Technical Assessment of Wave Energy in Portugal

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Abstract—The ocean waves have a high potential to become a reference among the renewable energies with economic viability. In recent years this source of energy has led to a growing interest from the scientific community, as well as studies and technological developments on the issue which have been more frequent with greater detail. However, despite this growth, there remains some difficulty in the perception by the general public of this potential as well, some work to do by the governments and the industry to push this technology to the front lines. In this sense, this paper aims to bring light to this "new" form of energy by assessing and characterizing the marine resource, presenting the most used methods for extraction of wave energy, understand how they work in general and one of them (Oscillating Water Column - OWC) in particular, quantify the energy that we can harness through the OWC system and model it in MATLAB/Simulink® environment.

Index Terms— Doubly Fed Induction Generator, Oscillating Water Column, Wave energy, Wells turbine

I. INTRODUCTION

The occupancy percentage of the oceans on Earth's surface makes them the largest concentrator of solar energy. Solar energy is characterized as the source of all energies, giving rise to thermal gradients, tidal currents, tides, winds and waves. Oceans cover about 71% of the earth's surface and thus represent an extremely abundant energy resource with the potential to meet a large percentage of energy the world needs. In recent years there has been a resurgence of the interest in wave energy in general and particularly in Europe. The use of this form of energy has the potential to supply several European countries such as Ireland, UK, Denmark, Portugal, Spain and others. Worldwide, the technical assessment of the production potential of energy from the oceans, is about 100 000 TWh/year [1]. Once created, the waves can travel thousands of miles at sea without significant energy losses, only decreasing in intensity as they approach the coast due to interaction with the seabed. Also, the waves are a regular source of energy whose intensity can be predicted several days in advance before their arrival, being inclusive, more predictable than wind and solar energy.

The Portuguese coast has privileged conditions for the development and utilization of wave energy. It is estimated that the resource available in Portugal is about 300 GW. In Portugal it is estimated that the available resource to be about 15 GW and 6 GW for the Autonomous Regions [2]. Portugal is located in a region whose oceanic resource is considered high average, where the average annual value of wave power is about 40 kW/m. Beyond the resource potential should be highlighted also, the favorable weather conditions, the existence of connection points to the electric grid along the coast, relatively deep water near the coast and tradition in the marine industry with good infrastructure located near the potential sites of installation of conversion parks, of wave energy into electricity.

II. WAVES AND WAVE ENERGY CONVERTERS

To better understand the process of harnessing wave energy we should first clarify some of its main properties. The dominant factors in the waves formation, are the depth and the toponography of the sea floor, the water distance on which the wind blows (known as fetch) as well its speed, being this later the dominant factor. The mathematical description of periodic progressive waves is complicated. Some authors have recommended ranges of application of the various wave theories. Therefore, a number of regular wave theories have been developed to describe the water particle kinematics associated with ocean waves of varying degrees of complexity. Fortunately, the earliest (and simplest) description, attributed to Airy in 1845, is sufficiently accurate for many engineering purposes. This linear wave theory describes ocean waves as simple sinusoidal waves. The part of the wave profile with the maximum elevation above the mean water level (MWL) is called the wave crest, and the part of the wave profile with the lowest depression is the wave trough.

The wavelength (λ) of a regular wave at any depth is the horizontal distance between successive points of equal amplitude and phase (for example, from crest to crest, or trough to trough), and the wave height (H) is defined as the total distance from the trough to the crest. The wave period is the time interval that a wave takes to cross the zero point three times in a row and the wave amplitude (a) is half the height i.e. is the vertical distance between the wave crest and the MWL. The characterization of the sea state for a given location, using the statistical analysis, is given by the significant wave height (Hs or H1/3) and a wave period. If the time series is analyzed statistically, is usual to use the average...
wave period \((T_w)\) but if the spectrum of sea conditions is obtained by measurements at sea, it is used the energy period \((T_e)\). The significant wave height, \(H_{rms}\) (m), is derived from statistical analysis and represents the average of one third of the highest waves analyzed during a time interval \([4]\). To determine the characteristics of the wave energy devices, the most widely used parameters are the mean square value of the wave height, \(H_{rms}\) or the significant wave height \((H_s, H_s \approx 4H_{rms})\) and the energy period \((T_e)\).

The depth of the water plays an important role in the trajectory of the water particles. The movement of the water particles is circular in deep waters and becomes more horizontal as the depth diminishes. The depth also affect the group velocity of the wave, its energy and height as they approach the shore.

The group velocity, defined as the velocity of a wave group moving together, is used to represent the motion of the waves energy and tends to be slower than the wave speed \([4]\). The wave propagation velocity decreases with the decreasing depth and hence also the wavelength decreases according to the following equation:

\[
\lambda = \frac{\omega}{k} = \frac{\lambda}{\pi} \tag{1}
\]

The specific energy per unit area \((E_s)\), contained in a wave is given by:

\[
E_s = \frac{1}{8} \rho_{\text{agua}} g H^2 \tag{2}
\]

Where, \(\rho_{\text{agua}}\) is the density of the sea water \([kg/m^3]\) and \(g\) the acceleration of gravity \([m/s^2]\). The power of the wave is the combination of the potential and kinetic energy from the waves moving with velocity equal to the group velocity perpendicular to the wave front. Typically, the power transported by sea waves is measured in kilowatt by wave front meter (kW/m).

For regular waves, in deep waters, its output per unit length of the wave front \((w/m)\) is given by \([4]\):

\[
P_w = \frac{1}{2} C_g \rho_{\text{agua}} g H^2 \tag{3}
\]

For irregular waves, in deep waters, its output per unit length of the wave front \((w/m)\) is given by \([5]\):

\[
P_w = \frac{1}{2} C_g \rho_{\text{agua}} g H^2 \tag{4}
\]

Over the years, various kinds of WECs have been developed. There is currently about 100 kinds of wave energy extraction systems which can be found in \([6]\). Despite the wide variety of designed systems, it remains unclear what the winning technical approach will be and only a few have achieved the development phase of implementation in real sea. This is due to the great constraints that this technology faces, as the existence of seas typically irregular in amplitude, phase and direction, the need to predict storms and extreme states, the more efficient operation in locations far away from the coast and consequently, the higher costs of development and installation, integration difficulties with electrical machines etc. This way, it will be presented only the most studied models which are currently implemented.

A. Oscillating Water Column (OWC)

The Oscillating Water Column (OWC) was one of the first systems developed to exploit the wave energy. The OWC operating principle, is based on the transformation of the wave movement into pneumatic energy. This pneumatic energy can be converted into mechanical energy with the use of a turbine which, in turn, is used to drive an induction generator \([1]\). The OWC has a portion of the chamber structure submerge, with an opening, through which the sea enters and causes the air compression. The turbine in turn, is installed above the interaction zone between sea and air as you can see in figure \(2\).

A OWC system can be a fixed system, built in a coastal zone for example, which has some advantages like easy maintenance and installation, or can be floating and in that case will be located offshore. The first type of OWC (coastal), is considered the first generation system as it was the first to be produced and installed in reality. Since 1985, several prototypes were installed in countries like Norway, India, Japan, the UK and Portugal (Azores). The plant on the island of Pico, built between 1995 and 1999 was pioneer in the world to introduce electric energy generated from sea waves in a power system. One of the disadvantages of fixed OWC systems, is the low level energy characteristic of shallow waters, compared to the high energy level of deep waters. In this regard, it were developed OWC floating systems to take advantage of zones of greater depth, that enable higher levels of energy.

\[
\begin{align*}
\text{Figure 2 - OWC scheme [3].}
\end{align*}
\]
wave park) before connecting to the submarine cable, which is static on the seabed.

C. Wave Dragon

Wave Dragon is a floating wave energy converter, designed to be installed in more than 20 meters depths [9]. Its operation principle is based on the already known and proven method, of hydroelectric power plants operation. Basically consists of two steel or concrete structures that reflect the waves and concentrate the incident wave to a ramp with double curvature (elliptical and circular). Part of the water that is transported by the incident wave, climbs the ramp and is temporarily stored in a large reservoir raised above the average level of the free surface of the sea. The stored water is then released to drive the energy extraction system, constituted by turbines.

D. WaveRoller

The WaveRoller device was developed by AW-Energy's. Consists of a hinge plate, anchored in the seabed at depths of moderate water (up to 20 m) and oriented perpendicular to the direction of propagation of the waves, oscillating like a pendulum, reversed due to the motion of the water particles. The kinetic energy generated by the oscillatory motion described by the hinge plate is used to produce electricity, using pistons coupled to an electric generator. There is currently, a wave farm in Portugal (Peniche) installed at 900 meters from the coast, constituted by three units of 100 kW each, connected to the electrical grid.

E. Archimedes Wave Swing (AWS)

The Archimedes Wave Swing (AWS) is a system developed by Teamwork Technology BV (NL) [12]. Its operation is based on a submerged hollow steel structure, consisting of two concentric cylinders whose relative movement between them is created by the incident wave action. The lower cylinder is fixed to the seabed while the upper one moves vertically. In its interior, the air is pressurized to a point such that it balances the weight exerted by the water column on the outer upper structure. When the crest of a wave approaches, the hydrostatic pressure increases on top of the structure, forcing the top cylinder to compress the air within until it reach a balance. The reverse happens when the trough of the wave passes and the cylinder expands. The relative linear motion between the cylinders, is converted into electricity through the power extraction (PTO) system. From this linear movement is possible to directly produce electricity using a linear electric generator.

III. OWC SYSTEM COMPONENTS

In the OWC analysis and in the Simulink model, the OWC system was divided in 3 major components; the pneumatic chamber, the Wells turbine and the induction machine.

A. Pneumatic chamber

The pneumatic chamber is the element of the OWC system which establishes the relationship between the hydrodynamic and aerodynamic field via the free water surface by which its vertical oscillatory motion causes a pressure change. This chamber also prevents the PTO engine to make direct contact with the harsh sea waves and mitigates the impact of storms on the complete system. The interactions within the chamber, are somewhat complex to analyze to the extent that, the turbine characteristics affect the response of the chamber which in turn influences the hydrodynamics of the device and vice versa. So it was tried to model the behavior of the pneumatic chamber in a simple way to avoid relatively time-consuming simulations. To do this, based on [13], it was assumed that the maximum amplitude variation of the air pressure (Pa) within the pneumatic chamber of the OWC for each sea state, could be modeled by the following expression:

$$\Delta P = \frac{8 \pi \rho \omega^2 H^2 \delta}{\lambda^2 A}$$  \hspace{1cm} (5)
• \( \rho_{\text{water}} \): Density of sea water = 1025 \([\text{kg/m}^3]\)  
• \( v_{\text{wave}} \): Speed of wave propagation \([\text{m/s}]\)  
• \( H \): Wave height \([\text{m}]\)  
• \( r_{\text{duct}} \): Duct radius \(\approx 1,15[\text{m}]\)  
• \( \lambda \): Wavelength \([\text{m}]\)  
• \( A \): The cross-sectional area of the duct = 4,15 \([\text{m}^2]\)

In order to provide a pulsating characteristic to the pressure variation, it was defined that their amplitude behaves like a sinusoid and because of the unidirectional direction of rotation of the turbine, becomes possible to use the absolute value.

This approach is not very far from reality, as shown by figure 7:

![Figure 7 - Pressure variation in Pico pneumatic chamber registered by three sensors](Image)

**B. Wells turbine**

The Wells turbine was invented by Prof. A. A. Wells in the mid-1970s and has been deeply studied and internationally recognized as the most suitable for equipping OWC systems. This kind of turbine has a robust and simple symmetrical blade design, which means that it always rotates in the same direction, regardless of the direction of the airflow through the turbine, so that no device is needed to rectify the airflow. In the study of the turbines is common to use dimensionless coefficients for their characterization. The advantage of these coefficients results from the fact that by the proper combination of physical variables important in the operation of the turbine, it’s possible to compare geometrically similar machines irrespective of their size and rotation speed. The turbine is subjected to a pressure drop \( \Delta P_t = p - p_v \) where \( p_v \) is the pressure loss which occurs in the valve in series (if the valve is fully closed or does not exist, \( p_v = 0 \)). The characteristics of the Wells turbine can be written in dimensionless form by [15]:

\[
\phi = \frac{Q_t}{\rho_{\text{air}} w_m D^2} 
\]

\[
\Psi = \frac{\Delta P_t}{\rho_{\text{air}} w_m D^2} 
\]

\[
\Pi = \frac{P_{\text{mec}}}{\rho_{\text{air}} w_m D^2} = \frac{T_m}{\rho_{\text{air}} w_m D^2} 
\]

The equations (6), (7) and (8) give, respectively, the dimensionless coefficient of flow, pressure and power in a given geometric configuration where \( D \) is the outer diameter of the turbine rotor (in our case it will be equal to 2,3 meters), \( w_m \) is the rotation speed expressed in radians per second, \( \rho_{\text{air}} \) is the specific air density \( (1,225 \text{ kg/m}^3) \), \( Q_t \) and \( \Delta P_t \) are, respectively, the flow rate and the pressure \([\text{Pa}]\) difference to which the turbine is liable. \( P_{\text{mec}} \) is the mechanical power \([\text{W}]\) developed by the turbine and \( T_m \) the turbine mechanical torque \([\text{Nm}]\). As it may be observed in the equations (6), (7) and (8), in this type of turbine the power and torque developed can be computed based on the power coefficient and the torque coefficient respectively, whose relationship against the pressure coefficient, composes a characteristic curve of the Wells turbine under study. For our model we will use the curves obtained in laboratory tests given by [15] where it can be seen (figure 8) that the dimensionless power coefficient, \( \Pi \), has a maximum for a given value \( \Psi \) known as \( \Psi_{\text{crit}} \).

![Figure 8 - Characteristic curve of the power coefficient as a function of the pressure coefficient](Image)

Thus, when \( |\Psi| = \Psi_{\text{crit}} \), the mechanical power, \( P_{\text{mec}} \), has a maximum value for a given speed of rotation, \( w_m \). It is appropriate to limit the amount of pressure which the turbine has to support, preventing that \( |\Delta P| \) exceeds a critical value \( (p_{\text{crit}}) \), from which may endanger equipment. If \( \Psi > \Psi_{\text{crit}} \), the turbine suffers aerodynamic losses, i.e. for a given rotational speed, the power decreases rapidly with increasing magnitude of the pressure drop to which is subject the turbine. This known behavior of the Wells turbine, is known as stall effect and according to the performance curve (Figure 8), our \( \Psi_{\text{crit}} \) is approximately 0.065. From [15] it is known that the pressure drop is proportional to the flow rate with a proportionality constant of 99 \text{ Pa s kg}^{-1} \text{ and the value of the critical pressure corresponds approximately to } p_{\text{crit}} = 10,5 \text{ kPa}.

**C. Generator**

The power input of the turbine is a parameter that varies both in short term (waves fluctuations) as in long term (sea conditions), which leads to fluctuations in the power delivered by the generator to the grid. Furthermore, the power drawn by the system is also affected by the stall effect of the Wells turbine. This behavior force the implementation of control measures which helps to attenuates these fluctuations. The air velocity that drives the turbine is variable due to the sea waves, so in order to use the most of the available energy in each moment, the turbine must adjust to the incoming air flow conditions. This is achieved by adjusting the blades of the
turbine and / or by varying the rotational speed of the turbine [3] [16]. In our case the turbine geometry is rigid, so the adaptation to the conditions of the sea must be made from the variation of the rotation speed. The stall effect can be avoided if the turbine accelerates fast enough in response to the incoming air flow, which can be achieved by modifying the torque/slip characteristics of the generator, allowing the system to reach higher speeds. The average speed of the turbine-generator group determines the power delivered to the network and depends on the available power in sea waves. If the available power is low, then the system will operate at a lower speed, running at a higher speed if higher wave power is available. This implies that the generator to be used in network connection, should be a variable speed type. The generator typically used in OWC systems is the doubly fed induction machine (DFIG). The DFIG is directly connected to the network through the stator, while the rotor is connected to the grid through a variable-frequency converter (VFC) which usually, is only required to handle a fraction (25%-30%) of the nominal power to achieve total control of the generator. The VFC consists of two four-quadrant IGBT PWM converters ( rotor side converter -RSC- and grid side converter -GSC-) connected back-to-back by a dc-link capacitor. The dc-link allows bi-directional power flow between the machine's rotor circuit and the grid, providing thus the decoupling between the two AC sides, which are at different frequencies. Furthermore, there is also a RL filter on the network side which mitigates the harmonics in the current due to the switching converter. The GSC controls the DC voltage and the reactive power exchanged with the network. Its aims to keep the capacitor voltage constant regardless of the amplitude and phase of the rotor power. The RSC function, is to control the active and reactive power of the generator. The active and reactive power of the stator can be controlled separately if the rotor current is controlled in the stator flux reference [17]. Usually the turbo generator module also includes a flywheel in order to smooth the output power curve.

D. Rotational Speed Control

The electrical equations of the DFIG, can be simplified using the field-oriented-control.

1) GSC - Grid Side Converter

So for the GSC, the switching strategy is based on current vector control in d-q coordinates (with the grid voltage as reference) using proportional integral controllers (PIs). To perform the control of the GSC, becomes necessary to measure the grid voltage, line currents and the DC voltage. It’s also needed a phase locked loop (PLL) to track the phase of the grid voltage, necessary for the application of coordinate transformation. With the axes transformation of abc-to-dq, the quantities (voltages and currents) change from a stationary system of axes to a rotating system of axes at synchronous speed. This yields the following relationships [17] [18].

\[
\begin{align*}
    v_d & = R_{L1}i_d + L_{L1} \frac{di_d}{dt} - w_L R_{L1}i_q + v_{d1} \\
    v_q & = R_{L1}i_q + L_{L1} \frac{di_q}{dt} + w_L R_{L1}i_d + v_{q1}
\end{align*}
\]  

In (9), \(v_d\) and \(v_q\) are the network voltages in d-q coordinates, \(v_{d1}\) and \(v_{q1}\) are the voltages in d-q coordinates generated by the GSC, \(i_d\) e \(i_q\) the output currents of the GSC, \(w_L\) the synchronous speed and \(R_L, L_{RL}\) the RL filter on the network side, responsible for mitigating the harmonic currents from the GSC. The control oriented by the grid voltage must be applied so that the grid voltage space vector, is fully aligned on the d axis resulting:

\[
\begin{align*}
    v_d &= V_g \\
    v_q &= 0
\end{align*}
\]  

Where \(V_g\) is the RMS grid voltage. The powers of the AC side are given by:

\[
\begin{align*}
    p &= \frac{3}{2} v_d i_d \\
    q &= \frac{3}{2} v_d i_q
\end{align*}
\]  

From (11), it can be seen that the active and reactive powers of the GSC can be controlled through the currents \(i_d\) and \(i_q\) respectively. The relation between the grid voltage and \(V_{dc}\), mediated by the converter, can be given by:

\[
v_d = \frac{\sqrt{3} m_{d1}}{2 \sqrt{2}} V_{dc}
\]  

Applying the Laplace transform in \(v_d\) and \(v_{q1}\), and doing algebraic manipulations, we obtain the Transfer Function (TF) of the current control loops, given by:

\[
FT(s) = \frac{I_d(s)}{V_d(s)} = \frac{I_q(s)}{V_q(s)} = \frac{1}{L_{RL}s + R_{RL}}
\]  

Where \(V_d's\) and \(V_q's\) are the output of the PI controllers. Applying the compensation terms of (9), the reference voltages in d-q axes of the GSC, are given by the:

\[
\begin{align*}
    V_{d1,ref}(s) &= -V_d'(s) + \left( w_L R_{L1} i_q + V_d\right) \\
    V_{q1,ref}(s) &= -V_q'(s) - \left( w_L R_{L1} i_d\right)
\end{align*}
\]  

Since the DC voltage variation determines the active power exchange between the converter and the network, the GSC regulates the DC voltage by regulating the output direct current component of the inverter (DC/AC). The quadrature component of the reference current is zero, in order that the GSC operates in a reactively neutral mode. The control system therefore consists of an outer control loop of the DC voltage and an inner current control loop. The grid voltage (\(V_d\)) is considered constant. In d axis, the dc reference voltage (\(V_{dc,ref}\)) and the voltage measured at the DC link are compared, and the resulting error serves as an input parameter for the PI voltage controller, which in turn sets the reference current value of the d-axis, \(I_{d,ref}\). The current \(I_{d,ref}\) is then compared with the \(I_d\) current and the resulting error is the input parameter for the PI current controller. The reference value of the d-axis voltage (\(V_{d1,ref}\)) is found after the sum of the compensation term. An analogous procedure is carried out in the control loop of the q axis, but as the GSC is not used to control the reactive power, a zero value is assigned to the reference current of the q axis (\(I_{q,ref} = 0\)). Finally, after applying the inverse transform of Park to \(V_{d1,ref}\) and \(V_{q1,ref}\), the resulting three-phase voltages (\(V_{a1,ref}, V_{b1,ref}, e V_{c1,ref}\)) are applied in a classical PWM modulation.
2) RSC - Rotor Side Converter

The RSC is responsible for the vector control of the rotor currents of the DFIG in the d-q axes, in synchronism with the position of the stator flux, thus making it possible to control the active and reactive power independently. The following expressions are based on the works [1] [19] [20] [18] [21]. By applying the field-oriented vector control, the stator flux linkage vector must be fully aligned on the d axis such that:

\[
\psi_s = \psi_{ds} = L_i i_{ds} + L_m i_{dr} = L_{ms} i_{ms}
\]

\[
\psi_{qs} = L_i i_{qs} + L_{il} i_{qr} = 0
\]  

Where \( i_{ms} \) is the magnetizing current of the machine (assumed constant), \( \psi_s \) the stator linkage flux, \( \psi_{ds} \) \( \psi_{qs} \) the stator linkage flux in d-q axes, \( i_{ds} i_{qs} \) the stator currents in d-q axes, \( i_{dr} i_{qr} \) the rotor currents in d-q axes, \( L_m \) the mutual inductance and \( L_s \) a coefficient related to the stator inductance. Considering \( \sigma \), the rotor leakage factor of the asynchronous machine give by:

\[
\sigma = 1 - \frac{L_m^2}{L_s L_r}
\]  

Since the stator is directly connected to the grid, the influence of the stator resistance is small then negligible, so it is possible to consider \( i_{ms} \) constant. Since also \( \psi_{qs} = 0 \), the following relationships are considered:

\[
v_{ds} = 0
\]

\[
v_{qs} = w_s \psi_{ds}
\]

\[
\psi_{dr} = \sigma L_m i_{dr} + \frac{L_m^2}{L_s} i_{ms}
\]

\[
\psi_{qr} = \sigma L_i i_{qr}
\]  

Where \( v_{ds} v_{qs} \) are the stator voltages in d-q axes, \( \psi_{dr} \psi_{qr} \) the rotor linkage flux in d-q axes and \( L_r \) a coefficient related to the rotor inductance. Substituting the rotor linkage flux expressions (in d-q axes), on the rotor d-q voltages expressions of the asynchronous machine and applying the Laplace transform, we obtain:

\[
V_{ds}(s) = (R_s + \sigma L_s) i_{ds}(s) - w_{sl} i_{r}(s)
\]  

\[
V_{qs}(s) = (R_s + \sigma L_m) i_{qr}(s) + w_{sl} (\sigma L_i i_{dr}(s) + \frac{L_m^2}{L_s} i_{ms}(s))
\]  

Where \( w_{sl} \) is the slip velocity and from the rotor voltages (23) and (24), the transfer function is given by:

\[
FT(s) = \frac{V_{ds}(s)}{i_{dp}(s)} = \frac{V_{qs}(s)}{i_{qp}(s)} = \frac{1}{\sigma L_{ms} + R_s}
\]  

Where \( V_{ds}(s) \) and \( V_{qs}(s) \) are the outputs of the PI current controllers. Applying the compensation terms, which are included in (23) e (24), the rotor reference voltages in d-q axes are given by:

\[
V_{dr,ref}(s) = V_{ds}(s) - \left( w_{sl} \sigma L_s i_{dr}(s) \right)
\]

\[
V_{qr,ref}(s) = V_{qs}(s) + w_{sl} (\sigma L_i i_{dr}(s) + \frac{L_m^2}{L_s} i_{ms}(s))
\]  

To control the currents in the rotor circuit, they must be measured, sampled and transformed in their d-q components oriented according to the reference (direct axis of stator flux). In this context, the electromagnetic torque, \( T_e \), (and consequently \( w_c \)) and \( Q_c \) can be represented as a function of the rotor currents, enabling the generation of reference values \( i_{dr,ref} \) and \( i_{qr,ref} \). The instant values of \( I_{qr} \) and \( I_{dr} \) are compared with their reference values generating error signals that will be used to determine the reference values \( V_{qr,ref} \) and \( V_{dr,ref} \) via PI controllers. Once the signals \( V_{dr,ref} \) and \( V_{qr,ref} \) are generated, these are transformed back into its a-b-c components and utilized to generate a PWM signal used to control the converters. Assuming once more, that the influence of the stator resistance is small, and therefore negligible, we have the following relations:

\[
T_e = -K_i i_{qr}
\]

\[
k_i = \frac{3}{2} \frac{\text{vpp}}{L_m L_s}
\]

\[
i_{qr,ref} = -\frac{T_{e,ref}}{K_i}
\]  

The reference value of the electromagnetic torque is calculated according to the instant mechanical torque and reference speed being given by:

\[
T_{e,ref} = \left( \int \frac{d\omega_m,ref}{dt} \right) + T_m + (D' \omega_m,ref).
\]  

Where \( D' \) is a damping factor. In this work, to simplify the control system, it was defined \( i_{qr,ref} \) to be zero [22]. For this control strategy, it is required that the position of the stator flux be determined. Knowing that the stator resistance is small (when compared to the inductive reactance), it was considered the stator flux space vector behind 90° in relation to the space vector of grid voltage. Finally, the slip angle (\( \Theta_{sl} \)) used in d-q transform is given by:

\[
\Theta_{sl} = \Theta_s - \Theta_r
\]  

Where \( \Theta_s \) and \( \Theta_r \) are the electrical positions of stator and rotor fluxes respectively. It is noteworthy that the electrical rotor position (\( \Theta_s \)) is a function of the mechanical rotor position (\( \Theta_m \)) and of the number of pole pairs of the machine (npp).

3) Reference Speed

The control of \( \omega_m \) and \( T_e \) made by RSC, aims to set a speed of the turbine-generator system, indicated to extract the maximum power possible from the waves while avoiding the turbine operation in stall mode. To avoid the stall effect of the turbine, it was created a reference value for the speed, \( \omega_{m,ref} \) (obtained from the characteristic curves of the Wells turbine) which must be applied to the control done by the RSC so that
the rotor speed is close as possible of the reference value at all times. The calculation of the reference speed \((w_{m, ref})\), is done by making the dimensionless pressure coefficient \((\Psi)\), tend to the value \(\Psi_{crit}\), which, according to the characteristics of the Wells turbine, results in the maximum power value of the turbine and therefore, avoids the stall effect. Thus, based on the formula (7), for a given pressure drop in the pneumatic chamber \((\Delta P)\), there is a specific speed value \((w_{m, ref})\), for the turbine-generator system that allows you to extract the maximum possible energy.

\[
w_{m, ref} = \frac{\Delta P}{\rho \Psi_{crit} D^2}
\]  

**Figure 10 - RSC Scheme [20].**

### IV. ANNUAL ENERGY PRODUCED BY A OWC PLANT

In order to estimate the amount of energy produced by a OWC system in one year, were developed two simple calculation methods, based on some of the expressions already presented. Then they were applied to Pico case and the results evaluated. To estimate the annual energy produced by a OWC plant, it is essential to have some characterization of the site where it will be installed. A global characterization of the wave climate of a particular location assumes that you know the average available power of the waves, the occurrences diagram, the average power distribution of energy flow per directions of wave propagation and the dominant spectral forms on site. The average power available from the waves is usually expressed in kW per meter of wave front and for our calculations, we will use a occurrences diagram. The occurrences diagram is a table with the probability of sea states defined by intervals of significant height and period.

#### A. First Calculation Method

According to [23], the conversion efficiency of wave energy into electrical energy through a fixed OWC device, is about 24%. Normally, the information and estimates of the average power available on the maritime resource of a specific site, are made for deep water and not for the shallow water areas where fixed OWC plants are installed. Therefore, it makes sense to consider the effects of energy dissipation due to friction (as a result of the interaction between the wave and the seabed) which appear to depths below 80 meters and become more intense for depths less than 10 meters. This influence of the depth, leads to, on average, a coastal device has only between 25% to 50% of the available resource at an offshore location [2]. Having the average available power \((W/m)\) of the maritime resource \((P_{w, av})\) of the site that we intend to evaluate, it is possible to make a general estimation for the performance of a OWC plant, evaluating first the available power of incident waves at the entrance of the plant (assuming that the value of \(P_{w, av}\) refers to deep waters).

\[
P_{w, owc} = P_{w, av} \eta_{wc, b}
\]  

In the expression (34), \(P_{w, owc}\) represents the average power \((W/m)\) available at the entrance of the OWC plant and \(\eta_{wc, b}\) the efficiency associated with the power losses of waves when moving from deep waters to shallow waters. The plant performance can be thus evaluated by:

\[
P_g = P_{w, owc} \eta_{low, cw}
\]  

Where \(P_g\) is the power output of the plant \((W)\), \(\eta_{low}\) the overall efficiency of the plant and \(cw\) the width of the plant opening \((meters)\). Finally the annual energy produced by the plant will be given by:

\[
E_{annual} = a.f \; hours \; P_g
\]  

Where "hours" is the number of annual hours \((8760)\), \(a.f\) is an availability factor (which takes into account the periods of maintenance and outages of the plant) and \(E_{annual}\) the annual energy produced by the plant \((Wh)\).

#### B. Second Calculation Method

Once you know the occurrences diagram of the site, it is possible to estimate the variation of pressure \((Pa)\) inside the pneumatic chamber through the expression (5), which takes into account the sea state on the site. The speed of wave propagation in shallow waters, is given by:

\[
\nu_{wave} = \frac{\lambda}{T}
\]  

Using (37) in (5) and considering for \(T\), the energy period values usually given in the occurrences diagram and for \(H\) the significant height values, the expression (5) simplifies to:

\[
\Delta P = \frac{8 \nu_{wave} H_{sig, dut} \rho_{water} \Omega}{T^2 A}
\]  

Once estimated the pressure variation, it’s necessary to calculate the mechanical energy of the turbine. To calculate the mechanical energy it will be used the dimensionless coefficients presented in the formulas (7) and (8). In a system with speed control, the pressure coefficient should have a value around the critical value which corresponds to the maximum power point, which in our case is:

\[
\Psi = \Psi_{crit} = 0.065
\]  

Thus, it is possible to calculate the speed rotation of the turbine, through algebraic manipulation of (7) yielding:

\[
w_m = \frac{\Delta P}{\Psi_{crit} \rho v D^2}
\]  

For the dimensionless power coefficient, \(\Pi\), evaluating the characteristic curve of figure 8, it can be seen that its maximum value is obtained when \(\Psi = \Psi_{crit} \approx 0.065\) and is equal to:
\( \Pi (\Psi \approx 0.065) \approx 0.00214 \)  

Being \( \Pi \approx 0.00214 \) the value of the maximum power point of the system. Having the \( \Psi, \Pi \) and \( w_m \) values, by algebraic manipulation of equation (8), it is possible to calculate the mechanical power in the mechanical shaft of the system through:

\[
P_{\text{mech}} = T_m w_m = \Pi \rho_av w_m^3 b^5 \quad (42)
\]

The value \( P_{\text{mech}} \) obtained from (42) corresponds to a peak value which occurs when the pressure reaches maximum amplitude given by (38). However, the pressure is variable and its oscillating nature is reflected in the turbine mechanical power, so the average \( P_{\text{mech}} \) should be calculated. To calculate the average value of the mechanical power \( (P_{\text{mech},\text{av}}) \), we use the relation to calculate the average value of a sinusoidal signal:

\[
P_{\text{mech}, \text{av}} = P_{\text{mech}} \times 0.637 \quad (43)
\]

Assuming an approximate efficiency for the generator coupled with the turbine (\( \approx 85\% \)), it is possible to estimate the power output for each sea state:

\[
P_g = \eta_g P_{\text{mech}, \text{av}} \quad (44)
\]

In the expression (44), \( P_g \) represents the electrical power (W) output of the generator for a given sea state, \( \eta_g \) the generator efficiency and \( P_{\text{mech}, \text{av}} \) the average mechanical power (W) at turbine shaft for a given sea condition. To obtain the annual value of energy produced by the plant, we will have to multiply the output power of the generator for each sea state, by its probability of occurrence during the year. By doing the same for all sea states and doing the total sum in the end, we obtain the average power generated by the plant. Multiplying the value of the average power produced by the number of operating hours of the plant, we obtain the value of the annual energy produced:

\[
E_{\text{annual}} = a.f \text{ hours} \sum (P_g \text{Prob}_{\text{mar}}) \quad (45)
\]

The expression (45) gives the annual energy produced by a OWC plant. \( E_{\text{annual}} \) is the annual energy value (Wh), \text{ hours} the number of annual hours (8760), \( a.f \) the availability factor, \( \text{Prob}_{\text{mar}} \) the occurrence probability of the respective sea conditions.

C. Results

The two methods were used to evaluate the performance of a OWC plant identical to the one in Pico (Azores). For the first method, according to [24] the \( P_{\text{w},av} \) is equal to 37.9 kW/m and it was considered for the \( n_{w,h} \) value, an intermediate efficiency of 37.5% according to the estimates of [2]. For the \( n_{\text{mech}} \) as mentioned before and according to [23], it was considered a value of 24%. For the second method, the turbine performance curve presented earlier represent the behavior of a turbine similar to the Pico one. For the occurrences diagram, it was used the one given by [24] and considered a generator efficiency of 85%. In the end it was obtained the following results presented on table 1. The project values pointed to an annual energy production between 400 MWh and 500 MWh [25] [26] although it was not specified the number of operating hours or the values of average power. The first method presents results more similar with the current estimates for the Pico plant.

Table 1 - Results of first method, second method, real performance of Pico plant and project values for Pico (N/A - not applicable or without information).

<table>
<thead>
<tr>
<th></th>
<th>First Method</th>
<th>Second Method</th>
<th>Real Performance of Pico plant [24]</th>
<th>Project values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power</td>
<td>40.9 kW</td>
<td>55.35 kW</td>
<td>21.2 ± 4 kW</td>
<td>N/A</td>
</tr>
<tr>
<td>Annual Energy (1425h)</td>
<td>58 MWh</td>
<td>79 MWh</td>
<td>45.2 MWh</td>
<td>N/A</td>
</tr>
<tr>
<td>Annual Energy (7306h)</td>
<td>298 MWh</td>
<td>484 MWh</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Annual Energy</td>
<td>N/A</td>
<td>N/A</td>
<td>247 ± 35 MWh</td>
<td>400-500 MWh</td>
</tr>
</tbody>
</table>

The efficiency values used in this method, were probably obtained based on all the experience and knowledge acquired over the years with real OWC plants and laboratory tests, providing thus a good approach to evaluate a performance of a OWC. The second method gave results above the current values but with possible good agreement with the project estimates. This difference in the values of both methods compared to the current values, can be related with many factors that affect the Pico plant performance (and are not accounted specially by the second method) which include: technical limitations and malfunction of the mechanical and electrical equipment as well, infra-structure wear [24] and possibly, an occurrences diagram not precise regarding the conditions at the entrance of the plant. Due to these, the second method should only be use with precise sea measures at the plant entrance.

V. SIMULATION RESULTS

The control and simulation of the power delivered to the grid, have been becoming an important topic, particularly when the number of distributed power generation systems increases. In this paper, two different schemes for an OWC system are simulated and compared. One with a speed control system like the one presented before and other without any control system with the rotor simply connected to a resistance for simulation purposes only. It will be shown how the controller avoid the stalling behavior and that the average power of the generator fed into the grid is significantly higher in the controlled case than in the uncontrolled. Both models, have an entry sinusoidal signal (dp) that pretended to simulate the pressure variation in the chamber (figure 11), but which varies of maximum amplitude during the time. So, up to 250 seconds the dp signal is given by \( dp = [4000 \times \sin(0.1\pi t)] \) Pa, then rose up to an maximum amplitude of 6500 Pa until the 400 seconds, rose again to 8000 Pa until the 550 seconds and finally it reached the 10000 Pa until the end. It can be seen in figure 12 that the dimensionless pressure coefficient assumes a value almost perfect, near the \( \Psi_{\text{crit}} \approx 0.065 \), for the 4000 Pa, even taking into account that does not have control system. However, for the other values of dp, \( \Psi \) reaches his limits becoming very far from the critical value. The \( \Psi \) limits were defined as 0.01 (minimum) and 0.09 (maximum), based on the turbine characteristic curve shown in figure 8 (obtained from laboratory tests). As a consequence of this behavior, the mechanical power developed by the Wells turbine is strongly affected as you can see on figure 13. Along with the pressure
variation, the mechanical power also changes, presenting a good performance during the 4000 Pa of pressure variation but, from that point on, it just got worse. For the 10000 Pa of pressure amplitude, the system was just able to deliver 15.5 kW of mechanical power against the 83 kW, for the 4000 Pa of pressure amplitude.

This behavior is explained by the stall effect that characterizes the Wells turbine. When the turbine does not accelerates fast enough in response to the incoming air flow, enters in serious aerodynamic losses limiting the electrical power produced by the system.

The improvement in the turbine mechanical power is evident now, showing much higher values such as 228 kW and 308 kW for 8000 Pa and 10000 Pa respectively, against the 18.5 kW and 15.5 kW also respectively, of the uncontrolled system (figure 15). The electrical power follows the same trend as illustrated in figure 16 with only a slight fall in times of changing the pressure amplitude, due to some instability on the speed adjustment to the new conditions.

Unfortunately, the oscillatory nature of sea waves spreads elsewhere in the system. In real systems to mitigate these fluctuations, it is usual the use of a flywheel which allows to absorb part of this fluctuations. In the Simulink model, initially, it was set a inertia value according to the actual value of the Pico plant (600 kg · m²) but to try mitigate the oscillations even more, it was used a higher inertia value of 900 kg · m². The results improved a little bit but not enough to eliminate the oscillatory effect. The voltage of the DC link between the two converters (GSC and RSC) responds well to the control performed by the GSC in a way that is maintained always close to the reference established for the system, 1600V. However, it presents some relevant interference in the moments of changing of the pressure maximum amplitude in the pneumatic chamber something that also occurred in the electric power of the generator (figure 17).
This paper tried to characterize qualitatively and quantitatively the energy associated with the marine resource in order to understand the fundamentals of the physical principles involved in different systems of extraction of wave energy. Of all systems analyzed, this work had emphasized the OWC device which is by far, the most studied and analyzed system for the use of this kind of energy.

A simplified approach was developed from which result two calculation methods for estimating the electrical energy annually produced by a coastal OWC plant. They were both applied to the Pico case and it was found that the first method gave values closer to the reality while the latter showed a more optimistic estimate and should only be used when having, sea measures at the plant entrance.

It was analyzed each of the major components of the OWC system (pneumatic chamber, Wells turbine and DFIG) and system (pneumatic chamber, Wells turbine and DFIG) and they were modeled in MATLAB/ Simulink® environment. Two variants of the OWC system were built. One with speed control of the turbine-generator group and other without speed control. It became clear that a OWC plant must be implemented with a speed control system to the extent that it is possible to significantly optimize and maximize, electrical energy production in comparison to the system without control, which is greatly affected by the stall effect of the Wells turbine.

VI. CONCLUSIONS

REFERENCES