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Methodology, procedures and equipment required for the laboratory testing of a modular and crosscutting Power Take-Off for wave energy converters

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CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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Foreword

CWA 50272:2021 has been developed in accordance with the CEN-CENELEC Guide 29 "CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization" and with the relevant provisions of CEN/CENELEC Internal Regulations – Part 2. It was approved by a Workshop of representatives of interested parties on 2021-02-10, the constitution of which was supported by CEN-CENELEC following the public call for participation made on 2020-06-10. However, this CEN-CENELEC Workshop Agreement does not necessarily include all relevant stakeholders.

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The following organizations and individuals developed and approved this CEN-CENELEC Workshop Agreement:

- CENTIPOD LTD., Mr. Alan McCall
- CIEMAT, Mr. Marcos Lafoz
- CIEMAT, Mr. Marcos Blanco
- CIMEAT, Mr. Miguel Santos
- CIEMAT, Mr. Luis García-Tabarés
- CORPOWER OCEAN, Mr. Matt Dickson
- Fabricom NV (ENGIE), Mr. Luka Vanderplancke
- HYDROCAP ENERGY SAS, Mr. Alain LARIVAIN
- NEW R&D – CNET (EDP), Mr. Christian Verrecchia
- NEW R&D – CNET (EDP), Mr. Tiago Lourenco
- OCEM Energy Technology, Mr. Mattia Mantellini
- OCEM Energy Technology, Mr. Miguel Pretelli
- WEDGE GLOBAL S.L., Mr. Aleix Arenas

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Introduction

As stated in the SET-Plan Ocean Energy, ocean energy must reduce costs in order to be more competitive. Despite the current improvement in the technological development of different solutions, the harsh environment of the oceans is the main cause of uncertainties in the reliability of wave energy conversion systems, presenting the main barrier for the development of its massive energy potential[1)]. The concept of reliability implies many issues, all of them related to minimize both the levelized cost of energy (LCOE) and the total expected life-cycle costs (operation, maintenance and failure costs). Since the wave energy conversion integrates many disciplines, the problem could be analysed from different perspectives. This CWA focusses in the reliability analysis of the device in charge of the energy conversion from mechanical into electrical, what is usually named power take-off (PTO). In particular, in the frame of the named modular and crosscutting PTO, which are defined by the existence of a unitary module with complete operative functionality and the ability to be adapted to different WECs in terms of available space, force, power, velocity and stroke. Since the testing of rotary generators has been addressed in greater detail in the literature [2], this CWA focuses on linear PTOs.

The PTO comprises the electric generator, power electronic converters, control devices and sometimes additional mechanical devices for the conditioning of the mechanical power provided by the prime mover.

Since the PTO system operation can be tested in a dry laboratory emulating the WEC operation conditions, preliminary commissioning of this important part of a WEC could be debugged and validated. An important reduction on the commissioning time could be achieved by this stage, saving important budget and reducing the potential failure risks involving the PTO equipment.

The CWA is defined in the frame of the stage III of full scale and mechanical loads at scaled tests of wave energy converters (IEC/TS 62600-103-2018 and IEC/TS 62600-3-2020 respectively) and the tests described below can be framed during the calibration and setup dry tests. According to IEC/TS 62600-103-2018, "*accurate calibration of the PTO arrangement is essential and shall be performed prior to experimental testing over the design frequency range to fully characterize the dynamic function of the PTO*". Although there are previous standards facing the tank tests of scaled or full-scale prototypes, including some similar power conversion system, not necessarily the final PTO is currently tested at this stage. The current CWA present the laboratory testing of a unitary module but completely functional full-scale PTO before the final integration into the WEC, and previous to the sea commissioning.

This CWA aims to facilitate:

— Testing different parts of a PTO under rated power and/or operational conditions.

— Testing the different parts of a certain PTO together and under operational conditions.

[1)] Gunn and Stock-Williams, Quantifying the global wave power resource. Renewable Energy, 44 (2012), pp. 296-304. https://doi.org/10.1016/j.renene.2012.01.101

— Characterizing a certain PTO in order to obtain a mathematical model. The model is useful to:

  — Evaluate the LCOE/evaluate other stage gate parameters;

  — Evaluate in different locations under different sea states;

  — Evaluate the performance under different control strategies;

  — Compare different PTO technologies or the same PTO with different WECs.

The CWA comprises the following information:

1) A methodology to test in dry laboratory the performance of a modular and crosscutting linear PTO.

2) The definition of the different procedures for testing a modular and crosscutting linear PTO.

3) The equipment suggested for the experimental tests of each component at the laboratory.

4) The description of application cases, with examples of the different stages and equipment used in previous developments, are included in a final Annex.

This document has been developed in the frame of the project H2020 SEA TITAN (Grant Agreement No. 764014).

1 Scope

This CWA establishes a methodology, procedures and the required equipment in order to test and validate in dry laboratories a modular and crosscutting linear PTO, used for wave energy converters (WEC). It considers common procedures for different types of PTO solutions, as well as operation ranges related to its final location.

Some examples of application of this methodology are presented in Annex A at the end of the document.

Initially, the concepts of modular and crosscutting power take-off or PTO, its components, and the actuator are defined. Additionally, a set of testing scenarios are defined, corresponding to operation at the location, as well as the control strategies to be followed by the PTO. Both subsystems will be operated together with the PTO and the actuator, governed by an upper level supervision system, operating in a hardware-in-the loop scheme. Finally, a whole set of required instrumentation is defined in order to measure the system variables, used subsequently to compile the PTO characterization report.

Regarding the types of WEC where this methodology could be applied, there is no restriction in the WEC topology. Any WEC where a linear PTO is suitable could be in the scope of this document.

The potential users of this document are:

— Developers of power-take-off, either focused on electric machines, power electronics, control systems, instrumentation, or integration of the whole equipment.

— Developers of wave energy converters.

— Experimental facilities where PTOs or WECs are tested.

— Research centres who develop complementary technologies for the PTO.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/TS 62600-1:2020, *Marine energy — Wave, tidal and other water current converters — Part 1: Vocabulary*

IEC/TS 62600-2, *Marine energy — Wave, tidal and other water current converters — Part 2: Marine energy systems — Design requirements*

IEC/TS 62600-3:2020, *Marine energy — Wave, tidal and other water current converters — Part 3: Measurement of mechanical loads.*

IEC/TS 62600-103, *Marine energy — Wave, tidal and other water current converters — Part 103: Guidelines for the early stage development of wave energy converters — Best practices and recommended procedures for the testing of pre-prototype devices*

IEC/TS 62600-30:2018, *Marine energy — Wave, tidal and other water current converters — Part 30: Electrical power quality requirements*

IEC 62506:2013, *Methods for product accelerated testing*

IEC 61439-1, *Low-voltage switchgear and control gear assemblies — Part 1: General rules*

IEC 61439-2, *Low-voltage switchgear and control gear assemblies — Part 2: Power switchgear and control gear assemblies*

3 Terms, definitions and abbreviation

For the purpose of this document, the following terms, definitions and abbreviations apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1 Terms and definitions

3.1.1
wave energy converter (WEC)
device that converts energy from surface waves to electricity or other useful forms of energy

[SOURCE: IEC TS 62600-1:2020]

3.1.2
prime mover
marine energy converter component that interfaces with a resource from which energy is converted

[SOURCE: IEC TS 62600-1 2020]

3.1.3
power take-off (PTO)
mechanism that converts the motion of the prime mover into a useful form of energy such as electricity

[SOURCE: IEC TS 62600-1:2020]

Note 1 to entry: The subcomponent of the PTO are: electric generator, power electronics, (interface), upper level control, and lower level control.

3.1.4
crosscutting PTO
a PTO with the capability to be used or integrated in different WECs

3.1.5
modular PTO
a PTO with the possibility to be divided in sections with full functionality but reducing the initial values of power or force

3.1.6
direct-drive PTO (DDPTO)
a PTO without interface between the prime mover and the electric generator

3.1.7
mechanical PTO
a PTO with a mechanic interface between the prime mover and the electric generator, such as a rack and pinion or a planetary gearbox

3.1.8
hydraulic PTO
a PTO with a hydraulic interface between the prime mover and the electric generator, such as a system with a hydraulic piston and a hydraulic motor

3.1.9
other PTO
this classification includes PTO based on new materials (triboelectric materials, dielectric elastomers, etc.) and PTO that cannot be categorized in the previous one

3.1.10
electric generator
device with the ability to transform mechanical energy into electric energy

3.1.11
power electronic converter
electronic equipment based on semiconductors to electrically connect the electric generator with the electric grid, or with an on-board isolated load

3.1.12
interface
device to connect the prime mover with the generator of the PTO, transforming the movement of the prime mover in a rotary movement – in the case of rotary electric generator – or in a linear movement – in the case of a linear generator –

3.1.13
lower Lever Control (LLC)
control device or platform that determines the power electronics references (semiconductor states) by means of the measurement of electric variables (voltages and currents) in order to impose a reference value of a mechanical variable (velocity, position, force, torque, etc.). This control algorithm could be run in a common control hardware with the HLC, or could be run in a specific control hardware

3.1.14
higher level control (HLC)
control device or platform that determines the value of a mechanical variable (velocity, position, force, torque, etc.) to be used as input reference in the LCC, and in order to optimise the energy extraction from the waves

3.1.15
preliminary tests
tests carried out over each subcomponent of the PTO according relevant standards related to each subcomponent

3.1.16
characterization tests
test carried out over the PTO in order to evaluate its performance (without taking into account any particular WEC). At least, the force capacity for each velocity, and the efficiency for each force/velocity pair of values would be evaluated. The HLC is not used in these tests

3.1.17
tests under operational conditions
test carried out over the PTO with the emulation of the behaviour of a particular WEC in a particular location

3.1.18
accelerated testing
set of operational tests produced in short time, defined according to the methodology included in IEC 62506:2013

3.1.19
power quality tests
set of operational tests where the quality of the power supplied by the electric generator are measured. They are defined according to IEC 62600-30:2018

3.1.20
grid compliance tests
test to check the impact on a specific electric grid by means of a electric grid emulator. These tests check a specific grid code requirement

Laboratory tests equipment terms:

3.1.21
mechanical actuator (MA)
device of the lab scheme to be connected mechanically with the PTO in order to impose a particular force or movement

3.1.22
electric grid (or on-board load) emulator (EGE)
device of the lab scheme to be electrically connected with the PTO in order to emulate the electric grid or on-board loads

3.1.23
emulator control (EM)
device of the lab scheme that controls the MA and the EGE. This control includes a model of the WEC behaviour and a model of the electric grid behaviour in order to carried out the particularization tests

3.2 Acronyms

PTO	Power take-off
WEC	Wave energy converter
LLC	Lower Lever Control
HLC	Higher Level Control
DDPTO	Direct-Drive PTO
EM	Emulator Control
EGE	Electric Grid (or on-board load) Emulator
MA	Mechanical Actuator

4 Description of the methodology for laboratory testing of modular and crosscutting PTOs

4.1 General

The methodology starts with the definition of the different components of the PTO. Subsequently, a set of laboratory tests are suggested to be accomplished for each component. Some components allow the whole set of tests, while some others only support a few of them. A complete matching of components with tests will be provided in the format of a matrix [component, test]. Depending on the particular technology to be tested, the number of combinations could change.

Additionally, the equipment required and suggested for the different tests is presented during the document, being associated to the particular tests.

4.2 Components of a modular and crosscutting PTO

The components of a modular and crosscutting PTO are:

1) Electric Generator. Electric machine that converts the mechanical energy of the prime mover in electric energy. It can be directly connected to the prime mover of the WEC – direct-drive PTO – or connected by means of an interface to the prime mover. The generator is composed by several generator modules, which are associated in several groups of modules. Each group of modules is driven by a power electronic converter.

2) Power electronics. Semiconductors and passive elements that control the electric power of the electric generator. Power electronics comprise several converter modules, and each converter module drives one group of generator modules. A converter module is composed by two different converters: 1) a generator side converter (GSC), which controls the electric power flowing from the generator; 2) the grid-tie converter (GTC), which controls the electric power flowing to the power grid.

3) Interface between the electric generator and the prime mover. Devices of the PTO that transfers and conditions the mechanical energy from the prime mover to the generator, e.g. a rack and pinion system that transforms the linear mechanical energy of a prime mover into a rotary mechanical energy on the shaft of a rotary electric generator.

4) High level control (HLC). In charge of defining the system operation according to the ocean wave and prime mover motion. Based on the mechanical variables' measurements of the prime mover, the HLC defines a force/torque command to be imposed. Given the modular characteristic of the PTO, a first way to define the force/torque command is to define the operational constraints of a single module, and then define the number of modules in the full WEC (N_{PTO}). In this way, the controller output force command (F_P) is the force per module rather than the total force ($F_{P\text{-}NET}$). Other possible way is to send $F_{P\text{-}NET}$ from the controller, and then divide it by N_{PTO}. Moreover, the WEC inertia must be included. An example of how to include the WEC inertia is presented in Annex A.

5) Lower level control (LLC). In charge of providing the required force/torque to the generator. The LLC receives the force/torque command from the ULC and calculates the necessary semiconductor states of the power electronics.

The particular systems will be firstly tested independently and secondly as a group.

4.3 The testing procedures at the laboratory

The testing objectives and procedures should be adjusted to the stage of development of the technology under consideration. For instance, at early stages one could typically find proof of concept tests, comparison tests, response surface optimisation tests and model validation tests; while, at later stages, the usual activities carried out are performance, reliability, shake-down, endurance, duration, climate and/or accelerated tests. Control systems should also be tested along the whole development path. Finally, power quality tests should be performed to evaluate the impact of a device/farm on the grid[2)].

Two main options for testing will be considered as a first decision, regarding the orientation of the movement at the laboratory. Considering the final orientation of the linear PTO, it is mostly common to be located in vertical, resulting a vertical movement. However, testing the complete system this way, reproducing exactly the same mechanical conditions in terms of transversal loads, leads to a very expensive testing infrastructure and sometimes even limitations due to the height requirement. As a consequence, it is common to develop the tests with a horizontal orientation of the PTO and the rest of mechanical equipment. The mechanical conditions during these tests are not equivalent to those during the real performance. Nevertheless, the tests will be developed in the most unfavourable conditions, ensuring that the system will never behave in harder situations.

As stated in the introduction, the present CWA refers to a relatively advanced stage of development. Consequently, the different tests proposed to be accomplished are described as following:

a) Preliminary tests:

- Set up of the test-rig and calibration of the actuators.

  - When implementing actual hardware, spring-mass-damper systems can be utilised to represent the WEC characteristics and allow for some control prototyping before performing the final testing. The parameters of such system need to be adjusted to match those of the WEC. Additional virtual controllers might be needed to achieve better dynamics matching, i.e. the correspondence between the closed-loop test system and the actual WEC's response. For an example on how to set-up a test-rig based on the aforementioned strategy, see Annex A.

  - Alternatively, hardware-in-the loop systems can emulate the WEC dynamics and allow for the study of control systems.

- Besides, actuator performance can be assessed by means of their frequency response functions, understanding how well the measured signals (e.g. force or torque) from the actuator respond to their respective desired commands.

- Preliminary safety operation of the power electronic converters can be checked by performing the insulation resistance and leakage current tests, according to IEC 61439-1 and IEC 61439-2. Ground resistance measurements between ground connection and the whole structure shall also be accomplished.

2) MARINET Project. Definition of standardized PTO Test Procedures. Feb. 2014.

— Modularity tests: The electric connections of the modules, both in the case of the active part of the linear generator modules and in the power electronic modules to drive them, must be compatible to connect between each other. The connection of different modules, both in series or parallel must be checked in a safe way. The electric connectivity must be also compatible with the mechanical connection of the modules in case of an increase of the total force or power of the linear generator by adding modules.

— Crosscutting capacity tests: Once considered that the scope of adaptation of the linear PTO module to a certain set of WECs, the electric adaptability must be verified in terms of power, force and voltage which values must be compatible with the module. Moreover, other variables of the module such as velocity, stroke must be according to the operation limits of the WEC.

b) Characterization tests:

— Literature on system identification of WECs has shown advantages in employing periodic signals when carrying out testing with WECs. Consequently, it is also desirable to work with these signals when evaluating WEC's PTO control and performance. This also reduces testing time.

— (synthetic profiles – such as trapezoidal reference velocity profiles to test PTO in constant conditions, sinusoidal reference velocity profiles to test PTO under different frequencies).

— The system response and dynamics can be initially analysed through frequency response functions (for instance to identify resonant behaviours).

— Power converter's LLC behaviour can be checked maintaining a low output current value at the GSC.

c) Modular series and parallel integration

— Voltage association of serial modules. In case of serial connection of both generator modules and power electronic modules, the voltage will be added. Voltage isolation must be ensured for each element of the serial chain.

— Electric current balance of parallel modules. In case of a parallel association of the modules, both in the case of the generator coils or the power electronic modules, the correct balance between the current circulating along the different parallel branches will be analysed, ensuring a perfect equalization.

— Synchronization of the modular control platforms. Control modules will be usually associated to different power electronic modules and will be low level control (LLC). The operation of the different modules will be commanded by a high level control (HLC) which will ensure the synchronization of the signals in order to ensure the correct operation of the power system, avoiding overcurrent and overvoltage during the combined operation of the modules.

d) Electromagnetic compatibility

The equipment used, especially the electronic equipment used for the instrumentation and control should be resilient to the electromagnetic effects produced by the power used during the tests.

e) Tests under operational conditions

— (real WEC scenarios – emulating a specific WEC in a specific sea state).

f) Thermal analysis

Although the thermal performance of the PTO will not be reached as it will be tested in a different environment than under real conditions, temperature will be instrumented in different parts in order to check the thermal evolution of the critical parts of the PTO. Mainly, power electronics and internal parts of the generator coils, as well as bearings [IEEE 1310-2012 “IEEE Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Rotating Machines”].

g) Cycling tests (accelerated tests)

In order to identify potential failure modes of the PTO and analyse them, accelerated tests must be performed for the complete PTO. Accelerated tests involving electrical, electronic, and mechanical parts of the PTO, allow to evaluate failures regarding the working cycles, temperature, current, voltages [IEEE 1043-1996 “IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils”], and velocity. The test lab facility system should be able of imposing the power cycling tests profiles in the PTO.

h) Grid compliance/power quality compliance

The power quality compliance tests will be carried out according to IEC TS 62600-30. The Grid compliance tests depend on the grid code to be applied based on the location of the PCC. E.g. the European grid code defines a requirement for energy generation systems connected through power electrics [COMMISSION REGULATION (EU) 2016/631].

The main source of incompatibilities when connecting a wave farm to the power grid are the oscillations introduced by the generated power. The power oscillations are regulated and limited in the grid codes of some countries, such as Germany or Ireland. The consequences of these oscillations – voltage and frequency oscillations – are regulated in all the grid codes. Testing these consequences require a test lab facility system able of emulating electric grids with different characteristics.

4.4 Combination of Modular and Crosscutting PTO components and tests

Table 1 illustrates the laboratory test matrix, which indicates the modular and crosscutting PTO components that should be evaluated when performing the different laboratory tests. Most of the tests involve all the PTO components, although not all are evaluated in every test, i.e. for performing “Test f – Cycling test” a ULC is needed, but no measurements will be taken from the ULC side since it is not subjected to temperature, current, or other cycling issues.

Table 1 — Laboratory test matrix considering the evaluation of the PTO components on the different tests

	Test a	Test b	Test c	Test d	Test e	Test f	Test g	Test h
Electric Generator		✓		✓	✓	✓	✓	✓
GSC	✓		✓	✓	✓	✓	✓	✓
GTC	✓		✓	✓	✓	✓	✓	✓
Interface (Actuator)	✓				✓	✓	✓	
HLC	✓		✓	✓			✓	✓
LLC		✓	✓	✓				

4.5 Equipment required for the laboratory tests

Specific equipment is required for testing at the lab the modular and crosscutting PTO. Among some other particular equipment, it should be used:

— Driving actuator, to provide the required dynamics to execute the desired tests. Several types of actuator can be used, as described in the application cases in Annex A.

— WEC emulator control. Control platform and models to reproduce the performance of the WEC at a certain sea location, based on the actuator.

— A signal data acquisition equipment is suggested to compile the data during the tests. Ideally, the data acquisition system should avoid potential electro-magnetic interference from the other elements in the equipment.

— Instrumentation equipment: Sensors (motion sensors, encoders, load cells, strain gauges, accelerometers,…), transducers, actuators, controllers, data acquisition systems, data loggers, communication and synchronisation systems, … All the necessary systems to:

  - measure and quantify the results of the experiments;

  - implement the desired control strategies.

An example of the necessary equipment for PTO tests for a WEC can be found in Annex A.

4.6 Connection and operation guide

In order to supply and operate the experimental installation for performing the different tests, the following steps must be followed:

— Step 1: Turn on the HMI in the operation room (control platform room).

— Step 2: Switch on the Transformers’ cabinet. Check that line-to-line voltages is ON.

— Step 3: Switch on the actuator grid-tie converter. Check that the converter is rectifying the AC to DC properly. Check that the statuses of the alarms are ok.

— Step 4: Switch on the generator grid-side converter. Check also that the converter is rectifying the AC to DC properly and that the statuses of the alarms are ok. Check that the DC voltage reaches the desired value.

— Step 5: Switch on the actuator power converter. Check that the statuses of the alarms are ok. Check the status alarm that it is communicating properly with the actuator grid-tie converter.

— Step 6: Switch on the generator converter (grid-tie + power). Check that the grid-tie converter is rectifying AC to DC properly. Set the DC voltage value to the desired value in the operation room. Check that the statuses of the alarms are ok.

— Step 7: Activate the control platform and charge the scenario to be tested at the HIL platform.

— Step 8: Install the control platform corresponding to the WEC technology to be tested, providing the appropriate parameters and commands according to the testing scenario.

— Step 9: Run the generator-side converter and run the actuator-side converter in this order.

— Step 10: Record the variables with the instrumentation environment in order to do a post processing of the information from the different tests.

— Step 11: In order to stop the system, the actuator must be stopped. The generator-side converter will automatically stop.

4.7 Results of the laboratory tests: Testing report and model generation

As a result of the laboratory tests, two deliverables will be mainly obtained. Firstly, a report including the results of the characterization tests for the different components. Secondly, the development of a mathematical model used to:

— Evaluate the LCOE /evaluate other stage-gate parameters.

— Evaluate in different locations under different sea states.

— Evaluate the performance under different control strategies.

— Compare different PTO technologies or the same PTO with different WECs.

Uncertainty ranges should be considered in cases where only limited amounts of data are utilised to fully characterise the WEC performance over a broad range of working conditions.

NOTE Apart from this general methodology, specialized tests or procedures could be also accomplished using the current equipment under request.

Annex A
(informative)

Application cases

A.1 General

The annex comprises several examples of application case where different linear PTOs have been tested using some of the procedures and equipment described in this methodology.

A.2 APPLICATION CASE 1: H2020 sea titan project – Grant Agreement No. 764014

A.2.1 General

This project proposes a crosscutting and modular PTO to be tested in a dry laboratory. The three-phase linear generator is based on azimuthal switched reluctance technology and is presented in the figure.

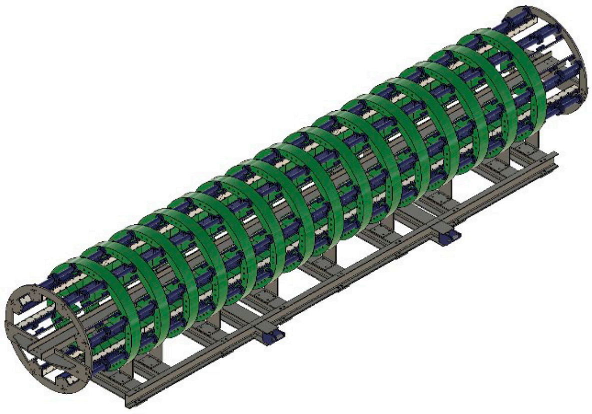


Figure A.1 — 3D view of the linear generator

A.2.2 Components of the modular and crosscutting PTO

This methodology allows to test the mechanical and electrical parts of a linear PTO. The tested PTO comprises the electric generator, power electronic converters and control devices, as well as the device used as an actuator to emulate a certain WEC behaviour in a certain sea location.

The different elements are presented as following:

1) Electric Generator

The crosscutting and modular linear PTO to be tested is composed by two modules as moving part and the required static part required to fit the specifications of maximum velocity, wave period and stroke.

2) Power electronics

Although the connection to the grid is provided by a power electronics converter which can be just one, the power electronics associated to the modules of the linear generator can be considered as a modular equipment, since they are connected to the different generator modules.

According to the voltage and current levels in this particular case, just one power electronics converter is required for two series connected modules. Table A.1 and Table A.2 present the particular technical specifications of grid-connection and generator-module power converters respectively.

Actuator grid-tie converter, connected to one of the branches of the transformers' cabinet, is shown in Figure A.2. The general characteristics of the equipment are detailed in Table A.1.

Table A.1 — Grid-connection converter characteristics

Electrical	
Operating grid voltage	230 Vac
Frequency	50 Hz
Max. current	150 A
Icu	36 kA
Operating DC voltage	450 Vdc
Rated power	50 kW
Mechanical	
Protection degree	IP 20
Weight	369 kg
Communication	
Internal protocol	Modbus TCP
BPCS protocol	Bus CAN

Figure A.2 — Grid-connection converter

The different components of the switchboard are displayed in Figure A.2. Control devices are highlighted in red, protections in dark blue, measurements in light blue, and power connections in light green.

Table A.2 — Generator-module power converter characteristics

Electrical	
Operating voltage	450 Vac
Frequency	49-222 Hz
Max. current	450 A
Icu.	36 kA
Operating DC voltage	450 Vdc
Rated power	50 kW
Mechanical	
Protection degree	IP 20
Weight	583 kg
Communication	
Internal protocol	Modbus TCP
BPCS protocol	Bus CAN

Figure A.3 — Generator-module power converter

The different components of the switchboard are displayed in Figure A.3. Control devices are highlighted in red, protection devices in pink, and connections in orange.

3) LLC In charge of defining the system operation according to the wave and the generator operation. The control is based on a digital signal processor (DSP) platform. Just one module is used in this application case.

The control of the WEC emulator operates as following.

The linear PTO generates energy based on the combination of the actuator motion and a proper control from the generator control platform. The command control variable for the generator is the force to be developed by the PTO. In relation to this control variable, the WEC control platform is in charge of providing the force command, based on the measure of generator velocity and according to the control strategies already programmed. This force reference is used by the linear generator control to ensure that the generator force command is equal to the mechanical force developed by the linear PTO. In order to guarantee the usefulness of the HIL scheme, the generator control must be calibrated properly. The generator converter control is illustrated in Figure A.4. The force command is translated into currents when passed through a look-up table, and the gate signals of the IGBTs are generated via a hysteresis band control. Besides, it is required to input the phase that needs to be activated in order to control the AMSRM generator. This input is calculated based on the generator's position, together with each phase activation/deactivation position. The latter is dependent on the speed and position and is calculated through a look-up table.

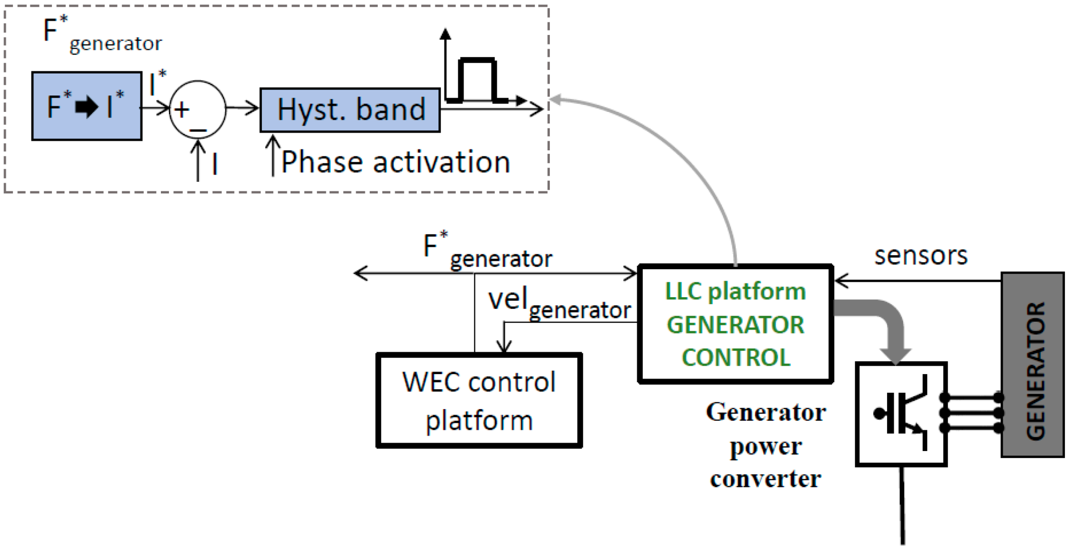


Figure A.4 — Generator converter control

The grid connection allows for injecting the generated energy to the network, as well as supplying power to feed the phases of the linear generator. It consists of the grid, a transformer and a grid-tie converter with its control. The control variable of this converter is the DC-link voltage, which needs to be fixed at a constant value in order to have a proper behaviour of the generator power converter. Figure A.5 shows the detailed control implemented in the converter, which eliminates the DC-link voltage error with a PI controller. After this, a Space Vector Pulse Width Modulation (SVPWM) strategy is performed in order to generate the gate signals of the IGBTs. The control scheme is presented in Figure A.5 and it is also based on a DSP platform.

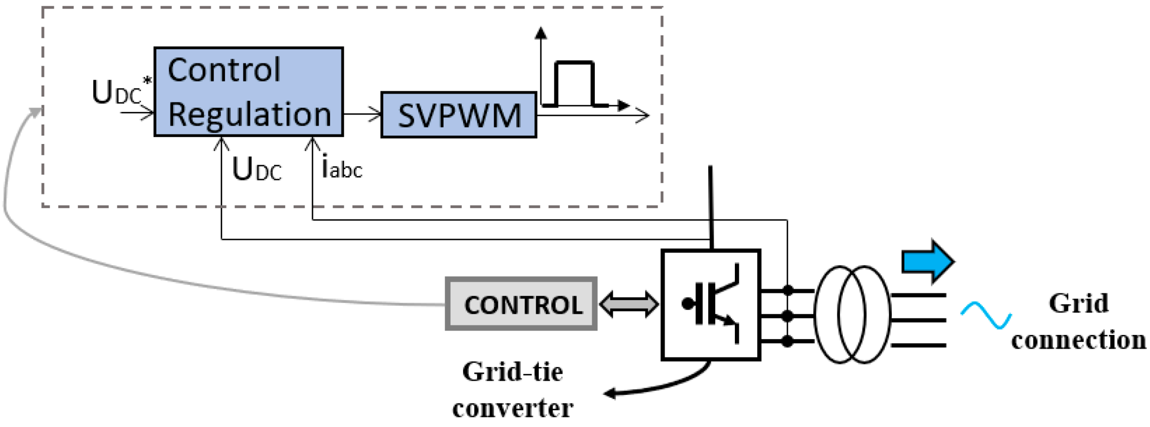


Figure A.5 — Grid-tie converter control

A.2.3 Equipment required for the laboratory tests

Specific equipment is required for testing at the lab the modular and crosscutting PTO. In the case of the example, it is used:

— **Actuator**

This is a particular solution of actuator, appropriate and especially convenient in the case of linear direct drive PTOs. The electric generator is divided into 2 sub-machines, giving the possibility to drive both in a different way.

This implementation requires the minimum length for the tests, just the length of the linear generator. However, once the PTO tests are finished the laboratory remains no testing equipment for further projects.

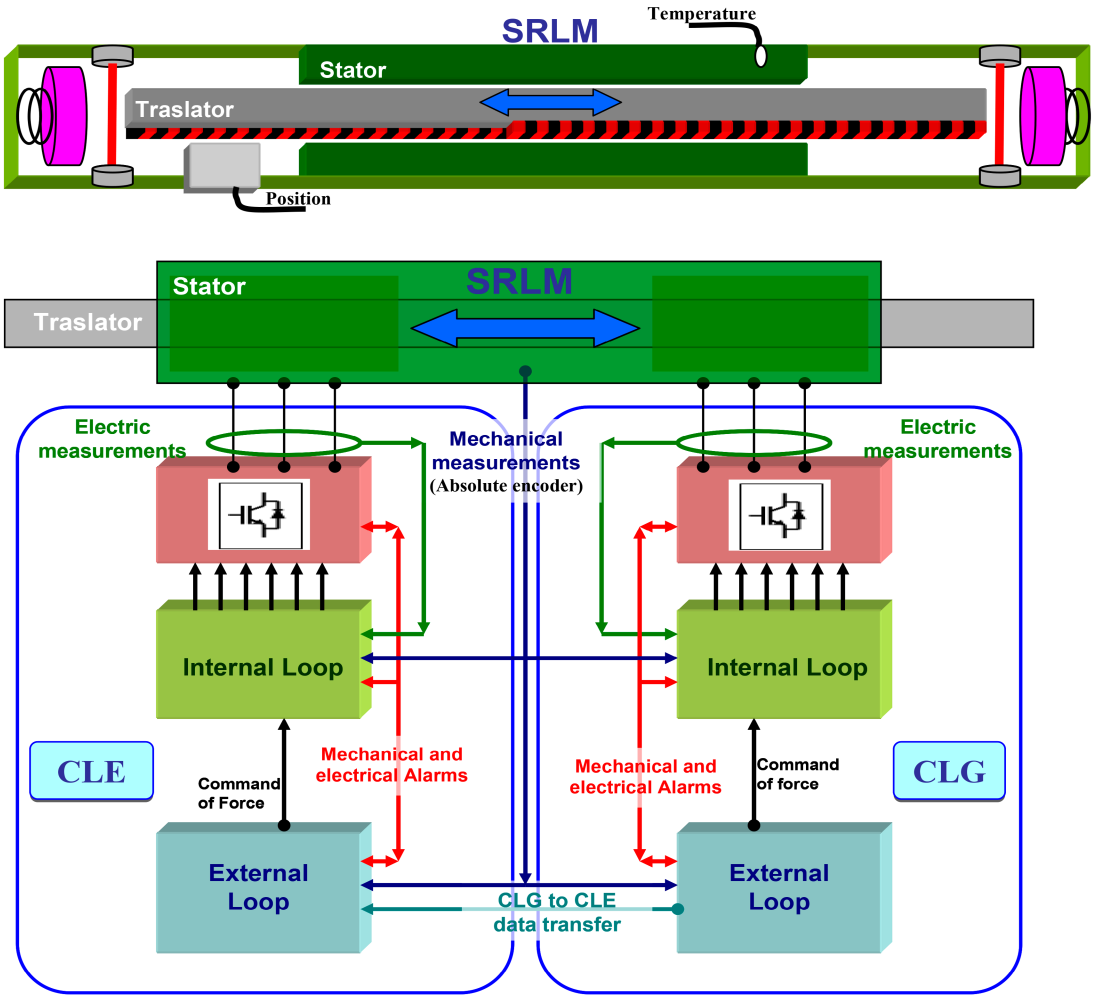


Figure A.6 — Electric schema for testing the machine using half of the machine as actuator and the other as generator

The experimental set comprised by the actuator and its control is responsible for sinusoidally pushing the linear PTO back and forth. The control variable for the actuator converter is the velocity, which is obtained from the W2W model implemented in the HIL platform. When characterizing the PTO, this velocity reference consists of controlled oscillations interleaved with constant velocity periods. The interaction between the HIL platform and the actuator control is schemed in Figure A.7. Firstly, the simulation of the W2W model generates a position reference for the actuator. This reference is compared with the actual position of the actuator, which is translated into a velocity reference when passed through a proportional control. After that, the velocity command inputs the actuator control. The velocity error between the velocity reference calculated by the HIL Platform and the measured velocity inputs a PI controller, resulting in the actuator force reference. Then, forces are translated into currents through a look-up table. At last, in order to generate the gate signals of the IGBTs the actuator control requires a PI controller followed by a PWM strategy, in contrast with the strategy implemented in the Linear PTO control.

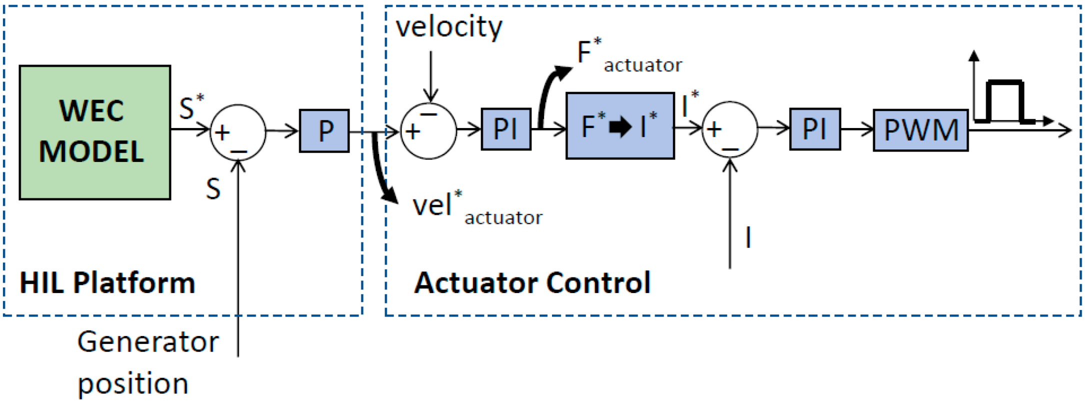


Figure A.7 — Interaction between the HIL control and the actuator control

— **Emulator control**

A control (Hardware-In-the-Loop) is set in order to reproduce different wave scenarios in order to validate the PTO as well as the control platforms developed by the different WEC technology developers. That permits to impose an oscillatory movement in one of the machines, emulating the wave effect (named actuator) while the other machine is behaving as a generator (named generator), operating with an optimal control strategy to maximize the power. Figure A.6 presents this schema.

In reference to the part of the power electronics, two power electronic converters are used to drive each part. They will share a common DC link and connected to the grid through a grid-tie converter, which supplies only the system losses, recirculating the power during the test through the DC-link. Both converters have an internal control loop in charge of deciding about the switching pulses to control the current around the reference level. An external control loop is in charge of providing the force reference to the system depending on different parameters and operation variables.

This option does not provide the possibility to test the linear PTO with full mechanical force, however it is fully electrically tested.

A.2.4 Hardware-In-the-Loop (HIL) scheme

The next step is to provide a control (hardware and software) scheme for the PTO tests. As previously mentioned, the control platform will be located in a room with direct vision to the laboratory but separated from it for security reasons.

The scenarios to be tested are based on real sea locations, characterized by their sea states. After providing time profiles of position and velocities, obtained from previous simulations in a Wave to Wire (W2W) model with a certain wave energy converter and controlled by a certain control strategy, the system behaves mechanically as the real one in a hardware-in-the-loop (HIL) scheme. This W2W model is analysed by means of a simulation environment in real time in the HIL platform. Figure A.8 presents the control scheme used for the PTO characterization and validation.

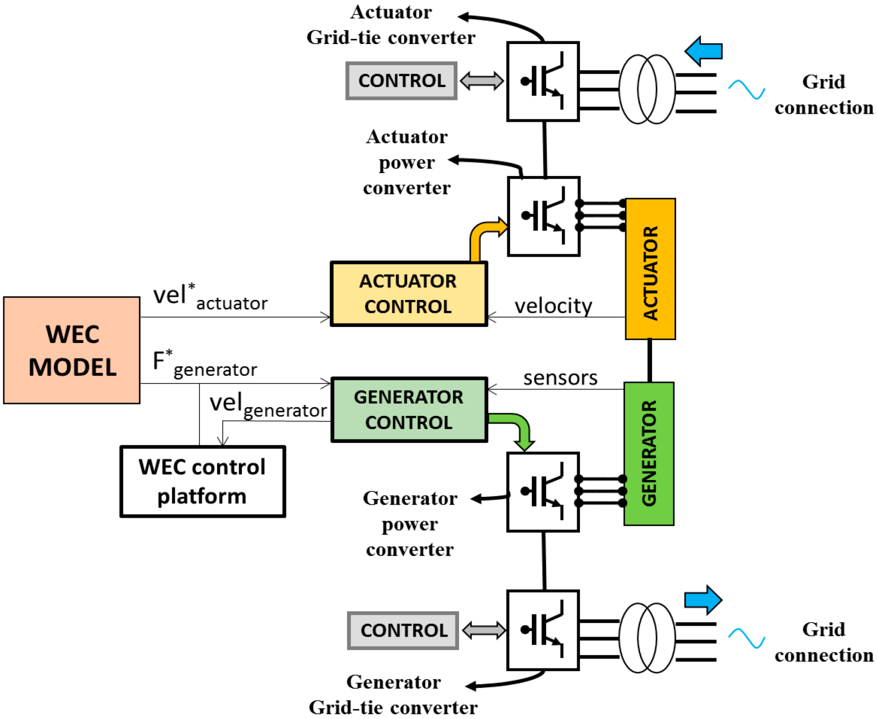


Figure A.8 — HIL testing scheme used for PTO validation

A.2.5 Laboratory Testing Facilities

A 3D representation of the laboratory for performing the SEA TITAN project tests is shown in Figure A.9, as an example. This 3D representation shows the complete laboratory testing facility with the location of the actuator and the relative position of the power converters, the linear generator and the actuator. Power converters and cabinets are positioned so they can be opened for revision and operation issues without interfering with other equipment. The control platform (HIL) is located in a separate room with direct vision to the laboratory set.

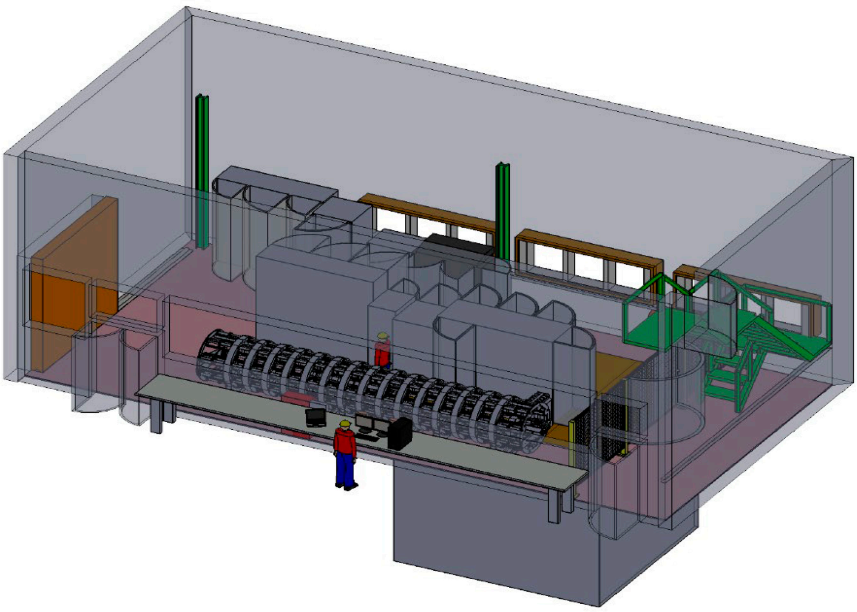


Figure A.9 — Laboratory testing facilities: 3D representation

A.3 APPLICATION CASE 2: Test-rig set up for WEC dynamics emulation

This annex will present an example of a dry bench testing method for PTO control strategies with an efficient matching of the dynamic behaviour of a model-scale wave energy converter, based on the work by G. Bacelli, S. Spencer, D. Patterson and Ryan Coe; "Wave tank and bench-top control testing of a wave energy converter", Applied Ocean Research 86 (**2019**) 351–366.

In order to be able to carry out PTO control testing, the WEC (a 1/17th scaled model) needs to be represented by a system with equivalent dynamics. In this case, a passive spring-mass-damper system was chosen, since it creates lower requirements for the actuators. Springs represent the hydrostatic restoring force; mass represents the inertia; and mechanical dampers reflect the radiation and viscous fluid damping.

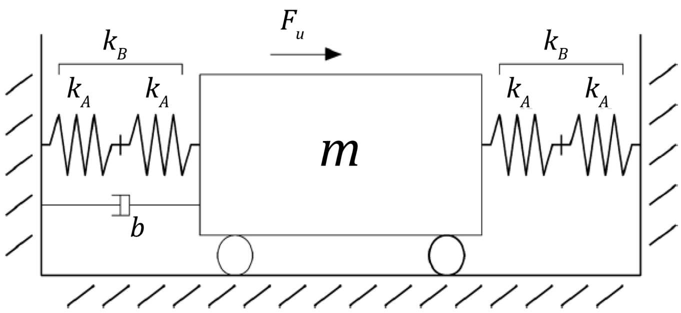
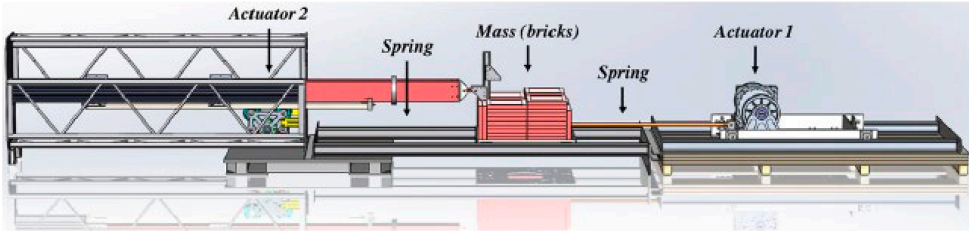


Figure A.10 — WEC spring-mass-damper system diagram (taken from [1])

An opposing configuration as shown in Figure A.10 was chosen, with the aim of allowing for bi-directional spring responses. Two individual springs in series were used in each direction since that was the best commercially available option. For an individual spring stiffness of k_A, the global stiffness of the system in Figure A.10 is found to be equal to k_A ($k_{GLOBAL} = 2 \cdot k_B = 2 \cdot ½\, k_A = k_A$). The global stiffness needs to match the linear hydrostatic stiffness of the model-scale WEC under consideration, which was measured at 23,9 kN/m. The actual commercial springs employed had a stiffness of 23,5 kN/m, and were pre-compressed so that only compression behaviour was allowed. The maximum travel of the spring system was set to match the maximum stroke of the model-scale WEC. The required inertia (to match the WEC's rigid body + hydrodynamic added mass) was provided in the form of 1 060 kg of paving bricks. Damping requirements were sufficiently met by the existing friction in the roller bearings in the system.

Figure A.11 presents the spring-mass-damper system attached to two actuators associated to heave (rotated 90°, left) and surge (right). Closed-loop controls on either heave or surge can then be assessed by using this test rig configuration: the PTO controller would act on one of the actuators, while the spring-mass-damper system and the other actuator would recreate the WEC dynamics and emulate the excitation produced by the ocean waves.

a) Panoramic photograph



b) CAD model

Figure A.11 — Assembled actuator and test-rig system (taken from [1])

The fidelity of the actuators can be evaluated by means of frequency response functions (FRFs) between the commanded and measured values (e.g. force or torque). Actuators response proved to be accurate within the desired working region of interest (frequencies up to 3 Hz), with resonance peaks clearly outside such region.

The FRF between measured torque and rotational velocity of the motor in the test rig in Figure A.10 is displayed in Figure A.12. Resonance peaks are found at frequencies of ~0.8, 30 and 40 Hz. The low-frequency resonance is caused by the spring-mass-damper system, and closely reproduces that of the 1/17th model-scaled WEC $\left(\omega_0 = \sqrt{k/m} = \sqrt{23{,}5\ kN/m / 1\ 060\ kg} = 4{,}71\ rad/s = 0{,}75\,Hz\right)$. 30 and 40 Hz resonant behaviours are probably caused by the stiffness of Kevlar belts in the actuator drivetrain.

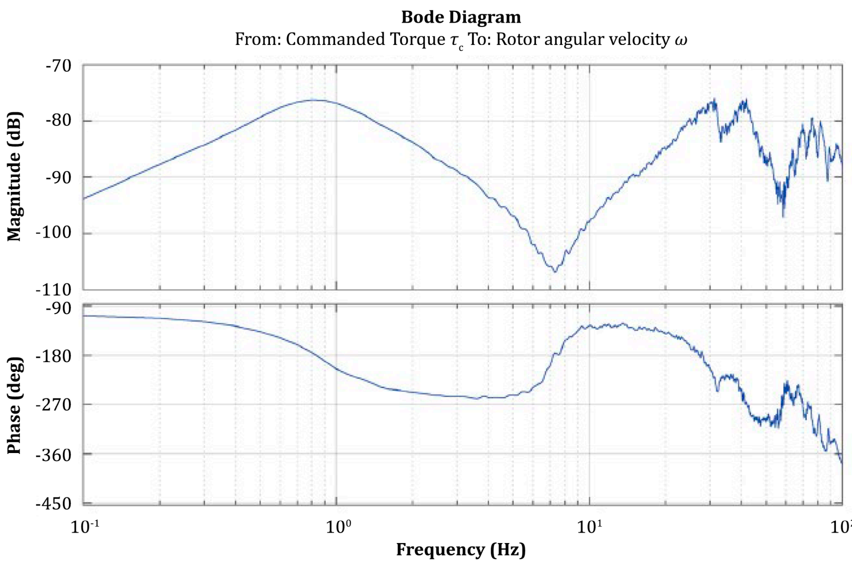


Figure A.12 —Estimated FRF between measured torque and rotational velocity (taken from [1])

While Figure A.12 represents a preliminary attempt towards the emulation of the WEC heave dynamics, an additional controller needs to be designed to obtain a better match between the closed-loop bench test system and the actual model-scale WEC. Although the spring-mass-damper system is able to provide relatively good second-order approximations, the system's response still requires some extra shaping. A virtual admittance controller is then proposed and designed, and can be seen in the block diagram in Figure A.13.

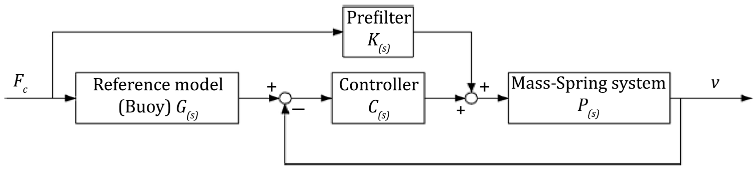


Figure A.13 — Block diagram of control system for dynamics matching (taken from [1])

where

$$G(s) = \frac{0,00595\,s^3 + 0,02057\,s^2 + 0,05642\,s}{s^4 + 3,488\,s^3 + 27,15\,s^2 + 49,02\,s + 128,9}$$

$$C(s) = \frac{9\,000\,s + 20,000}{s}$$

$$\hat{P}(s) = \frac{s}{1\,500\,s^2 + 850\,s + 25,00}$$

$$K(s) = \hat{P}(s)^{-1}\,G(s)$$

G(s) is the desired admittance; C(s) is a PI controller dedicated to reject disturbances and correct errors in the plant estimate (not to be confused with the global energy absorption PI); $\hat{P}(s)$ is the plant estimate, with force as the input and velocity as output, modelled as a spring-mass-damper; and K(s) is a filter.

The FRFs for the test WEC and the combined test-rig system can be observed in Figure A.14. The improvement in dynamics matching from the "initial plant estimate" (i.e. the uncontrolled spring-mass-damper system) to the "controlled system" is highly noticeable. The latter curve accurately matches the actual WEC behaviour ("desired WEC dynamics") for the frequency range of interest (0,2 to 0,8 Hz). In conclusion, now it can be stated that the test-rig system accurately replicates the WEC behaviour in the ocean, allowing for characterisation of PTO control strategies.

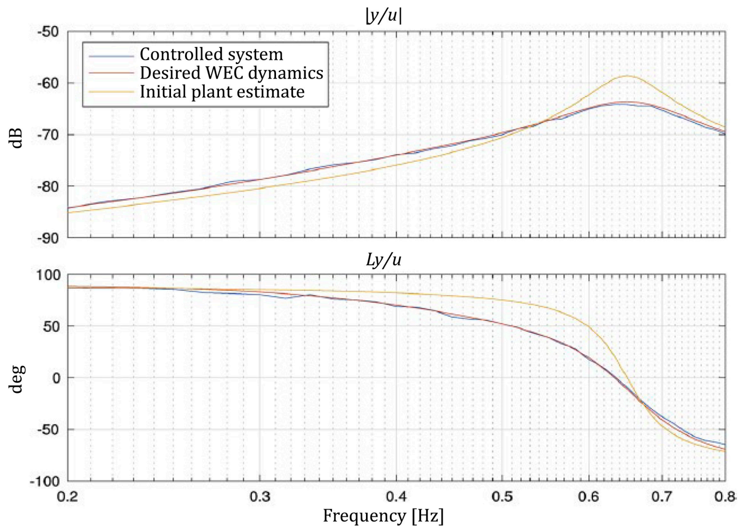


Figure A.14 — Frequency response function (in terms of magnitude and phase) for bench test system dynamics matching

A.4 APPLICATION CASE 3: Example of equipment for PTO testing

The Italian company UMBRA tested a ball-screw linear PTO for wave energy applications in the framework of their Wave Energy Scotland PTO Stage 3 project *EMERGE (Electro-MEchanical Reciprocating GEnerator)* [UMBRA Group; "EMERGE – WES PTO Stage 3 Public Report"; Nov. **2019**].

During the in-house dry PTO tests, the linear ball-screw generator was axially attached to an electro-mechanical actuator, which was controller so that pre-defined position profiles could be applied to the generator shaft. An electrical load was connected to the generator in order to emulate the power production.

The configuration and layout of the test bench set up is displayed in Figure A.15. The main objective of the testing campaign was to evaluate the PTO performance at a wide range of operating conditions (in terms of axial velocity and electrical damping factor). Besides, durability and reliability were also tested by mean of high-load accelerated endurance tests.

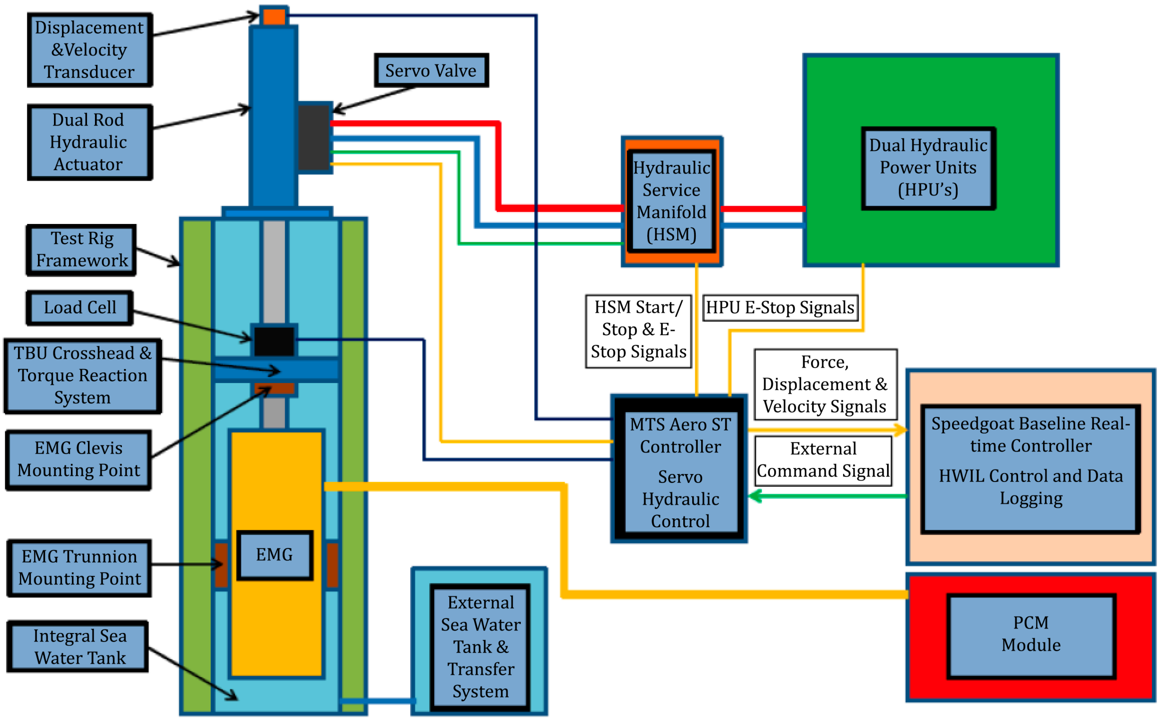


Figure A.15 — Diagram of hardware test bench unit architecture (taken from the information from UMBRA)

Bibliography

[1] G. Bacelli, S. Spencer, D. Patterson and Ryan Coe; "Wave tank and bench-top control testing of a wave energy converter". Appl. Ocean Res. 2019, 86 pp. 351–366

[2] IEC/TS 60034-18-33:2010, *Rotating electrical machines — Part 18-33: Functional evaluation of insulation systems — Test procedures for form-wound windings — Multifactor evaluation by endurance under simultaneous thermal and electrical stresses*