Conception of a Didactic Module for Teaching Renewable Energies – Wave Energy

Pedro F. B. do Vale Mateus
Instituto Superior Técnico / Energy Department
Technical University of Lisbon
Lisbon, Portugal
pedrobvmateus@ist.utl.pt

Abstract – This work aims to provide support tools for the teaching of wave energy in order to fill in the gaps that currently exist. It begins by reviewing the necessary conditions for the formation of waves, characterizing the energy available in them. Then, the state of art is presented, with a classification of the different methods for extraction of wave energy and reference to the principle of operation and the mechanisms for Power Take-Off (PTO) used. The oscillating water column (OWC) system is analysed with greater detail, exploring the relevant technical aspects and the main obstacles that should be taken into account when designing this kind of system with regard to electricity generation. As a demonstration of the problematic of electricity generation through the waves, it is used a simulation of the OWC system done in MATLAB®/Simulink®. Finally, the construction of a practical model, which includes two types of wave energy converters, is reported.

Index Terms – didactic model, oscillating water column, power take-off, wave energy

I. INTRODUCTION

At a time when the consumption of electricity continues to increase, and gradual awareness of the adverse environmental impact of fossil fuels begins to arise, it is imperative to look at and invest in clean and sustainable energy sources. Thus, the investment in renewable energy has been gaining force, driven by European directives that stipulate an incorporation of renewable energy on the electrical system.

Currently, the renewable energy sources with greater capacity are hydro, wind and photovoltaic. Besides those mentioned, there is one with great exploration potential, the wave energy.

In recent years, wave energy has gone through a cyclic process with phases of excitement, disappointment and reconsideration, which reflects the great difficulty that is to obtain a feasible solution. However, the persistent efforts of R&D (Research and Development) and the experience accumulated in recent years have helped improve the performance of the techniques of energy extraction, leading to some prototypes tested at full scale which have already proven their applicability and are close to the business stage.

II. THE RESOURCE

Knowing that 70% of the planet's surface is covered in water, the oceans can and should be seen as a huge energy resource that may be of great help in suppressing the growing energy needs on a global level.

The main factors in the formation of waves are the depth and topography of the seafloor, the distance of water over which the wind acts (fetch), and the wind speed, this last one being the dominant one. When the conditions necessary for its development are gathered, it becomes possible to predict the characteristics of the resulting waves quite reliably.

Figure 1: Illustration of motion of a particle in the ocean depth, and as a function of wavelength [1]

As illustrated above, when a wave is passing, the particles acquire a circular motion on the surface whose diameter is equal to the wave height and proportional to the depth. At a depth equal to half the wavelength of the orbit diameter is 25 times smaller than in the surface, being the influence of the seabed negligible. As one approaches the coast, the consequent decrease in depth results in an accentuated interaction with the seabed, ultimately causing the characteristics of the waves to change.
The Theory of Linear Waves, also called Airy Wave Theory, describes the movement of the linearized wave propagation, where it is assumed that the depth of the fluid is constant, the fluid is incompressible, non-viscous and homogeneous, and that the flow is irrotational (zero rotation). Thus, it can be taken as an approximation that the waves are represented by a sine wave with amplitude $A$ and period $T$, being the height of its free surface $\eta$ given by:

$$\eta(x,t) = A \cos(kx - wt)$$  \hspace{1cm} (2.1)

where $w = \frac{2\pi}{T}$ is the angular frequency of the wave, $t$ is the time, $x$ the direction of wave propagation and $k$ the wave number. The wave number is given by:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c_p} = \frac{w}{c_p}$$  \hspace{1cm} (2.2)

where $c_p = \frac{w}{k}$ is the phase velocity. For shallow water ($h < 0.05 \lambda$), comes that $c_p = \sqrt{gh}$ and for deep water ($h > 1/2 \lambda$), comes that $c_p = \frac{\beta}{2\pi} \lambda$. The group velocity, $C_g$, is also affected by the depth of the seabed. For shallow water comes that $C_g = \sqrt{gh} (equal$ to the phase velocity) and for deep water comes that $C_g = \frac{\beta}{2\pi} T$. This means that waves with large wavelength (period) will travel faster and that as the depth of the seabed decreases the velocity slows.

The waves propagate in an horizontal direction, with x-coordinate, and the height of the fluid is given by $z = \eta(x,t)$. Using the assumptions described above, we can make use of the "potential theory", which deals with potentials that satisfy the Laplace equation to model forces.

The velocity potential $\phi(x,z,t)$ is related to the velocity components of the fluid $u_x$ (horizontal) and $u_z$ (vertical) as follows:

$$u_x = \frac{\partial \phi}{\partial x}$$ and $$u_z = \frac{\partial \phi}{\partial z}$$

Due to the continuity equation for an incompressible fluid, the potential $\phi$ must obey to the Laplace equation:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$  \hspace{1cm} (2.3)

As boundary conditions, we have that the bottom of the ocean is a barrier layer, which causes the fluid velocity,

$$\frac{\partial \phi}{\partial z} = 0 , \quad z = -h$$  \hspace{1cm} (2.4)

and for the surface, the vertical movement of the fluid must be equal to the vertical component of velocity,

$$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial x} , \quad z = \eta(x,t)$$  \hspace{1cm} (2.5)

To solve the problem, one must add an additional boundary condition provided by the Bernoulli equation for time-varying potential flows, in which case it is assumed that the pressure below the surface of the fluid is constant and that for this calculation it takes a zero value since it does not interfere with the flow.

$$\frac{\partial \phi}{\partial z} + g \eta = 0 , \quad z = \eta(x,t)$$  \hspace{1cm} (2.6)

So, for a monochromatic wave (single frequency), the velocity potential $\phi(x,z,t)$ that satisfies the conditions (2.3) (2.4) and (2.5) is given by:

$$\phi(x,z,t) = \frac{w}{k} A \cosh (\frac{k(x+z+h)}{\sinh (kh)}) \sin (kx - wt)$$  \hspace{1cm} (2.7)

but $\eta$ and $\phi$ must also satisfy the condition (2.6), resulting in the angular frequency $w$ being equal to:

$$w^2 = g k \tanh (kh)$$  \hspace{1cm} (2.8)

As such, the angular frequency $w$ and the wave number $k$, the period $T$ and the wavelength $\lambda$ cannot be independently selected, since they are related.

Consider now that $z = A \sin \left( \frac{2\pi x}{\lambda} \right)$. The time dependence is irrelevant for this deduction.

The potential energy into a fluid mass element, $dm = \rho g \delta x \delta z$, which moves from $-z$ to $z$, is expressed by $\delta V = \delta m 2gz = 2\rho gz \delta z \delta x$. Consequently, the total potential energy of the raised section is:

$$V = 2\rho g \int_{x=0}^{x=\frac{1}{2}\lambda} \int_{z=0}^{z=A \sin \left( \frac{2\pi x}{\lambda} \right)} z \, dz \, dx$$

$$= \rho g A^2 \int_{x=0}^{x=\frac{1}{2}\lambda} \sin^2 \left( \frac{2\pi x}{\lambda} \right) \, dx = \frac{1}{4} \rho g A^2 \lambda$$  \hspace{1cm} (2.9)

Assuming equipartition of energy, the mean value of kinetic energy is equal to the average value of the potential energy, which makes the total energy at one wavelength equal to $E_{total} = \frac{1}{2} \rho g A^2 \lambda$.

To quantify the available energy in the waves, it is usual to use, as a measurement, the average density of energy per horizontal area unit ($E_{density}$), which is the sum of the average kinetic energy density ($E_{kin}$), with the mean value of the potential energy density ($E_{pot}$), which contributes with equal weight.

$$E_{pot} = \frac{1}{4} \rho g A^2 \frac{L^2}{m^2}$$  \hspace{1cm} (2.10)

$$E_{kin} = \frac{1}{4} \rho g A^2 \frac{L^2}{m^2}$$  \hspace{1cm} (2.11)

$$E_{density} = E_{kin} + E_{pot} = \rho g A^2 \frac{\delta x}{2} = \rho g A^2 \frac{h^2}{8} \left[ \frac{L}{m} \right]$$  \hspace{1cm} (2.12)

The wave power per period is the power density and can be calculated dividing the energy density of the wave by the period,
where $H = 2A$. The power associated with the waves is usually described as a power per wavefront meter and may be calculated by multiplying the energy density by the group velocity. For a deepwater wave the power is,

$$P_{\text{wavefront}} = \frac{E_{\text{density}} \cdot g \cdot A^2}{2\pi} = \rho_{\text{water}} \cdot g \cdot \frac{H^2}{16\pi} \left[ \frac{W}{m} \right].$$

(2.14)

In general, the wave power below surface level decays exponentially with $-2\pi h$. This property can be verified in the development of the Linear Waves Theory and is valid only for waves with depth $h > 0.5\lambda$.

$$E(h) = E(SWL) \cdot e^{-2\pi h} \left[ \frac{J}{m^3} \right]$$

(2.15)

Once created, the waves can travel thousands of miles offshore with virtually no energy losses [2], only decreasing in intensity as they approach the coast due to the already mentioned interaction with the seabed. It’s also very important to state that waves are a regular source of energy whose intensity can be predicted several days in advance before their arrival, being more predictable than wind and solar energies.

The higher energy density lies between latitudes $-30^\circ$ and $-60^\circ$ in both hemispheres, induced by the prevailing western winds that blow in these regions [3].

It is thought that Portugal has an available potential of 21 GW, 15 GW distributed in the continent and 6 GW in the autonomous regions. Thus, taking into account the rates of conversion into electricity, and local conditions, we can reach at a value of 10 TWh/year, 5 GW of installed power, possible to introduce into the grid which would be enough to satisfy about 20% of energy consumption in the country [5].

III. TECHNOLOGY AND ENERGY EXTRACTION

Devices for energy extraction from waves can be installed on the coast (onshore), in shallow waters (near-shore), and in deeper waters (offshore).

It is common to classify the devices according to the basic principle of energy conversion. Thus, it is possible to divide the devices into three main groups:

- Oscillating Bodies
- Oscillating Water Column
- Overtopping Devices

A. Oscillating Bodies

The oscillating body devices are usually installed offshore, if they are of the floating type, or near-shore, if they are submerged. The wave motion interacts with the devices so that they oscillate (mechanical energy).

The Archimedes Wave Swing device is a kind of air-filled piston that oscillates vertically with the pressure differences caused by the passage of the wave.
For a device like the Archimedes Wave Swing, the applied forces can be modeled by the equation of Newton. The mass of water is given by
\[ m = \rho_{\text{water}}AH_{\text{body}} \] where \( \rho_{\text{water}} \) is the density of water, \( A_{\text{body}} \) is the area of the oscillating body and \( H \) is the height of the wave. To determine the power transferred, \( P_{\text{transferred}} \), from the wave to the mechanism, we multiply the weight of water, \( F_{\text{water}} \), for the speed of the body, which is given by the stroke distance, \( l_{\text{stroke}} \) divided by half the wavelength.

\[ F_{\text{water}} = \rho_{\text{water}}AH_{\text{body}} g \quad [N] \quad (3.1) \]
\[ P_{\text{transferred}} = F_{\text{water}} \frac{l_{\text{stroke}}}{2} \quad [W] \quad (3.2) \]

The mechanism that extracts energy from waves is called Power Take-Off (PTO). This mechanism varies from device to device, and with the exception of linear generators, it uses conventional rotary generators to produce electricity.

A major difficulty of the wave energy converters lies in driving the generators. The oscillating body devices, because of its low speed oscillating character, are not directly compatible with conventional rotary generators, therefore an auxiliary system must serve as an interface between the device and the electric generator.

For oscillating body devices, the PTO mechanism used is hydraulic or an electric linear generator.

HYDRAULIC SYSTEMS
A hydraulic system consists of a piston, a hydraulic pump and a hydraulic motor. The wave motion moves the piston up and down, which in turn pumps hydraulic fluid pressurized to the hydraulic pump. The hydraulic motor, powered by the pump, creates the necessary rotational movement to drive a conventional generator, completing the conversion process.

Although small, the hydraulic machines can withstand large forces compared to the forces that electric machines with similar dimensions tolerate, rendering them first choice to capture energy from large devices that move with relatively low speed.
Because the rated power of the generator, $P_N$, is proportional to the voltage $U$, the current $I$.

$$P_N \propto UI \quad (3.3)$$

and taking into account the relation of these quantities on the linked flow, $\psi$, and the current density $j$:

$$U = \frac{dn}{dt} \propto j \psi \quad \psi = \int B \cdot n \, dS \quad I = \int j \cdot n \, dS \quad (3.4)$$

where $B$ is the magnetic flux density and $\psi$ the angular frequency, then we can write the relation:

$$P_N \propto UI \propto w \psi I \propto f(BL^2)(JL^2) \propto fB/L^4 \quad (3.5)$$

where $f$ is the frequency and $L$ a linear characteristic dimension.

We can induce from the above relation that, as the frequency (low) is a characteristic feature of the magnetic flux density and a constraint of the material, to a high power output we need machines with larger dimensions, which is not desirable because both the cost of the engine and the losses increase.

$\text{B. Oscillating Water Column}$

Devices for the oscillating water column (OWC) are usually installed onshore and consist of a pneumatic chamber in which the front wall has an opening to allow the waves to enter the interior. Wave action causes the water level in the chamber, known as the pneumatic chamber, to rise. Thus, the air in the chamber is propelled, generating airflow through an air turbine. When the wave recedes, causing a depression, the air circulates in the opposite direction, causing the turbine to move again in the same direction, which is possible due to the habitual use of a Wells turbine, which will be subject to further analysis.

As a result of wave action within the chamber, an airflow is displaced, $q$, and oscillation pressure is caused $dp = p + p_a$, where $p_a$ is atmospheric pressure (static) and $p$ is a dynamic pressure.

According to Bernoulli’s equation for incompressible fluids, dynamic pressure is given by $p = \frac{1}{2} \rho_{\text{air}} v_{\text{air}}^2$, which airflow multiplied by $q = v_{\text{air}} A_{\text{duct}}$, where $A_{\text{duct}}$ is the cross sectional area of the pneumatic chamber, gives us the term due to the kinetic power of the air $P_{\text{kin}} = \frac{1}{2} \rho_{\text{air}} v_{\text{air}}^2 A_{\text{duct}}$, which is common in the analysis of wind turbines. The total power available to utilize in the OWC is then given by:

$$P_{\text{OWC}} = [p + p_a]q \quad (3.5)$$

$$P_{\text{OWC}} = \left( p + \frac{\rho_{\text{air}} v_{\text{air}}^2}{2} \right) v_{\text{air}} A_{\text{duct}} \quad (3.6)$$

$\text{AIR TURBINE}$

The use of air as the working fluid has the advantage of its high speed, which does not happen with waves’ low speed.

The air turbine is part of a system that also includes a capture mechanism and an electric generator (Figure 10), the interaction between the first two components being an important parameter for a good system performance.

The turbine typically used for oscillating water column systems is a Wells turbine, which has the ability to maintain rotational direction whatever the direction of airflow and also provides reasonable performance for a wide range of states of sea waves. Its disadvantages include the difficulty of starting, the low efficiency (40% to 70%), and a stall condition, which causes the Wells turbine efficiency to fall abruptly at high flow.
C. Overtopping Devices

Overtopping devices can be fixed or floating. They consist of a container whose walls are above the sea level; when they are overtopped by waves, the water passes through a number of low fall turbines (typically Kaplan turbines) producing energy. These systems have an operating principle that can be compared with the conventional mini-hydro.

![Figure 12: Principle of operation of overtopping](image)

Hydraulic power ($P_{\text{hydraulic}}$) which can be harnessed by water turbination is the result of the product of water flow passing through the turbine ($q_{\text{turbine}}$) by the height of fall of water ($h_{\text{fall}}$), and by the density of sea water and the gravity acceleration.

$$P_{\text{hydraulic}} = q_{\text{turbine}} h_{\text{fall}} \rho_{\text{water}} g \ [W] \ (3.7)$$

IV. OSCILATING WATER COLUMN SYSTEMS

Currently, the most common turbine in OWC systems is the monoplane Wells turbine with fixed pitch blades. This turbine has the unique ability to rotate in the same direction regardless of airflow direction. The blades are symmetric and are disposed at an angle of 0° relative to the plane of rotation.

![Figure 13: Forces acting on a Wells turbine](image)

The speed of the air, $W_{\text{air}}$, consisting of axial flow velocity through the turbine, $V_{A}$, and the tangential velocity of the blades, $V_{T}$, originate forces dependent on the blade angle of attack $\alpha$. These forces are a lift force, $F_{L}$, normal to $W_{\text{air}}$, and a drag force, $F_{D}$, parallel to $W_{\text{air}}$. Those can be expressed as a tangential force coefficient, $C_{T}$, and axial, $C_{A}$:

$$F_{T} = F_{L} \sin \alpha - F_{D} \cos \alpha \quad (4.1)$$

$$F_{A} = F_{L} \cos \alpha + F_{D} \sin \alpha \quad (4.2)$$

To a blade subject to a reverse and oscillating airflow, as is the case, the magnitudes and directions of $F_{L}$ and $F_{D}$ vary during the incident wave period. However, the direction of $F_{T}$ remains unchanged, which means that the turbine has the property of being "self-rectifying", that is, irrespective of the direction of air flow, the direction of rotation of the turbine remains unchanged.

The performance of the turbine is limited by the appearance of the stall effect. This effect causes a reduction in the lift force when the angle of attack is high, that is, when the ratio $V_{T}/W_{\text{air}}$ is low.

As seen in equation (3.6) available for pneumatic power, $P_{\text{OWC}}$ is given by

$$P_{\text{OWC}} = dp \ q \ [W] \quad (4.3)$$

where, $dp$ is the pressure pulse generated by the water column and $q$ is the airflow.

The torque coefficient, $C_{T}$, is given by,

$$C_{T} = T_{t} / K r_{t} \left[ v_{\text{air}}^{2} + (r_{t} w_{t})^{2} \right] \quad (4.4)$$

where, $T_{t}$ is the torque of the turbine, $K$ is a constant, $r_{t}$ is the radius of the turbine and $w_{t}$ is the angular velocity of the turbine. The variable $v_{\text{air}}$ is the axial velocity of the air $V_{A}$ of Figure 13, and the product $(r_{t} w_{t})$ is the tangential velocity of the blades $V_{T}$ of Figure 13. The torque of the turbine, $T_{t}$, is the tangential force, $F_{T}$, multiplied by the radius of the turbine, $r_{t}$, thus the torque coefficient, $C_{T}$, can also be called coefficient of tangential force. The constant $K$ is given by

$$K = \rho_{\text{air}} b c \frac{n}{2} \quad (4.5)$$

where, $\rho_{\text{air}}$ is the density of air, $b$ is the length of the blades, $c$ is the width of the blades and $n$ is the number of turbine blades.

The power coefficient, $C_{a}$, is given by,

$$C_{a} = (dp \ a / K [v_{\text{air}}^{2} + (r_{t} w_{t})^{2}]) \quad (4.6)$$

where the area of the turbine, $a$, is given by $a = \pi r_{t}^{2}$. The axial force, $F_{A}$, is the same as the product $(dp \ a)$, therefore the power coefficient, $C_{a}$, can also be called coefficient of axial force.

We can then write the torque of the turbine, $T_{t}$, equal to

$$T_{t} = dp \ C_{T} C_{a}^{-1} r_{t} a \ [Nm] \quad (4.7)$$

The flow coefficient, $\phi$, is,

$$\phi = v_{\text{air}} (r_{t} w_{t})^{-1} \quad (4.8)$$

and the airflow, $q$, is given by,

$$q = v_{\text{air}} a \ \left[ \frac{m^{3}}{s} \right] \quad (4.9)$$

The efficiency of the turbine, $\eta_{\text{turbine}}$, can be written as

$$\eta_{\text{turbine}} = T_{t} w_{t} (dp q)^{-1} = C_{t} (C_{a} \phi)^{-1} \quad (4.10)$$

The torque and power generated by the turbine can be calculated based on coefficients of torque and power versus the coefficient of flow (Figure 14 and Figure 15).

From equation (4.8) one can conclude that when air velocity increases, the flow coefficient also increases, causing the stall effect. This behavior can also be seen in Figure 14, when the coefficient of flow approaches the value 0.3 (this value may vary depending on the turbine).
The waves will cause the airflow that drives the turbine to be variable. In this case, the turbine is of fixed geometry, which does not allow adjustment of the blades, forcing adjustment to be made in the generator. This implies that the generators to be used for connection to the network are of the type VSCF (variable speed, constant frequency). This type of generator uses power electronics to achieve the control of frequency and voltage output.

Among the solutions available in the range of VSCF generators we find the following alternatives:

Of the alternatives shown, the generator typically used in OWC systems is a double-fed induction generator (DFIG). The great advantage of the DFIG is that power traffic to the network can be done through the rotor and stator. With the converters connected directly to the rotor, there is no need for them to be dimensioned for the rated power of the machine (sized to 25% -30% of nominal power), thus avoiding the frequent power limitation of semiconductors.

The power input to the turbine varies both in the short term, as a result of the wave oscillations, and in the long term, due to the inconstancy of the sea conditions, which will cause fluctuations in the power delivered by the generator to the load. Furthermore, the power extracted by the system is limited by the stall effect of the turbine. This behavior makes control measures necessary, which alone are not sufficient for power quality to be guaranteed in the network/load, but mitigate these fluctuations. Some of the possible control strategies are [11]:

i. Controlling the rotation speed

The stall effect can be avoided if the turbine rotates fast enough in response to airflow, which can be achieved by modifying the torque/slipping characteristic of the generator, allowing the system to reach higher speeds.

The AC/DC/AC converter consists of one converter connected to the network (grid-side converter, GSC), and a converter connected to the rotor (rotor-side converter, RSC) which in turn is connected to the first via a capacitor. The GSC controls the dc voltage and the reactive power exchanged with the network, its purpose being the maintenance of a constant capacitor voltage, regardless of the amplitude and phase of the power of the rotor, while the RSC controls active and reactive power of the generator [12].

ii. Control of airflow

Control of airflow takes as input the pressure in chamber \( dp \) in order to control the power generated by the generator preventing stall, and can be reached by two different but complementary methods. One method consists of a valve (by-pass relief valve) installed at the top of the pneumatic chamber (Figure 10) controlled so as to open in a way that the threshold pressure does not exceed the value which takes the stall effect. The other way is to use a maneuver valve (fast-acting valve) installed in series with the turbine (Figure 10).

Possible solutions to the energy storage can be classified based on storage time and amount of energy storing involved. For a short-term storage the options are flywheels, superconducting magnetic energy storage (SMES) and supercapacitors. For longer times, possible solutions are compressed air storage systems (CAES), batteries and pumping systems.

As stated above, the delivery of power to the load is naturally subject to oscillations of the resource. These oscillations cause the energy availability to be variable minute to minute, daily and seasonally. Thus, it becomes necessary to use a energy storage system, in order to balance the production and consumption of electrical energy, which is suitable to meet
these slow and fast oscillations. A possible solution to this problem may involve the implementation of a storage system that combines batteries and supercapacitors. In this case the slow component of oscillations is treated by the battery while the fast component of oscillations is handled by a module of supercapacitors.

V. OWC SYSTEM SIMULATION

The complete system includes a model for the pneumatic chamber, which is connected to the turbine model, which in turn is connected to the generator model via a gearbox.

![Complete system used for simulation of an OWC device](image)

The air pressure within the pneumatic chamber can be expressed by [13]:

$$dp = \frac{8n^3P_{water}v_{water}A^2r_{duct}}{\pi a^2}$$

(5.1)

where, $r_{duct}$ is the radius of the cross section of the pneumatic chamber and $a$ the area of the conduct.

The implementation of the Wells turbine model in Simulink® was based on the equations (4.3) to (4.10) and in the curves presented in Figure 14 and Figure 15. To simplify the model, we defined the following variable:

$$y = \frac{dp}{v_r^2}$$

(5.2)

whose behavior depending on the flow coefficient is illustrated below.

![y versus flow coefficient](image)

Although it is not common to use a synchronous machine in such applications, it was the machine chosen to the performed simulation because it is a machine of simple implementation and it suits the purposes of simulation.

This configuration aims only to demonstrate the problems associated with this system and does not correspond in any way to a possible solution to implement in reality, in part because the battery required to high power systems would have to be of unacceptable dimensions and also because, as we will see, the generated power quality does not allow the interconnection with a battery.

One shall take as input a pulsating pressure, $dp$, in the chamber illustrated in the following figure.

![dp pressure in the pneumatic chamber](image)

The turbine, for this wave spectrum and for a certain conditions of the downstream system makes available the following mechanical power:

![Pt mechanical power available at the turbine outlet](image)

As shown in the previous figure, the turbine, initially at rest, is unable to rotate fast enough to keep up the pressure in the pneumatic chamber therefore the mechanical power produced by turbine during the first 30 seconds undergoes a strong attenuation. This behavior is the stall effect and may be illustrated by the next figure, which shows that the flow coefficient is greater than 0.3 within the first 30 seconds.
As shown in the figure below, the rotational speed of the turbine is influenced by the stall effect and the oscillatory behavior shown is no more than the effect of the oscillatory nature of the waves.

It should be noted that these oscillations, prejudicial to the proper functioning of the system, have a considerable range, and will be felt in the generated power, uncovering one of the huge barriers to the utilization of wave energy.

One way of reducing the oscillations is to increase the inertia of the system, as can be seen in the next figure.

As mentioned above, the electrical power generated by the synchronous machine has an oscillatory behavior with a pronounced slope. Also, as expected the frequency of the generated voltage is not 50 Hz.

The battery used in the simulation is of the Li-Ion (lithium ion) type and has a nominal voltage of 230 V, a capacity of 50 Ah (clearly inadequate in a real application) and it is considered that the SOC (state of charge) is initially at 20%.

As can be seen in the figure below, despite the use of an L.C. filter oscillations are felt. Voltage oscillates between 249V and 244V and current between 0A and -68A. It is noted that SOC increases over the time, which means that the battery is charging, however, in a real application these fluctuations would not be acceptable.

Most tanks use two mechanisms to generate waves, one which uses an oscillating paddle, flap-type, and other in which the paddle is used as a piston, piston-type.

The flap-type is used to create waves with characteristics similar to those encountered in deep water. The piston-type is used to simulate waves in areas where the depth is smaller than half the wavelength.

The “Simplified Theory for WaveMaker Plane Waves in Shallow Water” states that the volume of water displaced by the wave generator should be equal to the volume of water on the crest of wave formed.

If we consider a displacement distance $S$ of a piston paddle, and a tank with constant depth $h$, then the volume of displaced water is given by $Sh$. The volume of water on the crest of the wave is [14]:

$$\int_0^{L/2} \frac{H}{x} \sin(kx) \, dx = \frac{h}{k}$$  \hspace{1cm} (6.1)
Equating the two volumes is [14]:

$$Sh = \frac{H}{h}$$

which can then be rewritten as [14]:

$$\left( \frac{H}{h} \right)_{\text{piston}} = kh$$

(6.2)

where \( \frac{H}{h} \) is the relationship between wave height and the displacement of the paddle. To a flap-type paddle volume of displaced water will be by half of the piston paddle displaced, so that the amplitude of the wave will have an amplitude twice less. So it follows that [14]:

$$\left( \frac{H}{h} \right)_{\text{flap}} = \frac{kh}{2}$$

(6.3)

Unfortunately the water use was not possible, due to the fact that the necessary dimensions to build a reasonable wave tank would make impossible is own purpose, so it was decided to construct two types of wave energy converters, namely a oscillating water column (OWC) system and a oscillating body system.

![Figure 27: Prototype](image)

**VII. CONCLUSIONS**

This work lead to the conclusion that wave energy has enormous potential as a renewable energy source, and that its viable exploration is hampered by the aggressive and oscillatory characteristic of marine environment.

We sought to characterize qualitatively and quantitatively the energy associated with the resource according to its characteristics, in order to understand the fundamentals of the physical principles involved in the different technologies for extracting energy from waves.

The different methods for harnessing wave energy were cited, highlighting the aspects to be considered, in terms of power generated, when designing wave energy converters.

It was examined with particular attention the oscillating water column (OWC) system, from the operating principle and different components, to the dynamics and problems associated. In order to facilitate the understanding of the process of extracting wave energy, a simulation was carried out in MATLAB®/Simulink®, through which the discussed aspects have become visible to the reader.

A prototype model that includes two types of systems for converting wave energy was constructed. The model makes it easier to visualize the basic principles involved in the process of energy extraction, despite the impossibility to use water.

**REFERENCES**


