A novel double-sided flat rectangular linear permanent magnets synchronous generator for sea wave energy application

Juan Antonio García-Alzórriz, Joan Grau, Ricardo Córdoba, Jordi Muela

Escuela Universitaria de Ingeniería Técnica Industrial. Universitat Politècnica de Catalunya
Comte d'Urgell, 187. 08036 Barcelona. Spain
juan.antonio.garcia-alzorriz@upc.edu, joan.grau@upc.edu

Abstract

In the renewable energy field, sea wave energy is one of the less explored markets, mainly due to hard environmental and technical requirements related to this source of energy. Last years, a wide range of new technologies have been developed concerning this technology. Among this, it has been considered the use of the oscillatory action of sea waves as a way to move the linear generators for direct drive coupling.

This report presents the benefits of double-sided flat rectangular linear permanent magnets synchronous generator magnets with flux concentrators on its poles for direct coupling with a specific sea wave energy point absorber.

1. Introduction

The continuum increasing of the global energy demand and the actual geopolitical situation of the main energy resources on which modern society are based, the fossil fuels, are making that governments and many companies are making big investments in research in order to develop new energy sources. These new energy sources must meet certain requirements so they can achieve their goal of moving and change the current global energy global view. Those are:

- Availability of the energy source at the own territory (to achieve energy independence partial or totally).
- Unlimited energy source.
- Non-polluting or with a minimum environmental pollution.
- Finally, and probably the main one, it must be economically competitive.

In front of this situation, many eyes have turned towards the seas and the oceans in search of a cheap an clean energy with high availability. The energy potential of oceans is presented in three main forms: waves, tides and thermal gradients.

The sea waves are a tertiary energy form coming from solar radiation. The incident solar radiation on earth generates the wind, and this, due to friction and small pressure perturbations over the sea surface generate the waves. Waves can travel long distances without practically losing energy, and consequently, all their energy finally goes to the continental coasts, which makes us see two of the most interesting aspects of this energy:

- Relative proximity to points of potential consumption.
- And the most attractive, the low intermittency in his availability (although not in his intensity).

Unlike other renewable energy sources such as direct solar radiation or wind, which show a high intermittency in their availability, the waves are characterized by high availability near the continental coast.

It's estimated that at coasts, the global average density of wave energy is about 8 kW/m, and that in certain coastal areas particularly favorable this value can go from 25 up to 60 kW/m, values which give us an idea about the exploitation potential of this energy.

Currently, there are several technologies in different technological maturity stage which try to exploit the wave energy. We can even say that the vast majority are in an embryonic state and still have a long road to walk. The main technologies which currently are being investigated to exploit the energy of the waves are:

- The point absorbers.
- The oscillating water columns.
- The attenuators.

2. Point Absorbers

A point absorber (figure 1) can be defined basically as an element capable of transform the kinetic and potential energy of waves into translational mechanic energy. This is done thanks a floating element which moves relatively to another element because of the wave elevation.

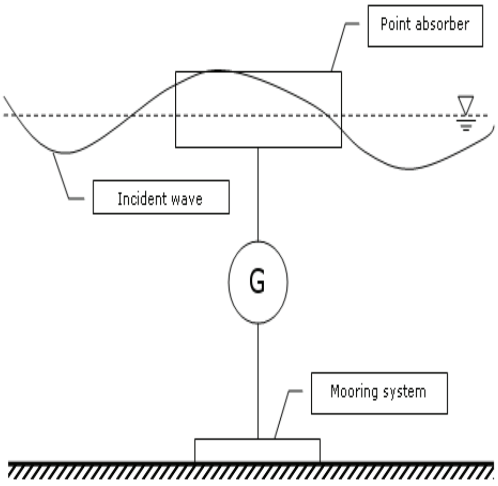

Fig. 1. Point absorber diagram

This technological configuration of wave energy exploitation presents a series of advantages and disadvantages concerning the other technologies mentioned. However, all the technologies of wave power must overcome a series of common disadvantages that are the main technological challenge presented by this kind of renewable energy:

- The low speed: A typical ocean wave of period 10 seconds will give us a frequency of 0.1 Hz, when the vast majority of the commercial generators must work at a frequency 500 times higher.
- Irregularity: Despite the high-availability of wave power, it has the disadvantage of having a very irregular behavior, which complicates seriously the optimization of a system for achieving high performance and an optimal operation in the multiple working ranges that will operate. And not only that, this wide range of working conditions can easily cause that the generator may be requested to work over his rated power.

3. Linear Generators

Once known the point absorbers technology, it is easy to see that there are two kinds of generators that we can use for the conversion of kinetic energy of the system into electrical energy: a rotating generator, or a linear generator, which fits in a much more natural way with the system's motion.

It's obvious that in first case we are facing a very mature technology, and together with the use of complex mechanisms consisting in pulleys, gears, gearboxes and flywheels, it allows the conversion of linear motion into rotational motion and the exploitation of wave power using commercial generators currently available. Notwithstanding, they still require a specific development to be able to overcome the disadvantages associated with this technology.

Nonetheless, after hard investigation we have found very interesting to open a new technological way for the exploitation of this kind of energy using linear generators. These generators allow us to exploit the energy of the sea waves using point absorbers in a direct way without the need to use complex and expensive mechanisms for doing the conversion from lineal movement to rotational which, among other inconvenient, it adds losses to the system and increases the technical complexity, the necessity of maintenance and the final costs.

A system as shown in figure 2, incorporating a linear generator and two floating bodies, one at the surface and the other submerged, could be a simple and efficient system to exploit the energy of waves.

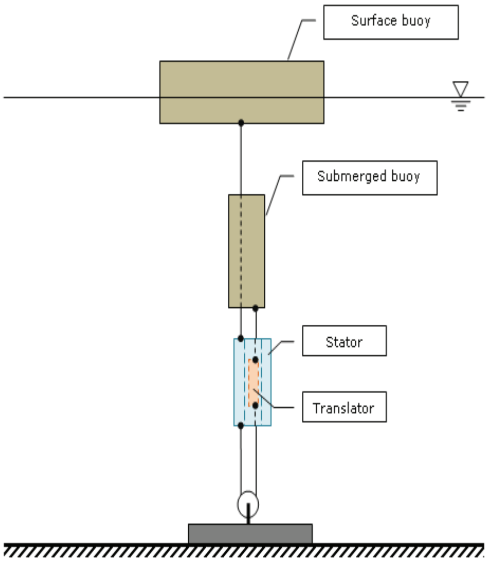

Fig. 2. Linear generator system

The reason to use a 'double' point absorber (figure 2) is that it allow us get twice the speed in the system with a lineal generator, given the fact that we can simultaneously move the translator and the stator in the same direction but in opposite sense. Furthermore, this design allows a more efficient exploitation comparing to the only one floating element.

The technology of linear generators is a young field and with a long-way to explore and there is no doubt that the wave power is an excellent motivation for developing these generators, perfectly adapted to the natural behavior of this energy and allowing an efficient and cost effective exploitation of an abundant, clean and economical energy.

4. Double displacement of linear generator

Permanent magnet linear generator can be constructed in a number of different configurations depending on which part of the machine acts as inducer or induced, or which that part is fixed or mobile, always with the target of achieving a better adaptation of the machine to the application. All designs have two components: the inductor (formed by permanent magnets) and the armature. In a classical design of the machine, one of both components, stator, is mechanically fixed. On the other hand, the second one is mobile (the rotor in rotating machines and the translator in linear machines).

However, for sea wave energy technologies both sides should be mobile. Due to low speed of wave energy absorbers, their behavior can be improved if both components are mobile, moving in the same direction but in opposite sense (figure 3).

This singularity in the displacement allows to double the operating speed of the machine (the relative speed between the two sides is double that obtained if one side is fixed).

The low specific speed of wave energy absorbers and their use in marine environments are main factors in the design of the generator. Given that their function is to achieve reasonable efficiency at low speeds, the design must be optimal when it comes to its energy efficiency and manufacturing costs, and also, given the peculiarity of its location- the sea- it has to be as robust as possible.

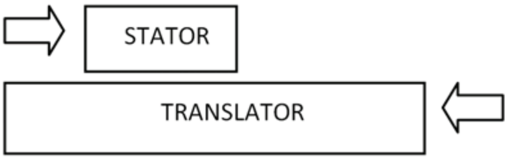

Fig. 3. Double displacement of linear generator

In permanent magnet generators, one of the most relevant advantages is that one of its parts (inductor) does not have electrical connection. The absence of wires and contacts in the inductor provides a degree of simplicity when constructing it, and a benefit of fewer components to maintain and control. The simplicity of the design is vital for equipments working in a maritime environment.

Usually, stators and translators have different lengths. The ratio between lengths is one point to consider in the design. This ratio has to allow the machine to work more efficiently in relation to the energy produced and the cost of the machine. In the proposed design, with two moving parts, the optimal ratio is that one is two times larger than the other. This ratio ensures that the entire volume of the small part is always active, to move within the other, without crossing. The difference in length defines the maximum work path of the generator (half of the path for each opposite sense of displacement).

Another aspect to consider in the design is choosing which of both parts (big or small) must be the induced or the inducer. In the projected generator the longest is the inducer (that is where the permanent magnets are housed) and the shorter is the induced. The stator moves over the translator without exceeding its limits, thus all stator coils will be always active. If the option was the opposite (the stator size being two times the translator size), in order to keep the same machine efficiency, it would be required the use of electronic switching elements to switch off parts of the stator winding, which during the displacement, would be outside the armature (translator). In the decision have prevailed aspects of simplicity, efficiency and robustness, for the reason already mentioned, the generator has to work in a marine environment.

5. Flat rectangular geometry vs. cylindrical geometry

Most designs of linear generators are based on cylindrical geometries. Their main inconvenient is that the way the stator is guided trough the translator is very complex because the air gap between both must be minimum. This generates a loss of efficiency and difficulty to construct it apart from the fact that fabricating a cylinder is always much more expensive.

The machine proposed has a flat rectangular geometry with less constructive difficulty than the cylindrical one and also allow a simple and robust guiding system along the whole length of the machine, allowing the translator and stator move in opposite senses , ensuring a minimum constant air gap.

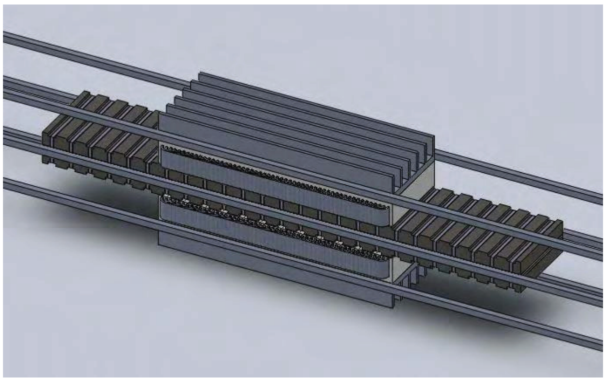

Fig. 4. Guidance system of a machine flat

The flat machine allows us to work with lateral guides, so that the translator and the stator are guided along its entire length, allowing minimizing the air gap between two parts of the machine during the displacement. In practice this translates into a need for smaller air gap and consequently a decrease in the required volume of magnets for the same power.

6. Implementation of flux concentrators at poles vs. surface mounts magnets

Normally in permanent magnet machines, magnets are placed superficially working directly as the magnet pole. In this case we have chosen to implement flux concentrators at poles in order to improve the distribution of flows. Figure 5 shows the geometry of the translator with flux hubs at poles and magnets, and figure 6 shows the geometry of the translator with surface mount magnets.

Fig. 5. Detail of the proposed translator with flux hubs at poles

Fig. 6. Detail of a classic translator with surface mount magnets

The proposed design gives several improvements: the volume of the magnets necessary is lower than the classical one. Additionally the distortion of the waveform of the voltage is also lower compared to the results usually obtained in generators with surface mounted magnets.

From the results obtained in the comparative study between generator with flux concentrators and the other ones with surface mount magnets, it has been found that in flux concentrators the total harmonic distortion of the signal generated is significantly lower. For the same power, the required the volume of magnets is less than 17% less than the required volume in surface mount magnets, a very relevant fact as the magnet has the major costs of the machine.

If the comparison is with generators with similar harmonic distortion to the induced voltages, the required volume of magnets is about 20% lower. Table 1 reflects the results of several studies on the distortion of waveform generated and it clearly shows the benefits of using flux concentrators.

Table 1. Distortion comparative of the two machines, with translator with flux concentrators at poles and translator with surface mount magnets at different levels of load.

Load Pu	THD Flux concentrators [%]	THD Surface [%]
1	1,2	5,18
0,75	5,15	6,36
0,5	7,14	6,72
0,25	9,41	6,86
No load	10,75	6,85

Figures 7 and 8 show the distribution of magnetic field lines from the generator with flux concentrators at poles and surface mount magnets.

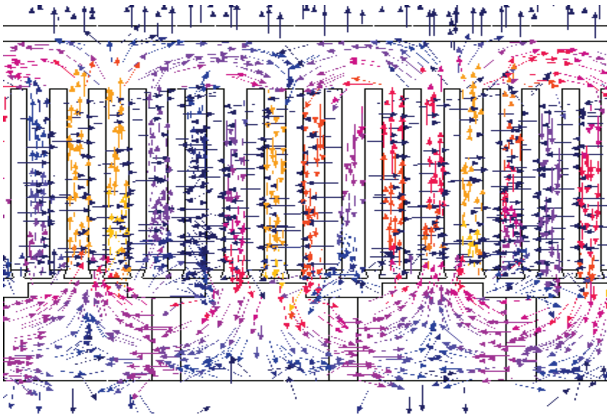

Fig. 7. Magnetic fields in magnets of a translator with flux concentrators.

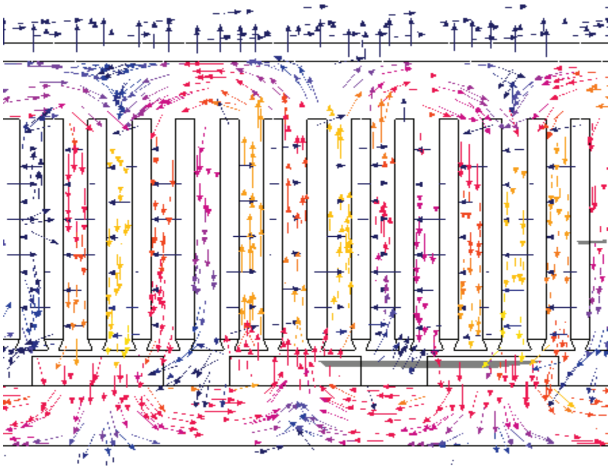

Fig. 8. Magnetic fields in magnets of a translator with surface mount magnets

7. Double-sided linear generator vs. on one side

The benefits described above can be obtained partially if the generator only has one side. The figure 9 shows the flux dispersion that occurs in the bottom of translator. There is a big flux dispersion in lower part of the translator. This loss partially cancels the gain provided by the implementation of flux hubs at poles. The solution adopted to avoid these flux dispersions is that the machine is made up of two identical and symmetrical parts over the axis of translation (figure10). Each of them shields the other, preventing that the bottom of translator has flux dispersion. In practice, the machine behaves as two independent electromagnetic generators.

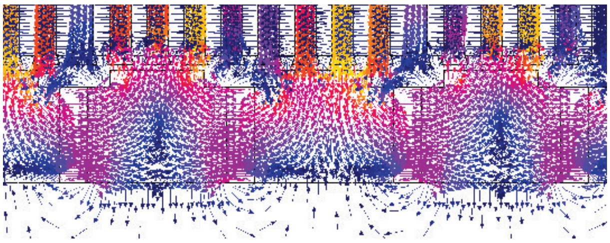

Fig. 9. Flux dispersion through the translator bottom

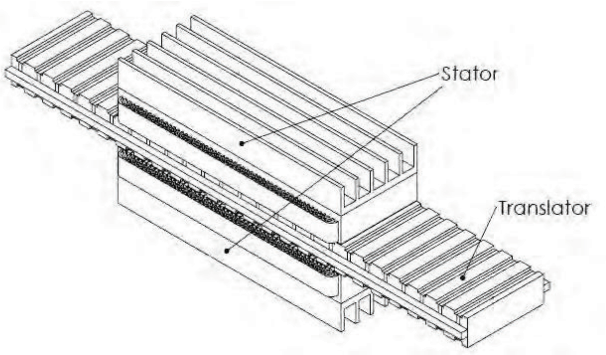

Fig. 10. Double-sided linear generator

In figure 11, and in more detail in the figure 12, it is visible the magnetic lines in the proposed double-sided machine, where there is no loss of magnetic field.

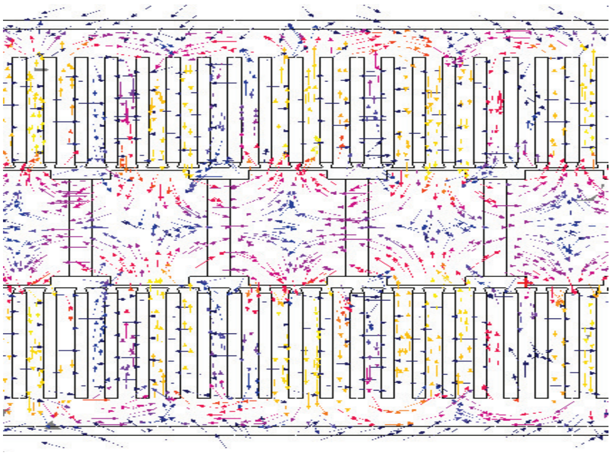

Fig. 11. Magnetic fields in a machine with flux hubs and double-sided

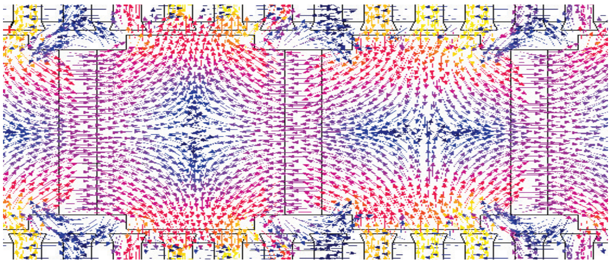

Fig. 12. Detail of magnetic field in flux hubs

Implementing the flux concentrators allows a design of translator poles which does not conditions the choice of the dimensions of the magnet, beyond the volume required for the intended generated power. This decoupling of the magnet over the design of the translator has allowed the establishment of appropriate dimensions of the magnet so that it works at the point of maximum energy.

8. Fractional windings vs. integers

Another aspect to be considered in the design is to improve the quality of the induced voltage (less distortion of the waveform) using concentric fractional pitch windings instead of whole step.

The figures 13 and 14 shows , respectively, the voltages of three phases, in nominal terms, for stator concentric fractional winding step 1.5 and the frequency spectrum of the voltage of one of three phases. The graph shows almost no harmonics. For the signal represented the total harmonic distortion is 1.12%.

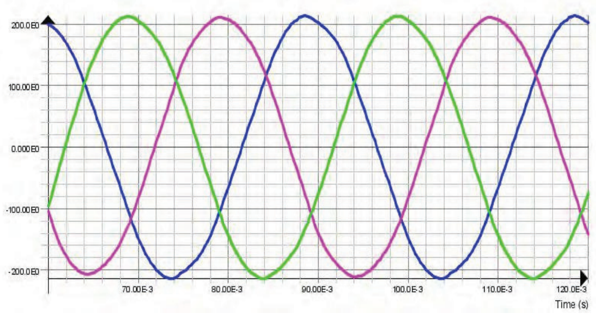

Fig. 5. Voltages of the three phases with concentric fractional pitch winding step 1.5

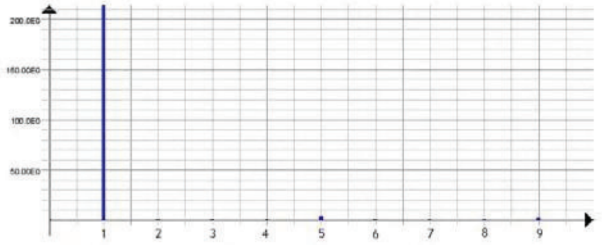

Fig. 14. Frequency spectrum of the voltage of one of the three phases with concentric fractional pitch winding step 1.5

Table 2 show the parameters of the generator designed by finite elements.

Table 2. Specifications of double-sided flat rectangular linear permanent magnet synchronous generator

Number of phases	3	**Rated power[W]**	4063
V RMS phase at no load [V]	184,1	**Efficiency at rated power [%]**	91,12
V RMS phase at rated power [V]	151,2	**Force [Nm]**	2.229,4
I RMS phase at rated power [A]	8,9	**Air gap[mm]**	1
Speed [m/s]	2	**Magnet (NdFeB)**	N35H
Frequency [Hz]	33,33	**Path[mm]**	360
THD voltage phase [%]	1,12 %	**Number of poles**	12

9. Conclusions

All results obtained by finite elements show the great benefits of the implementation of flux concentrators in double-sided linear generators: low distortion waveform (1.12%); high efficiency (91.12%), despite the limitation of low speed of movement of point absorbers wave energy; finally a 20% less volume of magnets that generator with surface mount magnets.

Problems of mechanical interfaces, such as gearboxes, hydraulic systems, ... has driven the need to design high-speed electric generators. The direct drive feature has become more efficient and reliable, but linear generators are electrical and mechanical problems still to overcome. Therefore, as results show, the implementation of double-sided flat rectangular linear permanent magnets synchronous generator with flux concentrators can be the most suitable choice for direct drivers for sea wave energy point absorbers , both economically and efficiently.

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