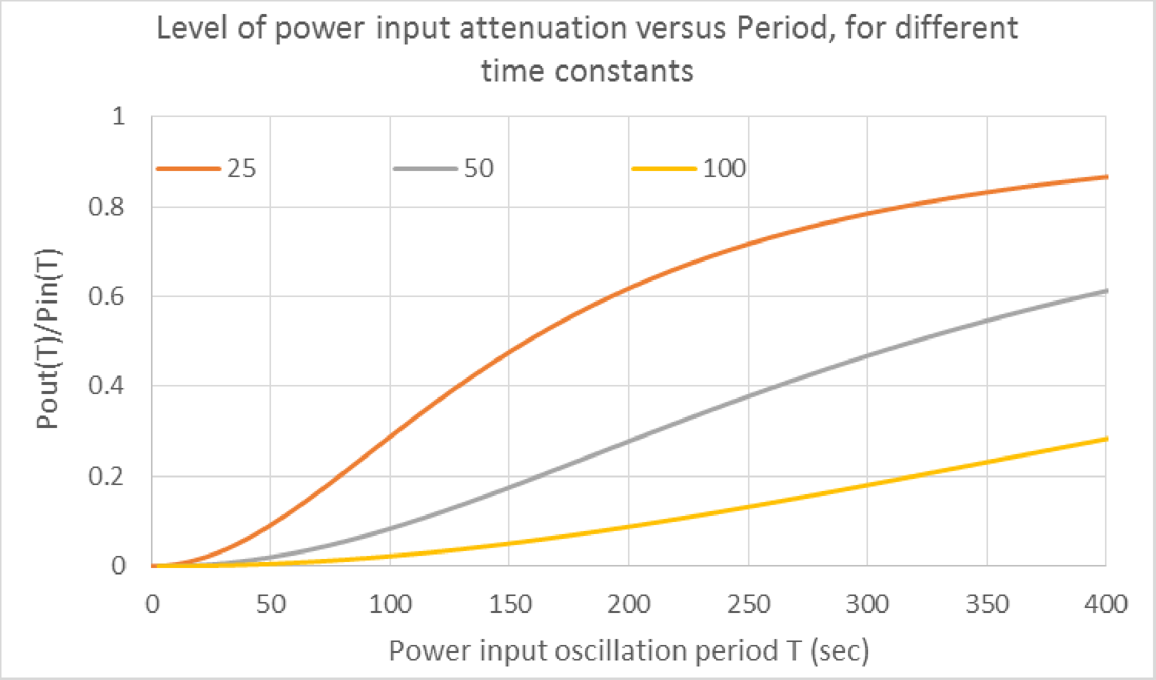
$$E(s) = P_{out}(s)(\tau s + 1)\frac{\tau}{\tau s + 1} = P_{out}(s)\tau$$

So across all frequencies, the size of storage required to enable a given time-constant increases as the product of the smoothed output power range and the time constant required to achieve that range (and hence the achievable time constant ultimately increases in proportion to the energy storage).

So for a 1st order linear process the achievable time-constant:

$\tau = \textit{Energy storage capacity / Output power range}$

The output power range itself remains a function of the input power envelope spectrum, according to the defined time-constant, τ. This is plotted in Figure 10 for 3 different time-constants, showing that to achieve an output power range of around a tenth the input power range across groups 100 seconds apart requires a time constant of around 50 seconds.



- Figure 10 Power Range Ratio as a Function of Power Input Oscillation Period for Various Smoothing Time Constants

Note that this smoothing requirement stems not from the peak input powers wave-to-wave but from the oscillations in the envelope due to wave grouping.

The frequency content of the wave envelope (often described as ‘groupiness’) is an interesting topic with subtle differences in interpretation according to different methods of describing the low frequency components. For example, the Hilbert-Huang transform method (a form of intrinsic mode decomposition) shows substantial envelope oscillations components down to much lower frequencies than indicated by Fourier transform, which misleadingly represents long period oscillations indirectly as beating of high frequency components [Huang and Shen 2014].

Real world input power envelopes, the result of the incident wave power envelope, do maintain components into periods of minutes meaning that the required energy store to enable complete smoothing tends to minutes of average output, and the order of 1 minute of average output to smooth across typical groups of a minute or two apart while maintaining a power output range less than double the average.

An example using absorbed power from an operational full scale WEC is given in Section 5.2.7.

5.2.3 Potential role of prediction in reducing storage requirements for smoothing

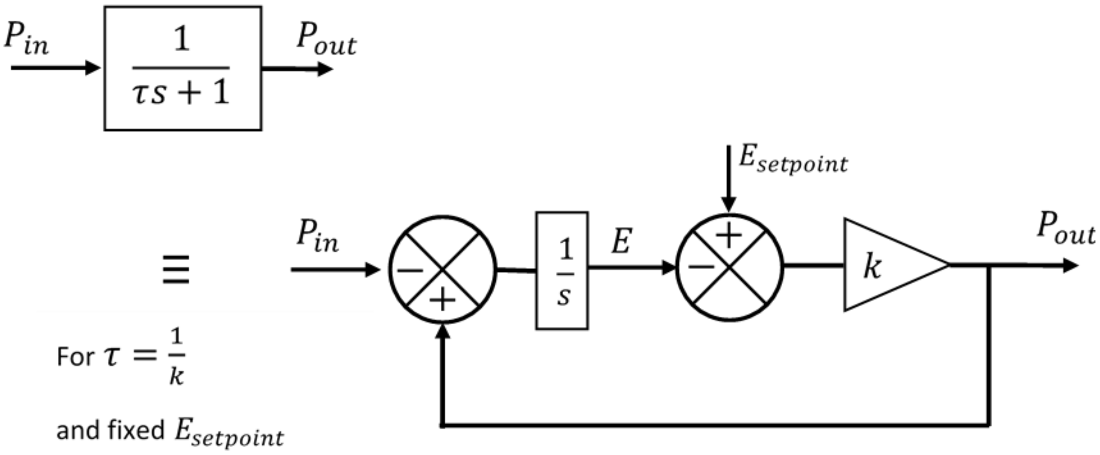
If the power input was known in advance then the controller could effectively run down the energy store in anticipation of increases and vice versa, timing the inflow and outflow of energy to minimise the requirement for stored energy. This would allow a smaller energy store to provide a given level of smoothing.

The potential benefit of prediction may be quantified in the 1st order model by applying a non-causal filter with the same low-pass smoothing characteristics but with zero phase shift from the input power.

Around half of the required storage is due to the phase shift induced by the causal smoothing process, with around half still required to provide the underlying attenuation of the power envelope. This is demonstrated for the real data example in Section 5.2.7.

5.2.4 Equivalent controller

As shown in Figure 11, the first order filter model described above is equivalent to a closed loop proportional control applied to the stored energy. However, the closed loop implementation accounts for measurement and output errors to regulate the stored energy around a set point value.



- Figure 11 Equivalent 1st Order Low Pass Filter and Closed Loop Fixed Set-Point Control of Stored Energy

The set point value must be set to provide enough range above and below for the expected distribution, according to the selected time-constant (controller gain).

5.2.5 Integral term

The closed loop implementation acts to manage the energy stored to lie at a set point, as required to maintain control of the stored energy while delivering smoothed power output. Adding an integral control term (PI control) removes steady state error, effectively allowing the closed loop control action to itself set the average power output component about which the smoothing action occurs (so power generation is maintained for zero error).

However, depending to the relative size of the integral term, this also introduces a resonant peak in the power response that can act to amplify rather than attenuate power input fluctuations at certain periods. The integral gain should therefore be kept to a relatively small fraction of the proportional gain such that it acts only over long time periods. Band rejection compensation may also be applied in the controller path (e.g. through a band attenuation filter) in the integral control.

The use of small integral gains with associated long response times requires careful design of start-up procedures and initialisation of the controller to avoid very long period oscillations impacting operations on start-up of generators.

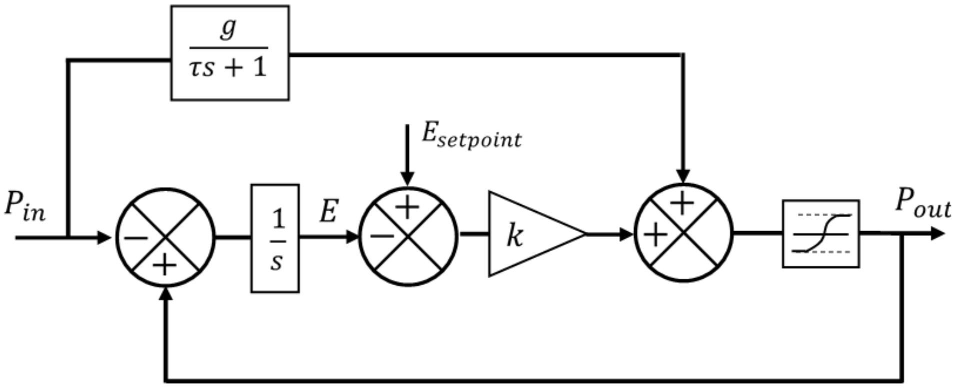
5.2.6 Maximising capability within power output and storage limits

With absolute limits on the power output associated with a practical generation system, and determined by economic compromise against energy storage, the gain of the controller may be increased (and hence associated linear time constant and smoothing decreased) to beyond saturation levels. This gain increase and saturation can make slightly more use of the available output power range to convert the incoming power while remaining within the storage limits.

For the real example power input data treated in Section 5.2.7, the power output range may be set around 20% lower for a given time constant before the required energy storage begins to rise again relative to the pure linear requirement.

A feedforward term based on derived measurements of the input power can maintain the dominant linear smoothing function during saturation and is also likely to be helpful in dealing with any non-linearities in the storage system measurements. For example, the fluid pressure in a gas storage accumulator is non-linear and hysteretic with respect to stored energy but is easily measured but not a very good proxy for stored energy, while measurement of input flow or power derived from fixed geometry and speed measurements provides accurate input to a feedforward term.

As in any control system with output saturation, care must be taken if using a closed loop integral term with saturation limits to avoid ‘wind-up’ of the integrator during periods of saturation.



- Figure 12 Controller Block Diagram Including Limits on Power Output Demand Going to Generator

In Figure 12 the demand going to the generator may correspond directly to the limitations of the plant, or may be enforced by grid level demand management systems. A feedforward term provides direct injection of the smoothed output demand, with the gains *g* and *k* scaled to allow correction by the closed loop terms to maintain the energy storage set point.

In using the output power saturation to reduce storage requirement the rate of change of output power will be higher in accordance with the increased gain and reduced time constant. With increasing controller gain this approach tends toward a two state output - maximum power whenever the storage is above a set-point and minimum when below, thus the minimum storage requirements ultimately become a non-linear function of the power range only.

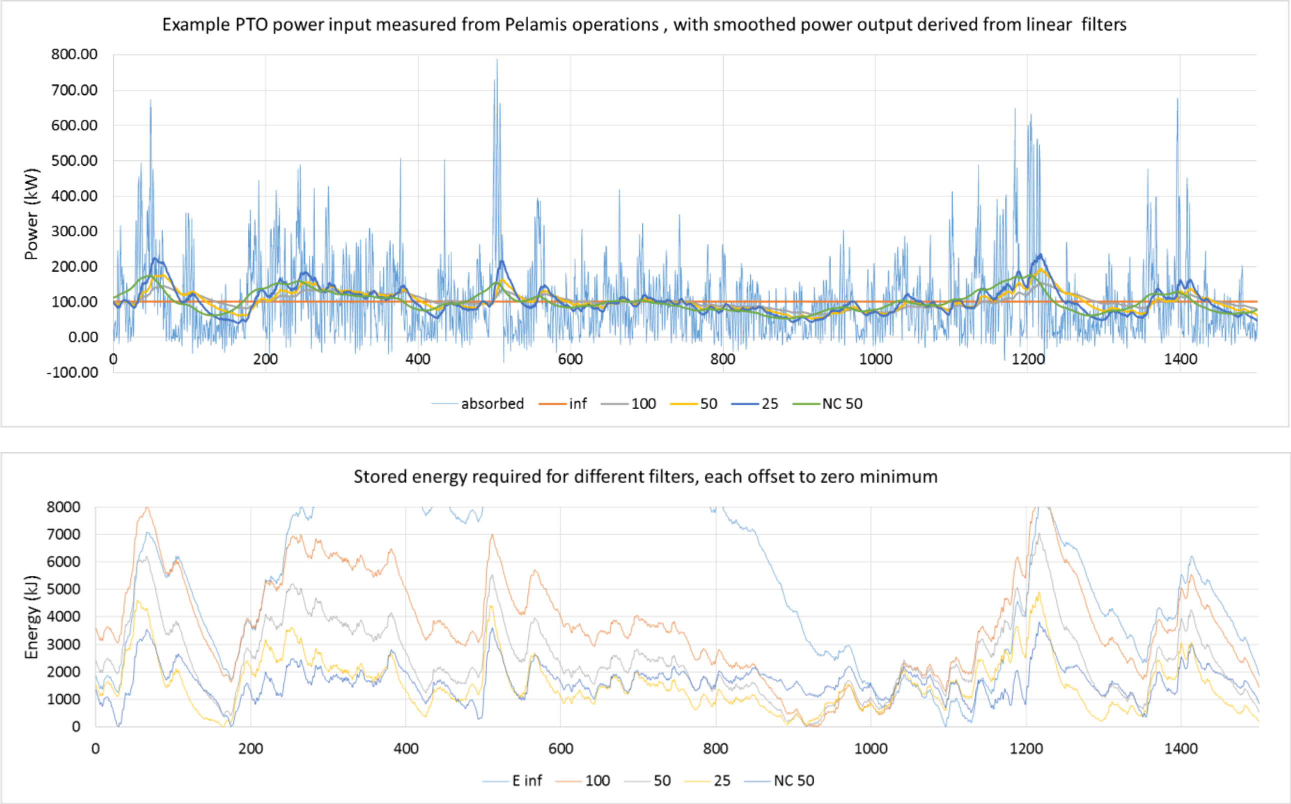
This approach of setting a higher control gain can achieve a significant but not game-changing reduction in PTO output rating (and associated cost) for a given storage capacity (or vice versa) where the smoothness requirement is stated simply in terms of range. Saturation at the power limits is likely to be an accepted feature of the system to achieve the right economic compromise while meeting constraints.

The choice of rating in general, and the associated energy storage requirement, is likely to be informed by the annual average yield impact of marginal changes, such that the optimum economic balance is achieved between additional rating and additional energy sold over the year. This design process must be made in light of the control method and PTO requirements to achieve the required level of smoothing.

5.2.7 Real data example

Some practical data can provide a useful steer. Figure 13 shows the instantaneous absorbed power at one joint of the Pelamis wave energy converter operating in moderate seas, with the 1st order filter applied at 3 different time constants. The form of the power input is similar at different scales so this may be used as a useful general example.

A non-causal filter is also shown with zero phase shift but equivalent cut-off period to a 50 sec time constant. The full time-series treated here is 1 hour long but only 1500 seconds are shown for clarity. The most significant aspect of this empirical example is the presence of long return period oscillations in the envelope and the implications for smoothing requirements.

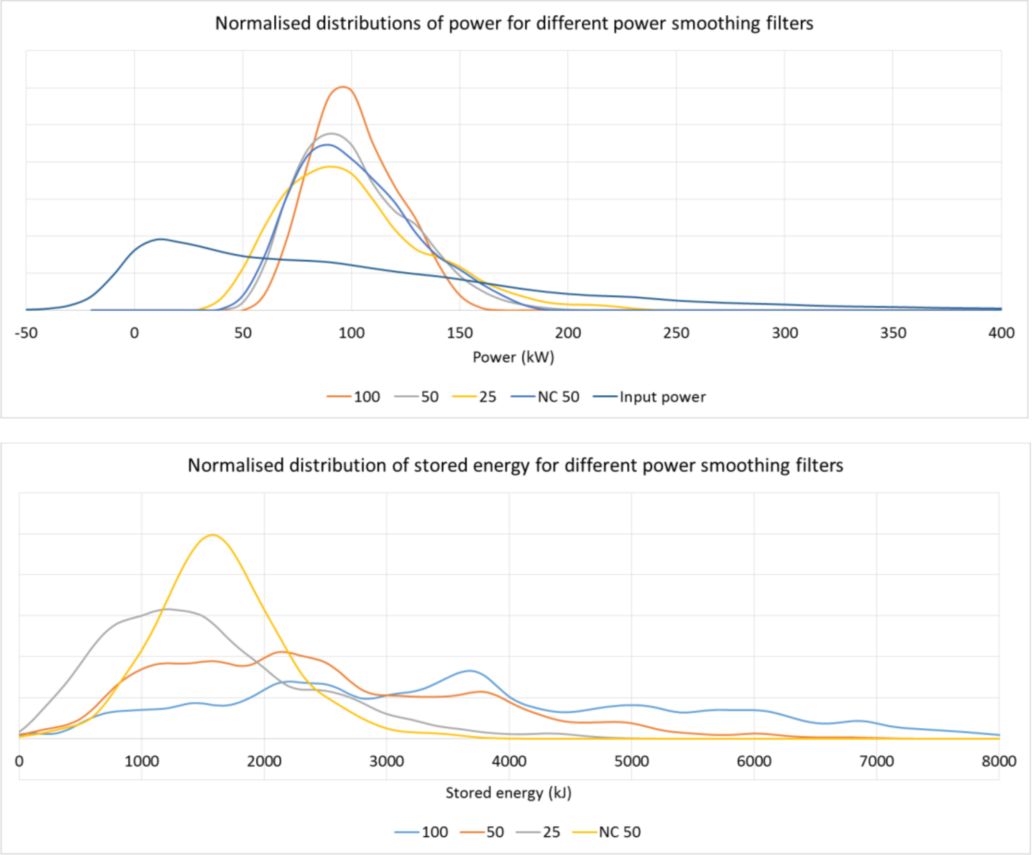


- Figure 13 Instantaneous Power and Stored Energy at a Pelamis Joint for Various Time Constants. (Raw data courtesy of Wave Energy Scotland).

The corresponding empirically implied energy store requirements are shown in Figure 14, set by integrating the net power and offsetting the minimum value to zero. It can be seen that the storage required is proportional to the time constant as expected.

In the normalised distributions for the time series, the area under these curves between two points on the x-axis is the proportion of time spent in that range. Note that the absorbed power is highly asymmetrical with a very long shallow tail (extending up to 800 kW), while the smoothed power distributions have a more symmetrical distribution and smaller ranges (by definition of the applied filters). The economic impact of curtailing their range by simply venting excess power can be estimated in terms of the relative areas under the curves above and below the limit.

Notably, the smooth power distribution for the predictive filter (NC 50) is of similar width to the corresponding causal filter (50) but the energy range required is only marginally higher than the casual filter providing half (25) the smoothing period time constant.



- Figure 14 Normalised Power and Stored Energy Distributions for Various Smoothing Time Constants

Statistics from this example data set are tabulated in Table 1Table 5, demonstrating the important trends and relationships using real input data.

	Power statistics for linear smoothing of 1hour real input power data				
Time constant	inf	100	50	25	NC 50
max (kW)	101.7	154.9	194.4	236.6	176.4
min (kW)	101.7	65.7	53.3	40.4	53.8
avg (kW)	101.7	101.6	101.6	101.6	101.6
range (kW)	0.0	89.2	141.1	196.3	122.6
range /avg	0.00	0.88	1.39	1.93	1.21
Max / avg	1.00	1.52	1.91	2.33	1.74
Energy range used (J)	15685	8924	7053	4906	6129

- Table 5 Power Statistics for Various Smoothing Time Constants

5.2.8 Using statistical measures to set smoothing control parameters

The required set-point of stored energy level and the maximum smoothing of power output to maintain the energy within given bounds may be quantified in terms of the proportion of time the stored energy is likely to spend outside a given range (e.g. below zero or above the maximum capacity).

This may be determined live in an operational context to provide adaptive control functionality. If real data is available, the mean and distribution (or best fit standard deviation) of the stored energy may be derived directly from measurements over a given time window.

If the standard deviation of the stored energy is estimated, and a form of distribution assumed, the mean of the stored energy required to achieve a given proportion of time spent below a certain value may be similarly estimated. Hence this measure may be used to define a mean set point value for a given control (smoothing) setting or vice versa.

While different definitions of smoothness may be adopted (e.g. rate of change or absolute range), the greatest smoothing possible is achieved by making maximum use of the storage available so this implies increasing the smoothness of the output until the storage is fully utilised in each condition. However, in smaller seas it may be more beneficial to maintain a given smoothing function while reducing the mean stored energy. Wider practical implications for whole system conversion efficiency will influence the choice of control parameters within this framework.

In smaller power regimes (small sea states) the choice may be made to provide greater smoothing or to use a smaller range of the available energy store. The latter may be desirable if there are side effects of running at a higher level of stored energy. For example, when using gas pressure with a fluid based PTO, the associated working pressure may induce greater losses at high pressure than at low pressure. Or a battery storage system might operate more efficiently when using fewer banks.

Different designs of WEC and PTO system are likely to have different characteristics of storage (round trip) recovery efficiency related to storage levels and rate of change. For example, a gas pressure based system may operate more efficiently when the rate of change of energy stored is minimised, while the power generation system may conflict with this by operating most efficiently when outputting constant power. Such a conflict would suggest a compromise based in minimising overall losses in the conversion train that can be fine-tuned from operational data if the various systems are well instrumented and/or modelled.

An adaptive control strategy should take all these factors into account when scheduling the power smoothing parameters in changing conditions. Similarly, the selection of storage capacity and PTO output ratings should take full account of the control requirements and implications for performance.

5.2.9 Minimising the mean energy set point for assumed normal distribution

Assuming stored energy W follows a normal distribution, as might be expected for a narrow band input spectrum with complete attenuation of individual wave frequencies, the expected proportion of time spent below a given acceptable working minimum W_{base} is theoretically given in terms of the mean μ and standard deviation σ as:

$$\Pr(W \le W_{base}) = \frac{1}{2}\left[1 + erf\left(\frac{W_{base} - \mu}{\sigma\sqrt{2}}\right)\right]$$

By setting the above expression to an acceptably low value, an expression may be derived for the mean required to achieve this as a function of standard deviation.

Rewriting as:

$$\int_0^{\frac{W_{base}-\mu}{\sigma\sqrt{2}}} e^{-t^2}\,dt = \frac{\pi}{2}\left(2\cdot \Pr(W \le W_{base}) - 1\right) = const$$

it can be seen that, for a prescribed value of $\Pr(W \le W_{base})$, we can write:

$$\frac{W_{base}-\mu}{\sigma\sqrt{2}} = const = \frac{-b}{\sqrt{2}}$$

where

$$b = \frac{\mu - W_{base}}{\sigma}$$

for all values of μ and σ satisfying (1) for a given value of $\Pr(W \le W_{base})$,

$$\Rightarrow \mu(\sigma) = b\sigma + W_{base}$$

giving a linear relationship between the standard deviation of stored energy and the mean required to achieve an acceptably small proportion of time spent below a given value. A similar approach applies to the stored energy rising above a given value (and over-topping the storage system).

An adaptive control method could use the measured distribution of stored energy to manage the control parameters directly by using a fitting and extrapolation function to the measured distribution.

5.3 Grid Code Compliance

The Grid Code defines a number of requirements for the specification of equipment and associated control for connection to the onshore electrical network. It covers WEC arrays in the same way as it covers wind farms. The Grid Code will differ slightly between countries; currently there is a drive toward harmonising codes between European countries.

Typically, for a WEC array the subsea export cable will connect to a local onshore grid network at an electrical substation. In addition to housing transformers and isolation equipment, the substation will accommodate the equipment required for conditioning of the electricity supplied from the array to meet the local grid connection requirements. The connection point to the local grid of the electricity generated from the array is commonly termed as the Point of Common (POC) connection

There are a number of different parameters that must be monitored and corrected in order to ensure that the power quality meets grid compliance. The main standards that define the required parameters of the power control are described in:

- Recommendations for the connection of embedded generating plant to public distribution systems above 20 kV or with outputs over 5 MW. Engineering recommendation G75/1.

- Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom, Engineering Recommendation G5/4-1, Issue 1, 2005
- Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom, Engineering Recommendation P28, Issue 1, 1989
- Planning limits for voltage unbalance in the UK for 132 kV and below, Engineering Recommendation P29, Issue 1, 1990

It is beyond the scope of this study to provide a detailed analysis of the electrical parameters to be controlled but the main ones to be considered are:

- Voltage range fluctuation (Flicker)
- Frequency
- Power factor
- Harmonics
- Power output control
- Fault control

For the development of a commercial scale offshore WEC array, it is likely that a hub collector would be provided for all the WEC's in the array within which the intra-array voltage would be stepped up by an offshore transformer for export by one or two subsea cables.

To permit installation and removal from the array, the relevant WEC will need to be initially isolated from the electrical network. This can be controlled through either an electrical isolator that is local to each WEC in the array, or through control of an electrical isolator at an array node or hub (potentially the shore substation itself). The disadvantage of using a network hub is that multiple WECs would be isolated when removing or installing a single WEC, preventing multiple WECs from generating during these operations.

The minimum control requirements to operate an isolator safely are:

- Control output to Isolator (open/closed)
- Control output to the earth switch (open closed)
- Feedback status of the isolator (open/closed)
- Feedback status of the Earth switch (open/close)
- Monitor voltage and current levels throughout the array network.

Power conditioning equipment may be contained in the onshore substation, in the individual WECs and/or in the array transformer hub. While there is no common model that can be used for the variety of WEC technologies in development, WECs can be broadly categorised both by where electricity generation takes place and by where any electrical power conditioning takes place. Conditioning may be local to the generation (on or off the WEC) or in the onshore substation or other electrical hub. For WECs that have generation and some conditioning on-board, the array may still require some level of power conditioning onshore to control the aggregated supply of electricity from all the individual WECs.

One of the major control requirements and challenges for a WEC array is the regulation of the power output into the grid. The type of generating device and power smoothing systems included in the PTO will predominantly define the electrical power conditioning hardware required at the substation to meet all grid and hence electrical control requirements.

For each WEC array grid connection agreement there will be a number of requirements relating to the control of the power at the POC. The simplest method of power control is a defined cap, whereby the array output is required to be constrained below a certain power output level, which in turn may be fixed or for larger arrays dynamically set by a centralised grid management centre. A more complex cap level is delta control were the output is required to be kept at a fixed level below the output power currently available, this allows a percentage of power to be available in case of increased demands by the network. In addition to a cap a gradient limit may be defined in order to limit the rate at which the array can increase its output power.

To meet these requirements at the array level, corresponding power output control is likely to be required at the individual WEC machines in addition to power conditioning and control at the substation.

6 Control Implementation Requirements

6.1 Introduction

Whereas the objective of Chapters 4 and 5 was to explain technically and mathematically the core, real-time, dynamic control requirements of wave energy, the aim in the current chapter is to outline the decisions to be made when selecting and configuring the hardware for real-time control. As well as describing core functional requirements, the chapter also addresses the architecture and some of the practicality and compatibility requirements that need to be met by the sensing and control systems.

6.2 Control Hardware Requirements

6.2.1 Introduction

All high level functional requirements for the system hardware should be considered at the initial design stage. Integrated control systems generally require a substantial investment of time and some iterative based development experience to understand how to use and implement them correctly. Discovering that a control system falls short of requirements once an investment has been made will prove costly.

For WEC applications, controller hardware generally needs to accommodate centralised and distributed processing and to be compatible with the input/output and communications devices that interface with the PTO and WEC systems described above. The control hardware is required to:

- Enable real time and non-real-time control of all systems according to control functional requirements
- Ensure machine integrity and enable all required diagnostics and safe autonomous operation of subsystems. This may require local autonomous control and protection capability at the sub-system level.
- Have sufficient processing capacity to provide all required functionality with sufficient headroom for further software upgrades
- Provide real time data capture and event logging capability
- Maximise economic availability by using high MTBF components in combination with hardware and network redundancy and individual subsystems
- Present industry standard interfaces where possible
- Use industry standard “off the shelf” components, where possible
- Be modular and scalable
- Be robust for the operating environment including motion/vibration, temperature, water ingress and humidity
- Allow robust remote updating of software and firmware.

Real time control hardware is now commercially available and well proven and tested within the automation industry, it is difficult to conceive why there would be a requirement to develop bespoke control system hardware for WEC control at the demonstration stage. It could however be plausible to reduce build costs for volume manufacture in the future.

Commercial Off-The-Shelf System (COTS) hardware with a proven reliability track record should always be used in preference to the development of bespoke system, unless it is not possible to achieve the functional control requirements from COTS hardware. There are a number of reliability advantages to using COTS hardware, firstly is that it will generally have under gone rigorous testing to ensure it is compliant to known standards. Figures for MTBF are generally available based on accelerated lifetime time testing and FMEA analysis allowing quantitative reliability analysis to be conducted for the integrated designs, and to inform the iterative design process. In addition any associated software will have a complete suite of tested tools for development and simulation of control processes.

A degree of flexibility is required in the control architecture to accommodate developments in functional requirements stemming from operational experience and ongoing research and development. Generic and modular design may limit susceptibility of the whole system to component obsolescence.

6.2.2 Environmental considerations for the hardware

It is essential the controller CPU remains at a temperature within the normal defined operating range; this is typically achieved by the use of a fan with most conventional systems. However, cooling fans have the lowest mean time between failures amongst all other hardware components in the system and should be avoided if possible; they are usually not a serviceable item. It is now possible to specify industrial controllers that have fanless cooling systems. Estimates of thermal loading and heat transfer characteristics are required to specify for the resulting local temperatures of control enclosures, and any additional cooling systems required.

Avoiding mechanical hard drives in remote data storage avoids the vulnerability of damage from vibration, slamming etc. within the WEC.

It is also important to ensure that the central processor has capability to process data and issue output commands within the required cycle time – defined with respect to control latency and control stability as discussed in Chapter 4. Sufficient headroom (multiples of initial requirements if possible) should be available for major expansion of control software. It tends to be more ancillary processes, including diagnostics, and handling of interfaces and data capture that dominate CPU requirements and development creep.

It is important to define any motion that hardware will be subjected to in order to ensure equipment that is not operated outside the manufacturers’ specification. This includes any WEC motion and, likely to be of greater concern, any vibration induced by PTO equipment or shock loading. Where required, equipment should be mounted on suitably rated, anti-vibration mounts and the vibration it is exposed to monitored during trials.

The orientation of the installed equipment should also be considered. For some systems the certified operating temperature range will vary depending on orientation.

Where a selected hardware system does not meet the required specification for motion it will be subjected to during operation, the manufacturer may be open to testing and recertifying the equipment to the required specification.

6.3 Control System Topology for Real Time Network and Monitoring

6.3.1 Introduction

Effective real time control requires a hardware/firmware/software system to sample inputs, to process them according to suitable algorithms and to apply resulting outputs to control actuators/drivers with sufficiently low latency for stable operation. A compact WEC with single control hub may not require a real-time network of control devices, instead handling input and outputs locally to the central processor.

However, multi-body WECs with distributed control devices handling inputs and outputs (e.g. actuator control electronics, sensor arrays) require a real-time network linking these devices to a central control process, itself providing real time control and/or supervisory adjustment of parameters and interface to high level clients (e.g. human machine interfaces).

6.3.2 General signal processing and estimation processes

Low level signal processing may be undertaken in a distributed and hierarchical fashion according to the devices selected to receive and transmit I/O. Distributing control and measurement devices may have the advantage of providing local fault handling and control functionality in the event of communications network failure. Control actuation may be similarly distributed and integrated locally with inputs and control processes operating autonomously or in combination with higher level processes.

6.3.3 Real-time diagnostic processes

Real time diagnostic processes are required where immediate automated action is defined in response. Some fault diagnostics may be built into hardware I/O devices (for example, detection of electronics faults in drivers or transducers) and may drive an automated process using redundancy to compensate. Others require real time processing of multiple signals, for example, load monitoring where action may be taken to protect other systems in the event of partial failure. These processes may in turn feed into the alarm system described in Section 7.2.3.

6.3.4 Network cabling

If a distributed control system is used there will be a requirement to communicate data between control devices, most commonly in modern systems this will be implemented by using a real-time Ethernet protocol. Earlier generation systems used RS422 or similar serial data communication systems.

The CAT5/6 cable system that comply with the TIA 568 standard would typically be used to provide the network link between controllers. This type of cable and associated connection system functions without problems when the cables can be easily segregated from other types of cable i.e power cables and there are not multiple connections or splices, or excessive distance, in a cable between controllers. However, bandwidth and data corruption can be a significant problem from multiple connection within a data cable and from electro-magnetic interference (EMI) radiated from adjacent power cables. Any loss of data or bandwidth can cripple the ability of the real-time a control system to perform its required function. Copper based communication systems are also highly vulnerable to moisture, a particular challenge in the marine environment.

The preferred method of data communication, including local real-time networks, is multi-mode fibre optics. Fibre optics provide are immune to EMI interference and data corruption at connection points through crosstalk. Additionally fibre optic cables are immune to damage from water ingress on subsequent corrosion.

6.3.5 Requirements for array level communications and control

Large scale deployment of arrays of WECs offshore requires network interconnection of machines for communication route to the shore based network.

Local wireless communication networks may interact with optical fibre and/or copper based networks subsea. Local wireless networks should allow seamless introduction of communication and control systems based on support vessels (NB WiFi systems are currently unlikely to be suitable for real time control communications due to synchronisation and robustness issues). Long range and satellite wireless communication systems are available with the specifications to provide back-up and perhaps primary remote communications.

As discussed in Chapter 4, controlling multiple WECs under a single real time control process (combining specially separated degrees-of-freedom) has the potential to substantially increase the overall power absorbed by the wave farm. Any implementation of real-time wave prediction would require the real time network to extend to the corresponding wave measurement and prediction systems.

The control hardware network required for this is more demanding than for an individual machine due to the larger and more dynamic distances involved. Subsea optical fibre networks could provide the necessary bandwidth and latency over an array. Specification for real time intra array communications should be considered at the development stage and in the design of subsea communication networks.

Wireless Ethernet communications are not suited to high rate real time control but other standards and methods of wireless real time communication are available, although robustness may remain a severe restriction in this environment.

6.4 Sensing Systems

6.4.1 Introduction

As for any control system, measurements play a crucial role in providing information on system inputs and status.

Required high level measurements include:

- Inputs on WEC response,
- Inputs on PTO systems required for real time control processes, and for
- Inputs on local wave conditions and environmental loading for use in operations planning and decision making
- Data collection for WEC Performance assessment and operational review

The control system acts on the basis of measurements made by transducers of various types, fed into processes estimating the physical values of interest, whether through a direct calibration of individual sensors (e.g. using a position sensor attached across a single degree-of-freedom to directly measure that relative motion) or through more sophisticated combinations and models (e.g. using 3d combinations of multiple inertial measurements to derive relative motions in an inertial reference frame).

All instrumentation, sensors and electrically controlled devices will be interfaced to the data acquisition and control system through dedicated i/o hardware. Given the diverse range of signals that are required to be monitored and controlled, the use of a modular expandable system is generally preferable to hardware designed to meet specific requirements.

Some monitoring requirements are likely to be typical across different WEC types. For example, the electrical generation systems, switchgear, and environmental condition monitoring. Whereas the monitoring requirements for the primary take-off system will vary dependant on the type of system used (e.g. hydraulic, mechanical, pneumatic or other type).

It is highly likely that not all required instrumentation will be available with the same type of electrical interface, although generally a number of different options will be available for any single device. It is therefore important to consider the flexibility of the control system interface hardware and the ability to easily expand the interface as required. Careful consideration should be given to the type of electrical interface used to ensure the signal is not attenuated or corrupted between the sensor and the input hardware. In order to reduce excessive wiring, consideration should be given to using remote data acquisition modules that can use a single network cable to multiplex data from multiple sensors back the main controller. Similarly, output control signals can be multiplexed to allow remote control of for example a bank of switches or drivers serving remote PTO actuation systems.

Integrated diagnostics may be included in the transducers themselves or in combination with the input hardware, particularly to detect faults in the sensor hardware or wiring. The type of diagnostics available is dependant of the type of sensor or device being actuated. For example, i/o hardware may be configured to remotely diagnose whether a sensor has failed or if it is a cable that is damaged. Such systems serve to inform higher level diagnostic systems including multiple input redundancy systems (voting). Including diagnostics in the hardware also serves to dramatically improve commissioning and maintenance efficiency.

6.4.2 Wiring and connection system for distributed sensors

The connection of distributed sensors and local control devices involves many cables meeting different functional requirements. Typically, the functional categories will be for power, communication, sensors, and electrical output actuation. The material make up of these cables should be considered against the specific environment in which they are required to operate. General factors to consider are:

- Chemical resistance
- Vibration and shock
- UV exposure
- Temperature
- Water resistance
- Heat and Fire
- Gas and Fume production when exposed to fire
- Humidity

It is often found that these properties may be not all be found in a single cable option so a careful compromise is required. For example, a cost effective cable choice with the highest level of water resistance may not also be able to provide the highest level of chemical resistance.

Connectors are generally embodied in control hardware, with a variety of industry standards of varying suitability for the marine environment. Spring clamp terminals are becoming predominant over screw terminals, with the advantage of positive latched connection and easier assembly with better controlled installation forces.

6.5 Control System Standards, Reliability and Cost

6.5.1 Introduction

Adoption of common standards has clear compatibility benefits but also helps to promote overall system reliability and can help reduce costs by reducing the level of bespoke engineering.

6.5.2 Standards

WECs are still a developing technology and as a consequence there are not yet specific standards to which WEC control system hardware must comply. However, UK government research bodies are working with developers and the IEC in order to develop guidelines and regulations specifically for WECs.

There are however current relevant standards in the UK that should be applied and adhered to, these are:

- UK Health and Safety at Work Act 1974
- The Electricity at Work Regulations 1989 and BS7671

The CE mark is used to certify that equipment meets certain safety and functional standards. The “CE” compliance mark is required for any control system hardware sold in the European market. Unless bespoke hardware is required, i.e. if supplied by a commercial, off-the-shelf (COTS) manufacturer, then equipment should be supplied with a CE stamp. It is not typically a requirement for WEC developers to have all equipment CE certified and it should be noted that if equipment is supplied with a CE mark this does not guarantee the product meets all the safety requirement for the specific required application.

If COTS hardware is used then it will almost certainly comply with a number of IEC and EN standards. The most common standard applied to COTS control system hardware is IEC 61131 (programmable control systems), but there are numerous other standards that may be applicable depending on the type of hardware used. A discussion with the supplier is recommended to ascertain what standards are relevant to the specific application. It is likely that the selected equipment will not have been used in a WEC application previously, so it is always recommended to discuss with equipment manufacturer the detailed application and environmental requirements for the hardware to ensure that it will comply. The WEC developer may require the manufacturer to implement further tests on their hardware.

6.5.3 Control System Reliability

Achieving the reliability required for a remotely operated offshore system is a challenge for control systems, and meeting this challenge requires a major focus to be placed on system level design for reliability with implications throughout the control system. In addition to high component level reliability, this is likely to require the control system to have a high level of fault tolerance (e.g. redundancy) incorporated at all levels, in order to maintain a high level of availability despite individual faults accumulating. The appropriate choices here are subject to complex analysis of the failure paths, fault effects, and component reliabilities of specific designs. For some systems this may potentially be with a reduced operating specification.

Protection systems should be incorporated at all levels of control system, including hardware and software, to prevent user or complexity emergent errors from causing equipment from being operated outside specifications. Protection systems may be layered to provide benign fault paths in general, such that complex situations beyond the scope of specific treatment are inherently robust against inducing damage. To take a specific example, all electrical hardware should be designed with local protection throughout to ensure that the only damage due to an electrical fault is as local as is practically possible to the point of fault, and that this damage is itself is contained to reduce the risk of fire. Connections for inputs, outputs, power supply and communication connections should be selected to ensure that erroneous connections may not be made and/or damage not sustained by incorrect connections.

Redundancy may be achieved by the duplication of equipment in combination with adaptive networks and processes. Careful design can achieve extremely high levels of fault tolerance without introducing excessive additional cost over non-redundant systems. In particular, robust communications networks can allow for seamless fault handling with effective tolerance against multiple failures with only a single layer of redundancy. At the main controller level this can be achieved by incorporating a hot swap dual controller system. In the event of a controller failure control is automatically switched over the other slave controller. At the Input / Output interface level duplication of system critical sensors can allow for additional input data at a different level of detail and for better signal estimations in normal service. Redundancy can also be incorporated into the control power supply system where individual component level reliability may be problematic.

Design of all systems should be with respect to a target life and maintenance programme. Where components cannot be designed to meet the required machine life, due to fatigue, aging or wear, they shall be clearly identified and an appropriate inspection or replacement interval defined in the context of an on-going Operation and Maintenance (O&M) programme.

6.5.4 Cost

The control system should be designed so that it can be manufactured at the lowest cost possible without compromising the reliability. Where additional cost is incurred to improve efficiency, a cost benefit analysis exercise should be carried out to ensure that this cost is economically justifiable.

7 Further Requirements for the Control System

7.1 Introduction

Although the requirements for real-time control and the associated complexities are particular to wave energy, there are other requirements for a successful control system. These include effective human-machine-interfacing, the ability to identify and respond to fault events through diagnostic processes, safe deployment, recovery and maintenance and the ability to provide comprehensive and well-structured data archives for instance for performance verification. An additional requirement is to be able to determine and to respond to the characteristics of the wave environment.

7.2 Front End and High Level Control Sub-Systems

7.2.1 Introduction

A WEC's supervisory control system will typically have a number of distinct elements, all working in an integrated manner. The system will include:

- diagnostic processes running on various timescales and with various degrees of automated response,
- alarm systems to provide user warnings of abnormal events or conditions,
- human machine interfaces providing operator information on the devices, the array and the balance-of-plant.

7.2.2 Intermediate and high level diagnostic processes

Real time diagnostic processes are required where immediate automated action is defined in response. For example, load monitoring where action may be taken to protect other systems in the event of partial failure. Application of redundant systems also rely on detection of failure to make use of them. These process may in turn feed into the alarm system.

Diagnostic processes that do not require sample level rapidity of automated response can be conducted either in the supervisory control environment, still allowing quasi real-time alarms and automated response, or in post processing for periodic review. Moving away from the real time environment allows for greater application of processing power and increasing sophistication.

Diagnostics conducted over long periods require separate processes running on recorded data as described below. These include fatigue and wear statistics but may also include highly specialised processes designed to detect developing problems before faults manifest and effect operations.

7.2.3 Alarm system

Diagnostics must be integrated with an automated alarm system to alert personnel and systems of abnormal conditions potentially requiring control or operational actions. Alarms may be based on single transducer signals or on sophisticated diagnostic processes, but follow a consistent form of triggering and logging.

Due to the environment and continuous operation it is generally not possible to safely operate a WEC without an automated alarm system integrated with the control functions. It is the alarm system that alerts people to any problems on the machine and these alarms may also be associated with automated responses where such a response can be clearly defined in advance.

The alarm systems requires its own detailed specification including flexible definition of individual alarms to a common framework. Common problems in the implementation of alarm systems include ‘alarm flood’ when single events trigger excessive separate alarms, excessive user interaction with set-points, unhelpful messages, etc. In practice, managing the rate of spurious alarms is as important to a successful system as detecting real faults.

The role of the alarm system is likely to change through the development process as the wider WEC systems and behaviour is progressively refined and understood from testing of prototypes at sea through to management of mass deployed assets. However, well designed alarms are just as important at each stage. The alarm system should operate with a standard protocol suitable for interface consistently with different software clients and over remote networks.

Well informed guidance on the design and functional requirements is included in: “Alarm systems - a guide to design, management and procurement” is published by The Engineering Equipment & Materials Users Association (EEMUA).

7.2.4 Human Machine Interfaces (HMI) and wide area network interfaces

A familiar hierarchical approach may be taken to Human machine interfaces to allow both high level monitoring of alarm states with limited additional information, down to fully detailed subsystem signal and driver information.

The interfaces should be as intuitive and consistent as possible throughout different systems, and at different levels of the interface hierarchy to avoid confusion.

Potential faults should be made visible and useful responses to them should be enabled through control action, particularly in safety critical areas. Where possible and robust, responses should be automated. The role of fault handling systems in the technology development process is discussed in Chapter 8.

Human monitoring requirements should be generally minimised to reduce associated costs and to reduce risks associated with the requirements of human response to faults

Interfaces maximise the information coming from the operational testing through processing and making it accessible in the most useful form.

The underlying communication mechanism should minimise the bandwidth required to run a given human interface and allow for flexibility in creating different clients. For example, a carefully designed command line and massage passing structure may allow for very low bandwidth control over a serial modem, but also allow a sophisticated graphical interface to be built around it.

WEC level HMI

Direct remote control of parameters and control services must be available at the machine level for monitoring engineers able to take action in ways not automatable (i.e. with diagnostic capability and with solutions to meet previously unforeseen problems, or problems with excessive combinations and subtlety to automate for proactively within realistic development resources).

Human monitoring of individual WECs is especially important and intensive during development, where the development of experience is gained and maximum flexibility of response action is required to deal with unforeseen issues.

Both human inputs and automated adaptive control processes are required to be able to adjust parameters of the real time control processes in response to changes in conditions. A robust interface is required across any different hardware platforms with the facility for error handling, constraints, and interlocks to be applied to input (e.g. at HMI level) and output (e.g. at firmware level) processes.

Interlocks against user error are required at the machine level to prevent accidental damage to the machine or subsystems. To take an obvious example, the response control parameters should be restricted to values that may not result in damage to the machine. The degree of protection should be commensurate with the level of risk and the consequences and may function in tandem with hardware interlocks in special cases such as electrical switchgear and mooring connection systems.

The WEC level HMI also needs to support maintenance and commissioning processes as described in Section 7.3.

Farm level HMI

As with existing wind farm control systems and interfaces, the normal view of Wave farm from an operational perspective is expected to be at the farm level, with multiple machines represented by summary statistics and status indications. This may be treated as a hierarchical extension of the individual WEC representations all within the same interface framework, or it may be a separate client using the same communications and command protocol.

Utility interface

A customer facing interface is required, including certain command structures, to enable management of the generating plant within wider constraints of the electricity and supply network. Various industry standard tools exist for integration of data and commands with existing interfaces software, for example OPC, but there is no agreed standard across the energy industry. This interface would be required to enable basic Start/Stop and limit commands to be met across the farm as a whole. Existing wind farm systems are a good reference for the likely functional requirements for integrating wave farms into utility asset management systems.

High level network monitoring/management

The control and communications network itself must be monitored and alarmed across all services, allowing redundant communication line to be used and faults logged for repair.

7.3 Control Functional Requirements During Deployment and Maintenance

7.3.1 Introduction

Earlier discussion focussed primarily on sub-systems and functional requirements during normal operational power production. The complete functional specification however must also consider control actions during fault conditions and control actions required during the non-operational phases of deployment, maintenance and recovery.

7.3.2 Mechanical and electrical connection systems

Individual WECs must be isolated from the mains power export circuit of the array for fault handling and routine maintenance.

Floating WECs are expected to be disconnected and connected from their moorings for maintenance and servicing. This requires robustly controlled and highly reliable actuation and monitoring systems, for example, remotely operated latching mechanisms, electrical, and communications connection systems, interlocks on release mechanisms, cameras, position and proximity sensing, and moisture and insulation resistance monitoring. Winching systems may also need to be remotely controlled for offshore installation and/or removal operations.

Where the connection and disconnection system is remotely operated, very robust control and hardware interlocks are required for security and to guard against accidental release due to malfunction or human error.

Shore based plant may use more conventional electrical and mechanical isolation systems with potentially less onerous control requirements.

7.3.3 Vessel and forward operating base control hardware

Floating WECs are likely to require remote human operation of services including connection systems and response control, from vessel when undergoing install/removal operations and towing.

Vessel based hardware must be physically robust and compact, the associated software interfaces must provide clear summaries of information and controls for the particular job in hand, avoiding operator confusion.

7.3.4 Maintenance and commissioning services

Dedicated tooling and monitoring services allow for maintenance and inspection activities. For example, oxygen monitoring sensors for confined spaces, auxiliary drivers for general remote testing purposes, and dedicated testing systems for safe remote actuation via the control system.

Examples of these systems include pressure testing controls and hardware for rapid and safe recommissioning of fluid based PTOs, or auxiliary inputs for diagnostic DAQ systems, such as vibration sensors.

7.3.5 The HMI as an aid to maintenance, commissioning and vessel based services

The WEC control HMI should also allow and support maintenance and commissioning activities where possible, including sensor diagnostic and calibration information, and direct access to dedicated sensing and tooling actuation. During commissioning Factory acceptance testing of sub-systems may be conducted with dedicated routines and using specialised interfaces, and common maintenance activities may be similarly supported for maximum efficiency of operations.

Although operations and maintenance strategies will vary dependant on WEC design and individual developer's specific policies, for all WECs there will be a requirement in the project life to install and remove the WEC from site, potentially to tow it long distances, to complete commissioning procedures, and to complete sea trials of some description. An easily portable and readily accessible platform from which a WEC can be controlled is advantageous. Specifically, a portable control system enables:

- Location independent control of the WEC. The use of certain vessels or vessel types is therefore not restricted and control can be easily set up at quayside locations with minimal facility requirements (only power required);
- WEC control to be undertaken from a vessel bridge. This has a positive impact on both the safety of an operation by keeping control personnel off the deck and in improving communications with the vessel master;
- Mobilisation to be completed without the need for specialist time or equipment, and with reduced mobilisation and demobilisation times (and hence costs);
- Engineers have full access to all the information available for fault finding and resolution during these critical times.

To avoid user confusion, a vessel based system should be consistent with other interfaces, although some features may need to be extended or locked off depending on the operation being undertaken.

Ideally, such a system will meet the following set of requirements:

- Provide a wireless communication link with the WEC (preferably dual frequency or with dual redundant protocols for fault tolerance);
- Include redundancy on all communications equipment included and the ability to switch remotely between hardware if required;

- Provide a suitable enclosure for securing communication equipment on top of vessel bridge (allowing maximum line of site in all directions and minimum antenna cable routing);
- Provide an omni-directional communications link for a 250m radius (line-of site minimum) around the WEC;
- Provide a wireless network link to computers in the vessel bridge (and an Ethernet back-up for fault tolerance);
- Be transportable in packages small and light enough to be readily moved/lifted by hand down ladders;
- Provide all equipment with adequate protection against damage during transport (including impact damage and potential accidental submergence in water);
- Provide an uninterruptable power supply for all communications equipment housed in communications box. The capacity of UPS unit will be defined by the maximum duration of critical operations;
- Provide power connections for communications box enabling both 110V and 240V connections.

It may also be necessary for specific WEC critical systems have dual control functionality and redundant communication links. In this case, it must be ensured that either system cannot interfere with the other. Additionally, both systems should have equivalent naming conventions and functionality where at all possible to avoid unnecessary human confusion.

7.4 Data Capture, Post Processing, Management and Data Mining

7.4.1 Introduction

Fault diagnostics, performance assessment, fatigue assessment, and many other activities require access to recorded long term data in an organised form. The volumes of data associated with multiple continuously operating machines requires automated processing and storage of derived statistics and specialist interfaces to quickly extract useful information.

Automatically driven control system alarm and event logs, and data capture including fault diagnostics/indications are essential for reliability analysis and fault finding, and continuous improvement in availability. This may be supplemented in service by manually driven maintenance logs and fault reporting systems, able to cross reference log and data records.

Data flows from the same measurements used as inputs to the control system, control system processes, and from dedicated data capture hardware. This data must be captured in a consistent, time synchronised, fashion and transmitted from the individual WECs for storage in a manner suitable for post processing: long term diagnostic processes, fatigue damage counting, data mining, performance assessment etc.

Control events, commands, parameter changes, and alarms must also be logged in a synchronised time-stamped manner for direct comparison with other recorded data.

7.4.2 Control requirements for WEC performance assessment

The IEC technical specification IEC/TS 62600-100 covers the requirements for power performance assessment of marine energy convertors (wave, tidal and water current converters), including a number of minimum requirements for data acquisition from the individual WEC control systems and the farm control system. IEC TS 62600-100 implies that WEC and wave farm control systems must meet the following functional requirements:

- The sea state incident at the WEC must be measured at a location with representative wave resource and with minimal interaction between the WEC and WMI (Wave Measurement Instrument). As a minimum the measurements from the WMI must allow calculation of the significant wave height (Hs), the wave energy period (Te) and the Wave energy flux (J). It is additionally recommended that spectral shape, directionality of the waves, the directional frequency spectrum, and currents are measured. The required calibration, accuracy, resolution and limitations of these measurements are defined in NDBC:2009 Technical Document 09-02.

- For AC grid connected devices, power output measurement must be made at the WEC power output terminals (the point where the output power is in the form of AC at the network frequency).

- Power measurements must be subject to a suitable anti-aliasing filter and recorded measurements must include the mean, standard deviation, maximum and minimum in each sample period.

- Power transducer measurements must be based upon measurements of current and voltage on a minimum of two phases. Electrical transducers should be class 0.5 or better, should be calibrated to traceable standards and shall meet the following standards:

  Power transducers: IEC 60688;
  Current transducers: IEC 60044-1;
  Voltage transducers: IEC 61869-3.

- Power measurement devices to measure export power should be rated to at least 1%-200% of rated power.

More general requirements from the technical standard for data measurement appropriate to this report include:

- A minimum sample frequency of 1Hz for wave measurements and 2Hz for power measurements;

- A minimum sample duration of 20mins and a maximum sample duration of 1hour.

- Synchronisation between data measurement systems;

- Date and time stamping using ISO 8601;

- Records to be annotated with quality control flags;

- Records to be recoverable in ASCII format.

There is no mention in IEC/TS 62600-100 of what, if any, selection or omission of available of data is appropriate to represent the WEC performance. It seems reasonable, for the purposes of separating availability from other performance characterisation, to select for data that is fully representative of the WEC's performance at 100% availability, i.e. selection for period when the WEC is "switched on" and operating normally. Indeed, to enable performance guarantees, comparison against a pre-defined power matrix is also required. In this case, it is necessary to exclude any periods of operation where assumptions do not meet those assumed when the reference performance (i.e. power table) was generated.

In order to achieve a robust method of data selection, a simple set of selection criteria must be defined that is appropriate for the WEC. Methods of recording and retrieving these data must be available from the control system. For example, logs of control settings in use, the presence of faults, and any user intervention (e.g. planned shutdown and testing activity), and position and heading measurements in conjunction with sea conditions may all be relevant in this context.

A significant omission from the IEC/TS 62600-100 is that all calculated outputs are based on generated power instead of absorbed power. While generated power calculations are reasonable for mature WEC technologies and are the ultimate demonstration of performance for a WEC, it is also important to separate out the effects of PTO efficiency from power absorption in earlier stage technologies. This enables proper quantification of the WEC's fundamental potential to generate power without introducing the complications of system design and efficiently into the calculation. Additionally, it provides valuable information about system efficiency from which targeted improvement programmes can be defined. To enable this the control system must be capable of measuring/calculating the absorbed power of the WEC and this functionality, through the integration and monitoring of appropriate sensors, should be built into the control system.

7.5 Control Considerations and Sensing the Wave Environment (the System Input)

7.5.1 Introduction

The fundamental input to any WEC is of course the wave environment and depending upon the sophistication of the control strategy, information may be needed either on the characteristics of the prevailing sea state or, more challengingly, on approaching incident waves in real time. The WEC control system needs that information to ensure high productivity whilst safeguarding the plant against adverse loads and conditions..

7.5.2 Wave and other direct measurement systems

High level requirements to be met by the wave monitoring system are to provide:

- Inputs on local wave conditions and environmental loading for use in operations planning and decision making
- Forecasts of energy production, enabling effective market trading

- Data collection for WEC Performance assessment and operational review, including empirical validation of power tables and detailed ongoing technology development.
- Inputs on local wave conditions and environmental loading for use in non-real time adaptive WEC response control, on a variety of time-scales
- Short term wave forecasting (of varying degrees of accuracy and coherence) as an input for real time response control.

Direct measurement of local wave conditions is a large and complex topic that may only be briefly summarised here in direct relation to control functionality. The reader is referred to Chapter 4 of ‘Ocean Wave Energy: Current status and Future Perspectives’ for further background information on the state of the art in measuring and representing the wave resource.

A wave energy (or amplitude) spectrum represents the statistics of the local wave conditions in terms of component frequency and direction. The assumption of linearity is generally implicit in this representation and the methods used to derive it. These spectra may be further reduced into single parameter representations with additional loss of information, for example significant wave height, energy period, and mean wave direction.

The time history from which a spectra was derived may be recovered for simply derived spectra (e.g. discrete Fourier transform) but not for the more sophisticated probabilistic methods (e.g. maximum entropy, Bayesian method) that are required to derive useable directional spectra in the reasonably short time-windows commensurate with capturing changes is underlying climatic conditions.

The applicability of a spectrum measured at one location in representing the spectrum at another nearby is a function of the proximity, local site effects (e.g. bathymetry, reflections, etc), and the period of time being represented. A wave measurement device (e.g. wave buoy) can provide a representative spectrum for the waves incident on a local WEC, within a few hundred metres or even a few kilometres depending on the local site characteristics.

Further improved estimations may be obtained by combining multiple wave measurement sources and by applying detailed knowledge, models, and empirically informed mapping techniques for the site.

Extensions of these methods (e.g. Bayesian Directional method) using simultaneous wave measurements at multiple locations may retain directional phase information and hence offer the potential of deterministic short term wave prediction (for a few tens of seconds), projecting the wave field over the area of a wave farm. Such methods may use a combination of multiple measurements and sophisticated signal processing techniques, perhaps making use of deterministic models of the wave physics including any important local site effects. Short term wave prediction using different approaches has been the topic of active research and development over the last few decades.

Spectral quantities (e.g. significant wave height, energy period, and directional information) may only be defined with respect to historically measured time windows of a given length, with increasing uncertainty (error) for shorter windows. They are therefore always out of date to some extent (be it a few minutes or a few hours for ocean waves), and a compromise must be made between increasing the resolution and losing the currency of spectra derived from correspondingly longer time-windows as they effectively average over the underlying climatic shifts in the wave conditions being measured.

Moving windows of different sizes (and hence delays) may be used to provide continuous updates for a range of latency and resolution, and therefore to provide a more immediate measure of changes in conditions within the error bounds of expected statistical variations overt time.

More generally, estimation processes may also take multiple spatially separated wave measurements to give faster and more accurate estimation of directional wave spectra and potentially form inputs for sophisticated whole-wave-field measurement and projection.

The challenge of deriving and expressing spectral (frequency domain) information in pseudo-real-time with minimal delay is a familiar one in other signal processing applications, and a variety of time-frequency processing techniques have been developed accordingly. These include Wavelet transforms, Hilbert transforms, and Empirical Mode Decomposition. Using such techniques to derive effective instantaneous frequency and amplitude at the WEC location could prove to be extremely valuable in offering predictive capability for response control, but would still require effective real time measurement of the entire local wave field, enabling deterministic prediction of the waves forward to the WEC location. Application of time-frequency processing techniques and multiple input estimation techniques may offer a valuable seam of research for short term ocean wave measurement.

7.5.3 Potential for short term wave prediction systems

To reach the ultimate limits of absorption possible form either individual WECs or for arrays as a whole, advance information is needed on the individual waves locally incident on the individual WECs. The measurement and estimation systems to do this are the topic of research, commonly referred to as ‘deterministic sea wave prediction’ but systems are not yet available for deployment. It is expected that useful systems may become available with the potential to make us of different wave measurement technologies and processing techniques. To implement such a system would require the real time control network to extend across the WEC array and include these wave measurement systems for integrated real-time processing in the response control algorithms.

Wave prediction systems could be very usefully applied as a control input even if they only provided a loose advance indication of fluctuations in the wave amplitude envelope i.e. advance warning of groups and lulls rather than precise surface elevation dynamically phase locked with the WECs. This is especially true for wide bandwidth WECs with the potential to benefit from reduced influence of motion constraints more than fine adjustment of their frequency response. This ‘start simple’ approach may provide a useful avenue of incremental development for any prospective short term wave prediction technology.

There are a number of ways in which direct wave measurements may be applied in the control system and these are discussed in Sections 4.7 and 4.8.

7.5.4 Forecasts

Site specific forecasts of wave and wind statistics (in terms of spectral parameters, and average and peak wind speeds) are increasingly accurate and available. Like familiar broadcast weather forecasts, these use continuously updated feeds of satellite and other sources of meteorological data to feed highly sophisticated numerical models interpreted on a statistical basis. Wave forecasts make use of wave generation and transport models fed with the meteorological forecast wind data and with direct wave measurements from buoys and satellites. Local site models may include varying levels of sophistication of tailoring to the local coast line and bathymetry. Specialist commercial services have developed to serve the general coastal, offshore, and shipping industry.

Forecasts obviously decrease in accuracy with length but also with other factors dependent on the regional conditions and resulting influence on modelling statistics.

Operational planning and yield forecasting

The role of forecast of this type is limited in response control for absorption, perhaps offering the potential to supplement trends in spectral measurement used to set absorption parameters. However forecasts are invaluable for other aspects of operations and asset utilisation. In particular, the planning of downtime and intervention to maximise availability, and to minimise operational risks and costs.

Meteorological forecasts are already used routinely to assist in the marketing of electricity from wind farms, allowing suppliers to bid on the basis of predicted output. A similar situation would need to evolve for large scale wave energy deployment.

Forecast information should therefore be integrated with high level networks and human machine interfaces.

8 Development Strategy for the Control System

8.1 Introduction

Running themes in Chapter 4 were that design development and control development must be parallel and interactive activities and that, although fundamentals must be established at the concept stage, the sophistication and refinement of the control system can be built up gradually as the WEC progresses through its various stages of development. Control should not be regarded as a set of processes that are developed and applied retrospectively once the wider system has been finalised. Rather, control should be viewed as an integral system element which can be considered in design option trades-off and which should go through development and prototyping in a process of staged progression. This is wholly consistent with the TPL/TRL trajectory being encouraged by Wave Energy Scotland, introduced in Section 2.1.

In the current chapter, a number of sub-elements of that general message are examined. Firstly, the challenges of simulating control in wave tank tests is examined. Secondly, the report looks at some of the issues that need to be considered in moving from simulation based control development into real hardware. Thereafter, two case studies are presented. The first case study identifies the core steps involved in evolution of the real time controller for the Pelamis WEC. The second case study looks at the migration strategy adopted by Artemis in moving the controller for its digital displacement hydraulic transmission system from development to implementation.

8.2 Representing Control in Tank Testing

Tank testing presents some specific challenges in the representation of control, due to scaling effects and the representation of PTO systems. The Froude scaling applicable for wave energy dictates that the accelerations are the same in the scale tests as in the full scale system, to keep the dominant relationship of inertial and gravitational forces similar between scales. This in turn means that time must speed up (i.e. higher frequency waves not just smaller) in the scaled tests by the square root of the scale, and forces are scaled by the cube. Hence different order controlled impedance terms (i.e. damping, stiffness, and mass) are scaled differently to each other: mass with the cube of scale, damping with power 3.5, stiffness with power 4 (as are the corresponding physical effects in the overall system dynamics).

The dynamic similarity of the physical and controlled impedance poses no particular difficulties, but the tank test model is unlikely to represent many characteristics of the real physical system and therefore special care is required to ensure these are understood as either insignificant to the model behaviour and results, or able to be interpreted meaningfully.

For example, the structural properties of the model, and hence the stiffness of controlled load paths in particular, may be very different due to different materials and design details. The different scaling of forces and stress capacity may be fortuitous, since the model scale is inherently less loaded for a given structural design. Forces scale with the cube, so the stresses on a perfectly scaled structure would be linearly reduced (keeping stresses the same at scale would require the force to scale with the square). Depending on construction methods, this advantage may be counteracted to some extent by the different materials used in models, with implications for stiffness and deflections under a given stress regime. In any case, it is important to assess the implications of structural effects on the control representation so that any necessary design changes or mitigations may be put in place.

Similarly, the transmission of controlled loads may be subject to other effects in the model that are exaggerated or diminished compared with full scale. For example, gearing arrangements may have greater backlash and lower stiffness compared with full scale PTO, leading to stability issues for the model not present in the full scale system or vice versa.

Electronic control using electric motors may provide good emulation of a wide variety of PTO systems at full scale, provided the control hardware and electronics can achieve the required frequency response and effective control gains stably in combination with the model dynamics. DC motors may be sufficiently well calibrated to provide open loop application of force proportional to driving current, greatly reducing the complexity of force measurement systems required.

Programmable digital controllers allow for flexible application of control parameters and also for the application of non-linear control processes, including different fixed load limits that are common features of proposed PTO systems. The ‘speeded up’ nature of scale model tank tests means that to avoid stability problems the sampling frequency is likely to be required to be similarly faster, and latency lower, than at full scale. Stability limitations are compounded by any structural or mechanical compliance less favourable in the model than at full scale. This may make some aspects of the specification of real time control hardware and software more demanding in the tank than at full scale – although this is offset by dramatically lower complexity with the absence of real PTO and auxiliary systems, allowing relatively low specification controllers to focus on the basics real time response control task. This may however include aspects of PTO modelling within the control process.

Control hardware for tank models may be best arranged on or off the model, depending on the WEC under test. Complex multi-degree of freedom systems are more likely to benefit from fully integrated hardware and consolidated power supplies with minimal cable routes for power and communication, avoiding multiple trailing or hanging wires interfering with the tests.

Alternatives to electronic implementations include more direct and passive physical embodiments of the full scale PTO, such as orifice dampers or check valves to represent air turbines or fluid pressure systems. The latter can represent basic resistive systems but, like the PTO systems they represent, lack flexibility and controllability. Accurate direct measurement of forces, pressures, and motions is still required to quantify and characterise performance.

8.3 Process of Testing and Roll-Out

8.3.1 Introduction

In this section, experience-based advice is provided on the requirements that arise in managing the roll-out of control into real hardware.

8.3.2 The importance of disciplined management

In common with good software engineering practice, version control software (for example, ‘subversion’) and rigorous associated procedures should be applied during the development process and for ongoing continuous development and improvement.

Unit testing should be included along with any new features included in the build process of new releases. By calling functions on fixed inputs with known results, that new builds of software/firmware may be routinely and efficiently checked for any inadvertent introduction of errors into existing functionality.

Changes to software and firmware, and bug fixes in particular, should also be managed carefully and take advantage of management systems. For example, ‘Trac’ is open source change management software allowing issues to be raised by multiple users and tracked through to implementation of changes and release notes.

Release notes should be associated with any updates deployed, including reference to feature changes and bug fixes (against the change management system) cross-referenced against the code.

Formal test procedures of both software and firmware versions should be conducted, using physical test benches and simulation plug-ins as required. These test procedures should be updated and reviewed regularly as any bugs not caught by them are identified and as new features are developed.

Integrated testing of hardware and software is an extremely valuable and efficient investment. This approach, also commonly referred to as ‘hardware in the loop’ testing allows for interactions between processes running on different devices to be testing together as they respond to emulated signals and direct introduction of faults.

Use of common code between simulations and real machines is strongly advised. The major benefits of this approach are:

- A single implementation means minimal repeated work
- Minimal errors in transcription or adaptation between different platforms
- Simulation testing of the actual code implementation as well as the algorithms

Modular code (plug-ins) provides future proofing for future control hardware and platform development

Feature changes or significant bug fixes should be developed in a separate branch from the trunk. Once code has been written, reviewed, and tested to standard, the work may be merged back into the trunk. This approach prevents the trunk from containing features spread over several check-ins. and implies that the trunk should always contain working code with full providence.

Prior to full roll out on operational machines, individual control processes (for example individual device firmware) should undergo staged beta testing (for example on individual services or WEC within a farm for periods of time) to mitigate the impact of any issues not caught by bench testing.

8.3.3 Early operational testing

During demonstration testing, written logs should be kept by the monitoring personnel. These should be electronic and if possible integrated with time-stamps. This is particularly important during tests of new processes, systems, and in new conditions.

After each install, engineers working on any aspect machine operations AND machine design and development are encouraged to go through summarised reports of these logs to maximise their understanding of machine operations and offer any insight and priorities they may have.

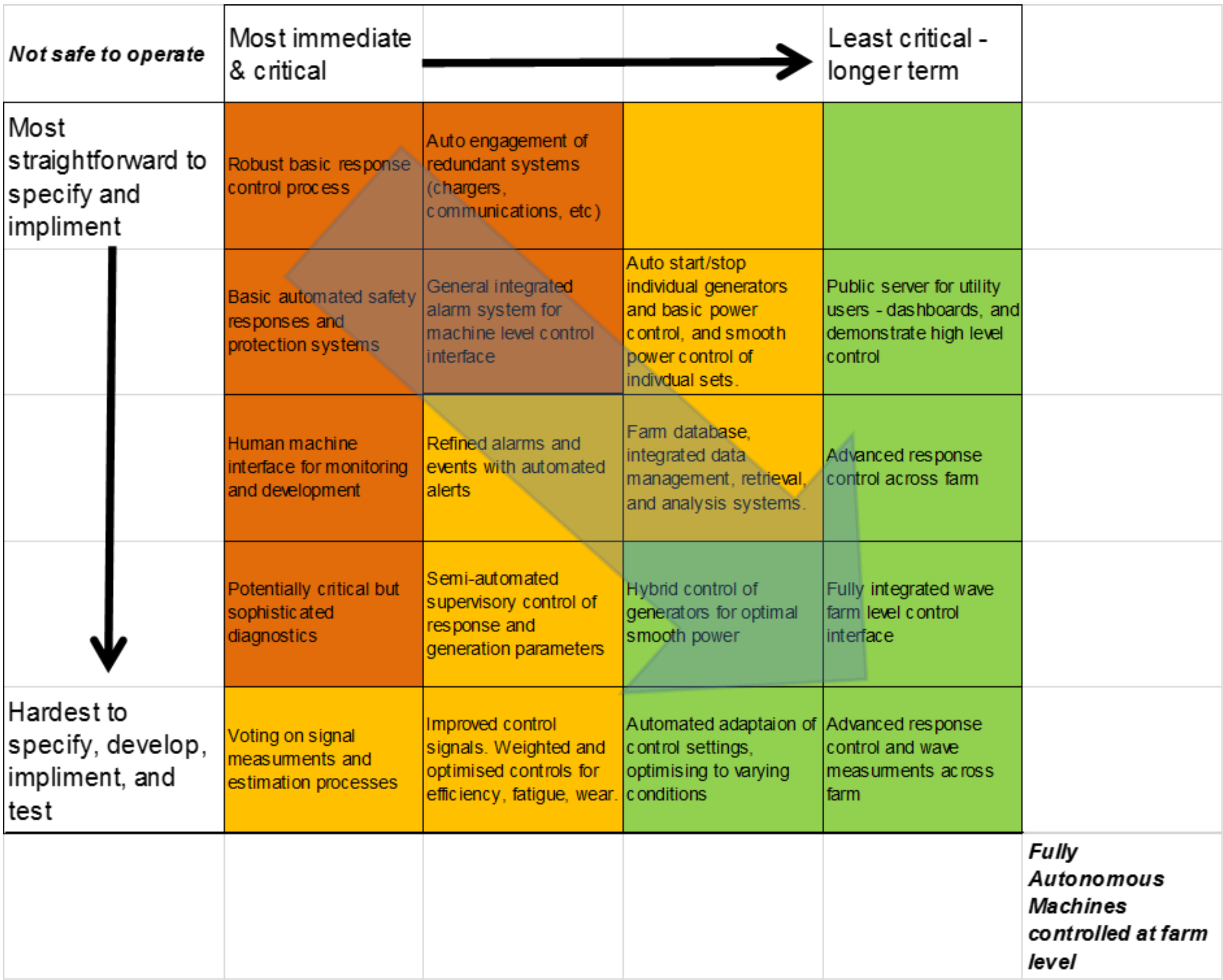
8.3.4 Control development and implementation strategy

A successful control development strategy must make use of available engineering resources and knowledge to enable progression of the wider technology demonstration programme. Control, more than other aspects of the WEC design, can be subject to continuous improvement and adaptation to new information gleaned in the field. This approach relies on sufficient flexibility in the control hardware platform and modularity and maintainability in software design.

Figure 15 shows an example set of high-level objectives for software development prioritised with respect to criticality and level of effort required to implement. Progress is from top left to bottom right. These objectives will be specific to a given control system and wider technology development plan, and will break down into many other tasks with multiple interdependencies. The top left represents the most safety critical functions that also require the least work to implement - these are the highest priority. The bottom right represents the least safety critical functions that are the most difficult to implement – these are vital for long term operations but can assume a lower priority during early phases of development and while engineering resources are likely to be severely limited. With additional resources, it is possible to progress much of the programme in parallel for accelerated results.

Developers should bear in mind the Pareto principle that suggests 80% of effects come from 20% of the causes, so if these 20% can be cogently identified then early control system development can be prioritised to produce maximum early benefit.

In developing a control system, developers should strive for a combination of robust safety features, automated diagnostics, robust control strategies, and reliable implementation.



Not safe to operate	Most immediate & critical			Least critical - longer term	
Most straightforward to specify and impliment	Robust basic response control process	Auto engagement of redundant systems (chargers, communications, etc)			
	Basic automated safety responses and protection systems	General integrated alarm system for machine level control interface	Auto start/stop individual generators and basic power control, and smooth power control of indivdual sets.	Public server for utility users - dashboards, and demonstrate high level control	
	Human machine interface for monitoring and development	Refined alarms and events with automated alerts	Farm database, integrated data management, retrieval, and analysis systems.	Advanced response control across farm	
	Potentially critical but sophisticated diagnostics	Semi-automated supervisory control of response and generation parameters	Hybrid control of generators for optimal smooth power	Fully integrated wave farm level control interface	
Hardest to specify, develop, impliment, and test	Voting on signal measurments and estimation processes	Improved control signals. Weighted and optimised controls for efficiency, fatigue, wear.	Automated adaptaion of control settings, optimising to varying conditions	Advanced response control and wave measurments across farm	
					Fully Autonomous Machines controlled at farm level

- Figure 15 Prioritisation Strategy for Control System Development

8.4 Case Studies

8.4.1 Introduction

This section contains two case studies. The first describes the core steps that marked the development and change to the real time controller for the Pelamis WEC. The second looks at how Artemis migrated the controller for its digital displacement hydraulic transmission system from development to implementation.

8.4.2 Pelamis control case study

The Pelamis WEC[16] is a multi-body, hinged line absorber which has undergone a long period of technical development. Correspondingly, this has led to the accumulation of one of the most significant bodies of experience in control and control development of any wave energy device.

In this section, various important aspects and high-level steps in the development of the real time controller are described. These comprise the stepped, quantised control approach,

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[16] Pelamis wave power ceased operating in 2014 as its overall economic and business case failed to convince the investment community at that time.

experience in using resistive control to achieve cross-coupled resonance and, finally, investigation of more advanced control using multiple inputs and outputs.

Quantised Control

The Pelamis wave energy converter was developed with a novel PTO system in parallel, using discrete digital control of the pressure in a number of hydraulic cylinders to provide quantised control of the PTO force from a slowly varying (effectively constant) pressure from the energy storage system. This approach offers fully reactive power transmission with very high efficiency over a wide range of powers, as no rotating machinery lies in the flow path. However, generating the stepped (quantised) approximation to a continuous force is a control challenge in itself that introduces distortion relative to the ideal smoothly varying PTO force.

Generally speaking, the Pelamis control challenge lay mostly in the control of the PTO system and in artefacts associated with this. The control challenge cannot be separated from either the conceptual design of the WEC, or the PTO system that must apply the control forces through the response motions.

Furthermore, the implementation of multi-faceted control systems integrated all aspects of control, diagnostics, communications, and interfaces. These practical and high-level aspects were found to dominate the required effort relative to that needed for the practical application of response control theory. The algorithms required to successfully measure, diagnose, alarm, protect, and control the low level function of the PTO system may require greater application of effort than the high level response control processes.

Cross-coupled resonance

The Pelamis is a line absorber consisting of multiple rigid tubes linked by hinged joints, 2 axes at each (pitch and yaw), each with a PTO system. The original concept was for control to be predominantly resistive but cross-coupled at the joints to induce resonance in the whole system dynamics, through the channelling of the response to a sloped snaking motion. This approach was successfully proven in the tank and in numerical models but relied on high levels of damping to induce strong resonance. While the cross-coupled, sloped resonant response approach was applied successfully at full scale, applying very high damping coefficients proved challenging with real PTO hardware. Early numerical simulations used unrealistically high damping coefficients, leading to over-estimates of yield from these simple control methods. The control and PTO models were revised following experience with intermediate scale models and first full-scale experience at sea, as the limitations resulting from practical effects of control hardware and PTO were understood and characterised.

Multiple-Input-Multiple-Output control

Work continued on more generalised approaches to take advantage of the multiple degrees of freedom in the line absorber concept. These multiple degrees of freedom provide for Multiple-Input-Multiple-Output (MIMO) control for a hardware platform able to work with all inputs and outputs in a single process. Such a system was fully demonstrated on the Pelamis prototypes but the challenge of providing robustly stable MIMO control settings in a real world environment, through real PTO systems meant that all but the final few years of operational demonstrations passed with the machine controlled with cross-coupling only between axes on the same joint (pitch and yaw) as originally envisaged.

MIMO control was fully implemented on the Pelamis P2 WEC control system. Numerical simulations and optimisation methods, along with a variety of constraints and stability tests, were used to produce MIMO control settings for given ranges of sea state – dramatically increasing the capture width of the machine in long period wave components. These processes were first validated in tank tests, where power capture was doubled in individual sea states as expected from simulations.

A MIMO control optimisation process was adapted for application with the real quantised PTO system and further developed and tested in time-domain simulations of the real machines in realistic sea states. Due to the ‘brute force’ stochastic optimisation methods applied, statistical testing methods were adopted for robustness assessment of candidate controllers, optimised in parallel. Given the large number of parameters, robust roll out of the new controllers onto real machines relied on software transcription systems, direct from the simulation environment. This process of software testing was described in Section 8.3.

MIMO controls were systematically tested in real machines at sea using new methods of comparative performance assessment, switching between controls at regular intervals in synchrony with spectral measurements. This allowed statistical comparison over a population of measurements, as required when the exact wave profile experience by the machine in unknown and is typically plus or minus 15% the incident power indicated at the nearby buoy. The results of the first stage of MIMO testing showed a consistent 20-40% uplift in power compared with the previously applied independent joint controls. Substantial further gains were expected as processes and control frameworks/algorithms/parameterisations were developed.

8.4.3 Artemis Intelligent Power case study: selection and experience of development platforms

Artemis Intelligent Power is an Edinburgh based technology developer which was spawned in 1994 to develop ideas from Edinburgh University on digital displacement hydraulics that had their genesis in wave power. The technology has been demonstrated in automotive and wind energy applications and there is currently a renewed interest in applying it to wave energy applications.

The software and control system platform decisions made in the early days of technology development tend to have profound effects later on. As staff experience and comfort and a library of tools and models is built up, it becomes increasingly difficult to migrate to other platforms. It is wise to invest in a powerful, scalable, and industry-standard toolchain from the beginning.

In terms of time-domain simulation of mechanical/hydraulic/electrical coupled systems, Artemis found the SimScape/SimHydraulics/SimMechanics tools to be good choices, although there may be better, more specialised tools available from other vendors in each individual domains. For instance, both Amesim and Dymola have a better user interface for hydraulic system design, which makes their models easier to understand for non-specialists. For wave energy, the integration of Mathworks tools with hydrodynamics code to form WEC-Sim is a powerful argument to select Mathworks tools for the upfront design of WECs.

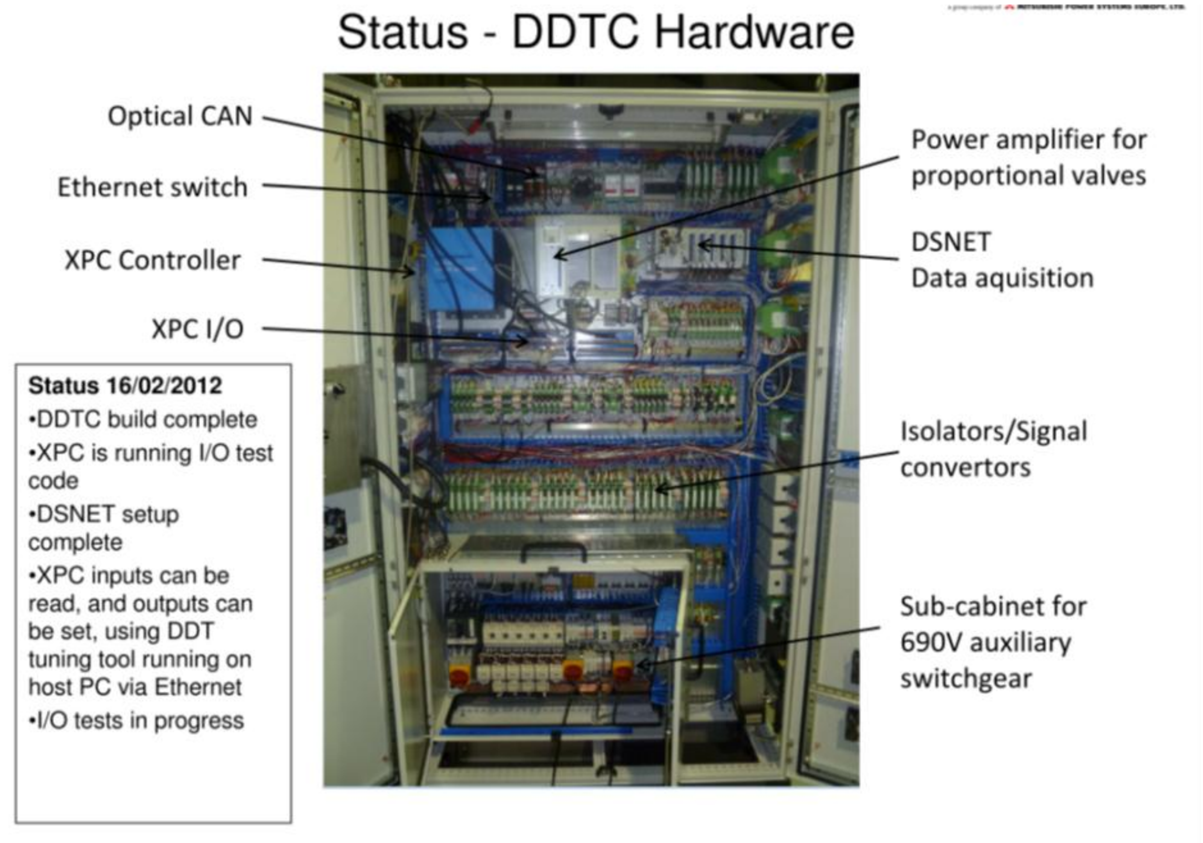
From Artemis' experience, Mathworks' toolchain is unsurpassed is in the area of model-based design, code generation and rapid control prototyping. Combined with suitable hardware, it allows the control system for a complex multi-domain problem (like a WEC) to be developed completely in the PC simulation model, and then seamlessly transferred to prototyping hardware for experimentation and Hardware-in-the-loop testing, and finally production hardware for deployment.

This is exactly the process Artemis has been through for the Digital Displacement transmission of the Mitsubishi Heavy Industries offshore wind turbine, for which they have prime responsibility. They found that selecting suitable hardware for deployment of their control algorithms was not a trivial matter and they have tried a number of such platforms. This experience may be useful to wave energy developers facing similar challenges.

As model-based design developed through automotive applications, there are powerful systems suitable for automotive use (eg DSpace) but these often lack the type and scale of I/O, and potential for distributed systems, required for WECs, and they don't offer a path towards deployment in production.

Matlab itself has a relationship with Speedgoat, who make rapid control hardware based on PC architecture called "XPC". Artemis selected one of their products for the first 2.4MW DD wind transmission built in Japan in 2012. Figure 16 shows the control cabinet, in which the Speedgoat XPC is the blue box.

Artemis found these XPC devices very powerful for R&D, with huge processor power and memory, but limited in expansion potential and networking, and completely unsuited to harsh environments. In order to interface them to the 2.4MW wind turbine, considering particularly the risks of lighting strike, it was necessary to include a large number of external signal isolators/converters. This was not considered a viable production solution. After this experience, it was decided that much more rugged and proven hardware was required, with expandable I/O (like a PLC).

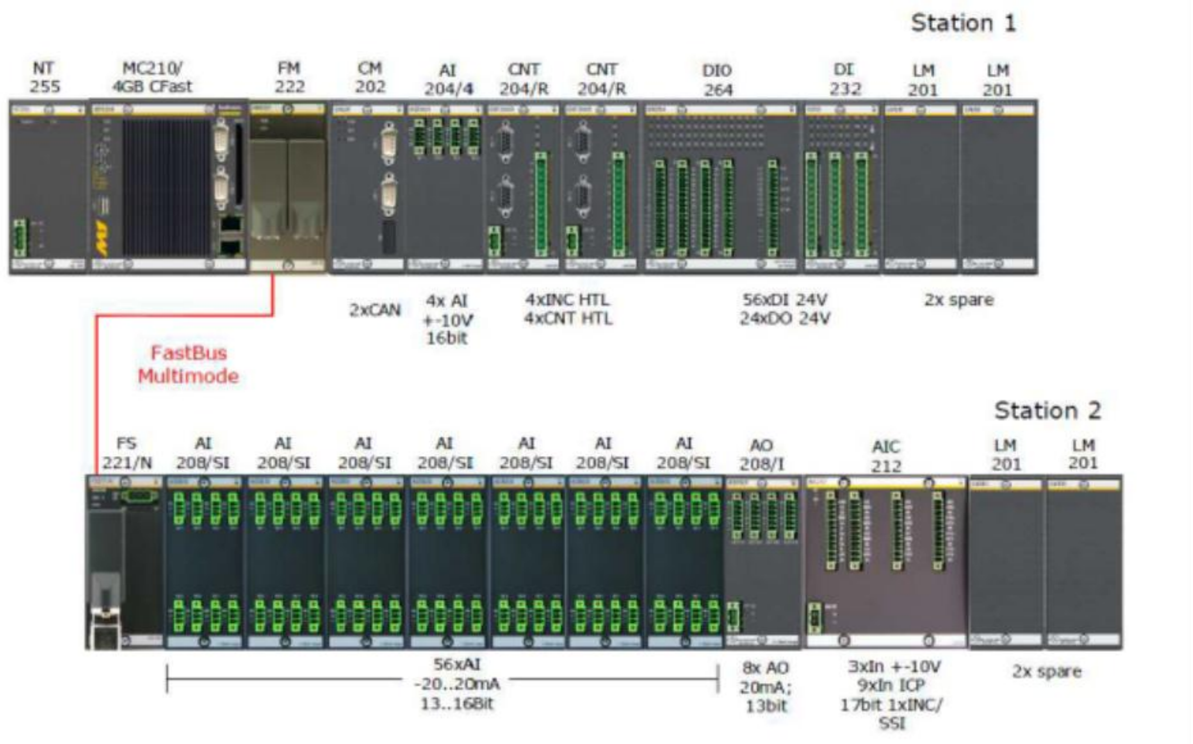

Status - DDTC Hardware

Status 16/02/2012
- •DDTC build complete
- •XPC is running I/O test code
- •DSNET setup complete
- •XPC inputs can be read, and outputs can be set, using DDT tuning tool running on host PC via Ethernet
- •I/O tests in progress

- Figure 16 Artemis Intelligent Power Digital Displacement Transmission Control Cabinet

After an industry wide search Artemis settled on the Bachmann M1 system for both development and production, and now recommend it for similar applications. Based on PC processors, it offers good processing power, which was important in this application because some of the real time control processes need to run at 1000Hz sample rate. It has a powerful real-time operating system that allows mixing of Simulink, directly-written C++, and PLC code operating at different rates and priorities, with a friendly SCADA monitoring and supervisory interface. The backplane module system allows dozens of I/O modules to be linked together, and distributed systems are also supported. There are thousands of Bachmann systems in operation in wind turbines around the world that share many environmental challenges with WECs. Bachmann provide an easy route to integrate Simulink-generated code with their M-Target product, and Artemis report good support from them during their development project.

Figure 17 shows the configuration of modules used in the 7MW turbine system:



- Figure 17 Modular Control Rack for 7 MW Wind Turbine with Digital Displacement Hydraulic Transmission

This looks much like an industrial PLC, and can easily be configured to have hundreds of digital and analog I/O channels through the extendable modules, including specialised modules like condition monitoring analysers. However, unlike a PLC it is capable of running real-time Simulink code, and therefore providing a seamless link from simulation to deployment.

Artemis developed all of the control software (including Stateflow for the state machine and Simulink for the continuous controllers) completely in the Simulink environment that included a model of the wind turbine dynamics. Artemis verified the control system in a Hardware-in-the-loop test using their 1.6MW test rig also using XPC hardware, before it was deployed it to the real wind turbine using the Bachmann M1 hardware.

9 Conclusions

Control has a pivotal role to play in achieving affordability for wave energy. Control directly influences all the core metrics that determine WEC system levelised cost of energy – performance, reliability, survivability, cost-base and practicality. Although it is possible to design a WEC with passive broadband performance and minimal need for real-time control, such systems have excessive capital cost. For now, it appears that only less bulky devices will have acceptable capital cost, but that only advanced control can ensure such devices are able to perform with sufficient productivity to be affordable.

The WEC landscape as yet lacks convergence. For now, in developing a useful statement of the fundamental requirements for low-level control, it is useful to take a generic approach and then to tailor this to the specific WEC system in light of its control capabilities.

Although WECs have a wide range of high level control requirements, it is the low-level, real-time control that poses the greatest challenge and opportunity for wave energy.

There are a number of specific challenges in developing a system model for low-level performance control of WECS – these challenges are well defined but there is significant opportunity to explore solution directions further. The challenges relate to the dynamic and hydrodynamic cross-coupling in a multi degree-of-freedom system with frequency dependent coefficients, to non-linearities in the system excitation and coefficients, to the high gain environment and the effect of non-rigid load paths, to load and motion constraints that have to be observed and to the general non-causal response targets that ideally require accurate predictive capacity.

These complexities, together with others, limit the realisable benefits of optimal control and pragmatic targets and alternative control targets are worth further exploration.

The complexities also suggest that machine learning based approaches may be fruitful lines of R&D rather than focussing on high quality control based on tight system definition (the latter currently being the focus of much effort in the USA under its DoE sponsored wave programme).

The background analysis presented in this report, although adaptable, assumes for optimal impedance matching control, that the plant is the primary converter and that control is exercised through the PTO. Notwithstanding this, there are significant and promising lines of R&D that relate to incorporating front-end control capability in the primary converter.

Experience of Scottish companies in developing and deploying large-scale WEC prototypes over the last decade has built up substantial theoretical knowledge in WEC control but has also yielded very substantial experience in development processes and in implementing integrated control systems covering not only real-time, low level control but also high-level, supervisory functions. There are important lessons to be derived from that practical experience.

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