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Energy Procedia 20 (2012) 271 – 280
Energy Procedia

Technoport RERC Research 2012

Design of a Direct Drive Wave Energy Conversion System for the Seaquest Concept

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Abstract

In this work the investigation and design of a Direct Drive Wave Energy Conversion System for the Seaquest Concept is presented. It involves all the steps of the project, from the marine environment analysis to the problems linked to the connection to the grid, passing through the sizing procedure of an innovative arc-shaped electrical generator, in which the flux-switching principle has been applied, then through its analysis, optimization and performance verification by FEA, and then the study of the most suitable control strategies. Particular attention has been given to all the specificities this new particular generator presents: non-constant rotational speed, reciprocating motion, border effects. This arch-shaped generator has then been compared to a traditional rotating machine directly coupled with the shaft and moved by the pendulum

Keywords: Arch-Shaped Pendulum Generator; Direct Drive WEC; Flux-Switching PM Generator

1. Introduction

The energy of oceans is re-emerging among the renewable sources with promising development chances. The conversion of the very low speed reciprocating motion of waves through conventional devices usually requires a pneumatic or hydraulic interface, affecting efficiency and leading to possible wear problems. A direct drive wave energy converter, on the other hand, presents an electrical generator directly coupled to the buoy or WEC concept. This kind of system, while allowing to reach a higher efficiency, leads to a variety of new problems such as output voltage varying both in frequency and amplitude, very high torque, low power factor, among others. The direct WEC system can however be controlled with flexibility by a power

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doi:10.1016/j.egypro.2012.03.027

electronics interface to actuate an optimal control strategy needed to extract the maximum wave power from the ocean.

The aim of the project is expressed by the motto *Tolerance 100*: the goals are the total absence of any type of polluting emission and thermal waste, in the context of a totally sustainable and eco-friendly whole system, which should be able to conserve marine fauna and species, the nature of the environment (minimizing the visual impact), and finally should be easily removed allowing the previous environment conditions to be restored.

In the first design attempt, a feasibility study and a preliminary analysis of the whole converter system have been done: an analytical model and a numerical validation for each step of the energy conversion chain are developed to validate the theoretical behaviour of preliminary designs. The following steps involve a more precise analysis: firstly linear under the regular wave assumption, then spectrum analysis on significant sea states. Quasi-dynamic and transient simulations will be run to complete the analysis.

2. Model of the Direct Drive Wave Energy Converter

2.1. A. Hydrodynamic Model and Analysis

This work has started from a feasibility study of the innovative energy pendulum generator presented in the Seaquest Project, made by the Spanish Company Mecanica Industrial Buelna [1]. The operation principle is the direct conversion of the mechanical energy of the waves into electrical power; the core of the system is a pendulum which could swing activating the arc-shaped generator.

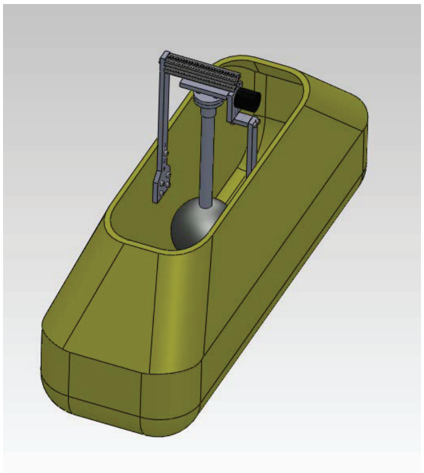

Fig. 1. The initial pendulum generator concept

It has been assumed that the mass is concentrated in a point representing the 15% of the total mass of the buoy. The length of the pendulum is taken as 50% of the diameter of the buoy. For the ballast, it has been considered 2,5 ton/m^3 density concrete, manageable material at a resonable price. There are other alternatives for ballast (i.e. sand, water) but they may pose problems for long-term life for a structure subjected to a high number of cycles of oscillation under the action of waves. The height of the ballast is calculated to get the desired depth, taking into account that it will fill the subset of floating horizontally always from the lowest point. The hydrodynamic parameters that allow getting the output power as a function of the wave frequency have been calculated for each geometry using AQWA® software. On the other hand, as for the stability calculations it has been necessary to assume certain values to obtain the centres of gravity, for hydrodynamic calculations it is necessary to obtain the moments of inertia. After the definition of the mass matrix and of the hydrodynamic parameters (mass coefficient and damping from

AQWA), the equations of motion of the freely floating structure without constraints of the anchor lines are solved.

The characterization of marine environment along with a numerical modelling and frequency-domain analysis, allowed to choose the best floating buoy shape based on the maximum energy extraction by the system [2]. Then, an hydrodynamic comparison between axysimmetric and elongated forms has been carried out: as the pendulum has to resonate with the forcing wave, the typical ocean waves peaks of resonance could be achieved only increasing the length of the shape, related to the peak of pitch resonance.

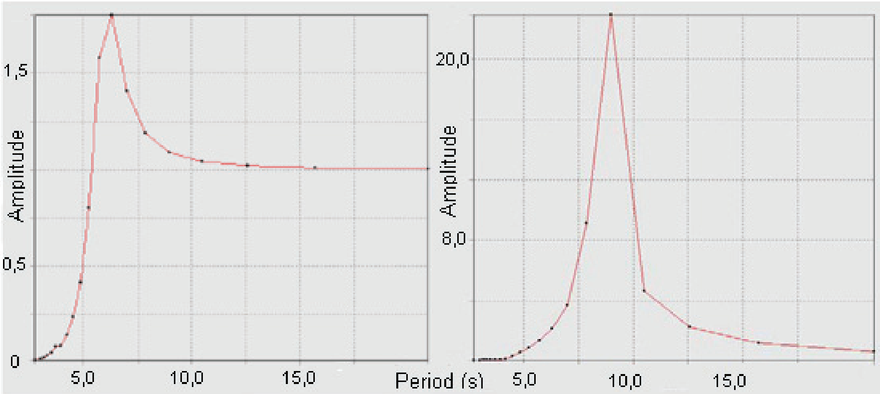

Fig. 2. Comparison between Response Amplitude Operators of axisymmetric (left) and elongated (right) forms

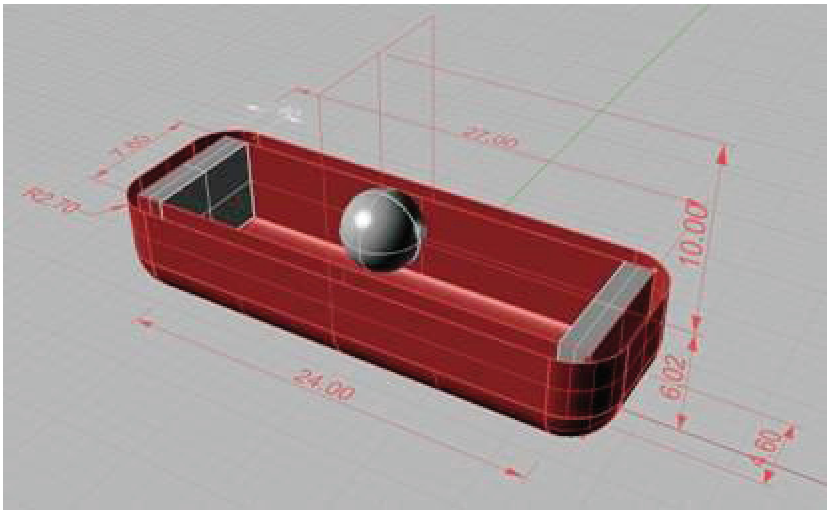

Fig. 3. Elongated form chosen: prototype proportions

2.2. *B. Electric Generator*

1) *Overview*

In this work an investigation has been carried out to verify the feasibility of two different concepts: a traditional rotating machine and an innovative arch-shaped generator, both directly coupled to the pendulum shaft. The design of these new types of generators is very demanding, especially in consideration of the very low, non-constant reciprocating speed; in addition, the arc-shaped generator presents border effects .

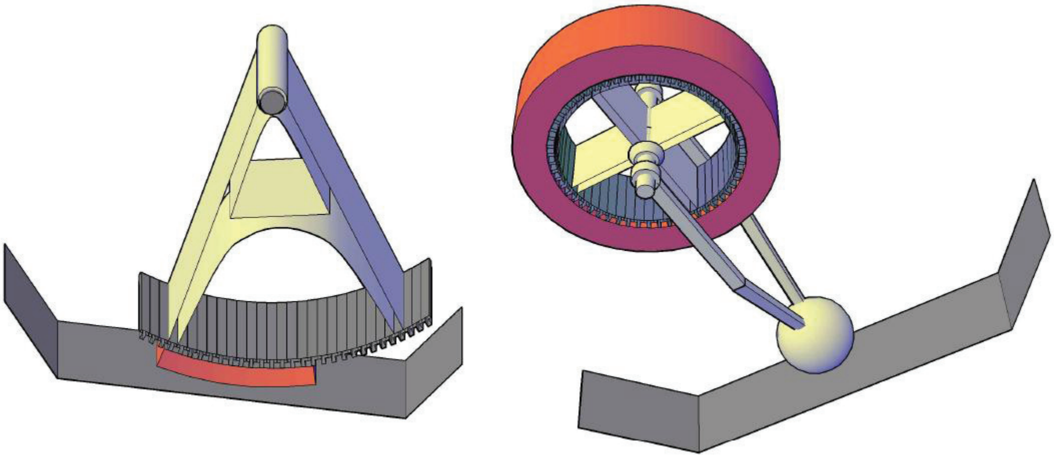

Fig. 4. The two concepts of generator compared: Arch-Shaped with the rotor on the pendulum tip and Circumferential with a sphere on the pendulum tip

As for the traditional machine, the pendulum tip is a simple iron sphere, so all the buoy opening could be exploited. In the arc-shaped generator, the pendulum tip is electrically active: an outer stator layout (with the rotor on the pendulum tip) has been preferred, allowing this configuration a better stator cooling. A flux-switching, permanent magnet generator has been chosen: the major advantages which lead to this choice are linked to the Permanent Magnets (absence of brushes, slip rings (both linked to wear problems), excitation coils, DC power supply and field winding copper loss), and to the Flux-Switching principle (rotor only made from iron, easier construction and heat dissipation, robustness, less volume required, giving a higher torque density, essentially sinusoidal back-EMF waveform as forecasted in [3].

Despite all the benefits mentioned above, the design phase is still a challenging task as an explicit mathematical expression of this novel machine is not yet available. The time-varying (assumed sinusoidal) pendulum angular position leads to a time-dependent induced voltage frequency and magnitude which should be handled by a specific power electronics converter. The number of rotor poles P_r, plays the role of an amplifier of both the induced voltage frequency and amplitude, so increasing it has been investigated in order to allow a better energy conversion.

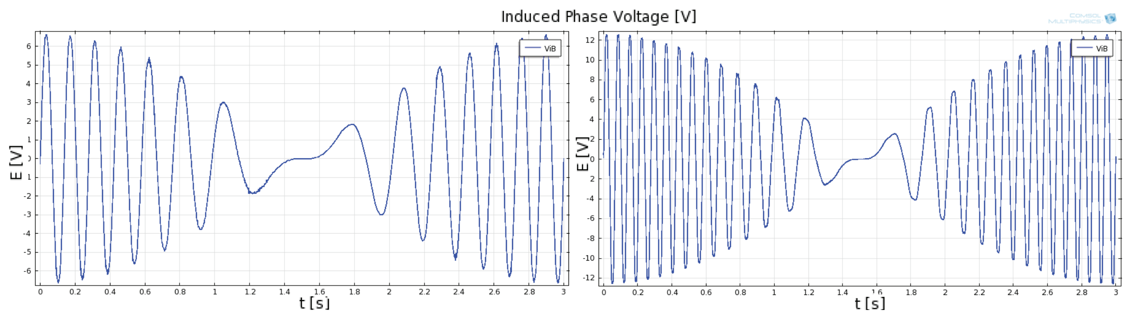

Fig. 5. Phase Voltage Waveform from a transient simulation, P_s = 12 (left) and P_s= 24 (right); the y-axis scale (Voltage) of the right figure is double

2) *Design*

Different design procedures are possible, depending on the project goal; the most important one is to reduce the very high torque, directly linked to dimensions, costs and a lower efficiency. A sizing equation has been derived adapting the procedure presented in [4] to this particular case; it has been obtained expressing the power in terms of the geometric and performance parameters of the machine; under the initial assumptions for k_σ (leakage factor), B_{t-ag} (magnetic flux density in the airgap, expressing the magnetic loading), A_{fc} (electric loading), c_s (stator tooth width to stator pitch ratio), λ (split ratio) and under the geometric constraint of aspect ratio $\frac{R}{L} = 2$, the geometric parameters are obtained: expressing the flux linkage variation as

$$\Psi(t) = -k_\sigma B_{t-ag} L W_{st} cos\left(2\pi P_{r\gamma}\frac{\vartheta}{\gamma}\right) \tag{1}$$

(L is the machine active lenght, W_{st} the stator tooth width), being the induced phase voltage its time-derivative

$$e_{ph}(t) = \frac{d\Psi}{dt} = n_{ph}\frac{d\Psi}{d\vartheta}\frac{d\vartheta}{dt} \tag{2}$$

the power is related to all the other parameters by

$$P = T\frac{\gamma}{\frac{T_{per}}{2}} = \frac{\sqrt{2}\pi}{4T_{per}}\left(\frac{P_{r\gamma}}{P_s}\right)k_\sigma c_s \lambda^2 D_{os}^2 L \alpha^2 B_{t,ag} A_{fc} \tag{3}$$

α is the stator angular sector, γ the angular elongation of the pendulum in a half period, D_{os} the stator outer diameter, while $P_{r\gamma}$ is the number of rotor poles crossing through the stator sector. It could be seen that the torque depends on the dimensions but also strongly on the electrical loading, which is limited in this application by the temperature rise due to the very low reciprocating speed. A high current is necessary to provide the torque, so the dimensions are considerable and this is one of the main reasons that led to the choice of a flux-switching machine

Respecting the initial prototype proportions, the small angular opening of the buoy limits the mechanical speed to a very low value leading to a very high torque (the magnitude, for a prototype rated at 10kW, is about 60 kNm) and the aspect ratio of air-gap radius to active length of windings allowed in the prototype leads to high copper losses. Overcoming these geometrical constraints could lead to the reduction of torque and so the dimensions of the generator and this aspect will be subject to further investigation.

3) *Optimization and Performance Analysis*

The generator analysis, aimed at finding the parameters of the equivalent circuit, is one of the milestones of the project sequence, as both the PE and Control strongly rely on that. Although the finite-element method is widely used to analyze the performance of electrical machines, a lumped parameter magnetic circuit model has been preferred for the first design stage, as proposed by [5], based on [6] researches on FSPM machines. In addition, this circuit, implemented in a numerical simulation, has allowed to make a series of parametrical analyses, studying the influence of a wide range of geometrical parameters (split ratio, magnet width, teeth and bridges proportions).

The initial design assumptions for rotor and stator parts dimensions have been refined to save material and increase output torque, made on the results obtained in [6], based on 2D and 3D finite element analyses.

To reduce the cogging torque, the suggestions given in [8] have been used.

After this first attempt to identify an optimum machine design, the predicted air-gap field distribution, back-EMF waveform and electromagnetic torque are validated by both two-dimensional (of a generator cross-section, neglecting end effects) and three-dimensional finite-element analyses, using the Comsol Multiphysics® software.

A specific procedure for iron loss calculation, taking into account also minor loss and excess loss, has been followed, with a detailed calculation for each iron part, with losses divided in hysteresis, classical and excess components [9].

The optimum time-stepping and mesh refinement have been thoroughly studied in order to save computational time.

Different simulations have been performed, in order to firstly refine the geometry, then optimize various machine parameters and finally obtain an equivalent electrical circuit, useful to predict performances.

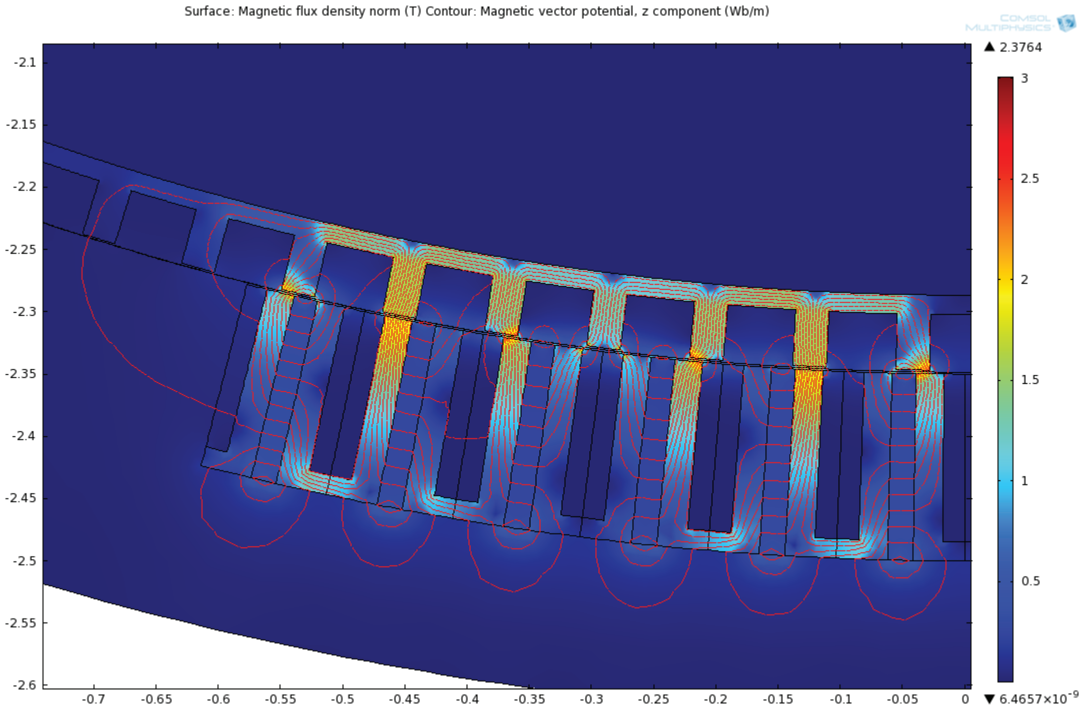

Fig. 6. Magnetic values plot at no-load, $P_s = 12$: a peak value of B = 1,8 T occurs in the teeth of phase B at d-axis position; the peaks in the corners (up to 2,38 T) are due both to the sharp edges and to numerical issues. It could also be noticed the high flux leakage occouring in the peripheral pole: this will reduce the flux linkage and so affect the inductance and the torque

All the specific effects linked to this particular machine have been investigated; the asymmetry of phase flux and back-EMF has been studied: in both the machines considered, phase A and C, which present a peripheral pole, link a total flux with an amplitude about 3% lower than phase B, and this affects the torque too. A strategy to reduce this effect, both varying geometry and magnetic remanence, has been studied.

A thermal investigation is carried out in order to find the conductor temperature, necessary to evaluate analytically the resistance (because of the copper resistivity temperature-dependence), to verify the resistance of the insulation and to evaluate the necessity of a forced-air / water cooling system, instead of a natural air circulation. As the machine is floating on the sea, the hull could be considered as a temperature boundary, with an inner layer temperature set. For the prediction of the temperature rise, both an analytical lumped-circuit method and 2D finite element analysis could be employed [10],[11]; while the former requires much less computational time, only a thorough numerical simulation could give a detailed temperature field distribution. Eddy current losses could cause higher temperature rise than that in the stator windings; these electromagnetic losses are considered additional heat sources. The interaction between thermal and electromagnetic fields is reciprocal: a too high temperature rise could not only increase copper losses, but also affect the performances of the magnets, especially if Ferrite or NdFeB are employed (the temperature coefficients for B_r and H_c is high). When it will be simulated the behaviour of the machine in real conditions (time-variable load), a transient thermal analysis will be performed.

4) *Results*

As regards to the arch-shaped generator, two machines with the same outer dimensions but a different number of stator poles have been compared.

In the same angular sector, the 12/14 machine will be simpler and less expensive to construct. The main

difference is the frequency of flux and induced voltage, making the 24/28 machine more suitable for very low-speed operation when coupled with a converter. The induced voltage, then, has a double amplitude. The influence of circumferential end effects is just a little lower in the 24 poles machine. The designed 12/14 machine has an optimal split ratio which is lower (0,935 instead of 0,97) making it possible to use larger windings in order to reduce the current density and the copper losses. A lower split ratio for the 24/28 layout, necessary to reduce copper losses (the most important of this machine), requires too long teeth compared to the bridges, making k_σ decrease. However, the lower split ratio of the 12/14 layout makes necessary more iron, but the half frequency leads to lower iron losses.
After an overall comparison, the design of the 24/28 machine has been abandoned because, with the geometrical constraints of the initial prototype, a machine providing the necessary electric loading would have very narrow stator poles to reduce copper losses but still present higher iron losses while having an optimal design would require a higher angular opening of the buoy, so it could be object of further studies. The asymmetric layout leads to high radial efforts: the airgap should be large enough, so as to avoid mechanical damage: this causes, in a 24/28 machine, very low airgap permeances compared to those of the iron parts, which will strongly reduce the flux density in the teeth, affecting the output torque. As proposed in [12], a solution could be a bath of oil and iron powder in the airgap to prevent wear and mechanical damage and allow to obtain not too small airgap permeances.

Table 1. Geometrical and Electrical Characteristics of the arch-shaped 12/14 and 24/28 generators

$P(kW)$	$T_{per}(s)$	$T(kNm)$	$\alpha(rad)$	$\omega_m(rad/s)$	$D_{os}(m)$	$L(m)$
10	6	60	0,496	0,165	5	1,25

P_s	P_r	$P_{r\gamma}$	λ	c_s	$V_{conv}(V)$	$I_{ph}(A)$	$R_s(\Omega)$	$L_s(H)$	P_{Cu}	P_{Fe}
12	20	14	0,935	0,23	200	35,6	0,213	0,130	808	202
24	60	28	0,94	0,25	200	32,6	0,244	0,0613	777	291

To compare the effectivness of this concept with a more traditional layout, a reciprocating machine with the poles spread all over the circumference has been analysed too.

Table 2. Geometrical and Electrical Characteristics of the circumferential 48/56 generator

$P(kW)$	$T_{per}(s)$	$T(kNm)$	$\omega_m(rad/s)$	$D_{os}(m)$	$L(m)$
10	6	20	0,524	1,5	0,375

P_s	P_r	λ	c_s	$V_{conv}(V)$	$I_{ph}(A)$	$R_s(\Omega)$	$L_s(H)$	P_{Cu}	P_{Fe}
48	56	0,8	0,25	200	39,8	0,167	0,0733	794	504

In this case, the very reduced elongation of the pendulum makes necessary a high number of poles. A 24/28 machine has been initially analyzed, but the very low frequency suggested to increase the number of poles to 48/56. The frequency and amplitude of the induced voltage of this machine are similar to those of the 12/14 arch - shaped generator. This configuration leads to a much simpler construction (no more airgap problems, radial efforts compensation), no border effects, less material used (-22% iron, while just the active part of the rotor is interested by iron losses, -10% magnets, same amount of copper), lower inductance.
Thanks to the high torque density allowed by the Flux Switching principle here employed, in this concept a high amount of material could be saved in comparison with analogue existing projects, as the 10kW linear generator for a Point Absorber device shown in [13]. The 12/14 arch-shaped generator presented above requires 26% less iron, 34% more copper and 60% less magnets.

2.3. Power Electronics Coupling

As shown in figure 5, the waveforms generated by this type of all electric WEC (wave energy converter) are incompatible with the electric grid parameters. Both frequency and amplitude of the terminal voltage needs to be modulated into the waveform, amplitude and frequency of the electric grid to which the electricity produced is going to be delivered. For such purposes, the standard way is to use a two stage transformation through some kind of power electronics coupling. The first stage transformation (AC/DC) consists on rectifying the alternating terminal voltage of the WEC generator into direct current and voltages and feeding it into a DC link bus equipped with a buffering element such as electrolytic capacitor or any other storage medium that can be used as electrical smoothing element for the fluctuating input coming from the WEC. After this first stage transformation, the rectified voltage is inverted (DC/AC) into a sinusoidal shape voltage with amplitude and frequency compatible with those of the electric grid at the point of connection. The DC current is inverted into alternating current with modulated amplitude corresponding to the fluctuations of the input from the WEC. This modulated current multiplied by the voltage at the grid connection point will result in a fluctuating instantaneous power as long as no energy storage is placed at the DC bus. The rectification stage of the power electronics coupling could be achieved by using passive interfaces (diode rectifier) or active interfaces (transistor based rectifier), depending on the control strategy to be implemented. Passive rectification will only allow the implementation of passive loading strategy as the flow of power is unidirectional, while active rectification will allow both, passive loading and optimal or suboptimal control of the WEC, due to the bidirectional power flow enabled by this type of interfaces. The main drawback of the passive rectification is that when the waves are very low the terminal voltage of the generator will also be very low and the operation of the WEC system under such condition will require a grid connection operation mode only as the DC bus need to be maintained at a voltage level always higher than the AC voltage to allow for the rectification of the currents. In such case, the second stage converter (DC/AC) will be controlled so as to keep the DC bus voltage always over the minimum value required for normal operation. The second stage of power electronics transformation will need to be implemented by active front end converters (transistor based) that would be able to control the power factor at the point of connection to the electric grid and a more flexible functioning of the conversion systems in case of faults on the grid side or loss of WEC generation. In the next stage of this research a thorough investigation of the two well established WEC control strategies (passive loading and optimal control) will be carried out through a detailed representation of the electric power take off as described later. .

2.4. Control Strategies

As J. Falnes said ([14]), *Absorbtion of waves means generation of waves*: an efficient control is required to tune the movement of the coupled mechanical and electrical device with the period of the incident sea wave. The energy extraction strongly depends on the choice of the control strategy, so it should be done carefully as it also influences the ratio between peak and average power extracted; the effects of non ideal power conversion will be taken into account too.

To compare the different control strategies, an hydrodynamic model of the buoy is introduced. As suggested in [15], the interaction with the wave climate is modelled using the hydrodynamic diffraction model, requiring some fundamental assumptions ([16]). A time domain study is necessary when irregular waves are considered; the system is described by the force equation

$$(M + a_\infty) r\ddot{\theta}(t) + \int_{-\infty}^{t} H_{rad}(t-\tau) r\dot{\theta}(t) d\tau + Kr\theta(t) = F_E(t) + F_L(t) \tag{4}$$

where on the left side appear the inerta, damping and stiffness terms, and on the right side the excitation force and the force applied by the PTO.

An electric analogue is adopted to represent the previously described system: the wave excitation force is represented as a supply voltage and the velocity corresponds to a current.

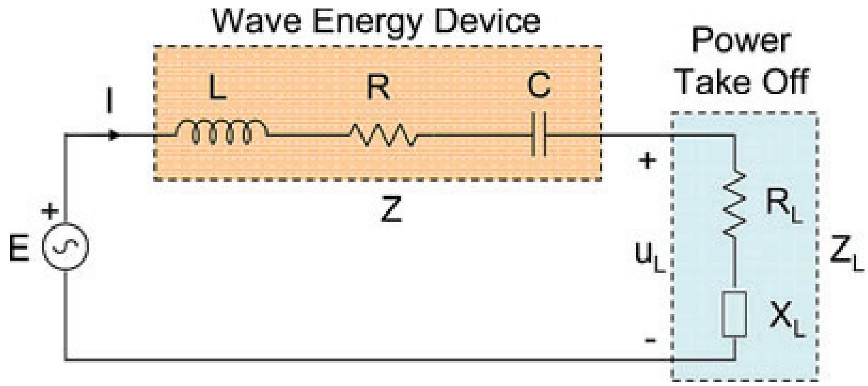

Fig. 7. Electric Analogue of the WEC, from [16]

The most common strategies, as latching control, passive loading and optimum control, are compared. An investigation will be carried out to see whether, under real wave conditions, an optimum control strategy, requiring a converter allowing a bi-directional power flow, could be superior, in terms of energy extraction, to the simpler passive loading, leading to a more limited power electronic overrating.
An integrating model, including hydrodynamic and electric parameters, is made to study the behaviour of the whole system.

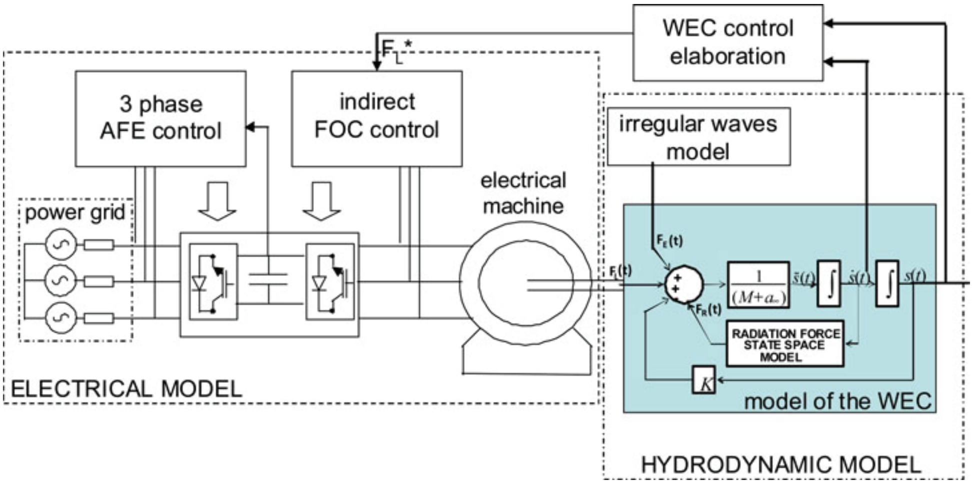

Fig. 8. Integrated simulation model of the WEC, from [16]

2.5. Grid Connection

The impact of a Wave Farm on the power quality of the grid depends on its operating conditions but also on the characteristics of the power system. The large impedance value makes the distribution system close to shore a weak grid, so the connection of a Wave Farm is a challenging task.
Specific analysis will be done aimed at guarantee that, under fault conditions, the system remains safe and provides power to the electric grid.

3. Conclusion

The initial results obtained are promising: despite the simplifications in the study and all the difficulties related to this particular layout, a futher study and development could lead to a cost-effective machine,

respecting the fundamental goal of a totally sustainable and eco-friendly whole system.
It should be noted that the values continue to be subject to further study and improvement and should therefore not be taken as definitive.

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