Study on a Wave Energy Based Power System

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***Abstract*-Huge quantities of clean energy can be obtained from the waves of the oceans and seas. As wave energy extraction technology is currently in a preliminary state of development any new results in this field should be of real interest. A direct driven wave power conversion system to be placed in the Black Sea near the Romania shores was proposed and analyzed. The paper focuses on its linear generator, respectively on its power electronic and control system.**

I. INTRODUCTION

The energy of the oceans and seas is a huge, yet unexploited renewable energy source on our planet the dynamic evolution of the ocean energy industry is emerging. An important feature of ocean energy resources is their high density, the highest one among the renewables [1].

The 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 seems to have the greatest general application [2].

The World Energy Council has estimated the global ocean wave power over 2 TW (which means 17,500 TWh/year) [3]. From this, it has been estimated that the practical economic contribution of the wave energy converters could be 2,000 TWh/year, similar to current installed nuclear or hydroelectric generation capacity.

Such generating capacity could result in up to 2 billion tones of CO_2 emissions being displaced from fossil fuel generation per year, similar to current emissions from electricity generation in the US [4].

The first wave energy device patent was registered in 1799 by Girard in Paris! Still then more than 1500 wave energy device patents had been registered. Historically, there have been two booms of interest in the research of wave energy, corresponding to the 1970's oil crisis and pollution concerns as well as concerns regarding natural resource reserves since the mid-1990's [5].

There are several compelling arguments for using the wave energy technology [6]:

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 dispatched to an electrical grid system.
iii.) The 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 (offshore) that they are generally not visible.

These are also some challenges when deploying wave power devices:

i.) To convert efficiently the continuous wave motion into electricity. The wave power is available at low-speed, high forces. The motion of forces is not in a single direction. Usually the electric generators operate at higher speeds and require a constant input.
ii.) The wave power converter devices has to survive storm damage and saltwater corrosion.
iii.) High total cost of the generated electricity. Wave power will only be competitive when the total cost of generation is reduced, or when other energy sources will not be available. The total cost includes the wave power converter's costs, installation & maintenance cost, and electricity delivery costs.

Wave power plants as all the power plants in general, require some sort of control. In the first place, start up, close down and emergency procedures have to be designed and implemented. Secondly, control is required to deal with variable grid requirements and the wide variations in power available to the plant.

The latter point is particularly critical in wave energy plants, since the oscillatory wave power is quite random and so difficult to predict as power, voltage and frequency. Hence the design of the control system for such wave power plant is critical [7].

The greatest power in the wave fronts is in the Atlantic Ocean South-West of Ireland, in the Southern Ocean and off Cape Horn. Large portions of the world's potential wave energy resources are also found in sheltered waters and calmer seas, which often exhibit a milder, but still steady wave climate, as the Baltic, the Mediterranean, or the Black Sea.

In [8] the way of computing the monthly mean power density of the wave energy in the Black Sea near the Romanian shores was presented in details.

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II. THE DIRECT DRIVEN WAVE ENERGY CONVERSION SYSTEM

The design requirement of a wave energy converter is to generate 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 [9].

The direct driven power take off system, which is intended to be used by us is the simplest possible. It uses a floating buoy joined together without intermediate mechanical systems with a linear generator. It works upon the difference in height between wave top and wave bottom [10].

The buoy, floating on the water's surface follows the motion of the wave [11]. The buoy is connected to a linear generator fixed on a concrete foundation, which stands on the bottom of the ocean (see Fig. 1).

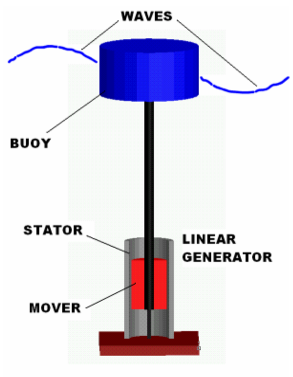


Fig. 1. The WEC system

The system is mechanically simple, with few moving parts. By optimizing the shape and operation of the buoy 90% absorption efficiency can be achieved [12].

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 to be set up near the Romania shore of the Black Sea: 20 kW power, 120 V maximum voltage, 1 m/s speed and 1 m maximum stroke.

III. THE LINEAR GENERATOR

Based on the previous experiences and the given requirements a novel permanent magnet tubular linear generator was designed and analyzed [13]. Its main structure is given in Fig. 2.

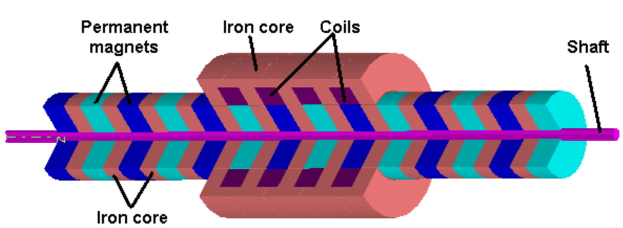


Fig. 2. The structure of the tubular linear generator

The 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. Each module has a ring type iron core having U-shaped cross-section with a coil inside.

In the structure given in Fig. 2 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 generator in study were obtained via finite element method (FEM) based numeric field computations [14]. Both steady state regimes (where the speed of the generator is constant) and transient regimes (where the speed is continuously varying) were taken in study.

Due to the lack of space from the plenty results obtained via FEM based simulations here, in Fig. 3, only the flux plots in two positions of the mover are given.

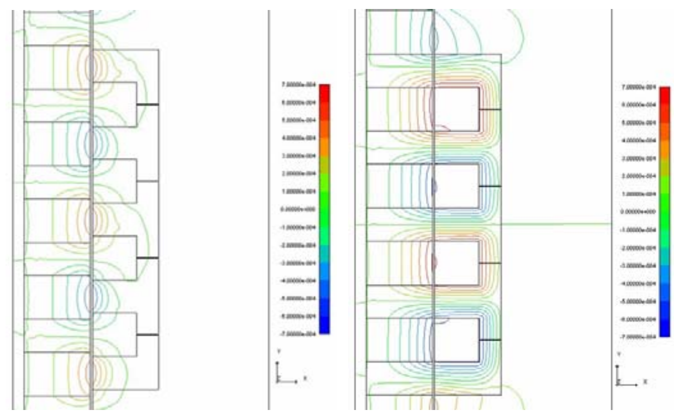


Fig. 3. The field lines obtained via field computations

By transient motion simulation the generated waveforms were computed for constant speed of the mover, respectively for one having sinusoidal variation, which is more similar to the actual movement of the waves. The generated voltage at a sinusoidal varying speed of the mover is given in Fig. 4.

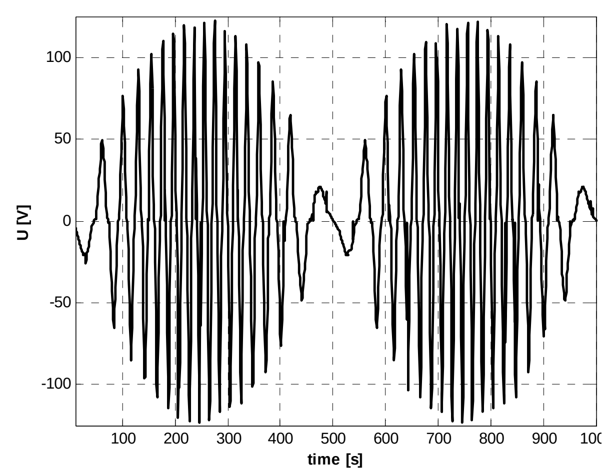


Fig. 4 The generated voltage

IV. The Power Electronics System

One of the main problems regarding the proposed wave power conversion system is the design of its power electronics [15].

As the movement of the waves is irregular both concerning the distance between two wave crests (which influences the frequency of the generated voltage) and the wave's height / speed (having effect over the magnitude of the induced voltage in the coils) also the amplitude / frequency of the voltage obtained from the linear generator varies between relatively large limits.

Therefore, it can be stated that the primary source for the power electronics is of ac one with a stochastic evolution of the amplitude and frequency, according to the irregular movement of the waves.

The mathematical model of the phase voltage given by the linear generator is a stochastic signal with both amplitude and frequency modulation.

As the power varies over a wave period and the average power is several times lower than its peak power, respectively to reduce the fluctuation in total power it is more economically reasonable to connect together more linear generators.

A higher output voltage is possible by series connection of the linear generators (LG), but due to the stochastic variation of the ac parameters, a dc addition must be chosen, like in Fig. 5 [16].

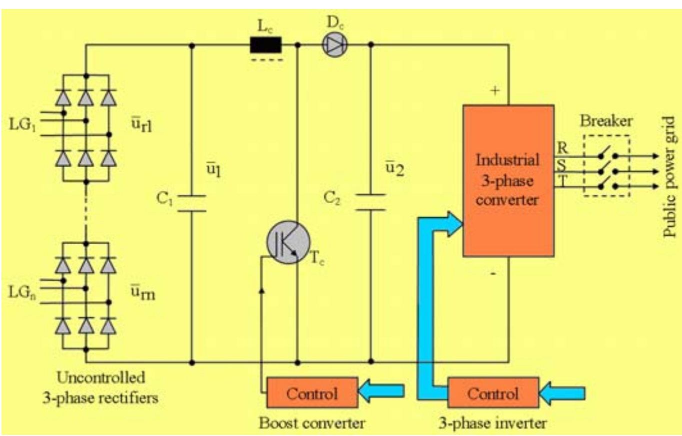


Fig. 5. Simplified structure of the power electric circuit

In order to reduce the fluctuations of the dc voltage, a power boost converter, based on IGBT transistor (T_c) is necessary, so that,

$$u_2(t) \cong \text{const.} \tag{1}$$

despite the variations of the voltages ($u_{r1},...,u_{rn};\bar{u}_1$).

The selection of the boost dc/dc converter is motivated by its ability to give an output voltage, $\bar{u}_2(t)$ higher than $\bar{u}_1(t)$, and the possibility to maintain, within certain limits, a constant $\bar{u}_2(t)$ voltage.

Its working principle is very simple: when the IGBT is conducting current is being drawn through the L_c inductor. At this time energy is stored in the inductor.

When the transistor stops conducting the inductor voltage flies back or reverses because the current through the inductor cannot change instantaneously. The voltage across the inductor increases to a value that is higher than the combined voltage across the diode and the output capacitor. As soon as this value is reached, the diode starts conducting and the voltage that appears across the output capacitor, is higher than the input voltage.

In a final stage the connection to the public power grid is possible by using an industrial 3-phase power inverter with internal voltage and frequency (U/f) control, Fig. 5.

The main problems of the inverter are related to line synchronization and to the active power control. The synchronization is a common problem of the power system solved in different ways (automatic synchronization).

The delivered active power (P) is controlled indirectly, through the inverter output voltage ($\tilde{u}_{line}$), and must be correlated with the extracted power from waves [17].

By a constant value of the line voltage ($\tilde{u}_{line,0}$), variation of the wave-power will change the $\bar{u}_1$ voltage.

The boost converter operates only in a strict domain of the difference:

$$\Delta u = \bar{u}_2 - \bar{u}_1 \tag{2}$$

The behaviour of the proposed power electronic system was studied by means of simulations. The simulation of the power electric circuit was performed in Simulink® using the SimPowerSystems™ blocksets [18].

The structure of the program follows the configuration of the power electric system given in Fig. 3 (see its main window in Fig. 6).

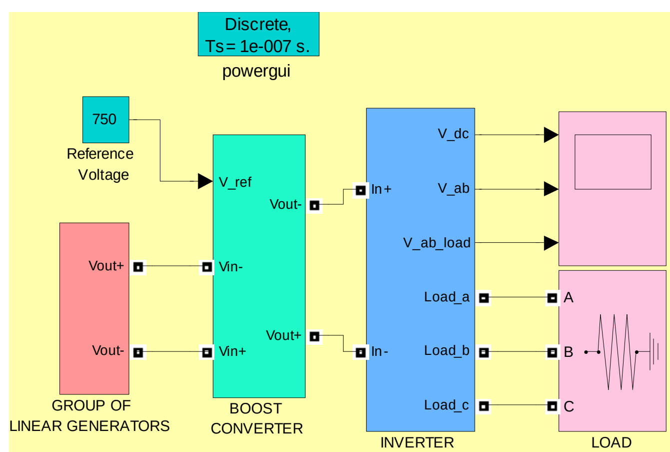


Fig. 6. The main window of the program

Several subsystems at different levels form the simulation program. Due to the lack of space here only two subsystems can be presented in details:

i.) the coupled linear generator group's model (Fig. 7)
ii.) the boost converter's model (Fig. 8)

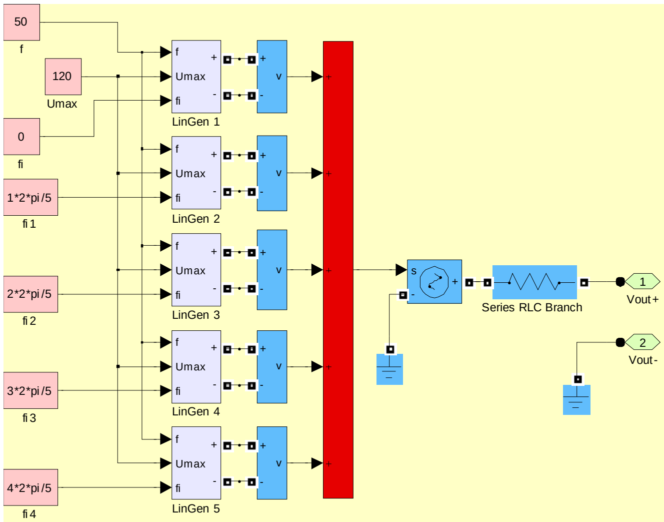


Fig. 7. The linear generator's subsystem

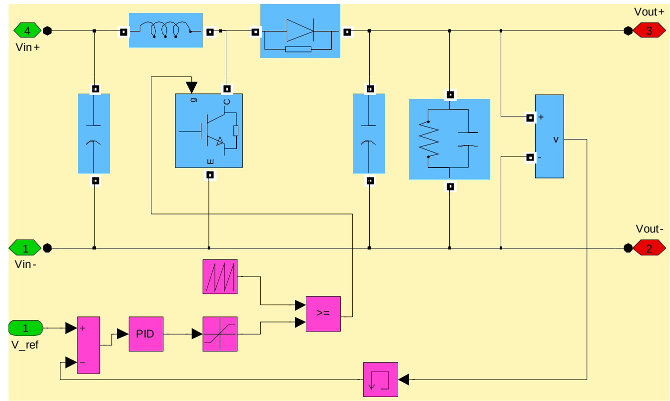


Fig. 8 The boost converter's model

Next in Figs. 9 and 10 the main results of the simulations are given.

The voltage produced by a single phase of a linear generator is given in the first plot of Fig. 9.

It can be clearly seen the sinusoidal envelope of the induced voltage due to the sinusoidal variation of the mover's speed due to the rise / fall of the buoy floating on the sea surface. The sinusoidal waveform is modulated by the poles of the linear generator. In the next plot all the three phases of a single generator can be seen.

In the third plot of the same figure, the rectified output of a single linear generator unit can be seen. It was obtained by passing through a three-phase rectifier of the three voltages induced in the phases of the permanent magnet linear generator.

Finally, the rectified voltages of the five linear generators forming a group were added resulting the voltage shown in the last plot of Fig. 9.

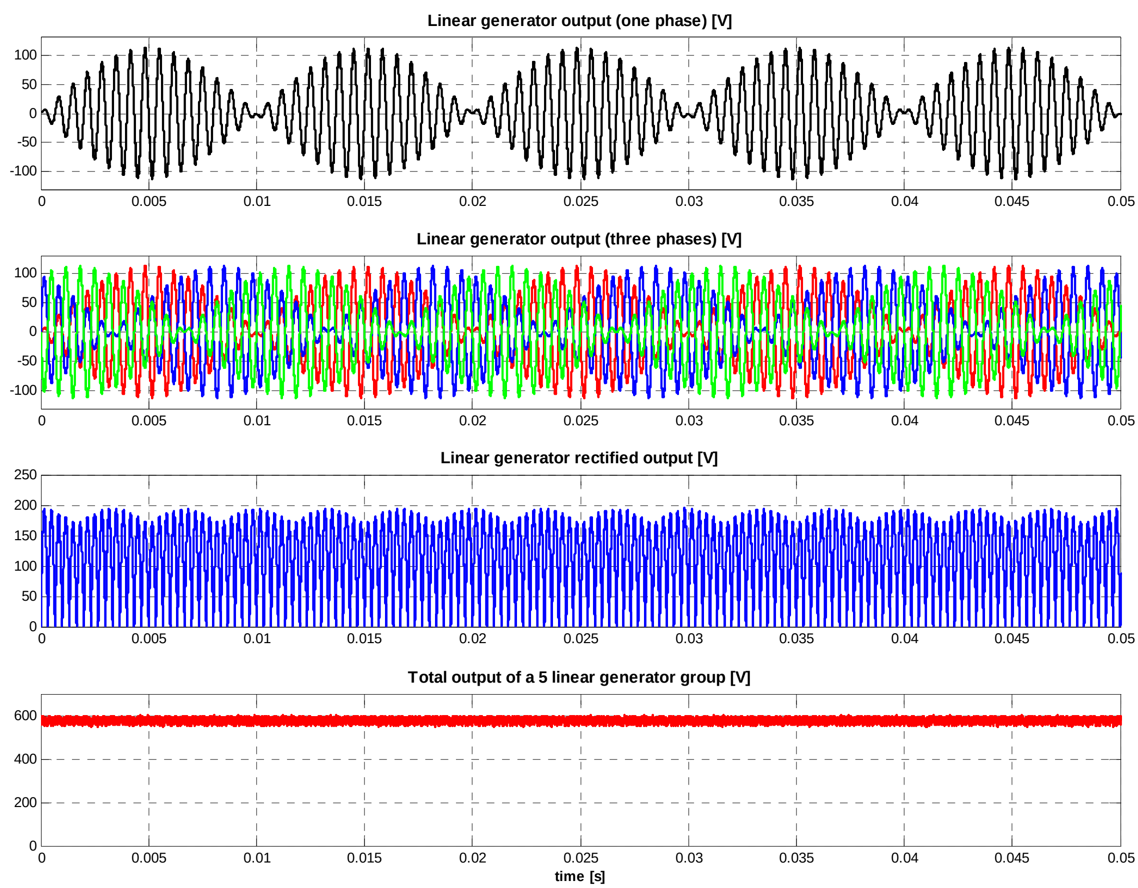


Fig. 9. Voltage waveforms at the output of the linear generators

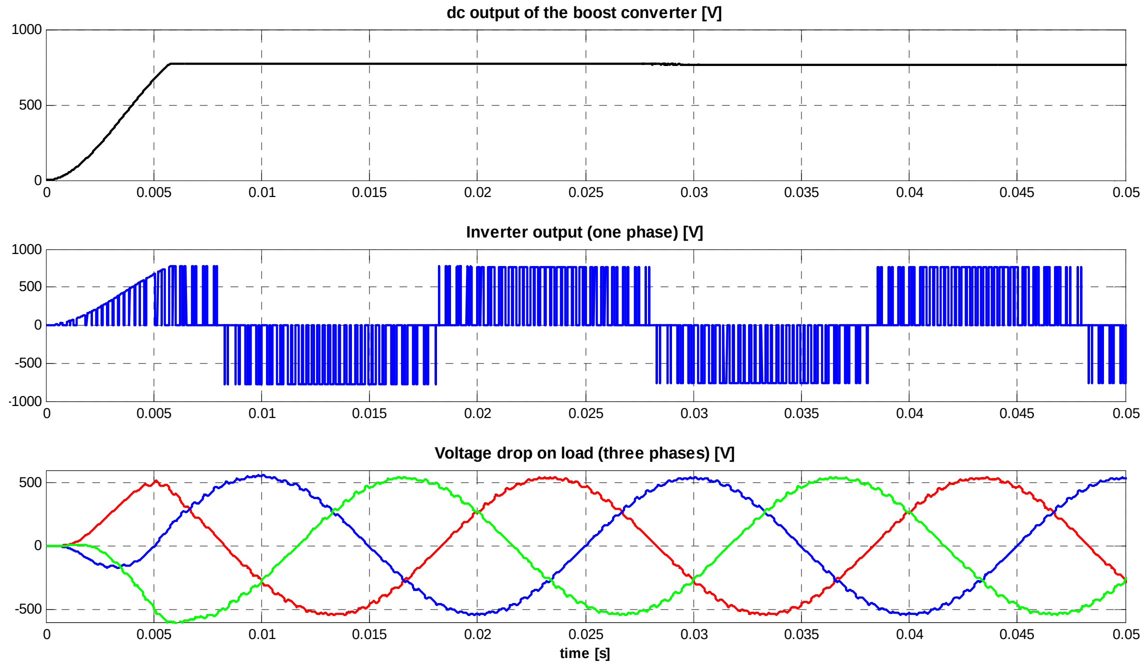


Fig. 10 Voltage waveforms of the inverter

In Fig. 10, the waveforms regarding the inverter, which connects to the grid the electrical system of the linear generators, are given.

In the first plot the input dc voltage (obtained from the boost converter) of the inverter is shown. As it can be seen, the boost converter assures for it an acceptable constant level, despite of the irregularly varying generator output voltages connected together.

In the last plots of Fig. 10 the chopped output voltage of the inverter, respectively the voltage drop on the three-phased load can be seen. As it can be observed, the voltage drops are near sinusoidal due to the efficient control of these waveforms.

As it was stated previously the main problem regarding the grid connection of the wave energy power converters is the irregularity of the generated power (as its voltage and frequency is concerned).

Finally the way how the power control system behaves at various input voltages, frequencies and phases was studied.

Different amplitudes and frequencies were imposed for the output of the five linear generators forming a power generation group. Also the distance between the generators was modified (practically the phase between the generated voltages were changed).

In the next figures the total output of the five linear generators, the dc output of the boost converter, respectively the voltage drop on the load was plotted versus time at different generation conditions.

In Fig. 11 the waveforms are shown for the ideal case:

i.) the generators are placed exactly in their designed position

ii.) all the generated voltages have the same (the rated) voltage and frequency.

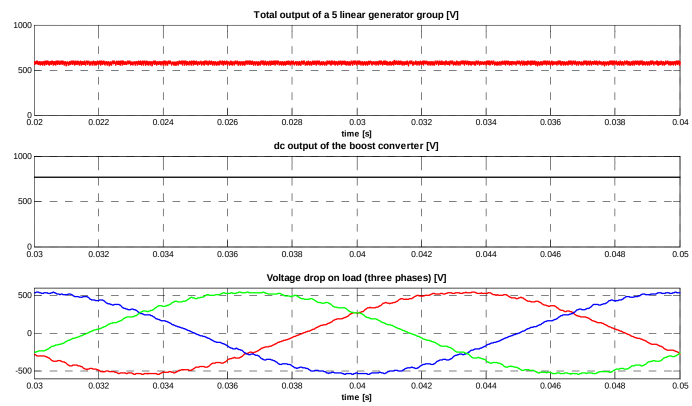
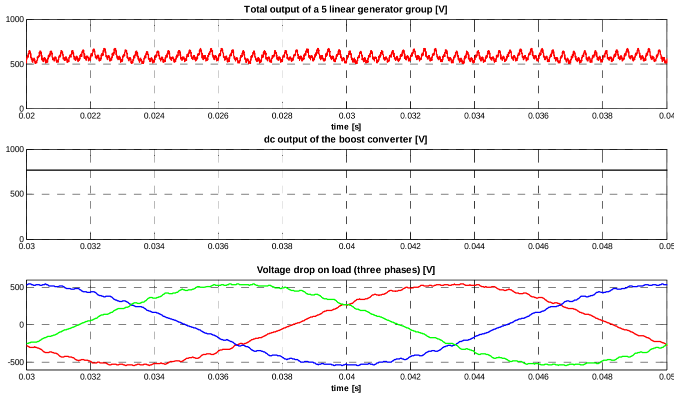


Fig. 11 The behaviour of the power system at ideal linear generator outputs

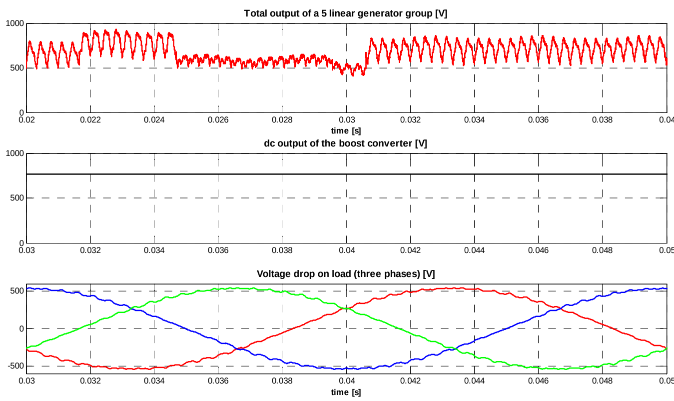
Next, in Fig. 12, the results for two extreme situations are given. In both cases the parameters of the generated voltages are widely varying.

It can be seen very clearly from the given results the total output voltage of the five linear generators are rather varying, but the dc output of the boost converter remains unchanged in comparison with that of Fig. 11. And of course in this case also the output of the inverter remains unchanged.

All these results again emphasize that the above presented control system of the boost converter was designed properly and the converter is able to deliver the same output dc voltage at very different input voltages.



a)



b)

Fig. 12 The behaviour of the power system at various linear generator outputs

V. Conclusions

A direct driven wave power conversion system to be placed in the Black Sea near the Romania shores was proposed. Its permanent magnet tubular linear generator was studied formerly [8], [13], [14].

In the paper, the results of the power electronics circuit's selection were detailed. These precisely controlled circuits enable the grid connection of the linear generators of the wave energy converters.

All the obtained results emphasize the correct concept of the proposed linear generators and of the power electronic system connected together.

The boost converter is able to deliver constant dc output at very various inputs. By this way a real problem of the wave energy power converters was solved.

The overall performances of the proposed wave energy converters exploiting the huge clean electric energy of the oceans and of seas were proved to be those excepted by the designers.

Finally it can be stated that looking at the technological advances done in the last years in this field there are serious reasons to hope that a major new, reliable and flexible source of affordable clean renewable energy will be enabled in the near future.

Acknowledgment

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