Comparative Study By Means of FEM Based Computations on the Linear Generators to Be Used In Wave Energy Converters

L. Szabó, *Member, IEEE,* I.-A. Viorel, *Member, IEEE*, C. Oprea

***Abstract*—New and renewable energy sources are very important for humankind in order to guarantee a sustainable power production in the future. Ocean energy is one of the largest unexploited renewable energy sources on our planet. Preliminary surveys show that wave power has a potential to supply a significant part of the future European energy needs. In this paper different types of linear generators to be used in wave energy converters will be proposed and analyzed by means of finite elements method (FEM) based numeric magnetic field computations. The best solution for a wave power plant to be set up near the Romanian coasts of the Black Sea will be selected upon this comparative study.**

***Index Terms*—Linear generators, marine energy converters, permanent magnet variable reluctance machines, renewable energy resources, wave energy.**

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 emissions by 2010-2012.

One of the tools available to achieve the goal is to increase the share of renewable energy in electricity production, 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 published in 2001.

The new and renewable energy sources can guarantee a sustainable power production in the future. By now wind power is at the forefront. Global wind electricity generating capacity increased by 24 percent in 2005 to 59,100 MW, which represents a twelve times increase from a decade ago.

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Ocean energy is a yet unexploited renewable energy source on our planet. The four promising technologies for deriving electrical power from the ocean are tidal power, wave power, sea current power and ocean thermal energy conversion. In our opinion from these possibilities the wave energy conversation could have 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 [1]. About 95% of this power potential is offshore, the rest being on the shoreline or near the shore. 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 [2].

Because there are no precise data regarding the wave energy potential in the Black Sea near the Romanian coasts 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 in order to estimate its wave energy potential [3].

The mean value of the power density was found out to be about 1 kW/m. This moderate power density is somehow compensated by relatively small wave power variability as compared with the seas with peak wave power densities. As this power source if for free, its exploitation also can be of interest.

There are several compelling arguments for using the wave energy technology [4]:

i.) By its high power density it is one of the lowest cost renewable energy sources.

ii.) The wave energy is more predictable than solar and wind energy, offering a better possibility of being dispatchable to an electrical grid system.

iii.) 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.

iv.) The wave energy conversion devices can be located far enough away from the shore for not to be visible.

Although waves represent a free and clean source of energy, its capturing inevitably needs large capital investments and has impacts on the environment, which must be taken into account [2].

II. Wave Energy Converters

The design requirement of a wave energy converter is to generate a useful electricity supply from the kinetic and potential energy of irregular ocean waves.

Numerous wave energy conversion (WEC) devices have been proposed that rely on different modes of wave motion or electrical generation systems to achieve these design objectives.

The WEC devices can be classified according to many different features including their location with respect to the shore, the wave mode from which energy is captured or the operation principle of the power take-off system [5].

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 [2]. The most complicated constructions are with direct mechanical linkage, respectively with pneumatic (for example the Oscillating Water Column system [6]) or with hydraulic systems (as Pelamis [7]).

The direct driven power take off system, which is intended by us to be used in the given application 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 with 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 [8]. The buoy is connected to a liner generator fixed on a concrete foundation, which stands on the bottom of the ocean (see fig. 1).

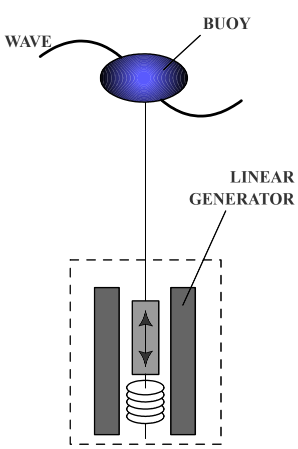

Fig. 1. Direct driven power take off system

The system is mechanically simple, with a few moving parts. Between the generator and the grid AC/DC, respectively DC/AC converters must be coupled. By optimizing the shape and operation of the buoy 90% absorption efficiency can be achieved [9].

Based on the particularities of the waves in the Black Sea, respectively on the selected wave power take off system the following main design data was established for the linear generator of the direct driven power take off system: 20 kW power, 230 V voltage, 1 m/s speed and 1 m maximum stroke.

III. Linear Generators Proposed to Be Used In Wave Energy Converters

The direct driven linear generators used in the proposed system operate at low speed and are placed under the water in hard to mount and to access places. Therefore only generators having special construction can fit the requirements. Anyway only permanent magnet machines can be useful hence they do not require supplementary supply for the excitation, or moving contacts.

Several linear generators with permanent magnet excitation are cited in the literature:

i.) Linear permanent magnet synchronous machines, both with surface and buried permanent magnets [10].
ii.) Vernier hybrid linear machines [11], [12].
iii.) Air cored permanent magnet tubular linear machines [2], [13].

Linear synchronous machines do not fit well to such small speed applications; hence these had not been studied by us.

IV. The Comparative Study on the Linear Generators to Be Used In Wave Power Take Off Systems

The linear generators taken into account during our studies are the following:

i.) Transverse flux linear generators
ii.) Vernier hybrid linear generators
iii.) Air-cored permanent magnet tubular generators
iv.) Iron-cored permanent magnet tubular generators

A. *Transverse Flux Linear Generators*

Transverse flux machines (TFM), fig. 2, are well fitted for low speed applications. Therefore first the transverse flux linear generators were taken into study.

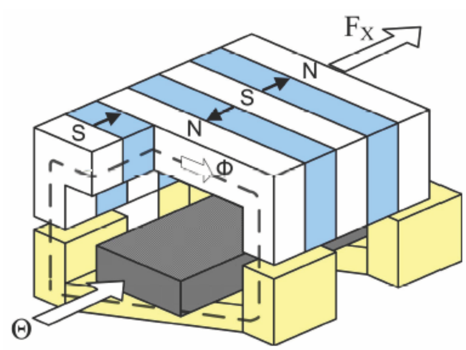

Fig. 2. Transverse flux linear machine

Taking into account all the possible permanent magnet TFM structures the following conclusions were stated out:

i.) Their main weak point is due to their inherent homopolar structure which implies quite large flux leakages and consequently an important value of the phase leakage inductance.
ii.) In both possible variants (with the permanent magnets on the stator or on the mover) the iron core's and the magnet's volume is quite large, which leads to a reduced ratio of the output power to active volume and to a larger costs.

iii.) Being a flat type linear machine the normal force (the attraction force between the two armatures) is very important and it is unbalanced, therefore the overall efficiency is reduced.

iv.) All the variants taken into account have quite complicated constructions and require expensive soft magnetic composite for the iron cores.

Therefore we did not continue the study this type of generators for the given application,

B. *Vernier Hybrid Linear Machine*

Vernier hybrid machines, which are also variable reluctance permanent magnet machines, are recommended to be used in compact direct drive systems for low-speed high-torque applications [14]. Therefore this type of machine was also studied by us in order to be applied in wave power take off units.

The Vernier linear generator proposed by us is built up of modules as that shown in fig. 3. Each module has an U-shaped iron core with a command coil. On the bottom of the poles are placed alternately magnetized permanent magnets. Selecting properly the number of the modules, respectively the shifting between them small step length can be achieved. The mover composed of several such modules runs over a teethed platen. Its teeth length is equal to the permanent magnet's length.

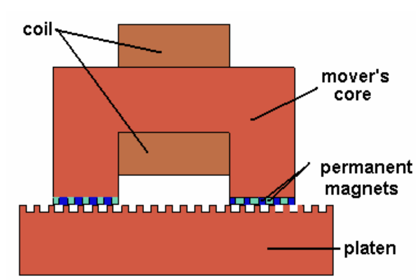

Fig. 3. The Vernier Hybrid Linear Machine

The magnetic field analysis was performed for a three phased variant. The obtained field lines at different positions during a teeth pitch long travel are given in fig. 4.

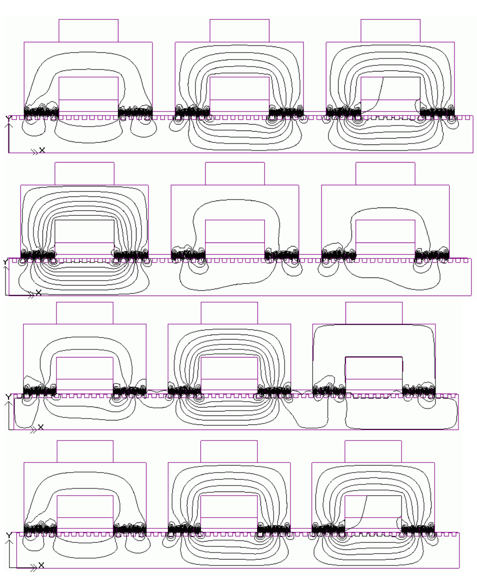

Fig. 4. The field lines in the Vernier linear generator

As it can be observed only a small part of the magnetic flux generated by the permanent magnets are flowing inside the coils, hence only small emf is produced. Beside this the small permanent magnets stacked together are placed on the bottom. Therefore the machine is hard to construct and to magnetize.

Neither this machine is suitable for the required application.

C. *Permanent Magnet Tubular Generators*

Tubular machines have a main advantage over the flat linear machines: the high attracting (normal) forces between the two armatures are balanced; hence much more simple guiding systems are required.

The permanent magnet tubular generators can be built up both in air-cored and iron-cored variant. The two variants were compared by means of field computations and the results were published in one of our previous papers [15]. In order to be able to correctly compare the two generators identical mover armature and coils were used in both variants. The induced emf for an identical movement of the two generators is given in fig. 5.

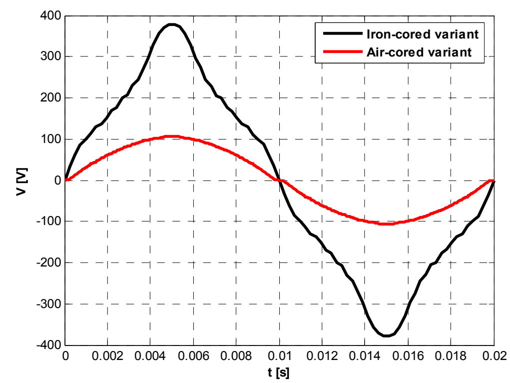

Fig. 5. The induced emf

As it can be seen in the figure the RMS value of the induced voltage in the iron cored variant is near 3 times greater than in the other case [15].

Finally it became clear, that only the iron-cored permanent magnet tubular generator fits the requirements for the proposed wave energy converters.

V. The Iron-Cored Permanent Magnet Tubular Generator

Based on the previous experiences and the given requirements a novel permanent magnet tubular linear generator was designed and analyzed. Its main structure is given in fig. 6.

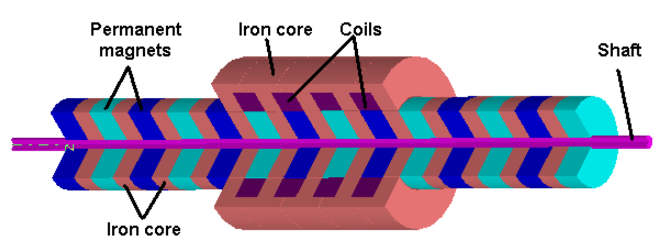

Fig. 6. The structure of the proposed tubular linear generator

Its mover consists of iron core rings fixed on a shaft alternated with permanent magnet rings magnetized in alternated radial direction. In the outer part is placed the winding and the stator iron core. This part of the generator is built up modularly in order to easy adapt the construction to different working conditions. Each module has a ring type iron core having U-shaped cross-section having inside a coil. By correctly shifting different number of modules and coupling together their coils various output voltages and different phase numbers can be obtained. In the structure given in fig. 5 four coils are coupled together forming a single phase of the machine. Mounting three correctly shifted such groups of modules together a three-phase generator can be built up. By moving the armature with the permanent magnets a varying magnetic flux will pass through the windings, generating emf.

The main characteristics of the linear generators in study were obtained via precise numeric field computations. In order to reduce at this stage of the researches the time of the simulations the 2D axial symmetric transient analyses of the proposed linear generator was performed. The obtained field lines for two positions of the mover are given in fig. 7, when the stator poles are aligned, respectively perfectly un-aligned with the iron core rings of the mover.

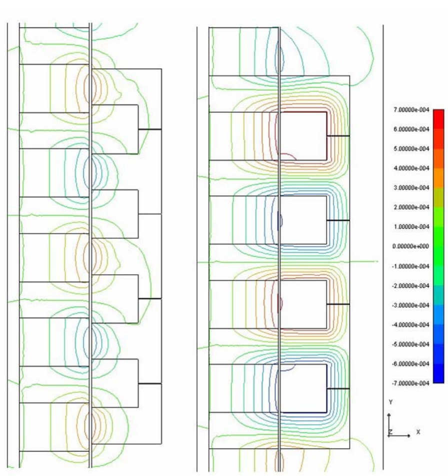

Fig. 7. The field lines inside the tubular generator

It can be easy seen that the change of the magnetic flux inside the core holding the coils during the travel of the mover is significant. Therefore the induced voltage in the windings at a constant 1 m/s speed of the mover is great, as shown in fig. 8.

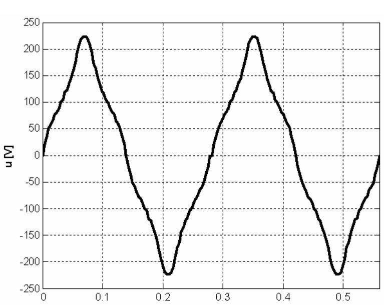

Fig. 8. The induced emf in a phase

VI. Conclusions

All the obtained results emphasize the correct concept of the proposed linear generators and the advantages of using iron cored tubular linear generator constructions for such applications. By minor changes in the design both the frequency and the amplitude of the generated voltages can be changed in a manner as to fit to any requirements of the power electronic devices connected together or to the wave conditions (amplitude and speed) of the location where the power take off system will be placed.

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