Linear Generators for Wave Power Plants to Be Set up Near the Romanian Coasts of the Black Sea

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Abstract ***– Generating power is of great importance in today's world. Due to the pending exhaustion of fossil fuels and to their environmental impact it is crucial to develop clean renewable energy sources. Ocean energy is one of the candidates being a huge, yet unexploited renewable energy source on our planet. Preliminary surveys show that marine power has a potential to supply a significant part of the future energy needs. Hence all the researches done in the field of the wave energy conversion should be of real interest and should support the increase of the share of renewable energy in the electricity production. Based on a study on the wave power potential of the Black Sea near the Romanian coast it was considered that it should be the most efficient to install wave power plants consisting of large arrays of small direct driven wave energy converters, having specifically designed linear generators driven by a point absorbing buoy.***

In this paper the wave energy potential of the Black sea near the Romanian coasts, a possible power take ff system, respectively the linear generators to be used in such wave energy power converters will be discussed.

Keywords: ***wave energy, marine energy converter, linear generator.***

I. INTRODUCTION

Climate change and both fuel price increases and security are the key issues that are driving the current energy supply sector, while the demand for electricity is forecasted to increase world-wide. Within the Kyoto Protocol (1997) and the last agreement at Marrakech (2002) the EU has committed itself to an 8% reduction of greenhouse gasses by 2010-2012. One of the tools available to achieve the goal is to increase the share of renewable energy in electricity consumption and the EU has set a target of 12% by 2010. As a result of these political commitments the renewable energy industry is developing around the world being one of the highest priorities of mankind. To these trends Romania also had been aligned according to the medium-term National Strategy for the power sector (Ordinance No 647/12 July 2001) [1]. In this is pointed out as the main future objectives are to develop efficient energy markets, to ensure higher quality and security of supply and to comply with EU standards regarding the rational use of energy and environment protection [2].

The new and renewable energy sources can guarantee a sustainable power production in the future. Wind power has been at the forefront, with installed European capacity of 58.000 MW in 2005. Ocean energy is a yet unexploited renewable energy source on our planet. Preliminary surveys show that marine power has a potential to supply a significant part of the future European energy needs.

The three most well developed technologies for deriving electrical power from the ocean include tidal power, wave power and ocean thermal energy conversion. From these possibilities the wave energy conversation has the greatest general application.

There are several estimations of the global wave power potential from 2 to 10 TW, which are of the same order of magnitude as world electrical energy consumption [3]. About 95% of this power potential is offshore, the rest being on the shoreline or nearshore. Of course all of it is not practical, but if any amount of it could be harnessed, it could mean a very great quantity of cleanly produced energy [4].

The power potential for waves can be described as units of power per meter of wave crest length. The greatest power in the wave fronts is about 100 kW/m in the Atlantic SW of Ireland, the Southern Ocean and off Cape Horn [5].

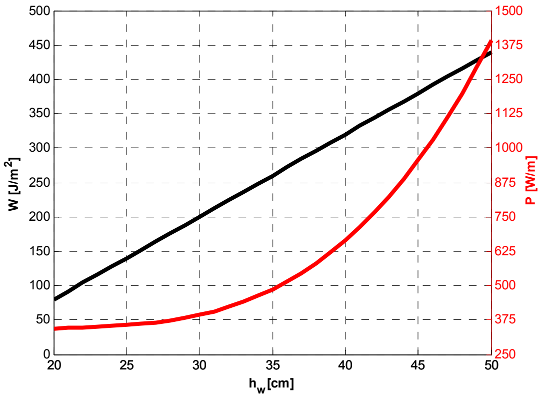
Large portions of the world's potential wave energy resources are found in sheltered waters and calmer seas, which often exhibit a milder, but still steady wave climate. Examples are the Baltic, the Mediterranean and the Black Sea [6].

II. THE WAVE POWER IN THE BLACK SEA

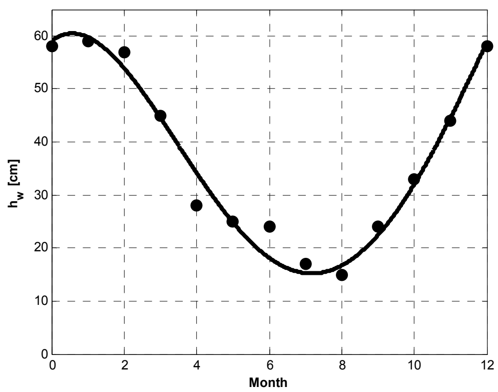
The wave power in the Black Sea is moderate. Precise data regarding the wave energy potential in the Black Sea near the Romanian coasts could not be found in any available bibliographical resources.

Hence we were constrained to look for indirect information on the wave energy potential from other similar sheltered seas and on other parameters of the waves in the Black Sea [7], [8].

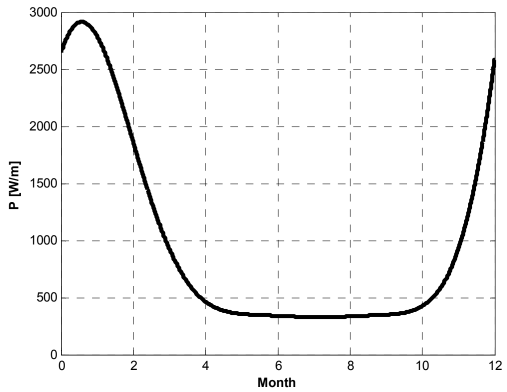
Relations between the mean wave height (h_W) and mean energy density, respectively mean power could be established for sea depths of 5÷10 m (Fig. 1a).



a) the mean energy and power densities vs. the mean wave height



b) the monthly mean wave heights



c) the monthly mean power density

Fig. 1. Statistical characteristics of the wave potential of the Black Sea near the Romania coasts

In [9] the monthly mean wave heights in the Black Sea obtained upon 35 years long measurements are given (see Fig. 1b). Combining the data presented in Figs. 1a and 1b the monthly mean power density of the wave energy in the Black Sea was computed by us (see Fig. 1c). The wave energy density is highest winter and autumn, coinciding with the greatest energy demand.

The mean value of the power density was found out to be about 1 kW/m. The low power density is compensated by relatively small wave power variability as compared with the seas with peak wave power densities. As we will see later also at this wave energy potential the exploitation of the wave energy could be of interest.

There are several compelling arguments for using the offshore wave energy technology [10]:

- By its high power density it is one of the lowest cost renewable energy sources.
- The wave energy is more predictable than solar and wind energy, offering a better possibility of being dispatched to an electrical grid system.
- With proper sizing, conversion of ocean wave energy to electricity is believed to be one of the most environmentally benign ways to generate electricity, hence it does not render any waste that has to be stored or destroys the environment.
- The wave energy conversion devices can be located far enough away from the shore that they are generally not visible.

Although waves represent a free and clean source of energy, capturing this energy inevitably needs large capital investments and has impacts on the environment, which must be taken also into account [4].

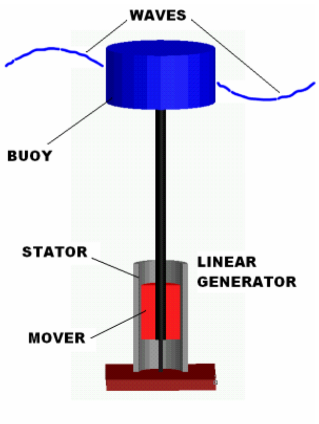
III. WAVE ENERGY CONVERTERS

The potential wave power can be converted to electricity via mechanical means. Harnessing the energy provided by oceanic waves has been developed for over the past thirty years via numerous technologies.

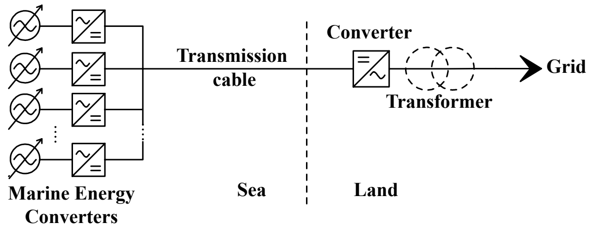
Several power take off systems, called Marine Energy Converters (MECs), were already proposed [4]. The most complicated constructions are with direct mechanical linkage, with pneumatic (for example the Oscillating Water Column system [11]) or with hydraulic systems (as Pelamis [5]).

The direct drive power take off system, which is proposed by us to be used, is very simple. It has the electrical generator and moving part of the device joined together with no intermediate mechanical systems. The simplest system uses a floating buoy connected to linear generator and work upon the difference in height between wave top and wave bottom.

The buoy, floating on surface of the water follows the motion of the wave [12]. The buoy is connected to a liner generator fixed on a concrete foundation, which stands on the bottom of the ocean (see Fig. 2a).



a) the floating buoy system



b) the power system

Fig. 2. The direct drive power take off system

The system is mechanically simple, with a few moving parts. Between the generator and the gird AC/DC, respectively DC/AC converters must be coupled, as shown in Fig. 2b. By optimising the shape and operation of the buoy 90% absorption efficiency can be achieved [13].

Several countries in the world have supported ocean energy development through R&D programs and other support measures. The European Commission is playing an important role in coordinating the development of the technologies; hence also our country should join the researches in this field. As in [14] is recommended, for Romania under the perspective of sustainable development better options than nuclear power are available for meeting the Romanian energy needs. These options are without the risk of disastrous accidents for the population, and do not generate long-term radioactive waste. The alternative energy options (among these also the wave energy) provide new opportunities for the Romanian population: decrease of energy expenditure, creation of new jobs and protection of the environment.

Romanian specialists have vast experience in offshore oil industry technology, which could be fructified in such national projects. It should be also mentioned, that several components of a 2 MW Archimedes Wave Swing (AWS) system to be installed in Portugal were manufactured in Romania and were floated round to Portugal in 2002 [15].

Many of the above-presented schemes consist of large mechanical structures, often located near the sea surface. Studying the particularities of the Black Sea near the Romanian coast we concluded that it should be more efficient to install wave power plants consisting of large arrays of small wave energy converters (of about tens of kW) having specifically designed linear generators driven by a point absorbing buoy [6].

IV. LINEAR GENERATORS FOR MARINE ENERGY CONVERTERS

The crucial part of such marine renewable energy devices is the efficient conversion of kinetic energy into electrical energy. Hence the optimal design of the linear generator used in such a system, the main topic of this research proposal, is a very important issue in the development of the entire power plant.

In the literature mainly the following linear generators are proposed for wave energy converting power plants:

- Linear permanent magnet synchronous machines [16] both with surface [17] and buried permanent magnets, Fig. 3, [18].

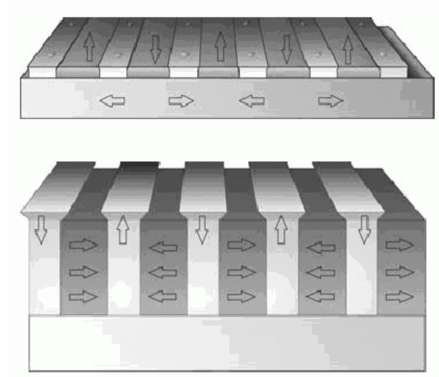


Fig. 3. Linear permanent magnet synchronous machines

- Vernier hybrid linear machines, Fig. 4, [4], [19], [20].

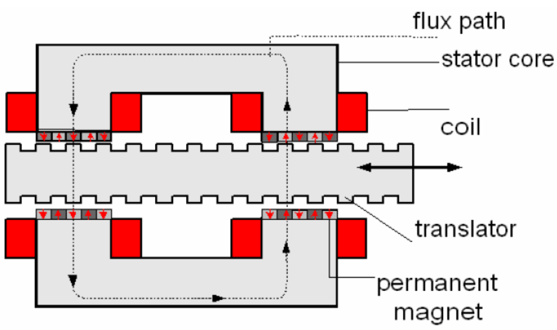


Fig. 4. Vernier hybrid linear machine

- Air cored permanent magnet tubular machine Fig. 5, [4], [21], respectively its iron cored variant [22].

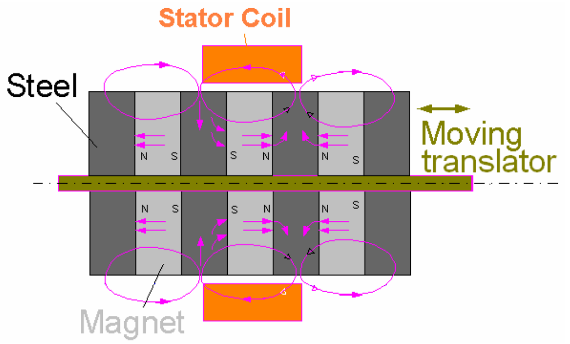


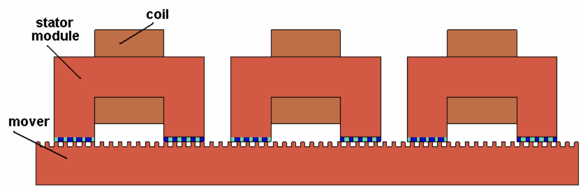
Fig. 5. Air cored permanent magnet tubular machine

The descriptions and the performances of the above mentioned machines had been studied from the point of view of their applicability in the power plants intended to be placed in the Black Sea. They have to have low power (of order of kW), they have to work at low speeds (up to 1 m/s) and to have short strokes (under 1 m). Of course as they are placed under the water in hard to mount and to access places they have to be maintenance free and to have great force density in order to have as low mass and volume as possible.

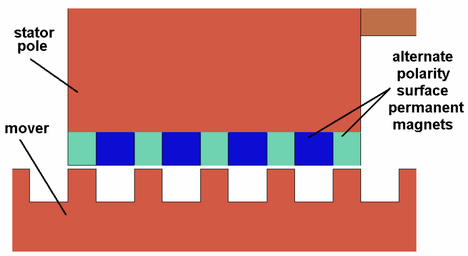
The linear permanent magnet synchronous machines are not fitted well for low speed applications and require a great amount of permanent magnets, hence there were not been studied by us. Our research was focused on the other two types of linear generators mentioned above, the vernier hybrid linear machine and the air cored permanent magnet tubular machine. Their study was performed using high precision 2D finite elements method (FEM) based field analysis.

A. The Vernier Hybrid Linear Machine

First the vernier hybrid linear machine was studied. The analysed three phase structure is shown in Fig. 6.



a) the three-phase structure



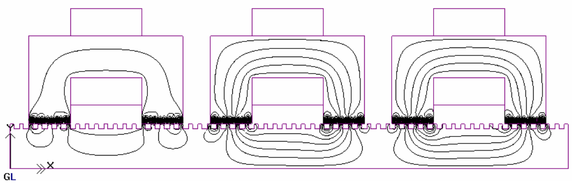
b) the air-gap area

Fig. 6. Vernier hybrid linear machine

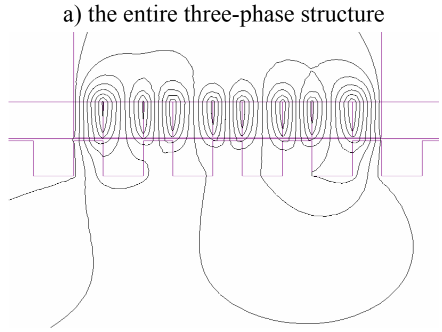
The stator is composed of independent, magnetically isolated modules of C-core shape. This modular structure is similar to that of the three-phase modular doubly salient linear motor intensively studied by our research team [23], [24]. The opposed magnetised permanent magnets mounted on the stator poles produce a magnetic flux path which crosses also the coils of the module's coil.

The modular approach provides a high degree of flexibility in the design and choice of power ratings.

In the next figures results of the FEM analyses of the vernier hybrid linear machine will be presented.



a) the entire three-phase structure



b) a zoom on the area under the left handed pole

Fig. 7. The field lines in the vernier hybrid linear machine

As it can be seen from the magnetic flux distribution of the vernier linear motor given in Fig. 7 the main part of the flux generated by the permanent magnets placed on the end of the poles closes between two neighboured permanent magnet and only a small part of it passes through the coils of the modules.

B. The Air Cored Permanent Magnet Tubular Machine

The solid model of this tubular linear machine is given in Fig. 8.

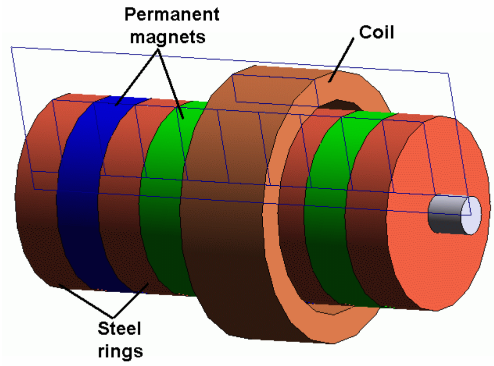


Fig. 8. Air cored permanent magnet tubular machine

The flux distribution through this tubular linear machine is given in Fig. 9.

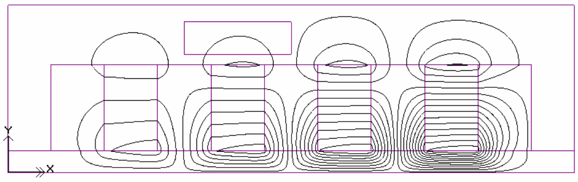


Fig. 9. The field lines in the air cored PM tubular machine

For this type of linear machine the same effect as in the above case can be observed: only a small part of the magnetic flux generated by the magnets passes through the coil of the machine, hence only small amount of emf will be produced in it when working in generator regime. In order to emphasize this statement the shaded plot of the magnetic flux density will be given in Fig. 10.

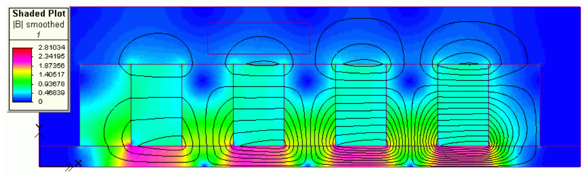


Fig. 10. The shaded plot of the |B| in the air cored permanent magnet tubular machine

As it can be seen the flux density values are very small in the outer part of the stator of the machine having the permanent magnets in its structure.

V. CONCLUSIONS

Both linear generator types taken into study have serious drawbacks, mainly because the magnetic flux generated by the permanent magnets is only in a little part directed through the coils.

In addition the air cored permanent magnet tubular machine requires a lot of magnets, and its power density is low. The best solution from the two studied linear machines seemed to be the vernier hybrid linear machine, but this due to its permanent magnets placed on the mover pole's surface are hard to construct and magnetize.

Taking into account all these observations it can be stated out that obligatory better solutions must be worked out for this specific application.

As the use of linear machines in wave energy based power plants supposes low speed at high forces and high force density, it is inherent to take into study in the future also the linear transverse flux machines. In the literature it often mentioned as a possible generator to be used in wave energy converters [11] [25], but no practical results were since reported. Studying diverse constructional variants [26] it was concluded that for the given application the linear variant of the transverse flux machine with permanent magnets on the stator and passive rotor (see Fig. 11) should be the best suited.

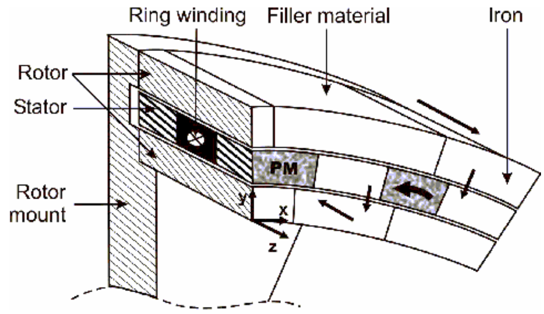


Fig. 11. Transverse flux machine with permanent magnets on the stator and passive rotor

Other linear generator variants could be based on the three-phase modular doubly salient linear motor mentioned already. Its novel construction principle was worked out by the members of this research group. It was built up in both linear and planar variant [27]. This novel linear machine topology also has advantages with regard to the cost of manufacture, since it requires axially anisotropic magnets, which can be magnetised simply by placing them in a solenoid impulse magnetising fixture. Its modified structures must be designed to fit the demands of the application in discussion. Tubular and polygonal variants were proposed to be studied in order to balance the tremendous attracting forces occurring between the armatures of the linear machine.

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