WP2: Marine Energy System Testing - Standardisation and Best Practice

Deliverable 2.11

Best practice manual for PTO testing

Status: Final
Version: 2.1
Date: 26-Mar-2015
ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC’s Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The initiative consists of five main Work Package focus areas: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research, Training & Dissemination. The aim is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

<table>
<thead>
<tr>
<th>Country</th>
<th>Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ireland</td>
<td>University College Cork, HMRC (UCC_HMRC) &lt;br&gt; Sustainable Energy Authority of Ireland (SEAI_OEDU)</td>
</tr>
<tr>
<td>Denmark</td>
<td>Aalborg Universitet (AAU) &lt;br&gt; Danmarks Tekniske Universitet (RISOE)</td>
</tr>
<tr>
<td>France</td>
<td>Ecole Centrale de Nantes (ECN) &lt;br&gt; Institut Français de Recherche pour l’Exploitation de la Mer (IFREMER)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>National Renewable Energy Centre Ltd. (NAREC) &lt;br&gt; The University of Exeter (UNEXE) &lt;br&gt; European Marine Energy Centre Ltd. (EMEC) &lt;br&gt; University of Strathclyde (UNI_STRATH) &lt;br&gt; The University of Edinburgh (UEDIN) &lt;br&gt; Queen’s University Belfast (QUB) &lt;br&gt; Plymouth University(PU)</td>
</tr>
<tr>
<td>Spain</td>
<td>Ente Vasco de la Energía (EVE) &lt;br&gt; Tecnalia Research &amp; Innovation Foundation (TECNALIA)</td>
</tr>
<tr>
<td>Belgium</td>
<td>1-Tech (1_TECH)</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Stichting Tidal Testing Centre (TTC) &lt;br&gt; Stichting Energieonderzoek Centrum Nederland (ECNeth)</td>
</tr>
<tr>
<td>Germany</td>
<td>Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Fh_GWES) &lt;br&gt; Gottfried Wilhelm Leibniz Universität Hannover (LUH) &lt;br&gt; Universität Stuttgart (USTUTT)</td>
</tr>
<tr>
<td>Portugal</td>
<td>Wave Energy Centre – Centro de Energia das Ondas (WaveC)</td>
</tr>
<tr>
<td>Italy</td>
<td>Università degli Studi di Firenze (UNIFI-UCRACIV) &lt;br&gt; Università degli Studi di Firenze (UNIFI-PIN) &lt;br&gt; Università degli Studi della Tuscia (UNI_TUS) &lt;br&gt; Consiglio Nazionale delle Ricerche (CNR-INSEAN)</td>
</tr>
<tr>
<td>Brazil</td>
<td>Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A. (IPT)</td>
</tr>
<tr>
<td>Norway</td>
<td>Sintef Energi AS (SINTEF) &lt;br&gt; Norges Teknisk-Naturvitenskapelige Universitet (NTNU)</td>
</tr>
</tbody>
</table>
DOCUMENT INFORMATION

<table>
<thead>
<tr>
<th>Title</th>
<th>Best practice manual for PTO testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Work Package Partners</td>
</tr>
<tr>
<td>Document Reference</td>
<td>MARINET-D2.11</td>
</tr>
<tr>
<td>Deliverable Leader</td>
<td>Eider Robles Sestafe TECNALIA</td>
</tr>
<tr>
<td>Contributing Authors</td>
<td>Joseba López Mendia TECNALIA</td>
</tr>
<tr>
<td></td>
<td>François-Xavier Faÿ TECNALIA</td>
</tr>
</tbody>
</table>

REVISION HISTORY

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Date</th>
<th>Description</th>
<th>Prepared by (Name &amp; Org.)</th>
<th>Approved By (Task/Work-Package Leader)</th>
<th>Status (Draft/Final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>28/11/14</td>
<td>Index draft</td>
<td>JL TECNALIA</td>
<td>n/a</td>
<td>Draft</td>
</tr>
<tr>
<td>1.1</td>
<td>21/01/15</td>
<td>Index defined</td>
<td>JL,FXF,ER TECNALIA</td>
<td></td>
<td>Draft</td>
</tr>
<tr>
<td>2.0</td>
<td>13/02/15</td>
<td>First document draft</td>
<td>ER, TECNALIA</td>
<td></td>
<td>Draft</td>
</tr>
<tr>
<td>2.1</td>
<td>26/03/15</td>
<td>Final version</td>
<td>ER, TECNALIA</td>
<td></td>
<td>Final</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENT

The work described in this publication has received support from the European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme through grant agreement number 262552, MaRINET.

LEGAL DISCLAIMER

The views expressed, and responsibility for the content of this publication, lie solely with the authors. The European Commission is not liable for any use that may be made of the information contained herein. This work may rely on data from sources external to the MARINET project Consortium. Members of the Consortium do not accept liability for loss or damage suffered by any third party as a result of errors or inaccuracies in such data. The information in this document is provided “as is” and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and neither the European Commission nor any member of the MARINET Consortium is liable for any use that may be made of the information.
EXECUTIVE SUMMARY

Currently, marine energy converters (MECs) present very high costs of electricity. There has not been a successful alternative that can pay for the costs of MW generation. Manufacturers and research teams are working on cost reduction and the electrical components of marine energy converters (MECs) and their associated control systems have been identified as one of the most promising areas for achieving such cost reduction.

Testing at sea involves high risk and high costs and hence, these tests are not affordable at design stage. Therefore laboratory scale electrical test infrastructures are used for prototype development in a controlled and repeatable test environment. Some of these facilities are offered within MARINET project and have hosted several research projects so far. They allow the MEC developer to address the many electrical challenges that exist in developing and deploying the MEC. These infrastructures provide a cost effective method of investigating different configurations of electrical components and control, and obtaining real measured data.

The use of electrical test infrastructures for the testing of devices is then imperative prior to prototype testing in order to reduce risks, complexity, and thus cost, during the development of the project. The advantages of such systems are manifold. Electrical test infrastructures can be used to compare and validate the numerical models that have been the basis of the design, and to check that the designs operate as theoretically predicted. They usually enable to test various generator and power electronics configurations under both normal and extreme sea states in a controlled environment and with repeatability guarantee. The infrastructures can also be used in the design and optimisation of control algorithms to maximise the efficiency of the MEC while maintaining proper power quality in the grid connection.
CONTENTS

1 OVERVIEW .................................................................................................................................................7
  1.1 ENERGY CONVERSION IN MARINE RENEWABLE TECHNOLOGIES .......................................................7
  1.2 TESTING AT ELECTRICAL PTO SIDE .......................................................................................................8

2 DESCRIPTION OF INFRASTRUCTURES ......................................................................................................10
  2.1 COMPONENTS .........................................................................................................................................10
  2.2 DIFFERENCES AMONG TEST RIGS .........................................................................................................10
  2.3 PHYSICAL LIMITATIONS .......................................................................................................................12

3 ELECTRICAL PTO TESTING: FROM THE MODEL TO THE EXPERIMENT ...................................................15
  3.1 ENERGY CONVERTER NUMERICAL MODELLING ....................................................................................15
    3.1.1 Wave ..................................................................................................................................................16
      3.1.1.1 Resource ........................................................................................................................................16
      3.1.1.2 Hydrodynamic modelling of a WEC .........................................................................................17
    3.1.2 Wind ..................................................................................................................................................18
      3.1.2.1 Resource ........................................................................................................................................18
      3.1.2.2 Aerodynamics of a wind turbine ...............................................................................................21
    3.1.3 Tidal ..................................................................................................................................................22
      3.1.3.1 Resource ........................................................................................................................................22
      3.1.3.2 Device modelling .......................................................................................................................24
  3.2 MODEL IMPLEMENTATION IN A TEST BENCH .........................................................................................24
    3.2.1 Implementation in the emulated part ...................................................................................................24
      3.2.1.1 Model adaptation .......................................................................................................................24
      3.2.1.2 Sea state testing conditions .......................................................................................................26
      3.2.1.3 Sea state testing limits ................................................................................................................26
    3.2.2 Implementation in the real part ..........................................................................................................27
      3.2.2.1 Generator control strategy .......................................................................................................27
      3.2.2.2 Grid connection control strategy ...............................................................................................28

4 AVAILABLE TEST PROCEDURES ................................................................................................................29
  4.1 GENERATOR-SIDE CONTROL. MEC CONTROL .......................................................................................29
  4.2 GRID CONNECTION CONTROL ...............................................................................................................30
  4.3 COMPONENT TESTING ............................................................................................................................33

5 CORRELATION BETWEEN EXPERIMENTAL TESTS AND SIMULATION RESULTS ................................34
  5.1 Validation of the simulation models through experimental testing ..........................................................34
  5.2 Example of not directly applicable modelling ..........................................................................................34

6 CONCLUSIONS .............................................................................................................................................37

REFERENCES ..................................................................................................................................................38
LIST OF FIGURES

Figure 1 - Power Take-Off typologies for wave energy conversion [1] ................................................................. 8
Figure 2 - Test bench physical configuration .......................................................................................................... 10
Figure 3 – Test benches views a) Conn, b) Tecnalia and c) SSMTB ..................................................................... 11
Figure 4 - Scheme of principle of the Resource-to-wire model [16] ........................................................................ 15
Figure 5 - Multidisciplinary perspective of the Resource-to-wire model .............................................................. 16
Figure 6 - Wave climate in the north of Norway ........................................................................................................ 17
Figure 7 - Wave spectrum and sea surface elevation ............................................................................................... 17
Figure 8 - Energy conversion chain in rotary PTO systems .................................................................................... 18
Figure 9 - Effect on the roughness on the wind profile [17] .................................................................................... 19
Figure 10 - Power spectral density of wind variability [17] ...................................................................................... 19
Figure 11 - Wind speed variation ............................................................................................................................ 20
Figure 12 - Histogram of a Rayleigh distribution - hours of occurrence vs wind speed ........................................... 20
Figure 13 - Wind power production at a specific location and wind turbine power curve in function of the wind velocity .................................................................................................................................................. 21
Figure 14 - Plane of blade rotation [20] ......................................................................................................................... 22
Figure 15 - Tidal current speed from a current meter installed at EMEC [21] ............................................................ 23
Figure 16 - Power spectral density of power output for the SeaFlow Device .......................................................... 23
Figure 17 - Example of scheme of operation of the simulation and test bench ......................................................... 24
Figure 18 – Froude scaling applied to the physical quantities of an OWC ................................................................ 26
Figure 19 - Back-to-back VSC configuration and its associated components [3] .......................................................... 27
Figure 20 - Test targets along the development stages ............................................................................................ 29
Figure 21 - Schematic of the HIL with the OWC model fully coupled with the turbo-generator [26] ...................... 35
Figure 22 - HIL schematic with pneumatic power generated by the OWC without influence of turbo-generator and the power control [26] .................................................................................................................. 35
1 OVERVIEW

Currently, marine energy converters (MECs) present very high costs of electricity. There has not been a successful alternative that can pay for the costs of MW generation. Manufacturers and research teams are working on cost reduction and the electrical components of marine energy converters (MECs) and their associated control systems have been identified as one of the most promising areas for achieving such cost reduction.

Testing at sea involves high risk and high costs and hence, these tests are not affordable at design stage. Therefore laboratory scale electrical test infrastructures are used for prototype development in a controlled and repeatable test environment. Some of these facilities are offered within MARINET project and have hosted several research projects so far. They allow the MEC developer to address the many electrical challenges that exist in developing and deploying the MEC. These infrastructures provide a cost effective method of investigating different configurations of electrical components and control, and obtaining real measured data.

PTO testing and particularly electrical aspects of PTO testing have been already addressed by several works within MARINET and other projects. When this is the case, the present report will directly refer to these previous works.

1.1 ENERGY CONVERSION IN MARINE RENEWABLE TECHNOLOGIES

Any marine energy converter presents a conversion system which transforms the marine energy absorbed by the device into another form of energy which is usable for other purposes [1].

Most of the technologies currently being developed are electricity-generating and therefore require the introduction of some type of electrical generator.

Usually high-speed rotary electrical generator is used which are almost standard for many other energy applications and are relatively reliable components in comparison with other elements of the energy chain. Linear generators seem to be the best option for many ocean devices like point absorbers because they can have the prime mover directly connected to the generator and no intermediate stages are needed. In fact, wave energy is the main application of these generators. However, for the moment, the real use of these generators is not common since mechanical strains are very high and, unlike rotating generators, they cannot store energy (kinetic) which helps in smoothing the output power.

Among rotating generators, we can distinguish between synchronous and asynchronous generators. Synchronous generators are typically in use in conventional power stations, where it is possible to control the power output by maintaining a virtually constant rotational speed. In marine energy technologies, regardless of the generator selected, a variable speed operation will be required particularly if taking into account the needs for sophisticated control strategies to improve power absorption and to meet the current grid connection requirements. This will imply the use of full power converters (in most cases) that will add full power control to the drive train. The selection of the generator will then be made considering the needed speed (asynchronous generators cannot operate at low speeds), size and weight, reactive power consumption allowance, efficiency, reliability and cost. A review of different rotational generator options for a specific type of wave energy device is discussed in [2] whereas a general outline is also given in [3].

Most of the existing marine renewable technologies are composed of one or several prime movers which are put in motion by the action of the water. In such cases, energy transmission to rotational generators often require intermediate steps for conversion involving either mechanical or hydraulic system to transform a variable bi-directional signal into a steady one-directional one. This is specifically the case of many wave energy technologies, whereas tidal devices based on either horizontal or vertical axis turbines are more similar to the systems used in wind energy and, as such, might allow direct-drive connection to rotational generator. Alternatively, gearboxes are interposed between the turbine and the generator [1].
The selection of the generator is usually made together with the power converter. Therefore, the whole drive train is selected or designed at the same time.

An overall classification of generator drive train topologies can be made between fixed-speed and variable speed solutions. The main difference is that the former are directly connected to grid and so the speed of the generator (and thus, the speed of the turbine) is fixed. While the later, use power electronics that uncouple the speed of the generator from the grid frequency. A better analysis was previously made in [3].

1.2 Testing at electrical PTO side

The MaRINET protocols for selecting devices to be granted funding for access to testing facilities, stipulated that the device development must follow the principles of the International Structured Development Plan [4], and it should be ensured that the 5 correct stage of development and design issues and questions are addressed before progressing on to the next stage.

The Structured Development Plan sets out the development stages required for a marine renewable energy concept to achieve commercial reality. This concept, based on proven steps established by NASA and widely used by many engineering research establishments, has gained acceptance worldwide through the International Energy Agency's intergovernmental collaboration 'Ocean Energy Systems Implementing Agreement' (OES) and through the European FP7 project EQUIMAR, which developed the concept using Technology Readiness Levels and other metrics. It is now used as the main development and assessment method in the US and Europe.

Generally, device developers carry out testing at an electrical test facility when their device proof of concept has already been validated, and the technology has been proven to work in small flumes (Stage 1: Concept Validation). The use of electrical test infrastructures are introduced when the focus of the device developer is moving to optimising the control and the challenges associated with grid integration (Stage 2: Design Validation and Stage 3: Sub-Systems Validation). Taking into account the effect that the control of the device has on the dynamics of the structure, engaging in electrical testing early on in the device’s development is considered good design practice, and
is highly advised. Other potential users of electrical test infrastructures are research groups working on control laws for a specific kind of device.

As stated in [5], up to now, most of the tests being performed in the Ocean Energy areas were, and still are, related to the testing of the physical prototypes, with the main objective of validating a determined concept. In fact, this proof of concept is still the bottleneck until a mature and reliable technology is achieved. For this reason, in many cases, the research and subsequent tests of the generator, power electronics and grid connection part are forgotten. This is a common mistake that can cause many problems like instability, inefficiency and underperformance of a prototype. As well as high delays and high costs provoked by poor behaviour of these parts.

Dynamic tests in Hardware in the Loop (HIL) test-beds are very extended in Wind Turbine testing where the validation of the physical concept is not a challenge anymore. It is expected that these tests will become essential for ocean energy in the near future, when the technology of the devices will not be so questioned and the control and grid connection will become the new challenge.

The use of electrical test infrastructures for the testing of devices is imperative prior to prototype testing in order to reduce risks, complexity, and thus cost, during the development of the project. The advantages of such systems are manifold. Electrical test infrastructures can be used to compare and validate the numerical models that have been the basis of the design, and to check that the designs operate as theoretically predicted. They usually enable to test various generator and power electronics configurations under both normal and extreme sea states in a controlled environment and with repeatability guarantee. The infrastructures can also be used in the design and optimisation of control algorithms to maximise the efficiency of the MEC while maintaining proper power quality in the grid connection.

MARINET project has highly contributed to give visibility to this aspect of MEC design and it can help to accelerate the success of new developments in marine renewable technology.

---

1 Part of this work has been taken from an article written by MARINET partners that is publication pending. The reference will be added after its publication.
2 DESCRIPTION OF INFRASTRUCTURES

An electrical test infrastructure allows manufacturers to address electrical issues when developing a device. It is able to emulate the dynamics of an energy converter that transforms the captured power into mechanical one. Although linear test rigs exist to assess linear generators’ performance, like in some point absorbers for ocean energy, the study will focus on rotary test rigs as it is the most common way to convert energy. Indeed, the principle of rotational energy conversion is found in wind and tidal turbines, air turbines in OWC, water turbines of overtopping devices as well as hydro-pumps in hydraulic PTO. This chapter describes the equipment of such an infrastructure and presents the physical limitations to consider when testing an energy converter.

2.1 COMPONENTS

The basic components in a test rig are two electrical machines facing each other. From one side an electrical motor, configured as the prime mover, is used to re-create the dynamic response exhibited by the device. On the other side a generator converts the mechanical power to electrical one. The shaft connecting them is usually composed of a flywheel to simulate inertia, a gearbox to adapt the speed and a torque transducer for measuring purposes. The prime mover is set in motion by a drive that is connected to a real-time development board. Over the experimentation, this component runs the device numerical model and sends electrical impulses corresponding to a torque or speed reference. Connected to the generator, a back-to-back power converter controls the rotational speed applying an electrical torque (by current extraction). This is done thanks to a programmable logic unit where control laws are developed. Typical researches consist of implementing efficient control laws to maximize power generation while enhancing power quality. The combination of generator (sometimes attached to a gear-box), back-to-back converter and the logic controller is the real part that will be embedded into the energy converter. The back-to-back converter is connected to an isolated grid and a resistive load bank that can dissipate energy. Figure 2 describes a schematic of a general test bench configuration.

2.2 DIFFERENCES AMONG TEST RIGS

As an example to the generic test bench described above, among others facilities of this kind there have been built for low voltage energy converters in University College Cork ‘Conn’ in Ireland, in Tecnalia in Spain and in Sandia National Lab ‘SSMTB’ in USA. Each one is composed of the same basic components: electrical machines, drives and converters and their parameters are summarised in Table 1. Different approaches are used to apply the motor and
generator torque references. In the Conn configuration, the PLC is the real-time unit that gives the torque reference for the motor rotation to replicate the rotational movement of the prime-mover (ex: turbine); and as well compute the optimal generator torque to apply for the control strategy. At the SSMTB, the same principle is applied and the torque references are computed by an industrial computer. In Tecnalia’s rig, the emulation and the control are separated for the system implementation. From one side, a real-time development board emulates the dynamics of the prime-mover and on the other side the PLC applies the control algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Conn</th>
<th>Tecnalia</th>
<th>SSMTB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal motor power</td>
<td>kW</td>
<td>22</td>
<td>15</td>
<td>11.2</td>
</tr>
<tr>
<td>System inertia</td>
<td>Kg.m²</td>
<td>1.25</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Drive train friction and losses</td>
<td>N.m</td>
<td>0.077</td>
<td>0.047</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 1 – Test bench parameters

The next figure shows an illustration of the 3 test rigs described above:

![Figure 3 – Test benches views a) Conn, b) Tecnalia and c) SSMTB](image)

There are other similar facilities that offer same kind of services but each of them has its own particularities that may make their use different for a user. When selecting a testing facility for experimental purposes, a fluid communication between the user and the infrastructure manager is mandatory. The user will always have the doubt if testing in one or another facility could reach different results.

With this motivation, a comparison of the facilities described above has been made with the experimentation of a vertical-axis tidal turbine. The idea was to adapt the same reference model on the 3 infrastructures and implement the control algorithm. The specific configuration of each electrical emulator was considered and special attention had to be paid to fit the power ratings. Therefore, different scaling techniques were adopted. The turbine emulation was made with both torque and speed controls to send the signal reference and the performance of each were assessed. The adaptation of the control algorithm was made taking into account the differences of the three
configurations. The work is pending for publication and the present report will be completed with the results of such experimentation as soon as the article is published.

### 2.3 Physical limitations

Electrical testing facilities have been designed under some physical constraints that must be taken into account when new devices are to be tested. Some of these constraints can be overcome by simple scaling, but when some parameters are scaled, some others become fixed and usually they do not coincide with the parameters of the device under test.

The work developed in [5] shows a selection of general constraints that this kind of facilities may have, as well as some solutions to overcome these limitations. Here only a brief summary is shown. In addition, some other constraints are analysed.

- **Maximum Power:** Physical components of the testing facilities have a maximum power that cannot be surpassed. The maximum power is usually the parameter to be scaled. The rest of parameters will comply with the scaling factor that results from the scaling of the power. As [6] evidences, the designed control law must consider that the ratio between maximum and mean power cannot be too high. Otherwise, the whole drive train will work completely underloaded to allow power peaks. This will imply low efficiency of the whole power transfer and low accuracy of the measurements. Other option would be to limit high power peaks to be able to work with power loads near the average power.

- **Rotational Speed:** The motor and generator of the facility will have a maximum rotational speed that cannot be surpassed. When the scaling has been done on the maximum power, the rotational speed is directly scaled using the same factor. If equivalence with the original device is desired, the rotational speed must be the one obtained after scaling. But most of the times, the resulting scaled rotational speed does not coincide with the one of the facility. As explained in [5], as the mathematical equations of the physical device are simulated, this problem can be easily overcome by applying a correction factor in the input of the model, so that the maximum speed is adapted to that of the facility.

\[
\omega_{\text{model}} = \omega_{\text{input}} \cdot \frac{\omega_{\text{scaled}}}{\omega_{\text{facility}}} \tag{1}
\]

- **Mechanical Torque:** This is the same case as with the rotational speed. The scaling factor obtained in the scaling of the power will be the one to apply to the mechanical torque. If this scaled torque does not coincide with the torque of the facility, again a correction factor can be applied. In this case, this correction will be applied in the output of the mathematical model so that the maximum torque of the model will be adapted to the maximum torque of the facility.

\[
T_{\text{out}} = T_{\text{computed}} \cdot \frac{T_{\text{facility}}}{T_{\text{scaled}}} \tag{2}
\]

- **Inertia:** Most of the facilities will work with a fixed inertia, or will allow a discrete number of inertia possibilities. As in the previous cases, the scaled inertia may not coincide with any of the possibilities offered by the facility. The most direct mechanical solution implies having a selection of interchangeable flywheels with different inertias. But this operation is slow and can result in disequilibrium of the whole facility. Other mechanical solutions [7][8][9] could also be used, but in all the cases they offer a discrete variety of inertia numbers. [5] shows an easier solution that has been used along the Marinet project and consists in the emulation of the inertia by means of mathematical equations on the simulated model. The complete mathematical demonstration can be found in [5].

These first limitations, are related to the physical part of the infrastructure that emulates the prime mover motion. I. e. the part of the infrastructure that represents the device itself, where, an electrical motor, configured as the ocean...
energy (OE) prime mover, is used to re-create the dynamic response exhibited by an ocean energy device given a specific set of input conditions. This is the part that may have different rated power, speed, mechanical torque or inertia than the device under test.

The real part of the infrastructure is the physical equipment on the electrical power take off side. This equipment is an exact scaled replica of the equipment that would exist on the full scale ocean energy device. But again, the testing facility will have a fixed configuration and parameters for the drive train and grid connection. And these characteristics may not coincide with the ones of the device under test. The following constraints must be taken into account and the feasibility and reliability of the tests when there are big differences will greatly depend on the purpose of them:

- **Drive-train configuration:** There are different options for the drive train configuration. The chosen topology will have effects especially on the cost, efficiency and controllability. Users may not intend to do any test related to cost. Regarding efficiency, it would be difficult to compare the tests performed in a test bench even if the drive-train configuration was the same. On the one hand, test facilities can use equipment that is acquired only for testing purposes and usually have oversized parts as they are designed thinking on durability and not in cost. In addition, each equipment can have a different efficiency even having similar configuration when changing the size or brand. Therefore, efficiency measurement tests are not completely accurate.

  On the other hand, if only the efficiency of each component needs to be known for its consideration in the control strategy, it would be enough with knowing the efficiency curves and will not affect the drive-train configuration.

  Most users will come to these facilities to test control strategies. If this is the case, as long as the power converter is fully controllable, the whole drive train configuration will not affect the control strategy.

- **Electrical generator:** It is part of the drive train and the above comments apply. Regarding the generator type, two main differences could arise:
  - Linear vs. rotating generator: Most of the MECs use rotating generators, and thus, test facilities are usually equipped with them. If the MEC under test is using a linear generator it will probably work with control laws that are motion specific and are not valid with rotating generators. The possibility of using the test facility will have to be studied in each particular case.
  - Synchronous vs. asynchronous generator: As long as the power converter is fully controllable this issue may not present major inconveniences. The asynchronous generator will have a speed slip against that of the voltage frequency. In addition, it will have reactive power consumption and be less efficient. But none of these aspects will affect the user’s control and experimental results in the test facility.

- **Power electronics:** Testing facilities will have a fully controllable power conversion stage and thus, this will not be a problematic equipment. There are different configurations regarding controllable power electronics, but their differences are more related to efficiency, reliability and cost and again, may not affect the performed tests.

  However, most of testing facilities use commercial power electronic converters. In these cases, low level control of the converters is usually a black box for the users. This will imply the impossibility to access and modify the modulation strategy, which is not usually the purpose of these tests. But also, the impossibility to modify the current and speed control loops where only external references and control parameters are tuneable. In most of the cases, these limitations do not affect the user’s purposes. But when more advanced control strategies are studied this can be a handicap. Especially when grid connection algorithms are the purpose of the tests, since these algorithms will be part of the internal control loops. When the access to the low level control is needed, the infrastructure manager will have to make sure that the control board code can be accessible, by communication with the converter manufacturer or by the design of an ad-hoc control board.
• **Sensors**: Testing facilities are usually equipped with much more measurement equipment than the final devices. It is up to the user the decision on what to use on the tests. It should be considered that not all the existing sensors can be installed in the final device at sea.

• **Control**: Testing facilities may have basic controls already programmed. These are useful for testing the emulation part after adapting the MEC model to the facility. However, these controls are not device specific and may not be the most suitable for the users MEC.

• **Connection voltage**: The testing facility will be grid connected in a laboratory environment. It is foreseeable that the facility connection voltage, as well as that of the generator and power conversion stage is not the same as the one required by the device. This is not an issue and no scaling needs to be done.
3 ELECTRICAL PTO TESTING: FROM THE MODEL TO THE EXPERIMENT

3.1 ENERGY CONVERTER NUMERICAL MODELLING

A Resource-to-Wire model represents the behavior of the energy converter by a numerical model which solves a set of differential equations by symbolizing the overall energy conversion chain from the kinetic energy of the wave (or resource) to the electrical power sent to the grid.

Internal deliverable “D 4.15 Report on Numerical Methods for PTO Systems” by HMRC [10] makes a complete analysis of all the subjects related to the numerical modelling for WECs. It distinguishes the modelling focus areas as: PTO modelling, structural, optimization, power systems and software packages for modelling. The main focus of the Marinet project is on experimental testing. Therefore, the generated reports regarding numerical modelling look at validating PTO models using experimental data. D 4.15 details the theory and concepts of scaling, the procedure and factors to be considered when applying physical model test results to an electrical test rig, and limitations in validating PTO models with experimental testing.

International experts identified the current approach of numerical modelling as one of the causes of the delayed development of the wave energy sector: “The modeling approach needs to be system level, more unified and needs a clearer understanding of the relative importance of the different components” [11].

With this motivation, several research works are trying to provide a system-level overview of a complete wave energy conversion system and present a corresponding modeling approach [12]. This introduces an integrated wave-to-wire model for the analysis of marine energy device applications that correctly represents all the steps of power conversion and power conditioning: from the hydrodynamic model of the single WEC to the aggregate effect of the grid integration in a farm. This approach extends the concept of a wave-to-wire model that is generally limited to the active front-end in the PTO [13], [14], [15].

The scheme of principle of a generic resource-to-wire model is represented in Figure 4 [16], where numbers represent the following:

1- Prime mover
2- Power Take-Off (PTO)
3- Electric grid or grid infrastructure
4- Energy storage device

![Figure 4 - Scheme of principle of the Resource-to-wire model [16].](image-url)
The integrated model must be approached under a multidisciplinary perspective as shown in Figure 5. On the one hand, the prime mover will be modelled by a hydrodynamic model, and the electrical machines, power electronics and grid connection require electrical models. WEC control will be the bridge between the hydrodynamic model and the electrical model. Thus, the interaction of subsystems through control is the basis of power conversion, delivery and conditioning.

There is a strong, mutual interaction between control strategies and the PTO. The PTO is the actuator of the control action. 

Control action: How we want the system to behave and what reference signals we consequently need to generate. 

Power Take-Off: How we practically apply the (control) reference signals in the real system.

Numerical models must consider the system as a whole. Even if each part can be modelled separately, an integrated model is needed for the definitive validation. A deeper analysis of numerical models is done in [10]. The following section gives an overview of how to perform the model of the prime mover motion depending on the resource.

### 3.1.1 Wave

#### 3.1.1.1 Resource

Waves are created by the friction of the wind blowing on the water free surface, this phenomenon is called fetch. In this area the waves are considered as wind waves and travel following the wind direction to become a swell. The resource of a specific site is characterized by its wave climate which regroups all the sea states. The basic parameters of a sea state are its wave height $H_s$, the period $T_p$, the energy and probability of occurrence during a year as in Figure 6. This matrix is specific for each deployment site and is crucial for the power assessment of a WEC.
Real waves are resulting from the superposition of several monochromatic waves, each one having its proper characteristics. It means that the ocean surface can be modelled as the sum of sinusoidal monochromatic waves with different amplitudes, wave periods, directions and phases. The sea states are represented by the wave spectrum describing the energy density on the different frequencies. The most standard form to represent a spectrum following the mathematical expression where $A$ and $B$ depend on $H_s$ and $T_p$:

$$S(\omega) = \frac{A}{\alpha^5} e^{-\frac{B}{\omega^\alpha}}$$

Several methods are describing the wave resource as for example the JONSWAP spectrum, the Pierson-Moskowitz spectrum, the Ochi spectrum or the Bretschneider spectrum. In Figure 7 the Brechneider spectrum is plotted over the frequency range for a specific sea state ($H_s=1m$, $T_p=10s$) and its reproduction of the sea surface elevation is illustrated.

3.1.1.2 Hydrodynamic modelling of a WEC

Referring to a Wave-to-Wire model is representing the behavior of the WEC by a numerical model which solves a set of differential equations by symbolizing the overall energy conversion chain from the kinetic energy of the wave to the electrical power sent to the grid.
The dynamics in most of wave energy devices (over-toppers being the exception) are described by considering the device as a rigid body able to move freely in the 6 degrees of freedom, where its position and orientation are ruled by components of translation (heave, sway and surge) and components of rotation (pitch, roll, yaw). A body at sea can extract energy from the 6 degrees. However the amplitude of the WEC’s frequency response, and so its capture capability, is more important in the heave and surge motion. For example, considering the Cummin’s equation derived from the 2nd Newton’s law $ma = \sum F$, the forces acting on a device in heave influence the hydrodynamics as described in time-domain:

$$m\ddot{x}(t) = F_{exc}(t) + F_{hyd}(t) + F_{rad}(t) + F_{PTO}(t)$$

Where $m$ is the mass of the device, $x$ the motion variable representing the position with its derivatives $\dot{x}$, and $\ddot{x}$, being respectively the velocity and the acceleration. $F_{exc}$ the excitation (or diffraction) force of the incident wave, $F_{hyd}$ the hydrostatic (or buoyancy) force, $F_{rad}$ the radiation force due to the body motion and $F_{PTO}$ the power take-off force (or load) absorbed by the device. Maximum generated power depends on hydrodynamics of the WEC. It comes from deriving the power with respect to the power take-off characteristics.

In the majority of the PTO system, except the linear generator, the WEC absorbs the energy from the waves to transform it into pneumatic, hydraulic or mechanical power. It is then turned into rotational energy that is converted in electricity in the generator as illustrated in Figure 8.

![Energy conversion chain in rotary PTO systems](image)

Additional details on WEC modelling in frequency domain and time domain are given in [10], as well as the principle and governing equations for the main PTO systems, such as the oscillating water column, the hydraulic and the overtopping PTO.

### 3.1.2 Wind

#### 3.1.2.1 Resource

To characterize the wind resource, it is commonly accepted to use the wind profile formula:

$$U(z) = U(H) \left(\frac{z}{H}\right)^{\alpha}$$

Where $U$ is the mean wind speed at a specified height $z$ where the mean wind speed is calculated from the reference height $H$ and $\alpha$ is the roughness of the area. For offshore application the roughness varies from $1e^{-4}$ m to $1e^{-2}$ m which is significantly lower than inland or mountain areas.
The wind speed variation can be represented at a specific site by a power spectral density such as the Kaimal, Davenport, Harris, Ochi and Shin methods. It is usually a mean value along a 10 min period. For example, the Kaimal spectra is obtained by:

\[
S_u(f) = \sigma_u^2 \cdot \frac{6.868 \cdot \frac{L_u}{U_{10}}}{\left(1 + 10.32 \cdot \frac{f \cdot L_u}{U_{10}}\right)^{5/3}}
\]

In which $L_u$ is an integral length scale and $\sigma_u^2$ is the square of the mean standard deviation specified in [18].

The adaptation of the PSD in time gives the wind speed variation of the Figure 11 for 10 m/s mean wind speed. The short term variations are due to turbulences in the air flow.
The characterization of the mean wind velocity is very useful for the estimation of the wind power generation. It may be done either from historic data or by a known distribution of mean speeds, using density functions such as the Rayleigh Distribution.

Since the power installed curve is available for a specific wind turbine, it is easily predictable the mean annual wind energy generation in a given location:

$$\overline{P_w} = \int_0^\infty P_w(U) \cdot p(U) dU$$

Coupling the power curve of the wind turbine (blue curve) with the density distribution gives the expected annual average energy production (green curve).
3.1.2.2 Aerodynamics of a wind turbine

The generation capacity of a wind turbine specifies how much power can be extracted from the device. The available power in a wind turbine is defined by the following equation:

$$P_{av} = \frac{1}{2} \rho \pi R^2 C_{p_{max}} V^3$$

Whith $R$ the blade length, $\rho$ the air density, $C_{p_{max}}$ the maximum power coefficient and $V$ the wind speed.

Wind turbine modelling is based on blade element momentum theory (BEM). This theory consists in matching actuator disk theory with the forces on the blades of a wind turbine. Each blade is made up of the distribution of different aerofoils along its length (from the root to the tip). From the actuator disk theory two expressions are obtained in order to assess both the thrust on the wind turbine and the absorbed power from the wind for a given set of aerofoils and an angular rotational speed [19].

$$dT = \rho \cdot U^2 \cdot 4 \cdot a \cdot (1 - a) \cdot \pi \cdot r \cdot F \cdot dr$$

$$dM = 4 \cdot a' \cdot (1 - a) \cdot \rho \cdot U \cdot \pi \cdot r^3 \cdot \omega \cdot F \cdot dr$$

Where $a$ and $a'$ are the axial and angular induction factors respectively, $U$ is the undisturbed wind velocity and $dT$ and $dM$ are the thrust and torque on each annular section of the wind turbine respectively. The thrust and the torque of the wind on the blades can also be determined by the aerodynamic properties of the aerofoils.

Figure 13 - Wind power production at a specific location and wind turbine power curve in function of the wind velocity
Where the tangential (which originates torque) and axial (a fraction of the total thrust) forces on each element of the blade is a result of the combination of the lift and drag forces. These forces depend on the incident wind velocity and the velocity of rotation, which defines the angle of attack of the wind on the element [20].

\[
dT = B \rho \frac{1}{2} U_{rel}^2 (L \sin \phi - D \cos \phi) c r dr; \quad dM = B \rho \frac{1}{2} U_{rel}^2 (L \cos \phi + D \sin \phi) c dr
\]

Supposing that the wind is axially and angularly slowed down from the velocity vector the expressions below are derived:

\[
U_{rel} = \frac{V_0 (1 - a)}{\sin \phi}; \quad U_{rel} = \frac{\omega r (1 + a')}{\cos \phi}
\]

Substituting these expressions in the previous equations and equalling with the thrust and moment of the actuator disk theory, the following values for \(a\) and \(a'\) can be defined [20]:

\[
a = \frac{1}{4 \cdot F \cdot \sin^2 \phi \cdot \sigma \cdot C_n + 1} \quad a' = \frac{1}{4 \cdot F \cdot \sin \phi \cdot \cos \phi \cdot \sigma \cdot C_t - 1}
\]

Where:

\[
\sigma = \frac{B \cdot c}{2 \cdot \pi \cdot r} \quad C_n = (L \cdot \cos \phi + D \cdot \sin \phi) \quad C_t = (L \cdot \sin \phi - D \cdot \cos \phi)
\]

The last expressions can be solved iteratively for getting the correct values of the induction factors. This allows the estimation of the incidence angle in each blade element.

A more detailed analysis of the modelling of wind turbine and control strategies is available in [3].

### 3.1.3 Tidal

#### 3.1.3.1 Resource

The characterisation of the tidal velocity can be associated as the method used for the wind resource. The difference resides in the fact that the speed also depends on whether the tide is flooding or ebbing, changing the fluid
direction, and its height, influenced by the moon attraction force. Current velocity due to tides is composed of a mean velocity and a defined turbulence. In Figure 15, an example of a time series from data acquired at the EMEC test site illustrate the variation of the tidal current speed during 48h. The high frequency variations are due to these turbulences and to the influence. As the power absorption of the turbine varies with the stream velocity at the power of 3, these turbulences have to be very carefully considered in the design and in the control algorithm to keep a convenient power fluctuation.

![Figure 15 - Tidal current speed from a current meter installed at EMEC](image_url)

In addition, waves interact with the current and the influence is not negligible. This impacts the structural and the blade design. Indeed, the fatigue loads of a turbulent flow subject to the influence of waves are essential considerations in the overall design process [22] as the bending moment can increase up to 50% of the mean value [23]. For example, the power spectral density of the SeaFlow tidal device [3] where the peak represents the excitation from waves.

![Figure 16 - Power spectral density of power output for the SeaFlow Device](image_url)
3.1.3.2 Device modelling

The modelling approach for the tidal turbines is very similar to the BEM method used for the wind turbines as it has been proposed by [24]. The only things to adapt on the assessment process are the density of the water (instead of the air’s) and the blades aerodynamic shapes and properties. As the water is more than 800 times higher than air, the design has to be even more robust. As a comparison with wind energy, there is a more important variety of turbine designs, they are classified in two categories: axial-flow turbines [25] and cross-flow turbines. A numerical model of a tidal turbine is done in [24] with the purpose of analyzing the farming of several turbines.

3.2 Model implementation in a test bench

As described in section 2, the electrical infrastructures are generally divided into two parts: the emulated part and the real part. As soon as in the conversion chain there is an exchange into mechanical rotational energy, the device can be implemented in a test bench. Whether the device converts energy from wave, tidal or wind; emulation is possible when the model offers a torque reference to the test bench motor.

3.2.1 Implementation in the emulated part

3.2.1.1 Model adaptation

A numerical model resolves a set of differential equations describing the behavior of the device. It is programmed in a computer code where the language will depend on the user familiarities and its requirements in terms of execution time. [10] shows a Sample of Software Packages Available for PTO Modelling. The list is not exhaustive, but attempts to highlight the different formats of available software from linear boundary element method (BEM) solvers, to computational fluid dynamics (CFD) approaches, and time domain analysis tools for moorings and power systems. It furthermore outlines that software solutions are intended for modelling the various aspects of the PTO systems, and although some of them can be computed offline and the results used in the next stage software, there is not a single software that is focused in all the studied areas.

In experimental test benches, a real-time board is used to run the hydrodynamic model code. At each time step, it reads a value of speed (or torque) coming from the sensors, resolves the model equations and sends a new torque (or speed) reference. The drive follows this reference and injects the current in the motor to match the requested value.

The dynamics of the testbench must also be taken into account and they have to be implemented in the device model.

![Image of scheme of operation of the simulation and test bench](image-url)
During the experiment, two models are therefore running simultaneously: a MEC model, and the HIL simulation. This allows real-time comparison and validation of the numerical computation with experimental data. Both of them have to be adapted to the test bench characteristics in respect with its specificities in terms of calibration, drive-train (friction, inertia) and scaling. The model for the HIL is compiled to the real-time digital to analogue board that sets a torque (or speed) reference to the motor via the associated drive emulating the rotational power of the PTO. The motor feeds the generator with mechanical power and the PLC applies the control algorithm for power maximization, setting a new reference of speed (or torque). This reference represents the new input to the system. The experiment runs in closed loop until the end of the time series.

**Scalability**

Full scale tested devices usually do not match the ratings of the equipment in the laboratory (prime-mover, generator, drive-train and power electronics). To get a reliable relationship between the HIL and the WEC, it is necessary to adapt the numerical models to match the specificity of the test bench. As described in [5], a model is said to have perfect similitude if it meets the three requirements of geometric, kinetic and dynamic similitude. The ratio between the forces of the scaled/adapted model and the real prototype has to be maintained for all the forces (inertial, gravitational, viscous, elastic and pressure). The scaling method has to be determined carefully regarding the dominant forces and try to keep the correct relationship. For example, as the motion of waves is strongly dependent to the gravity, the use of the Froude law is preferred because it preserves better the relationship with inertia.

<table>
<thead>
<tr>
<th>Physical Parameter</th>
<th>Multiplication Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Time</td>
<td>$\sqrt[3]{\lambda}$</td>
</tr>
<tr>
<td>Structural Mass</td>
<td>$\lambda^3$</td>
</tr>
<tr>
<td>Inertia</td>
<td>$\lambda^5$</td>
</tr>
<tr>
<td>Force</td>
<td>$\lambda^3$</td>
</tr>
<tr>
<td>Torque</td>
<td>$\lambda^4$</td>
</tr>
<tr>
<td>Linear Velocity</td>
<td>$\sqrt[3]{\lambda}$</td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>$1/\sqrt[3]{\lambda}$</td>
</tr>
<tr>
<td>Linear Acceleration</td>
<td>$1$</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>$1/\lambda$</td>
</tr>
<tr>
<td>Pressure</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Power</td>
<td>$\lambda^{3.5}$</td>
</tr>
</tbody>
</table>

**Table 2 Froude Scaling Rules for a selection of physical parameters [5]**

Usually the scaling factor is determined as a ratio of the maximal power, or the maximal torque, that can handle the equipment over the one of the device. An example of the use of Froude scaling and the adaptation to be made is made in [26] for an OWC wave energy converter.
3.2.1.2 Sea state testing conditions
The definition of the appropriate rated power for ocean energy technologies is largely dependent on the resource available at the deployment site. Previous work done in [1] defines the typical dynamic load regimes for marine energy devices, which implies the definition of a set of environmental conditions corresponding to the following four fundamental load cases:

- **Optimal operating conditions**: Condition under which the PTO should operate with the best efficiency. The PTO is designed to operate at this condition.
- **No-load conditions**: Minimum load or velocities under which the PTO should run. Lower bound for the PTO operation.
- **Extreme load conditions**: Maximum conditions at which the PTO can keep in operation. The objective of the PTO control in this condition is not efficiency but to maintain the operation and assure the safety of the equipment at the same time.
- **Extreme safety conditions**: Severe conditions at which for safety reasons the PTO is locked or allowed to be by-passed.

3.2.1.3 Sea state testing limits
The test bench is usually a fixed configuration and the components will have certain limits that cannot be surpassed (see 2.3). After the scaling, the device under test is supposed not to overcome these limits. But this will depend on the input sea state and the control law.

In this regard, an important data to be considered is the peak to average power ratio, and this requires the analysis of the instantaneous extracted power in addition to the average one [6]. Regarding the efficiency of the system, it is more important to have a high average power. If the device must harness instantaneous high power peaks, all the components must be designed for at least that power. But the average working power will be much lower. This will imply to negative effects:

- The components of the device must be designed to withstand the instantaneous high power peaks. The device will be big regarding the average power that will extract. This situation is economically inviable.
- As stated in 2.3, the components of the device will work underloaded and thus, with a low efficiency.
These problems can be addressed before any experimental testing. The peak to average power ratio can be obtained in the simulation stage. However, simulations withstand any extracted power and users tend to analyse only the average power without taking into account the big power peaks that instantaneously appear. It is thus, in the experimental testing stage where this fact is more noticeable. When adapting the device model to the facility limits, and during the scaling, the sea states that are going to be tested, and, for those sea states, the peak to average power ratio must be analysed.

The infrastructure manager may impose the limits for the infrastructure components and inform about the overall efficiency, but it is up to the users to decide the best peak to average power combination. This may completely depend on the control strategy and will oblige to impose saturations in the power peaks to respect the peak power limits of the facility [27].

3.2.2 Implementation in the real part

Section 0 showed the way of adapting the device model depending on the characteristics of the selected test bench. This model is implemented in the emulated part of the test bench and therefore, the behaviour of the simulated device is physically reproduced by the drive motor depending on the input.

The real part of the test bench is mainly composed of the electrical generator, the power converter and the grid connection as shown in Figure 19. There is usually a controller (i.e. a PLC) that is responsible for the whole operation of the power converter having, among others, the following tasks:

- State machine (or similar) to establish the operation modes and timing for the converter. When to start, stop, connect to grid, etc.
- Alarms: The controller will have access to all the measurements and can manage the alarms.
- Generator side control
- Grid connection

![Back-to-back VSC configuration and its associated components](image)

Figure 19 - Back-to-back VSC configuration and its associated components [3]

3.2.2.1 Generator control strategy

The generator side control strategy must also be adapted to the specific test bench. The control strategy is implemented in the real part of the test bench (see section 5 of [5]) and is responsible for calculating the set point of the generator speed (or torque) for each situation. Internally, the imposition of the generator speed (or torque) is done by means of the extracted current from the generator. I.e. if the generator must accelerate, the internal control extracts less current so that the kinetic inertia of the generator increases, and thus, the generator speed. The generator control strategy must then, be implemented in the programming language of the control system controlling the power converter, usually a PLC.
The controller will have the internal measurements of the power converter as well as the necessary external measurements such as generator speed or shaft torque. The generator control will determine the optimum speed (or torque) and this will be translated into a current setpoint for the converter.

### 3.2.2.2 Grid connection control strategy

The power converter is on the one side connected to the generator, and the generator control strategy is thus implemented in its controller. But on the other side, it is connected to the grid. If a robust grid connection algorithm is going to be programmed, it must be done also in the converter controller.

In the easiest control option, only the relation of active and reactive power setpoint can be programmed. Depending on the purpose of the test (i.e. power quality testing), the controller may have the necessary measurements such as instantaneous grid voltage and frequency so that a robust grid connection algorithm can be programmed. This may be done determining the grid injection current (in the determined magnitude and phase).
4 AVAILABLE TEST PROCEDURES

Testing at electrical facilities as the ones offered within MaRINET allows working in a controlled lab environment, reducing risks and development time before the deployment of the system. It can contribute to the optimum development not only of the power conversion stage, but of the MEC as a whole. The planning of these tests can be focused on the different design stages of each MEC. Section 9 of [5] describes the main purpose of the tests that can be performed in these facilities depending on the development stage of the device. The test can satisfy different requirements from the design validation to pre- and post-deployment testing. Some of the mentioned test can be interesting in more than one design stage, depending on the objective of the results.

Figure 20 - Test targets along the development stages.

Section 9 of [5] describes briefly the tests defined in Figure 20. Here a more detailed description of the generator-side control and the grid-side control will be shown.

4.1 GENERATOR-SIDE CONTROL. MEC CONTROL

Different levels of controls can be first simulated and then tested in electrical facilities:

- Tuning of controllers when the parameters are not exactly known. Experimental tests will show the accuracy of any control law when as it happens in reality; the exact parameters are not known or are time-varying in a non-controllable manner (delays, wear, etc.)
- Optimum efficiency control. Some MEC controls try to track the maximum efficiency curve of a turbine, without taking into account the effects of the inertia, or the influence of a highly varying speed in the rest of the components. Furthermore, the maximum efficiency point of the turbine may not coincide with the maximum efficiency point of the generator, converter and rest of the components in the device.
- High peak to average power controls. Many research works based only in simulation, describe the advantages of a particular control law without taking into account that the electrical components must be designed for the maximum peak power. Electrical tests help in the understanding of the compromise between high power extraction and component oversizing.
- Analysis of the effects of saturation.
- Analysis of generator control laws, and optimization.
- Investigation of varying inertia.
Validation of the control strategy with non-controllable delays: The control variable change is instantly applied when working in simulation. However, real application will imply delays that can make the overall loop unstable.

- Sensorless control: It may happen that not all the measurements used in the simulation stage are available in reality. The experimental tests can guide the users in the necessary steps to redesign the control strategy.
- Repeat actual sea/wind working conditions (based on field measurements) which lead to failures to debug the system.

## 4.2 Grid Connection Control

As any other grid connected converter, marine energy converters must meet the existing grid connection normative.

A general difficulty in the power quality assessment of any MEC is that the main applicable normative has been developed with focus on wind energy. National and International groups are now in the process of adapting these normative to the marine particular case where special conditions have to be taken into account. There is not therefore, a well-established normative to follow, and the reference documents may be still a draft in an attempt to adapt the wind energy normative, or a wind energy normative with no adaptation at all.

Grid codes vary country by country so there is a need to match a specific configuration to meet the demands of local grid code requirements. [28] and [29] make a review of the existing power quality requirements regarding marine energy converters as demanded by European TSOs Countries (including Denmark, Ireland, Germany, UK, Finland, Italy, Spain and Norway) which define the grid codes. These Grid codes have been developed to maintain a reliable and safe operation of power systems.

Regarding electrical testing, different aspects could be addressed:
- Steady state or normal operations conditions
- Voltage and frequency deviations
- Active and reactive power control
- Voltage control
- Power factor control
- Power quality
- Fault ride through requirement during grid disturbance, and active and reactive power support during grid faults.

On the other hand, the main reference for power quality measurements is the International Standard IEC 62600-30 [30] that is being prepared by IEC technical committee 114: Marine energy - wave, tidal and other water current converters.

This standard focuses on:

- Power quality issues and parameters (non-device specific and non-prescriptive) for single/three-phase, grid-connected/off-grid (including micro-mini grid) marine wave, tidal and other water current converter-based power systems.
- Establishing the measurement methods, application techniques and result-interpretation guidelines.

The key items of the standard are the following:
- Identify characteristic parameters, define and specify the quantities required to characterize the power quality impacts of marine energy conversion devices.
- Develop measurement procedures as pertains to marine energy devices. Outline standardized procedures for measuring the characteristic parameters, including test & measurement conditions, and test equipment requirements.
- Develop methods of assessing compliance with power quality requirements for utility and off-grid power systems.

Some electrical facilities are able to provide a programmable grid including different kind of disturbances to test the robustness of the designed system.
Table 3 shows a brief description of testing procedures that can be performed regarding power quality and grid connection operation.

### Table 3: Grid connection power quality testing.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Why?</th>
<th>Additional research</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage and freq. variations</strong></td>
<td>By means of controllable AC source voltage and frequency variations can be emulated to assess the behaviour of the device in normal operation, as well as the active (Pf) and reactive (QV) control system.</td>
<td>Most grid codes ask the devices/farm to work within a normal operation range of voltage and frequency. Generation systems based on power electronics makes total inertia of the system to decrease, additional active power control loop may reduce this effect.</td>
<td>Analysis of different solutions for the test bank that allow making voltage and frequency variations in to the connection point. For example: by means of a fully controllable AC source, the addition of an impedance...</td>
</tr>
<tr>
<td>Reactive Power Control behaviour</td>
<td>Check the behaviour of the devices with different reactive power/power factor targets.</td>
<td>Most grid codes ask to work with reactive power and/or power factor targets defined by the SO.</td>
<td>Implementation in the test bank of a high level control that generates the targets for the device.</td>
</tr>
<tr>
<td>Active Power Control behaviour</td>
<td>Check the behaviour of the devices under active power variations both due to resource variability or to respond to active power target modification.</td>
<td>Maximum active power ranges are included in many grid codes. Also the need of reducing the generation if SO asks to.</td>
<td>Implementation in the test bank of a high level control that generates the targets for the device.</td>
</tr>
<tr>
<td>Inertia and storage changes</td>
<td>Assess the impact of inertia and energy storage on the generation and on the grid.</td>
<td>Inertia and energy storage may smooth the generation and improve grid integration. The greater the variation of the resource the bigger the effect of the inertia and storage.</td>
<td>Study energy storage options to add to the test bank.</td>
</tr>
<tr>
<td>Faults</td>
<td>Analysed the behaviour of the device under voltage dips.</td>
<td>Grid codes define voltage dips that the devices and the farm have to withstand.</td>
<td>Definition of fault tests based on a specific grid code (Spanish) requirements and implementation in the test bank.</td>
</tr>
<tr>
<td>THD</td>
<td>Harmonics analysis.</td>
<td>Grid codes determine maximum THD values.</td>
<td>--</td>
</tr>
<tr>
<td>Flicker</td>
<td>Flicker calculation.</td>
<td>Grid codes limit P_{st} and P_{lt} values.</td>
<td>Flicker evaluation methods and implementation in the test bank.</td>
</tr>
<tr>
<td>Strength of the grid</td>
<td>This study has a twofold objective. In one hand to assess the impact of the device into different grids (weak-strong) and in the other hand to evaluate the effect of the strength of the grid on the device behaviour.</td>
<td>With the same generation and control system the obtained results can be completely different depending on the grid. As result the same farm may comply or not the grid code requirements depending on the connection point.</td>
<td>Analysed different solutions for the test bank that allow making voltage and frequency variations in to the connection point. For example: by means of a fully controllable AC source, the addition of an impedance...</td>
</tr>
<tr>
<td>Reactive Power Compensation</td>
<td>Improve transmission efficiency by means of reactive power compensation, including the capability of the device, into the transmission.</td>
<td>As the generation goes far from the connection point reactive power compensation in AC transmission systems becomes mandatory.</td>
<td>Studied reactive power compensation options to add to the test bank.</td>
</tr>
</tbody>
</table>
4.3 COMPONENT TESTING

Small-scale component testing is not the most extended test procedure in this kind of laboratories but can give to users important information about the device configuration prior to constructing larger scale prototypes which may result costly in manufacturing and testing themselves. In fact, for megawatt scale devices, installing a prototype is often a costly and time consuming matter thus it is common that large volume manufacturing start before field test can be completed. This has led to field failures which require expensive retrofits to mitigate [28]. These kinds of tests are quite more difficult to prepare as they imply hardware configuration changes. On the one hand, the component under test must be scaled to the facility’s rating. On the other hand, the laboratory must be prepared to substitute it. The former requirement can be easy as the component may have been manufactured for that specific purpose. The later, might imply the construction of specific adaptation components such as a new shaft. The components that are more likely to be tested are part of the drive-train:

- **Gearbox:** Most of the electrical facilities will be prepared to apply only torque, but when testing includes additional components such as bearing and shafts, additional non-torque load are required.
- **Electrical generator:** Due to the slow motion of the waves, slow speed generators are mostly used in marine applications. These generators have usually specific designs, and for obtaining of the electrical parameters a variety of tests must be done.
- **Power converter:** The testing of the power converter is not so critical as the basic operation is more predictable and dependant on the controller operation. However, it may result interesting to test the physical limits of the component in a laboratory environment. The power converter may have been specifically designed for the application, for example to withstand instantaneous high current peaks.
- **Controller:** Laboratory testing gives the possibility to work in every situation the marine energy converter may encounter and repeat any situation with the same or different conditions. It is very useful to test the controller with the final programme in a controlled environment where all the situations can be tested.
5 CORRELATION BETWEEN EXPERIMENTAL TESTS AND SIMULATION RESULTS

Prior to experimental testing simulation models are based on mathematical equations. These models represent the ideal behaviour of each of the components and do not show the real operation and interaction between them.

Numerical modelling is extraordinarily useful and needed for concept validation and facilitating incremental design improvements. Nevertheless, it is not enough for completely represent the behaviour of the MEC in real operating conditions. There are a several limitations that must be considered; the models often do not take into account the physical constraints, response times and delays, and the thermal characteristics of real equipment under normal and extreme sea-operating conditions. The use of electrical test infrastructures provides a cost-effective method of investigating the MEC performance, and obtaining real measured data in a controlled and repeatable test environment.

Electrical tests will help in obtaining a feedback from the experimental results to simulation model.

5.1 VALIDATION OF THE SIMULATION MODELS THROUGH EXPERIMENTAL TESTING

Simulation models can have different levels of complexity as shown in section 3.1 depending the purpose for what they are designed. In many cases, mathematical equations can be simplified and not all the effects need to be considered.

However, it is difficult to know where to fix the limits of simplifications. In addition, real physical components will always present a behaviour with certain variables that are usually not considered in the models. Besides these known effects, they can also present unpredictable effects that cannot be measured nor exactly modelled and will represent an accepted level of uncertainty the system must work with.

Experimental tests will show if the accuracy of the model is enough regarding the purpose for what it is designed. It may occur that some aspects like specific control laws have a completely different behaviour in simulation and in the laboratory. The laboratory will add to the tests a touch of reality showing the unexpected behaviours before a prototype is installed in the sea.

Some of these effects that have not been considered in simulation models can be added after experimental testing. Some others that cannot even be measured can be at least noticed and taken into consideration, to at least, be able to compensate the negative effect.

- Delays in power electronics, filters
- Uncertainties in the applied values
- Measurement errors: 1) intrinsic error of sensors; 2) error for working out of range (low ranges)
- Uncertainties in the physical data: Inertia, friction

There are other considerations that can complicate the implementation of the model in the facility. The most important is the need of working in Real Time. When the complexity of the calculations is high, simulations can work in variable or fixed step, and with simulation periods longer than real time. This is not acceptable when working in physical facilities. Usually variable step options must be substituted by fixed-step solvers which should not cause too many problems. On the other hand, it is mandatory that the models of the PTO work in real time. Sometimes the reduction of computation time is a complicated task that implies a reprogramming of some parts of the code.

5.2 EXAMPLE OF NOT DIRECTLY APPLICABLE MODELLING

MORE is a two-chamber oscillating water column device designed to generate a unidirectional and continuous airflow [26]. This kind of airflow allows the use of turbines with higher efficiency than those used in single-chamber
OWCs. The device is based on the patented Seabreath concept. The device is an elongated structure, made by an array of rectangular chambers with open bottom. The chambers are made to form a closed loop to feed only one turbine. It is conceived that the structure should be kept aligned perpendicularly to the incident waves. The MORE device was tested by the University of Parma, Italy in the Electrical PTO Lab in TECNALIA.

The hydrodynamic model of the MORE is a set of Matlab scripts and functions. Before writing the Matlab scripts a FEM simulation campaign was carried on to evaluate the pneumatic behaviour of the oscillating water columns. The input of the model is a regular sea state defined by the significant height $H_s$ and the wave period $T_s$, while at the output gives the pneumatic power of the air at the turbine inlet. The original idea is based on a fully coupled approach in which the pneumatic power is at the output of the primary PTO is affected by the behavior of the following elements of the overall conversion chain (Figure 21). Unfortunately this first modelling was not quickly usable for the needed real time environment (maximum time step of 10 ms). To overcome this limitation a sequential approach has been adopted, where firstly the OWC model was run alone, calculating the pneumatic power (vs the time) at the turbine inlet for a given sea condition and a rotor speed. Afterwards, the obtained pneumatic load is used as input of the air turbine (Figure 22).

![Figure 21 - Schematic of the HIL with the OWC model fully coupled with the turbo-generator [26].](image1)

![Figure 22 - HIL schematic with pneumatic power generated by the OWC without influence of turbo-generator and the power control. [26].](image2)
The main limitation of this approach is the assumption that the hydrodynamic load does not depend on the turbine state. This simplification leads to accurate results only if the computed rotational speed is not quite different to the one used to evaluate the pneumatic power.
6 CONCLUSIONS

Electrical test infrastructures provide a cost effective method of testing the power take-off of ocean energy devices, and obtaining real measured data in a controlled and repeatable environment. The set of deliverables developed within MARINET Project have demonstrated the methodology of integrating a MEC into an electrical test infrastructure, and adapting the MEC to fit to the physical limitations of the infrastructure.

MARINET project has highly contributed to give visibility to this aspect of MEC design and it can help to accelerate the success of new developments in marine renewable technology.

A variety of case studies with different concepts successfully tested in the available facilities can be found online in [31]. The reports describe the Project under test, the objectives of the test, adaptation methodology for the selected facility and testing results when not confidentiality issues arise.
REFERENCES


