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. It passes through an hydrodynamic study allowing to the choice of the best floating buoy shape based on the maximum energy extraction by the system, then the sizing procedure of an innovative arc-shaped electrical generator, in which the flux-switching principle has been chosen (for the first time for a low-speed – high-torque application), thanks to its high torque density, then through its analysis, optimization and performance verification by FEA, and finally the study of the most suitable control strategies. A particular attention has been given to all the specificities this new particular generator presents: non-constant rotational speed, reciprocating motion, border effects. This arc-shaped generator has then been compared to a traditional rotating machine directly coupled with the shaft and moved by the pendulum.

At every stage of the project, the fundamental goal of a totally sustainable and eco-friendly whole system has been taken into account.

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

1. Introduction

Ocean energy 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. In a direct wave converter, on the other hand, the electrical generator is directly coupled to the buoy; to reach the maximum energy extraction, resonance should be achieved, i.e. the translator should move at the same frequency as the excitation force. 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. The direct WEC system can however be controlled with flexibility by a power electronic interface to actuate an optimal control strategy needed to extract the maximum wave power from the ocean. A complex electronic power compensation and an optimal control strategy are needed as an interface with the traditional electrical grid, requiring voltage and frequency variables in very limited ranges.

As regards the operation principle, various conversion devices exist, involving an auxiliary fluid or directly exploiting different modes of the oscillatory motion of a body in water. In this particular project, among the hydrodynamic forces acting on the body, the pitch movement of a buoy hull is exploited.

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 preliminary analysis of the whole converter system has 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.

2. Model of the Electric Generator for the Direct Drive Wave Energy Converter

This work has started from a feasibility study of the innovative energy pendulum generator called *Seaquest Project*, made by the Spanish Company Mecanica Industrial Buelna ([1], [2]). 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 swings activating the arc-shaped generator.

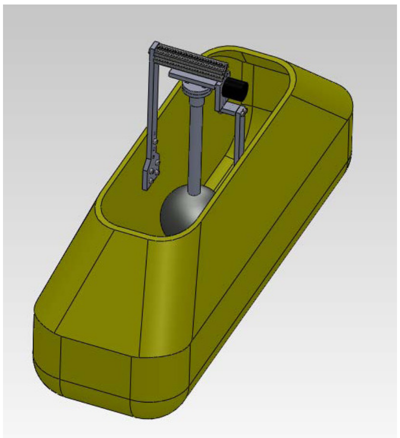

Figure 1: The initial pendulum generator concept

2.1 Overview

In this work an investigation has been carried out to compare 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 challenging, especially in consideration of the very low, non-constant reciprocating speed; in addition, the arc-shaped generator presents border effects.

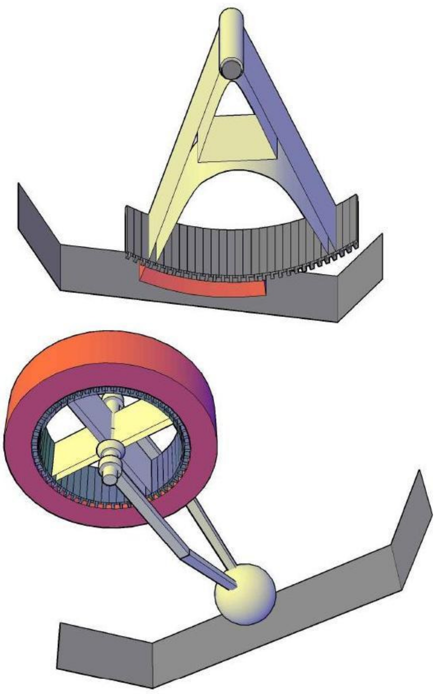

Figure 2: The two concepts of generator compared: Arch-Shaped with rotor on the pendulum tip and Circumferential with a sphere as pendulum tip

In the traditional machine, the pendulum tip is an iron sphere, so all the buoy opening is exploited., while 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]).

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.

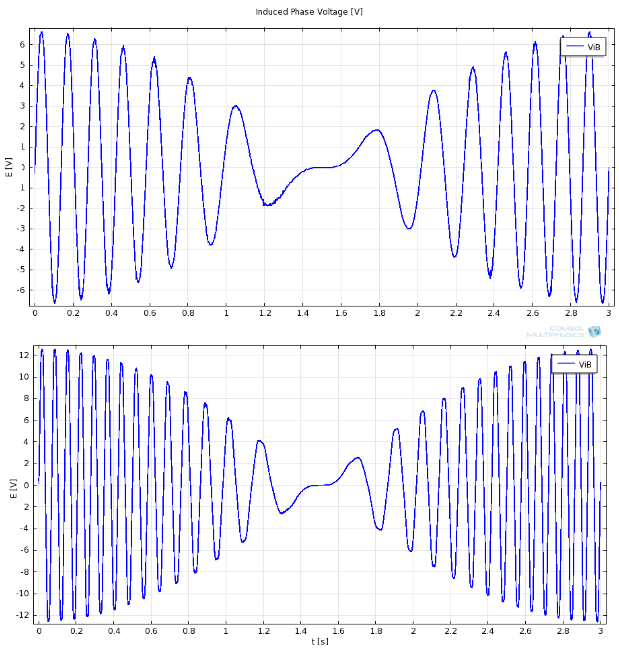

Figure 3: Phase Voltage Waveform from a transient simulation, $P_s = 12$ (above) and $P_s = 24$ (below); the y-axis scale (Voltage) of the second figure is double

2.2 Design

Different design procedures have been studied, respecting the project goals; the most important one is the reduction of 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), $B_{t\text{-}ag}$ (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), the geometric parameters for a preliminary sizing step are obtained.

Relating the power to all the other parameters it is possible to easily determine the dimensions required to achieve a certain energy production.

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, whose principle has been applied before only in high-speed, low-torque machines. 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

2.3 Optimization and Performance Analysis

Finite-element analysis, along with a lumped parameter magnetic circuit model (as proposed by [5], based on [6] researches on FSPM machines), have been widely employed.

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 [7], based on 2D and 3D finite element analyses.

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

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]), to determine whether it could be advantageous increasing the number of poles.

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.

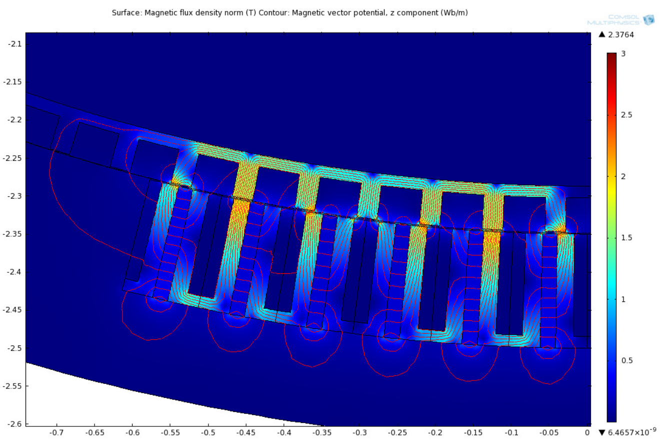

Figure 4: Flux Density Plot from FEA, $P_s = 12$

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, magnetic remanence and number of turns has been studied.

A thermal investigation is carried out in order to find the conductor temperature, necessary to evaluate analytically the resistance, 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.

For the prediction of the temperature rise, an analytical lumped-circuit method and 2D finite element analysis are combined (as in [10], [11]); while the former requires much less computational time, only a thorough numerical simulation can provide a detailed temperature field distribution. The interaction between thermal and electromagnetic fields is reciprocal: a too high temperature rise not only increases copper losses, but could also affect the performances of the magnets, especially if Ferrite or NdFeB are employed (the temperature coefficient for B_r and H_c is high).

2.4 Results

Two arch-shaped generators with the same outer dimensions but a different number of stator poles have been compared. With less poles, 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 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 cause, 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.

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 also analyzed.In this case, the very reduced elongation of the pendulum makes necessary a high number of poles. 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.

3. Power Electronics and Control

3.1 Converter

Both frequency and amplitude of the terminal voltage need to be modulated into the waveform, amplitude and frequency of the electric grid which the electricity produced is going to be delivered to. For such purposes, the standard way is to use a two stage transformation. 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.

3.2 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]).
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.

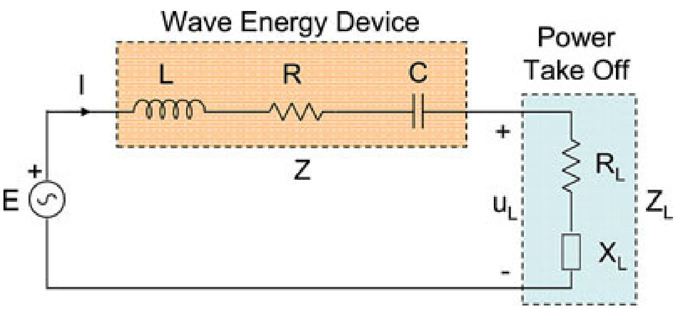

Figure 5: Electric Analogue of the WEC, from [16]

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 used to study the behaviour of the whole system.

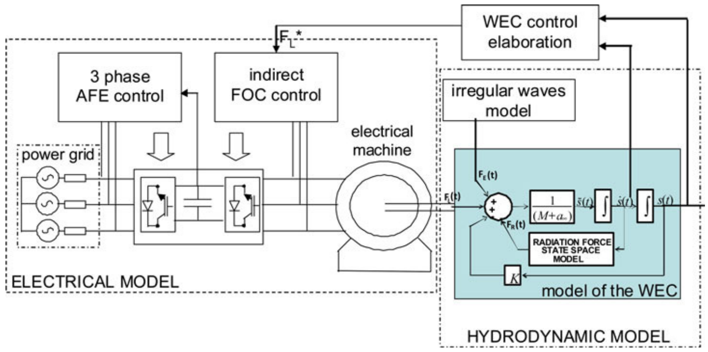

Figure 6: Electric Integrated simulation model of the WEC, from [16]

3.3 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.

4. 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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