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Optimized double sided linear generator for wave energy in São Paulo's coast

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Abstract- The main goal of this project was to design a linear electrical generator optimized to harvest energy from ocean surface waves of typical Brazilian shores, to assess its technical feasibility and to estimate its costs. We built a small scale model in order to test the proposed topology of an air cored double sided linear generator using NdFeB permanent magnets (PM). Next, we designed a full scale machine with rated peak values 5.09 kW and 107.3V. The cost of the electrical part alone is estimated in 8,460 Euros and the estimated *levelized cost of electricity* (*LCOE*) would range from 310.77 Euros/MWh to 772.76 Euros/MWh for a deployment off the coast of São Paulo state (SP).

Keywords- linear generator, wave energy, brazilian shore, permanent magnets, marine renewable energy

I. INTRODUCTION

Brazilian major consumer centers are next to its shores, making technical and financial interesting the study of energy harvest from the ocean.The large availability of ocean waves plays an important aspect for this type of energy, also power plants far from the main loads have a high cost in transmission lines, as in losses and system reliability.

Wave Energy Converters (WEC) are system which absorbs the kinetic energy of the waves and convert it to electricity, the term WEC is widely used to describe any equipment that converts waves energy into power. In these systems designers usually have to deal with the problem of low speed and large variety of posibles loads. To face this situation, wave energy converters are associated with mechanics system to increase the speed into a conventional one, with an intermediate state of conversion known as "power take off" (PTO), which converts the wave energy to the electric drive.

Currently, one of the most important equipment which converts wave energy using a linear drive is the *Archimedes Wave Swing* (AWS) [1]. Although it can generates meaningful power, this equipment has an output that varies in frequency, peak values and phase sequences, these due to the natural movement of the WEC and the absence of energy storage equipment. Therefore, for this system it is necessary to associate it with power converters with enough energy storage as DC, or it is also possible to concatenate multiples linear drives which would decrease the need for energy storage [2] and [3].

Past works show that are different ways of converting the wave energy into power. In [4] the author shows a permanent magnet linear drive with a double primary in C shape. The C shape makes possible to cancel the attraction force of the stator and its translator. In [5] it shows a tubular linear drive with air core with double primary. In this case care was taken to design the translator larger than the stator, avoiding that part of the stator stayed inactive during the end of the excursion of the translator. Others linear drives with different topologies are also shown in [6] and [7].

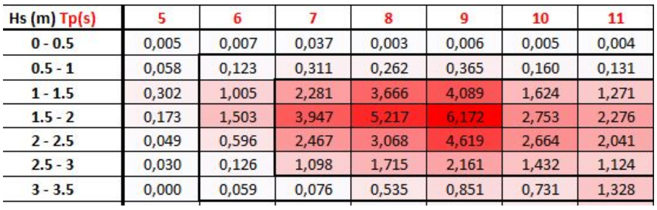
A usual divergence in designs is the translator core's design. It can be of either a steel material [7] or of a magnetically similar to air material. A comparison of these two possibilities is made in [8]. In this work the author shows that taking into account the auxiliary mechanical structure to maintain the designed airgap, the air core solution is proportional lighter.

For our application we chose a three-phase double sided linear electrical generator. The use of a linear generator solves the problem of conversion from the natural movement of the buoy to the generator, since complex mechanical parts between the waves and the machine are not needed. Being an air cored machine reduces the mechanical efforts in the generator's base frame. It also implies in a low synchronous inductance, that associated to the low operation frequency of the machine results in a high power factor and higher efficiency values. In order to get an constant and intense flux we used NdFeB permanent magnets, which were located in the static part of the machine.

The first part of this work is about the typical waves found in São Paulo's coast. The location choice was because São Paulo is one of the most important loads for the Brazilian grid. The wave data studies are summarized in section II. Sections III and IV describes the main points of this linear drive topology and characteristics. In section V are shown the results of this design and project.

II. WAVE DATA

Wave data were measured from a buoy 200 km off the coast of São Paulo at 25.5°S, 45°W at waters in 200 m deep. They were classified by peak period (Tp) (1 s to 25 s, 1 s steps) and significant height (Hs) (0 m to 8 m, 0.5 m steps). It was assumed that the machines linear velocity is equal to the vertical displacement of a buoy on a sinusoidal wave of frequency 1/Tp and amplitude Hs/2. The energy that could be converted by the generator was calculated for each wave category, as shown in the Table 1.



Hs (m) Tp(s)	5	6	7	8	9	10	11
0 - 0.5	0,005	0,007	0,037	0,003	0,006	0,005	0,004
0.5 - 1	0,058	0,123	0,311	0,262	0,365	0,160	0,131
1 - 1.5	0,302	1,005	2,281	3,666	4,089	1,624	1,271
1.5 - 2	0,173	1,503	3,947	5,217	6,172	2,753	2,276
2 - 2.5	0,049	0,596	2,467	3,068	4,619	2,664	2,041
2.5 - 3	0,030	0,126	1,098	1,715	2,161	1,432	1,124
3 - 3.5	0,000	0,059	0,076	0,535	0,851	0,731	1,328

Table 1 : Extractable energy, in %, for the most significant wave category measured off Sao Paulo's coast with highest distribution.

After the study of this real data of the waves in this location, we got that the machine should operate with a wave range of 1.25 m and a vertical velocity of the buoy of 0.55 m/s. This represents the most typical situation in the region.

III. SMALL SCALE PROTOTYPE

A prototype was built of this machine in a reduced size scale model. As a result, the data obtained shows that this machine have a low synchronous inductance, which can be neglected, however its winding resistance is very high, being the main loss in this design. In order to increase its efficiency, the winding resistance was reduced by decreasing its number of turns per phase and also by improving the iron saturation using an odd number of poles, thus reducing the saturation in the poles closer to the center of the machine and making it possible to reduce the iron thickness, making it lighter.

The stator was made with flat NdFeB permanent magnets. The Halbach magnet disposition [9] was studied for this application, however due to the high costs of this topology, with double the number of magnets, we chose a conventional double sided disposition for the magnets.

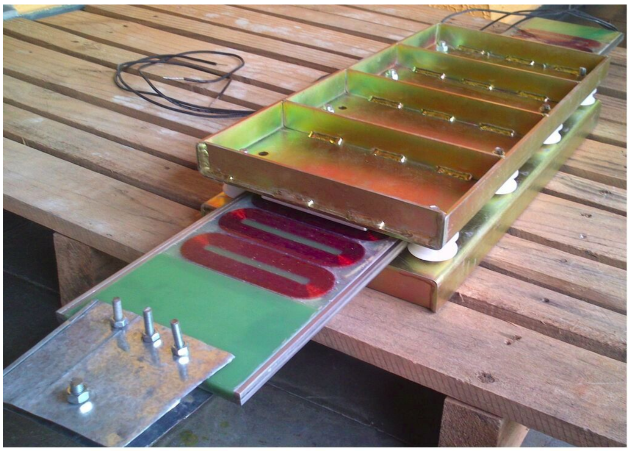


Figure 1 : Linear drive built prototype

Another important characteristic of this air cored machine is that the maximum extractable power is achieved when the load is equals to the internal resistance. This is due to the low translation speed (low electrical frequency) and small inductance that makes the generator's impedance to be almost purely resistive. In that case, the maximal power transfer condition is the best point to operate since it will be the point of lowest *LCoE.*

IV. FULL SCALE PROJECT

The full scale project initiated by evaluating the energetic distribution of the waves measured by the buoy off the coast of São Paulo. The extractable energy as a function of the maximum excursion was calculated for this site and it's shown in Figure 2. Since the cost of the generator will increase linearly with its length, it is possible to assess that a machine with a 1.25 m stroke will be the most cost effective in this sea conditions.

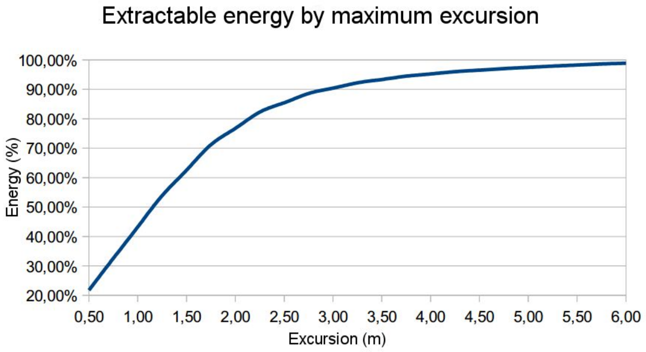


Figure 2 : Extractable energy, %, by maximum excursion, in meters.

Using the methods and theories tested in the small scale prototype, the stator could be design by simulating the magnetic fields of nine different arrangements. The best solution was one with 17 poles with the dimensions 50.8 mm x 12.7 mm x 304.8 mm and total length of 1.295 m. The 2D simulation for the selected option is presented in Figure 3.

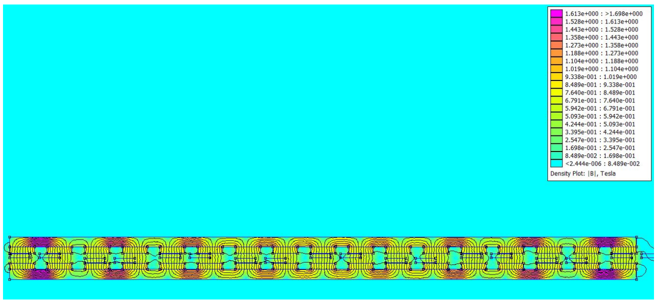


Figure 3 : Magnetic simulation of the stator.

Then 27 scenarios were calculated to choose the adequate coils that would maximize the output power and have an adequate voltage and current. The most significant 12 are shown in Figure 4. The optimized solution had a airgap of 22 mm between the stators parts, AWG14 windings and a tri-phase system.

The first version of the translator was twice the length of the stator and had 17 coils per phase. So, in a 1.25m excursion there would always be coils filling the stators magnetic field (active poles). Later, the number of coils per phase was reduced from 17 to 9 because of the increase in the energy generated, although it changes the voltage profile.

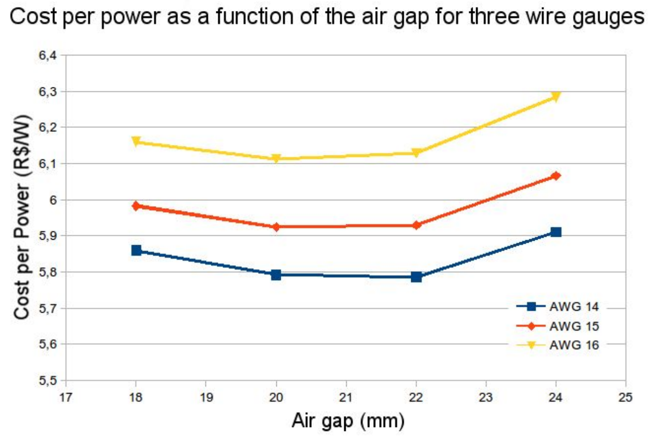


Figure 4 : Cost per power (R$/W) as a function of the air gap (mm) for three wire gauges (blue AWG14, red AWG15 and yellow AWG16)

As tested in the small scale prototype, the maximum output current is inversely proportional to the internal resistance. That can be achieved by reducing the number of coils, even though that affects the voltage profile, which can be minimized by removing copper from the outer parts of the translator, and reducing the voltage when the machine's speed is already slower. The Figure 5 shows the waveforms of the output power for various number of coils.

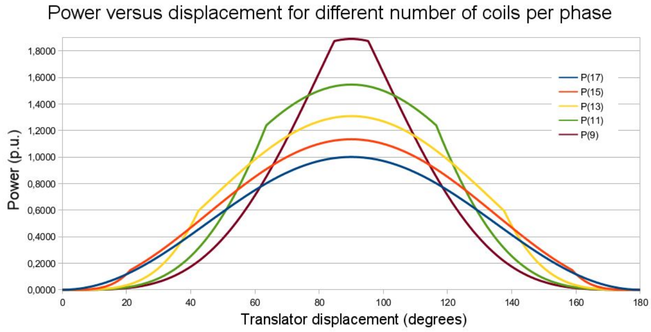


Figure 5 : Power profile, in p.u., versus displacement, in degrees. The colors indicate different number of coils per phase: blue 17 coils, red 15 coils, yellow 13 coils, green 11 coils and brown 9 coils.

A 3D sketch of the stator and translator was made to visualize the electrical building. Also, a simulink/ SimPowerSystems model, presented in Figure 6, was made to obtain the different waveforms in each condition. These waveforms are complex mainly for two reasons: the number of the stators active poles depends on the translator position (Figure 5) and for waves bigger than the maximum excursion the translator does not move.

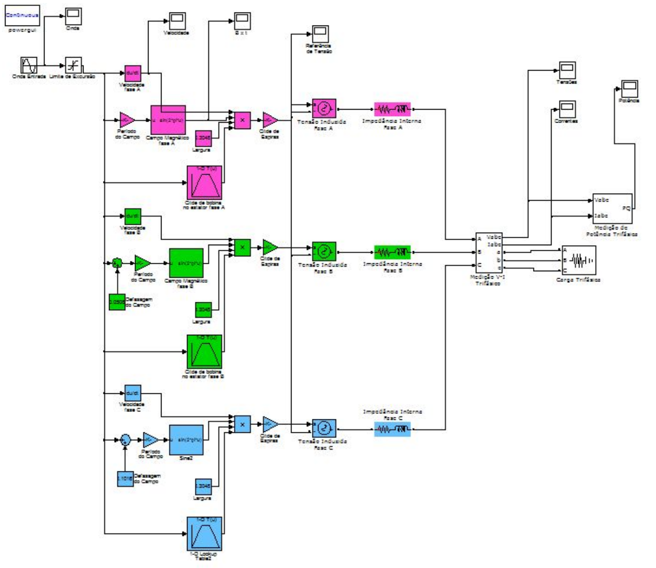


Figure 6 : Block diagram of the linear machine simulation on simulink.

In a simple case, the simulation's input would be a modeled sinusoidal ocean wave height over time, Figure 7a. Then the output would be a tri-phase voltage modulated by the translator speed, Figure 7b. The simulation can also output the currents and power for different input waveforms and impedance loads..

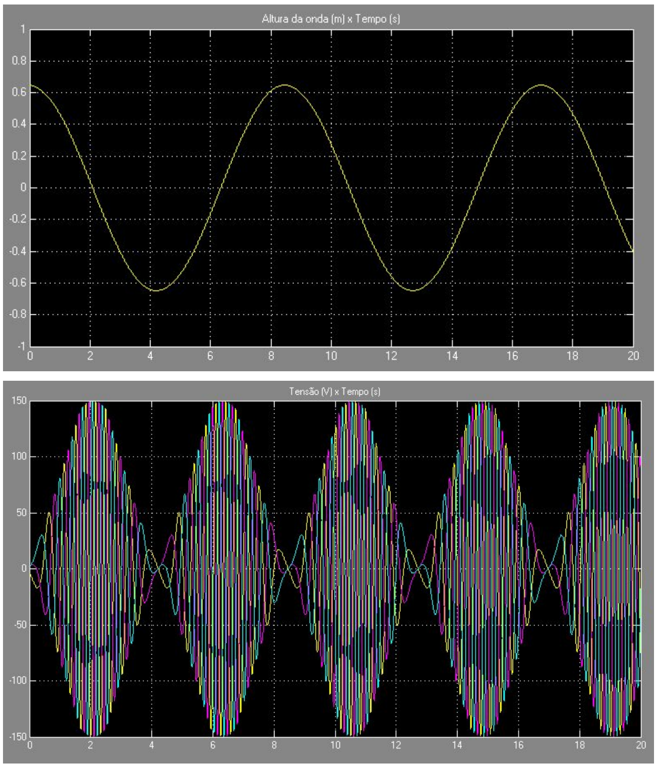


Figure 7a(top): Ocean wave simulations input waveform. **7b(bottom) :** Simulation tri-phase voltage output.

The final machine has rated values of 5.09 kW output power, 107.3 V per phase and 15.8 A current, with an approximately constant impedance of 8.29 Ω/phase resistance and 33.91 mH/phase inductance, as shown in Figure 8. At the most frequent wave height and speed, the maximum complex impedance would be 8.33|_5.30° Ω/phase.

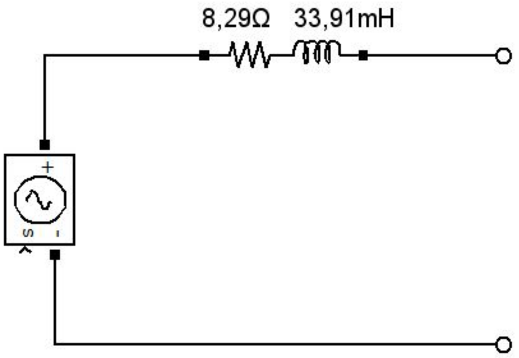
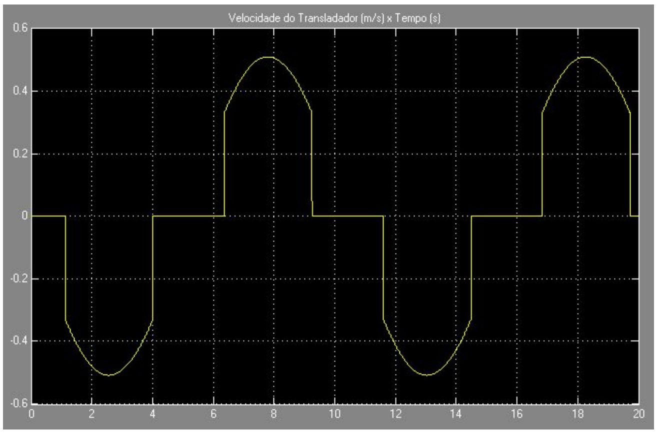


Figure 8 : Linear machine electrical model of one phase.

The simplified model presented above uses a voltage source that will be determined by the input ocean wave form and the generator's characteristics. To visualize the result, the simulation is used, especially in situations where the input ocean wave is bigger than the maximum excursion. In this case, the translator will halt for some time near the wave peak and trough. In that period, the output voltages and power will be null. This situation is shown in Figures 9a, 9b and 9c.



V. RESULTS & FINDINGS

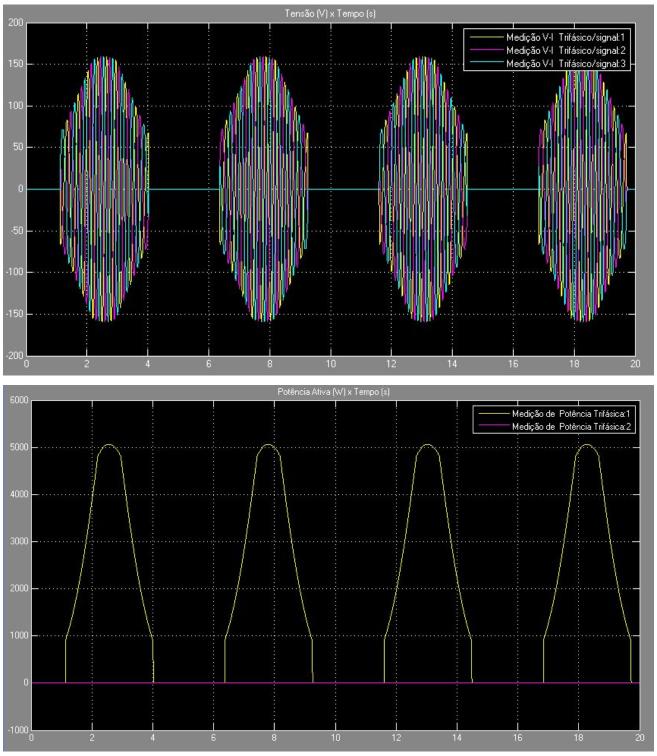


Figure 9a(top) : Translator speed for a ocean wave bigger than the maximum excursion. **9b(middle) :** Output tri-phase voltages. **9c(bottom) :** Total output power.

In the conditions of the coast of São Paulo (SP) it could generates 5.89 MWh per year, implying in a capacity factor (CF) of 0.1322. The CF has two components, one from the electrical characteristics of the machine and independent of the deployment site (0.3916 shown in Figure 10) and other directly linked to the relationship between the maximum stroke and the local wave conditions (0.3376 for SP).

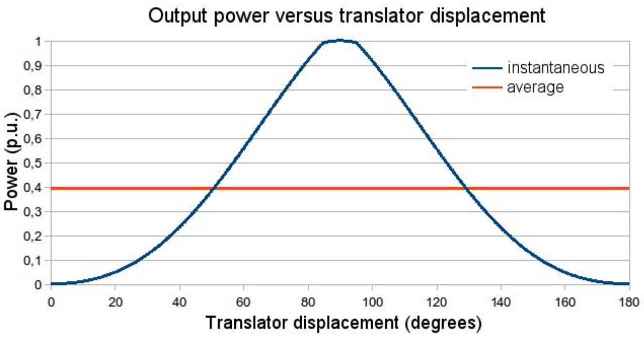


Figure 10 : Output power, in p.u., versus translator displacement, in degrees. Blue line is the instantaneous power and red is the average.

The CF for this machine in four other locations (two north and two south of SP) with available data was calculated ranging from 0.1322 in São Paulo to 0.1464 in a location further south. This data is present in Table 2.

Location	CF
RS	14,5%
SC	14,6%
SP	13,2%
RJ	13,9%
PE	13,6%

Table 2 : Calculated capacity factor for the linear machine used in 5 different locations in Brazil. The order is from most south, RS, to most north, PE.

The generators estimated cost, including workforce was of 8,460 Euros, being 57.6% the costs of the magnets. The average price of NdFeB PM is 100 Euros/kg in Brazil and impacts directly in the final cost, so future perspectives of air cored PM generators should take this aspect into account. Adding up the total workforce for making the stator, the coils and assembling, it represents about one third of the total cost. Figure 11 presents the relative costs share for the linear machine.

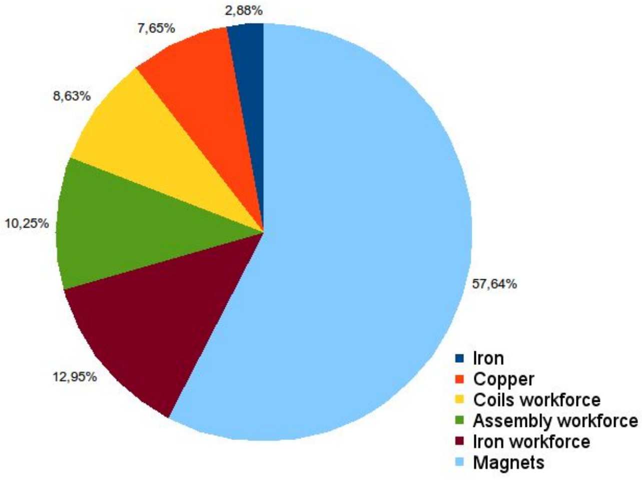


Figure 11 : Relative costs for the building of the linear generator.

The cost per rated power was of 1,663 Euros/W. A few scenarios of total material costs (electrical and mechanical parts), deployment and O&M resulted in a LCoE between 310.77 Euros/MWh and 772.76 Euros/MWh.

VI. CONCLUSION

The design studied in this work of a linear drive to convert the wave kinetic energy into electrical energy proved to have the advantage of lower mechanical systems to connect the buoy to the drive, thus increasing the energy efficiency of the process. However, the power generated in this model deeply depends on the translator excursion, and it needs to be specifically design for each range of waves speed and height. Using the air core, instead of the steel core, as expected decreased the magnetic field in the airgap, still this reduction was not meaningful.

Even though projects as this one are not yet economically competitive, researches like this are important to test new technologies and collaborate to a decrease in LCoE by better designs (technical gains), increasing scales and learning curves (technical, social and economical gains) and decreasing risks (financial gains). This shows us to a future scenario where ocean are a part of our energy resources.

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