Numerical Simulation of Control Strategies at Mutriku Wave Power Plant

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ABSTRACT
In order to de-risk wave energy technologies and bring confidence to the sector, it is necessary to gain experience and collect data from sea trials. As part of the OPERA H2020 project, the Mutriku Wave Power Plant (MWPP) is being used as a real condition laboratory for the experiment of innovative technologies. The plant is situated in the North shore of Spain and has been operating since 2011. It uses the Oscillating Water Column (OWC) principle, which consists in compressing and expanding the air trapped in a chamber due to the inner free-surface oscillation resulting from the incident waves. The pressure difference between the air chamber and the atmosphere is used to drive an air turbine. In that case, a self-rectifying air turbine is the best candidate for the energy conversion, as it produces a unidirectional torque in presence of a bi-directional flow. The power take-off system installed is composed of a biradial turbine connected to a 30kW off-the-shelf squirrel cage generator.

One of the novelties of the turbine is a high-speed stop-valve installed close to the rotor. The valve may be used to control the flow rate through the turbine or for latching control. This paper focuses on the development, the implementation and the numerical simulation of five control strategies including turbine speed and generator torque controllers. The algorithms were designed thanks to a numerical model describing one of the OWC chambers of the Mutriku power plant. Numerical results are presented for a variety of sea states and a comparison between the proposed control laws in terms of energy production and power quality is performed.

KEYWORDS
Wave energy, Oscillating Water Column, Wave-to-Wire model, control algorithms, torque control, Reinforcement Learning, Model Predictive Control.
1 INTRODUCTION

EU Horizon2020 Research and Innovation programme funded the OPERA project (Open Sea Operating Experience to Reduce Wave Energy Costs). The main objective is to gain experience based on the operation in open-sea of a floating oscillating water column wave energy converter. It has been demonstrated that advanced control algorithms acting throughout the power conversion chain, from the hydrodynamics of wave absorption to turbine aerodynamic and electrical equipment efficiency, could increase power production and device reliability; thus leading to a decrease of the Levelised Cost of Energy. In many cases research is limited to theoretical studies in the field, making experimental works necessary. The MWPP [1] seen in Figure 1 will be used as a testing facility for the novel biradial turbine and control algorithms before being installed in Oceantec’s MARMOK-A5.

Generally speaking, optimal control strategies in wave energy are based on the principle of phase and amplitude matching to create resonance between the waves and the device [2]–[4]. Research on point absorbers states that a significant increase in power absorption is obtained by controller based on phase matching such as reactive controller [5], [6] or latching. It complies the phase condition by changing the device natural frequency to match the one of the excitation of the incident wave. Latching is a more practical approach as it does not imply a bi-directional energy flow but needs a specific mechanism to hold the device in position and release it at the best moment [7]–[9]. Phase control applied to OWC systems is more challenging because the water column motion cannot be directly controlled due to fact that the PTO is not rigid as can be a hydraulic PTO for example. Instead, the air pocket adds non-linear effects and acts as a buffer in the energy conversion. Though scientific publications tend to tackle that subject [10], [11], even bringing the benefits predictive control strategies [12]–[14] there is not yet evidence of its practical application. The most common way to control the OWC is by adapting the damping created by the turbine by adjusting its rotational speed. In the literature, theoretical developments have been developed in that sense [15]–[19], and also present validation on dry PTO test rigs [20]–[24]. There are also public evidences of speed control application in real environment [25], [26].

Five dedicated algorithms for controlling the turbine were developed, and compared in this paper and subsequently tested in real sea according to the objectives of OPERA. These controllers are classified into two main families: adaptive controllers using operational data to decide the best instantaneous control action, and predictive controllers that perform an online optimization along a prediction horizon and have the capacity to adapt to the incoming waves. A summary of the main characteristics of these algorithms can be seen in the table below.

<table>
<thead>
<tr>
<th>Control Law #</th>
<th>Feedback/Adaptive/Predictive</th>
<th>Controls ...</th>
<th>Based on ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL0</td>
<td>Feedback</td>
<td>Generator torque</td>
<td>Optimal average turbine speed</td>
</tr>
<tr>
<td>CL1</td>
<td>Feedback</td>
<td>Generator torque</td>
<td>Rotational speed</td>
</tr>
<tr>
<td>CL2</td>
<td>Feedback</td>
<td>Generator torque</td>
<td>Chamber pressure</td>
</tr>
<tr>
<td>CL3</td>
<td>Adaptive</td>
<td>Generator torque</td>
<td>Hourly sea-state data, rotational speed, generator power</td>
</tr>
<tr>
<td>CL4</td>
<td>Predictive</td>
<td>Generator torque</td>
<td>Next wave information, IWS displacement, internal pressure rotational speed</td>
</tr>
</tbody>
</table>

Prior to any tests at sea, the controllers’ performances have been assessed using computer simulations via the same Wave-to-Wire (W2W) numerical model describing one chamber of the MWPP and each step of the energy conversion.

The paper is organised as follows: section 2 presents the hydrodynamic model upon which the W2W model is based; in section 3 the control laws are described; simulation results are shown in section 4 and discussed in section 5; finally, the conclusions are presented in section 6.

Figure 1. Aerial view of the MWPP

2 NUMERICAL MODELLING

Numerical models have been developed to represent wave to wire modelling. It comprises of a hydrodynamic model of one chamber of the MWPP, the biradial air turbine, and the electrical generator. Even though the latter is off-the-shelf it has been modelled so that the impact of wave power variability upon practical constraints is accounted for, such as low generator efficiency at low power levels. Three sub-
models are described in this section and are part of the global W2W.

2.1 INTERNAL WATER SURFACE OF A CHAMBER
OF THE MUTRIKU WAVE POWER PLANT

The equation of motion for the internal water surface (IWS) for each instant of time \( t \) can be represented in time domain using Newton’s 2\(^{nd} \) law describing as \( x \) the heave acceleration of mass \( M \):

\[
M \ddot{x}(t) = F_{ex}(t) + F_{rad} + F_h(t) + F_p
\]

The excitation force \( F_{ex} \) is the force exerted by an incoming wave on the IWS and is expressed as:

\[
F_{ex}(t) = \sum_{j=1}^{N} F_{ex}(\omega_j) \cdot A_j \cdot \sin(\omega_j t + \epsilon_j)
\]

where \( F_{ex}(\omega_j) \) is the frequency domain excitation force per unit of wave crest length over the \( \omega_j \) radial frequencies obtained in the hydrodynamic study, \( A_j \) the wave elevation amplitude, \( \epsilon_j \) is the wave random phases.

The radiation force \( F_{rad} \) is due to the water column motion on a still water surface (without waves) and damps the system. The resolution of this equation in time domain is made by computing the convolution integral:

\[
F_{rad}(t) = -\mu_{\infty} \ddot{z}(t) - \int_{0}^{t} K(t - \tau) \ddot{z}(\tau) d\tau
\]

where \( \mu_{\infty} \) is the IWS added mass at infinite frequency obtained via the hydrodynamic study and the kernel \( K \) is the radiation impulse response. The approximation of the radiation term and the resolution of the convolution integral are done by using the Prony method. First, the complex coefficients of the impulse function are obtained such that:

\[
K(t) \approx \sum_{i=1}^{N} \alpha_i \exp(\beta_i t)
\]

The convolution radiation term can be simplified as:

\[
\int_{0}^{t} K(t - \tau) \ddot{z}(\tau) d\tau = \sum_{i=1}^{N} I_i = R_{33}
\]

Using a differential equation:

\[
I_t = \beta_i I_i + \alpha_i \dot{z}(t)
\]

A 20-order approximation of the kernel was used in the present work. The matrices \( A, B, C, D \) are obtained and resolve the radiation problem through a subsystem to be integrated in the global state space system.

\[
I_r = A_r I_r + B_r \dot{z}
\]

\[
R_{33} = C_r I_r + D_r \dot{z}
\]

The hydrostatic force \( F_h \) is the force proportional to the IWS heaving position and the hydrostatic stiffness characterised by \( K_{33} = \rho_w g S_{\text{IWS}} \) with \( \rho_w \) the water density and \( S_{\text{IWS}} \) the surface of the IWS:

\[
F_h(t) = -K_{33} \ddot{z}(t)
\]

The validation was made by comparing the RAO given in the hydrodynamic study and running the time domain model in regular waves, as shown in Figure 2.

![Figure 2. Validation of the radiation approximation](image)

Finally, \( F_p \) force resulting from the pressure inside the chamber on the IWS – converted then to electrical power by the PTO. It is proportional to the pressure drop between the internal and the atmospheric pressure, respectively \( p \) and \( p_{at} \), and the water column surface \( S_{\text{IWS}} \).

\[
F_p(t) = -(p - p_{at}) S_{\text{IWS}}
\]

Finally, the equation of the IWS motion in heave is the following:

\[
\ddot{z} = \frac{F_{exc} - R_{33} \ddot{z} - \Delta p S_{\text{IWS}}}{M + \mu_{\infty}}
\]

The hydrodynamic coefficients used in the model have been obtained by using WAMIT as presented in [1] and using the geometry of Figure 3. The length facing the wave is 4.50 m and 3.10 m deep. The height of the water column at equilibrium \( h_0 \) is taken from the mean between the high and low equinoctial spring tide.

The time variation of the pressure inside the chamber is modelled as an isentropic compression/expansion of the air [12,23]. The dimensionless pressure is introduced as \( p^* = \frac{p}{p_{at}} - 1 \) and \( \gamma \) is the air adiabatic expansion coefficient.

\[
p^* = -u_o \frac{c_{at}^2 m_t}{p_{at} S_t (h_0+z)} (p^* + 1) \left( \frac{\gamma - 1}{\gamma (h_0+z)} (p^* + 1) \right)
\]

\[
c_{at}^2 = \gamma p_{at}/p_{at}
\]
In the model, the variable $u_v = \{0,1\}$ defines a safety valve located in front of the rotor turbine. Its position (0-closed or 1-open) defines the presence or not of a flow rate $m_t$.

### 2.2 BIRADIAL TURBINE MODEL

In turbomachinery, it is common to define turbines performance according to dimensionless aerodynamic parameters of dimensionless pressure head $\Psi$, mass flow rate coefficient $\Phi$, power coefficient $\Pi$ and aerodynamic efficiency $\eta_t$, expressed as [2].

\begin{align}
\Psi &= \frac{P_{at} \rho^2}{\rho \Omega^2 d^2} \\
\Phi &= \frac{m_t}{\rho \Omega^3 d^2} \\
\Pi &= \frac{P_t}{\rho \Omega^3 d^2} \\
\eta_t &= \frac{\Pi}{\Psi \Phi}
\end{align}

The turbine mechanical efficiency can be understood as the fraction of power the turbine is capable to extract from the pneumatic power. It is obtained mathematically by rearranging equations 16 and 17:

\begin{equation}
P_t = \eta_t \Psi \Phi \rho_{at} d^5 \Omega^3
\end{equation}

The turbine is of diameter $d$, $\Omega$ is the rotational speed in rad/s. The aerodynamic torque provided by the turbine is then $T_t = P_t / \Omega$.

In the present numerical model, the variations of the stagnation air density at the turbine inlet were neglected. The characteristics of the turbine used in the model can be represented by the relation $\Phi = f(\Psi)$, and $\eta_t = f(\Psi)$. The biradial turbine is shown in Figure 4. Biradial turbine installation in the MWPP (a) and characteristic curves the day of its installation in the plant along with its characteristic curves used in the model.

A safety valve installed at the turbine inlet will operate in high energetic sea states to prevent the turbine from overspeeding. The axial vibrations in high rotational speed can damage the generator rotor. If the threshold of the cut-off speed $N_{co}$ is reached, the valve closes and blocks the air flow. This valve actuation control is common for all the studied control algorithms. When the valve is closed, the torque $T_g$ is applied at the generator following the control law to reduce the rotational speed until a cut-in speed $N_{ci}$. When this value is reached, the valve opens and the turbine operates normally.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-off speed</td>
<td>$N_{co}$</td>
<td>2500</td>
<td>rpm</td>
</tr>
<tr>
<td>Cut-in speed</td>
<td>$N_{ci}$</td>
<td>2200</td>
<td>rpm</td>
</tr>
</tbody>
</table>

### 2.3 ELECTRICAL GENERATOR MODEL

The selected generator to complete the PTO is an asynchronous induction generator, which characteristics are listed in Table 3. Generator specifications
proportional to the maximum torque. It is possible to
in the constant torque region, the current limit is
by its current and voltage limits. Below the nominal voltage
operational limitation of an induction generator is defined
with peaks of production during short periods of
time. The present paper
the turbine and generator
power in the shaft coming from the turbine and generator
efficiency \( \eta_g \) including all the losses during the conversion from
mechanical to electrical power. These losses include:
• Iron Losses
• Winding Losses
• Mechanical losses and others

The precise detail of each of the losses is out of the scope
of the present paper. However the applied parameters are,
depending on the source of the power loss:
• Iron Losses:
  ▪ Hysteresis and eddy current loss coefficients; 5.01
and 4.8 respectively
  ▪ Thickness of the iron core, 0.64 mm [29]
  ▪ Iron cores of stator and rotor total mass 60% of the
total generator mass
• Winding Losses: Stator resistance has been fitted with the equation (19). 

\[
R_{stat} = 72584 \cdot P_{nom}^{-1.236}
\]

• Mechanical Losses have been fitted to those provided in [30].

The generator output power is computed considering, input
power in the shaft coming from the turbine and generator
efficiency \( \eta_g \). Besides, it can be expressed in
electrical terms with the line voltage \( v \) and current \( i \) and the
power factor which represents the phase shift \( \phi \) between
both.

\[
P_g = \sqrt{3} \cdot v \cdot i \cdot \cos \phi
\]

Due to the intrinsic nature of wave energy, the generator
will have to be operated over its rated capacity and deal
with peaks of production during short periods of time. The
operational limitation of an induction generator is defined
by its current and voltage limits. Below the nominal voltage
in the constant torque region, the current limit is
proportional to the maximum torque. It is possible to
operate a generator at maximum current periodically
keeping in mind that the temperature of the windings will
rise and cannot reach a certain threshold. Over the
nominal voltage the generator enters the flux-weakening
region, Figure 5. In the current configuration, the generator
is connected to a frequency converter which rated voltage
is \( V_{PE,nom} = 690V \). This configuration allows an overspeed
of the generator and shifts the voltage limit to a threshold:

\[
N_{os} = \frac{V_{PE,nom}}{V_{nom}} \cdot N_{nom}
\]

Theoretically, the maximal instantaneous generator power
peak can be expressed with the parameters of Table 3 as:

\[
P_{g,max} = \eta_g N_{os} M_{mm} T_{nom} \approx 100 \text{ kW}
\]

During operation close to the maximum power, the
practical generator limitation is the Class H insulation
standard stating the maximum temperature around 180°C.
If overheated the insulation of the windings could be
damaged. In practice the generator thermal behaviour has
to be carefully monitored and the production stopped
before reaching high temperatures. No thermal model has
been included in the generator model.

### 3 OWC CONTROL LAWS

Five control laws (CL) have been implemented into the
numerical model introduced in section 2. Additionally, a
base case has been simulated with constant speed so that
it is equivalent to the commonly known linearized constant
damping case per sea state. Control laws are developed in
this section specifying its theoretical basis as well as its
working principles and ranges. They all aim at controlling
the turbine-generator set rotational speed. It is the sum of
all the torques acting on the shaft over its inertia, and is
described such as:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>( P_{nom} )</td>
<td>30</td>
<td>kW</td>
</tr>
<tr>
<td>Rated torque</td>
<td>( T_{nom} )</td>
<td>190</td>
<td>Nm</td>
</tr>
<tr>
<td>Rated speed</td>
<td>( N_{nom} )</td>
<td>1500</td>
<td>rpm</td>
</tr>
<tr>
<td>Pairs of Poles</td>
<td>( N_{pp} )</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Max/Nom torque ratio</td>
<td>( M_{mm} )</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>( V_{nom} )</td>
<td>400</td>
<td>V</td>
</tr>
<tr>
<td>Frequency</td>
<td>( f_n )</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Runaway speed</td>
<td>( N_{run} )</td>
<td>4500</td>
<td>rpm</td>
</tr>
<tr>
<td>Insulation class</td>
<td>-</td>
<td>Class H (180°C)</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>( W_{kg} )</td>
<td>250</td>
<td>kg</td>
</tr>
</tbody>
</table>
The resistive torque \( T_{\text{res}} \) is the sum of the controlled torque \( T_{\text{ref}} \) and the torque losses calculated from the generator efficiency.

### 3.1 CL0: TURBINE CONSTANT SPEED

The base case scenario, serving as comparison for all the CL, uses a feedback PI-controller which follows a reference rotational speed for each sea state so that the turbine spins at a constant speed. As a matter of fact, there is no acceleration (eq. 23). These reference speed are obtained by the methodology described in [19]. It consists of an offline optimisation that finds the best fixed speed for a sea state generating the highest mechanical average power. In high sea states – SS11 to 14 – the optimal speed exceeds the maximum generator speed, which is also the cut-off speed forcing the valve to close (c.f. Table 2). Operation of the safety valve). During these sea states, the reference speeds are set to 250 rad/s that is the generator maximum available speed.

### 3.2 CL1: GENERATOR TORQUE CONTROL BASED ON ROTATIONAL SPEED

The CL1 control law is based on simple evidence that over a long time average, the power of the turbine is equal to the generator electromagnetic power. If the turbine operates at the best efficiency point, \( \eta_{\text{t, max}} \) in the characteristic curves Fig. 4b, then based on eq. 18:

\[
(24) \quad P_t = \eta_{\text{t, max}} \Psi_{\text{opt}} \Phi_{\text{opt}} \rho_{\text{at}} d^2 \Omega^3 = \text{const} \Omega^3
\]

Based on this equation, the following control law has been proposed (see [2] for further details):

\[
(25) \quad P_{\text{gen}} = \min(a \Omega^b, P_{\text{rated}})
\]

where \( a \) and \( b \) are two constants depending on the hydrodynamics and turbine geometry but not on the wave climate. The previous equation yields the following generator torque law:

\[
(26) \quad T_{\text{ref}} = \min\left(a \Omega^{b-1}, \frac{P_{\text{rated}}}{\Omega}\right)
\]

This type of law has been used with success for more than 18 years at the Pico power plant in the Azores archipelago [7-8].

### 3.3 CL2: GENERATOR TORQUE CONTROL BASED ON CHAMBER PRESSURE

The CL2 control law is based on evidence that for a given pressure drop across the turbine a maximum fixed pneumatic-to-mechanical conversion efficiency can be determined using equations (14-18). If the turbine operates at the best efficiency point, \( \eta_{\text{t, max}} \) as can be derived from Figure 4b, then:

\[
(27) \quad T_{\text{opt}} \approx \eta_{\text{t, max}} \Phi(\eta_{\text{max}}) d^3 \Delta p = \text{const} \Delta p
\]

where \( T_{\text{opt}} \) is the optimum torque head and power. The previous equation yields the following generator torque law:

\[
(28) \quad T_{\text{ref}} = k_0 + k_1 \Delta p
\]

where \( k_0 \) and \( k_1 \) are constant coefficients determined from experimental evaluation of turbine characteristics. As the pressure drop across the turbine can change drastically during the duration of a single wave, an average pressure value is used in the place of instantaneous pressure. Using average pressure in equation (28) allows for a more consistent power output, as well as less stress on the generator and power electronics. The average pressure value is taken from measurements within the plenum chamber and the resulting equation:

\[
(29) \quad T_{\text{ref}} = k_0 + k_1 \bar{P}_{\text{ch}}
\]

where \( \bar{P}_{\text{ch}} \) is the average of the absolute value of the chamber pressure. The value of \( \bar{P}_{\text{ch}} \) for these experiments is determined over a 5-minute moving average window. The length of the moving average window was selected to allow for a responsive, but deliberate, change in applied generator torque.

When applying CL2 in more energetic seas in initial simulations, overspeeding of the turbine occurred at a high frequency. To help mitigate this, a third term based on instantaneous was added to the algorithm. This third term was introduced to increase torque during high-pressure events to minimize fluctuations in turbine speed, and the resulting control law:

\[
(30) \quad T_{\text{ref}} = k_0 + k_1 \bar{P}_{\text{ch}} + k_2 (p_{\text{ch}} - \bar{P}_{\text{ch}})
\]

where \( p_{\text{ch}} \) is the instantaneous chamber pressure and and \( k_2 \) is a coefficient based on a percentage of the value of \( k_1 \) and sea state conditions, such that as available energy in the sea increases, the value of \( k_2 \) also increases.
3.4 CL3: REINFORCEMENT LEARNING

This control law is concerned with the application of Reinforcement Learning (RL) for the optimal control of an OWC. In RL, a control agent interacts with a controlled system by taking an action with a reward being recorded. The agent then might take a different action depending on the reward outcome leading the controlled system to move to a new state. The action selection process is modelled as a Markov decision process based on the value function, which expresses the estimate of the future reward. The agent is expected to learn an optimal behaviour over time for the maximization of the total reward [31]. The main advantage of using RL in controlling OWC is that it is an on-line, model-free algorithm which ensures that it can adapt to changes in the device hydrodynamics over time and is unbiased by modelling errors.

The output turbine power versus speed for different wave condition has the typical characteristic of a quadratic curve and can be obtained analytically such as

\[(31)\quad P_{opt} = \alpha \Omega^\beta\]

where the coefficients (\(\alpha\) and \(\beta\)) can be found using an off-line optimisation technique based on the W2W model or via the methodology used in CL1. In CL3, RL is used to find the optimal operation curve on-line and hence allow the system to adapt to operational (sea states) while being independent of the system model and its associated uncertainties.

RL is implemented to find the optimal curve relating maximum power and turbine speed by measuring the output generator power and adapt the generator torque without relying on the numerical model. The control law governed by eq. (31) can only produce maximum power if the optimised coefficients and the hydrodynamic model are all accurate. In addition, other control requirements such as limited power or limited speed can be integrated into the RL controller by introducing a penalty to the agent if any of the limits are violated.

3.5 CL4: PREDICTIVE GENERATOR TORQUE CONTROL

The aim of this non-linear predictive controller is to maximise the turbine-generator efficiency so the turbine is at its optimal point of operation. The proposed strategy computes the optimal resistive torque \(T_{ref} = a \Omega^{b-1}\) taking the overall power conversion into account in the optimisation process. During the prediction horizon, it optimally computes the best configuration of the slope and exponent parameters, and constitutes the control vector \(u = [a, b]\) which parameterises the control law that is applied during the re-planning time. The prediction horizon is set to twice the re-planning which is half a wave period. In this case we assume an ideal wave force forecasting.

The optimisation algorithm tends to maximise the cost function in eq. (32). It includes the turbine and the generator powers in order to include both efficiencies and constraints especially on the generator maximal extractible torque. The parameters \(\alpha_j\) and \(\beta_j\) are weighting parameters that allows setting priority to power absorption, or power conversion to electricity.

\[(32)\quad max J = \sum \alpha_j P_t + \beta_j P_g\]

A sensitivity analysis to define the values of these weights has been performed and the results is presented in Figure 6. It results that a higher weight is needed for the turbine power as its efficiency is more critical in comparison with the generator one. The improvements are shown as normalised values in respect with the worst case. As can be seen, the optimal values are \(\alpha_j = 90\%\) and \(\beta_j = 10\%\).

![Figure 6. Comparison of improvement for several combinations of \(\alpha_j\) and \(\beta_j\)](image)

Restriction on the generator maximal torque and the turbine threshold speed for the valve actuation are considered in the numerical model running the optimisation.

4 SIMULATION RESULTS

Simulations have been carried out with hydrodynamics and PTO modelled using the W2W model over a simulation of 1/2h which statistically represents a sea state. Results were obtained for all introduced control strategies in a set of 14 irregular sea states characterised by their significant wave height \(H_s\), peak period \(T_p\) and yearly occurrence \(OCC_{50}\) (see [1]). The defined characteristics of these sea states are presented in next table.
energy production AEP s

The following data from the Bilbao buoy April 2014 and correlated observed data from an ADCP installed by AZTI with the depth fitted (33) formulation was the effect of depth assuming non-modification of the JONSWAP spectrum a custom TMA spectrum approach. The spectrum has been developed taking into account the resource, a customised wave function used in the model that includes breaking waves. The waves have been modelled using the JONSWAP spectrum [13], which is a modification of the JONSWAP spectrum that includes the effect of depth assuming non-breaking waves. The formulation was the following:

\[ S_{TMA}(\omega) = S_{JONSWAP}(\omega) \Phi_{fct}(\omega, h) \]

In order to model the resource, a customised wave spectrum has been developed taking into account the effect of finite depth. The waves have been modelled using a custom TMA spectrum approach [32], [33], which is a modification of the JONSWAP spectrum [13] that includes the effect of depth assuming non-breaking waves. The formulation was the following:

\[ S_{TMA}(\omega) = S_{JONSWAP}(\omega) \Phi_{fct}(\omega, h) \]

In Figure 7, the \( \Phi_{fct}(\omega, h) \) function used in the model - Phi fitted - is not the theoretical one \( \Phi_{TMA}(\omega, h) \) parametrised with the depth in front of the MWPP wall. Instead, it uses observed data from an ADCP installed by AZTI Tecnalia in April 2014 and correlated for each wave frequency with data from the Bilbao buoy.

During low energetic sea states, the generator losses as such that energy production is very little. On the other side in high energetic seas the generator is stressed showing peaks near the maximum associated with a high standard deviation that reflects a high occurrence of those peaks away from the average electrical power.

In Figure 8 is a plot of the time series of torques and rotational speeds computed from each CL during operation in the condition of sea state 10. CL0 present the highest torque variations because the rotational speed is kept constant by the controller. Thus the generated power has the same shape as the turbine power, with no production each half wave. The other CL are all variable speed controls and enable smoothing of the output power because it makes use of the drivetrain inertia (eq. 23). The behaviour of the torque calculated in CL1 is very specific to this law that limits the output power to nominal values. When the torque demand is reaching values close to nominal, the final applied torque shows an inflexion. The shape of the time series in CL2 presents more variations because it is based on pressure variations. Looking at CL4, the torque demand presents jumps and drops. This means that a new set of optimal \([a, b]\) in the torque law are applied. In CL3, the torque is the highest, which traduces by the

<table>
<thead>
<tr>
<th>SS</th>
<th>Hs [m]</th>
<th>Tp [s]</th>
<th>Occ %</th>
</tr>
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<td>1.02</td>
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<td>6.11</td>
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<td>1.08</td>
<td>9.5</td>
<td>10.73</td>
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<td>10.5</td>
<td>9.31</td>
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<td>11.5</td>
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<tr>
<td>14</td>
<td>3.2</td>
<td>12.5</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Total 62.98%

Table 4. Mutriku sea states

\[
AEP_{SS} = \bar{P}_{elec} \cdot \text{OccSS} \cdot 8760 \text{ MWh}
\]

Table 5. Performance of CL0 fixed-speed controller

<table>
<thead>
<tr>
<th>SS</th>
<th>Average Power (kW)</th>
<th>Electrical power</th>
<th>Ref. ( \bar{\Omega} ) (rad/s)</th>
<th>AEP MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pneu.</td>
<td>Mech.</td>
<td>Elec.</td>
<td>Peak</td>
</tr>
<tr>
<td>1</td>
<td>1.36</td>
<td>0.50</td>
<td>0.03</td>
<td>0.09</td>
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<td>2</td>
<td>1.47</td>
<td>0.67</td>
<td>0.16</td>
<td>1.72</td>
</tr>
<tr>
<td>3</td>
<td>1.81</td>
<td>1.16</td>
<td>0.59</td>
<td>8.78</td>
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<tr>
<td>4</td>
<td>2.58</td>
<td>1.76</td>
<td>1.05</td>
<td>17.91</td>
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<tr>
<td>5</td>
<td>4.22</td>
<td>3.00</td>
<td>1.97</td>
<td>27.13</td>
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<tr>
<td>6</td>
<td>6.13</td>
<td>4.41</td>
<td>3.05</td>
<td>33.99</td>
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<tr>
<td>7</td>
<td>7.83</td>
<td>5.60</td>
<td>4.07</td>
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<td>8</td>
<td>10.47</td>
<td>7.51</td>
<td>5.68</td>
<td>50.45</td>
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<tr>
<td>9</td>
<td>14.73</td>
<td>10.63</td>
<td>8.32</td>
<td>68.51</td>
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<tr>
<td>10</td>
<td>18.10</td>
<td>13.11</td>
<td>10.33</td>
<td>76.08</td>
</tr>
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<td>11</td>
<td>24.88</td>
<td>17.89</td>
<td>14.86</td>
<td>95.76</td>
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<td>12</td>
<td>26.74</td>
<td>19.09</td>
<td>15.95</td>
<td>96.81</td>
</tr>
<tr>
<td>13</td>
<td>31.77</td>
<td>22.45</td>
<td>18.56</td>
<td>97.32</td>
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<tr>
<td>14</td>
<td>35.16</td>
<td>24.73</td>
<td>20.62</td>
<td>97.39</td>
</tr>
<tr>
<td></td>
<td>20.48</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following table sums up the production of the base case fixed speed control strategy. The yearly electrical energy production AEP stands for the average electrical power in function of the occurrence of each sea states (c.f. Table 4). It ideally assumes the plant is available 100% of the time, i.e. 8760 hours, and was computed such that:

\[
AEP_{SS} = \bar{P}_{elec} \cdot \text{OccSS} \cdot 8760 \text{ MWh}
\]

![Figure 7. Comparison of \( \Phi \)-functions](image-url)
lowest speed values. The speeds in CL1 and CL2 reaches several times the cut-off speed for valve actuation which traduces by a loss a power extraction.

Figure 9 presents the results of numerical simulations performed for all the CL upon 3 criteria corresponding to production performance measuring the AEP but also reliability and power quality issues. The instantaneous electrical power peak measured at the generator allows to assessing the CL in terms of reliability issues. An algorithm permitting the generator to reach the maximal power as explained in eq. (22) will penalise the life of the equipment. This analysis is completed by including the standard deviation of the generated power aiming at knowing how much the generator is operated over its average capacity. A high number represents more risk of damaging the generator and power electronic.

5 ANALYSIS AND DISCUSSIONS

A comparison of a statistical analysis from simulation results between each control law with respect to the constant speed CL0 has been assessed in Figure 9 pointing at the benefits and drawbacks of each of them. In terms of yearly energy production, CL1 produced almost the same than the base case scenario. Due to the small standard deviation of this strategy, for low energy sea states, the generator is always operating at low efficiency points. For high energetic ones, the upper limit in the instantaneous generator power (eq. 25), increases the rotational speed of the turbine and decreases the pressure. It results in a small decrease of the AEP in comparison with the other laws. However, the generator is never overloaded. CL2 performed better than the base case only during the lowest energy sea state conditions, though losses in the mid-energy seas were minor. CL3 obtained the 2nd highest global energy production, where the gains are focused on very low and medium energetic sea states. The highest improvement in terms of AEP was achieved by CL4 in every SS, expect for SS3 and 4, which increased a 5.40% in respect to the base case.

The true benefit of CL1 relies in reliability concerns as in none of the sea states the generator is overloaded. This means a longer equipment life and hence higher availability without compromising the AEP. CL2 had lower electrical power peaks than the base case in all conditions reaching twice the rated power. Under higher energy sea state conditions, it had a heavy reliance on the safety valve in order to protect the generator from overspeed conditions. Power peaks in high wave conditions reached twice the generator nominal power in CL3, still being better than the base case. CL4 was the worst case for generator stresses, where peak levels similar to the base case are produced.

Observing the electrical output power standard deviation, all algorithms performed better than CL0. This benefit is obtained by the torque controllers allowing variable rotational speed. CL1 offered the best power quality score showing values up to 3 times lower as the base case. It is important for producing power safe for injection to the local grid. In what concerns output power levels, a good score was obtained for CL3 showing electrical power standard deviation values between CL1 and CL2. Although CL4 produced the highest power peaks, the power variations were typically half of the base case.

In a word, CL1 is to be preferred for keeping highest generator availability while keeping a fairly good overall energy production. It should be noted that parameters $a$ and $b$ used in the methodology are not depend on the device hydrodynamics but only on the turbine characteristics. CL2 can be a good method to control the turbine and generator system at lower energy sea state
conditions. However, at higher-energy sea state conditions, it does not effectively protect the equipment, nor does the control law show increase in conversion efficiency when compared to other control laws tested during the simulations. Reinforcement Learning control may deliver slightly better performance than other controllers but has its real advantage in long-term application. Because the approach is model-free and continuously re-learns the optimal control parameters, it is expected that the control can perform well even in the face of performance degradation of the components (facilities, turbine, generator) over time. CL4 obtained the best score in terms of AEP, obtained from extracting more energy at wave power peaks and allowing the electrical equipment to reaching maximal risky operation range. In that case, a reliable thermal model is strongly advised to avoid overheating and possible failures. To avoid overloading the generator, this algorithm can include restrictions in the optimisation process which will strongly improve the reliability score in exchange to a lower overall production. Because it is a predictive controller, a wave force forecasting model is needed and will be included in future works.

As an overall analysis, the biradial turbine is not very sensitive to changes in speed and the operation range is such that any of controllers could reach high turbine efficiency range. That is one greatest advantages over the Wells turbines, and it easily explained by the “soft” decay of efficiency for values of $\Psi$ higher that the point of maximum efficiency.

### Table 6. Energy production comparison

<table>
<thead>
<tr>
<th>Sea State</th>
<th>CL0 kWh</th>
<th>CL1 kWh</th>
<th>CL2 kWh</th>
<th>CL3 kWh</th>
<th>CL4 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>48</td>
<td>95</td>
<td>77</td>
<td>96</td>
<td>111</td>
</tr>
<tr>
<td>8</td>
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<td>3 856</td>
<td>3 559</td>
<td>3 908</td>
<td>3 900</td>
</tr>
<tr>
<td>14</td>
<td>759</td>
<td>612</td>
<td>683</td>
<td>707</td>
<td>808</td>
</tr>
<tr>
<td>Total (MWh)</td>
<td>20.48</td>
<td>20.56</td>
<td>19.53</td>
<td>21.00</td>
<td>21.59</td>
</tr>
</tbody>
</table>

### 6 CONCLUSIONS

The aim of this paper is to present and compare several real-time control algorithms to control the biradial turbine designed and developed within the OPERA H2020 project. In this study, a numerical model of one chamber of the Mutriku wave power plant has been modelled along with its PTO system. The algorithms are presented and the performance results assessed and in terms of production, reliability and power quality. A comparison in respect to a constant speed base case scenario is provided for all the control laws so their benefits and drawbacks are known. Future works include the experimental validation of the control strategies using Hardware-in-the-Loop test rig. Furthermore, the final objective is to test them during real sea trials to control the biradial turbine installed in one chamber of the Mutriku plant in the framework of the OPERA project.

Figure 9. Comparison of energy production (top), electrical power peak (middle) and standard deviation of electrical power (bottom) as a function of the sea states
AKNOWLEDGMENTS

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REFERENCES


