Abstract—While the exhaustion of carbon based fuels has become a certitude, the use of alternative fuels became more popular in the last decades. The renewable energy sector emerged, providing an alternative to conventional energies; amongst them the wind and solar energies became extremely popular in the last decades, supplying important parts of the total energy required in countries like Germany or the United States of America. Besides these, the wave energy sector represents a huge, yet unexploited domain, which could prove to be a long time solution for the forthcoming energy shortages.

Index Terms—Electrical Generator, Linear Machine, Permanent Magnet, Renewable Energy

I. INTRODUCTION

The world energy demand is increasing constantly since the end of the 18th century, when the industrial revolution started in the UK and then spread all around the globe. Recent studies show that the natural reserves of carbon based fuels will only last for a few decades, given new deposits are not found, so adjustments have to be made in the way we produce and consume energy. Several solution were proposed to overcome this problem, starting with better ways of using the fossil fuels (mixing them with additive or improving the efficiency of combustion engines) or by looking for new energy resources. The search for alternative energy begun on a large scale after the ‘70’s oil crisis, when for the first time the world saw what it would be like if fuels would no longer be cheap and easy to find. Many research programs were started in that period, focusing on ways of using the Earth’s natural reserves without exhausting them. It was during that period that the renewable energies emerged as a possible long term solution and amongst them the wind and solar energy became the most popular, given the relative easy ways of transforming them into a transportable and storageable form.

In the last decade many of the high developed countries covered an increasing amount of their total energy demands using wind or solar energy. Besides these, renewable energies like the geo-thermal, bio-mass or ocean energy became a solution for specific locations: unlike the solar or wind energy, which are present almost everywhere on the globe, these forms of energy are rather scarce, so they can be used in some regions (the northern countries use geo-thermal energy for electric energy production or home heating, agricultural regions use the bio-mass for energy production and the regions with ocean coasts use ocean energy)[1].

II. WAVE ENERGY CONVERTERS

The generic term “ocean energy” refers both to wave and tidal energy and has a multiple source: Earth’s rotation around it’s own axis, determining the appearance of the tides; Moon’s orbit around Earth, causing daily high and low tides, reaching from 80cm to 16m [2]; the uneven warming of the Earth surface, causing air movement (winds) which, when traveling over the water surface, will determine small surface deformations that build up, causing waves. Unfortunately, the energy potential is reduced in all the closed seas, and the Black Sea is not an exception, the wave height reaching 0.91m in January and 0.32m in July [3]. Higher values are obtained near the Atlantic and Pacific Oceans shores, with suitable locations determined along the coasts.

Several solutions for harvesting this enormous energetic potential were proposed, some of them reaching the prototype stage, while only a few turned commercial. They are commonly referred to as WEC (Wave Energy Converters) and the most known are presented in the following lines, along with the working principle.

- LIMPET, an oscillating water column device;
- PELAMIS, floating device with several segments connected through joints;
- WAVE DRAGON, overtopping floating structure;
- ARCHIMEDES WAVE SWING, based on water column pressure;

Most of these devices use mechanical or hydraulic systems to convert the slow linear, reciprocating motion characteristic to waves into high speed rotational motion suitable for classic rotating generators. The major drawback of such a solution is that the overall system efficiency is greatly affected by the gearboxes, turbines or hydraulic systems used, with a lower reliability caused by
the large number of moving parts, while the advantages of using such a system are that by using off the shelf products the total price is slightly lower and the expertise in rotational generators is greater than for the linear versions.

For eliminating these mechanical systems a different approach was proposed: using linear generators connected directly to the wave energy absorber. Such a solution can be used for various WEC topologies, the simplest using a buoy connected to the generator moving part, while the stator is fixed on the ocean floor, like in Fig. 1 a). Another possibility is placing the stator above the ocean surface using two floaters, positioned in such a manner that the distance between them and the translator buoy is half the wave length, like in Fig. 1 b). Other solutions are to leave the stator floating beneath the ocean surface, Fig. 1 c) or to place the entire structure inside a sealed room made of two cylinders opened at one end (Fig. 1 d). Depending on the amount of water placed directly above the device the internal air pressure will cause the upper cylinder to move up or down along with the generator translator, producing electricity.

The up and down movement produced by an ideal wave can be approximated by a sine, resulting a cosine-shaped speed variation, with maximum speeds reaching up to 2m/sec, depending on the sea state; however, the speeds are usually between 0.5–1m/sec. The linear generator should be chosen considering these speed values and the working conditions, the general requirements being presented next.

This paper presents a linear electric generator that can be used in such systems, offering the great advantage of a smaller number of moving parts, improving the system reliability, a major concern for WEC. Similar generators can be used for electric energy production with solar energy powered Stirling engines or using Free Piston Internal Combustion engines, a solution for power production in remote locations.

**III. ELECTRIC LINEAR GENERATORS**

In order for a linear generator to be suitable for a WEC it should be able to provide high performances at low speeds and a simple structure, implying a high reliability.

**A. Structures**

Many solutions were approached in the last years, such as the three-phase permanent magnet synchronous generator, the switched reluctance generator, the coil-excited synchronous generator, the air-cored permanent magnet generator or the transverse-flux permanent magnet generator, but some of them were abandoned because of the problems involved, such as the mobile contacts wearing for the coil excited machines or the complicated construction of the T.F. generator [4]. For most of these structures the high magnetic forces in the normal direction require advanced bearing systems to be used, a problem that can be easily overcome by building tubular structures.

A study concerning the shears stress developed by various linear generator topologies pointed out that the Transverse Flux machines provide the highest force density in the airgap, but their complicated structures imply high manufacturing costs [5]. At the same time, because of their structure, only one- or two-sided structures have been reported, so high magnetic forces appear between the stator and the translator. Another solution is the Vernier Hybrid Generator, with a simplified construction at the cost of lower shear stress values than the TFM [6,7]. It has a passive translator with teeth, while the stator is made of “C” shaped parts, which have both the coils and the permanent magnets. The major drawback of such a structure is the high mover mass determining high inertia.

Perhaps the simplest solution, although with lower shear stress values, is to use tubular permanent magnets mounted between iron pole pieces in sandwich type structure to form the moving part and ring shaped coils mounted on the stator. In order to reduce the magnetic forces that will appear between the translator and the stator, the latter is made up of coils mounted on a nonmagnetic support resulting in a higher airgap, with negative influence on the generator performances [8,9]. A problem for all the above mentioned structures is the high magnetic losses that appear in the stator because of the high magnetic flux variation ratio, requiring the stator to be build of laminations.

While in one or two sided structures the use of laminations is not a problem, in tubular topologies such a construction is problematic. Because the magnetic flux lines are parallel to the movement direction, mounting the laminations perpendicular to the machine shaft (like in rotational machines) would mean that the magnetic flux must pass from one lamination to the next trough the insulation, resulting a large equivalent airgap and poor performances (due to high losses). For this reason the laminations must be placed parallel to the translator shaft, raising the problem of aligning them in the airgap, where they would come in contact, while at the outer part of the stator a gap would appear between adjacent laminations.
resulting a complicated construction process with high costs.

A solution for this problem is to replace the tubular topology with a structure with more statoric parts, varying from 2 to 8, mounted around the translator. As the number of stators is higher the approximation of the tubular structure is more accurate, but the manufacturing cost are higher. The present paper shows a comparative study between a tubular structure and a four sided generator.

B. Tubular vs. 4-sided linear generators

Three quarters of the two considered structures are presented in Fig. 2, for a better view of the components. Similar geometrical dimensions were considered and in order to obtained results that could be compared, the permanent magnet total volume was kept constant. The PMs are axially magnetized and are mounted so that adjacent magnet faces have opposite magnetic poles. The iron pole pieces that are mounted between the magnets have a double role: they allow opposing magnet faces to be mounted next to each other and they guide the magnetic flux line trough the airgap. Because the magnetic flux density variation in the translator is small these poles are constructed from massive iron steel material.

The simulations were performed using the JMAG Studio 3D environment, a FEM based program, Fig. 3 presenting the magnetic flux density repartition in the two structures, with differences between the repartition in the two models. The maximum magnetic flux density value is slightly higher in the tubular structure 2.47T, compared to 2.39T in the 4-sided variant.

The differences that appear can be noticed better in Fig. 4, where a section trough the middle of the translator poles and statoric teeth was considered, with the translator and stator fully aligned. The magnetic flux density values are higher near the PM edges, reaching 2.25T; as we get closer to the air gap the magnetic flux density values are lower due to flux leakages between the translator poles.
The two structures were compared dynamically, using the same software: a constant speed of 1m/sec was set and a total displacement equal to one pole (10mm) pitch was considered to be sufficient. Only one coil was modeled for each structure to reduce computational times and 80 turns were set for each model. The flux trough the coils and the induced voltage is presented in Fig. 6: although the magnetic flux density repartition differs significantly in the two structures, because the average airgap magnetic flux density is the same, the coil flux wave form is almost identical for the tubular and the four-sided generators. Since the induced voltage represents the time variation of the flux, it is natural that the wave forms of the generated no-load voltages are similar.

While the electrical performances of the two studied structures are almost identical, some differences appear regarding the geometrical aspects of the two generators. As expected, the coils of the four-sided are 37.5% longer, resulting higher losses due to the Joule effect. In the same time the iron required in the stator is 32.1% larger than in the tubular generator, so the iron losses are bigger too. The differences between the two translators were not considered because the magnetic flux density variations are small, their influence on the overall generator efficiency being negligible.

While the electric performances of the two generators are very similar the manufacturing difficulties of the tubular structure makes it less attractive than a four-sided topology. Based on these information and other technological restrains a four-sided linear generator prototype was constructed and tested to confirm the theoretical results.

The test bed uses an induction motor coupled trough a fix-rate gearbox to a rod-crank system that allows the conversion of rotational movement into linear displacement. Due to mechanical constrains speeds up to
0.2 m/sec were obtained for a 140 mm total displacement, so the induced voltages are inferior to those presented above. The generated voltage wave form obtained for a 28 coils stator and a 20 poles translator is presented in Fig. 7.

![Fig. 7. No-load measured voltage.](image)

**IV. CONCLUSIONS**

The need of developing new way of producing energy is crucial in the next decades in the perspective of carbon based fuels shortages. Electrical linear generators with permanent magnet can play their part in this, as they can be used in energy production systems based on renewable energies, with the major areas of interest being the Wave Energy Converters and systems using Stirling engines for transforming caloric heat from the sun into linear motion. Although the structure presented here is suited for both applications, there major differences involved, regarding the displacement of the translator or the movement speed. Depending on the application some modifications must be considered, especially regarding the reduction of moving masses for Stirling applications.

As shown here the performances of tubular and four sided permanent magnet linear generators are similar regarding the induced voltage or coil magnetic flux. The four sided structure is heavier for the same dimensions, implying larger losses. Adding the constructing difficulties for the tubular structure a four sided generator is preferred for electric energy production.

**REFERENCES**


