Lecture Notes in Electrical Engineering 1224

Salim Ziani
Mohammed Chadli
Sofiane Bououden
Ivan Zelinka *Editors*

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Salim Ziani · Mohammed Chadli ·
Sofiane Bououden · Ivan Zelinka
Editors

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Editors
Salim Ziani
Department of Electronics
University of Frères Mentouri Constantine 1
Constantine, Algeria

Mohammed Chadli
IBISC Lab, UEVE
University of Paris-Saclay
Evry, France

Sofiane Bououden
Faculty of Sciences and Technology
Abbes Laghrour University Khenchela
Khenchela, Algeria

Ivan Zelinka
Faculty of Electrical Engineering
and Computer Science
VŠB TU Ostrava
Ostrava, Czech Republic

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Preface

This proceeding book about the Advanced Control Engineering Methods in Electrical Engineering Systems conference contains accepted papers presenting the most interesting state of the art on this field of research. Presented topics are focused on classical as well as modern methods for modeling, control, identification, and simulation of complex systems with applications in science and engineering. Topics are (but not limited to): control and systems engineering, renewable energy, faults diagnosis-faults tolerant control, large-scale systems, fractional-order systems, unconventional algorithms in control engineering, signal and communications … and much more. The control of complex systems dynamics, analysis, and modeling of its behavior and structure is a vitally important problem in engineering, economy, and generally in science today. Examples of such systems can be seen in the world around us and are a part of our everyday life. Application of modern methods for control, electronics, signal processing, and more can be found in our mobile phones, car engines, home devices as for example washing machine is as well as in such advanced devices as space probes and communication with them. The main aim of the conference is to create periodical possibility for students, academics, and researchers to exchange their ideas and novel methods. This conference will establish a forum for the presentation and discussion of recent trends in the area of applications of various modern as well as classical methods for researchers, students, and academics. The accepted selection of papers was extremely rigorously reviewed in order to maintain the high quality of the conference that is supported by organizing universities and related research grants. Regular as well as student's papers have been submitted to the conference and, in accordance with review process, have been accepted after a positive review. We would like to thank the members of the Program Committees and reviewers for their hard work. We believe that this conference represents a high-standard conference in the domain of control, modeling, and analysis of dynamical and electronic systems. We would like to thank all the contributing authors, as well as the members of the Program Committees and the Local Organizing Committee for their hard and highly valuable work. Their work has definitely contributed to the success of the conference.

This event is supported by the Abbes Laghrour University, Khenchela, Algeria, and mainly financed by SONATRACH Society, SONELGAZ Society, DGRSDT (Direction Générale de la Recherche Scientifique et de Développement technologique) and ATRST (L'Agence Thématique de Recherche en Sciences et Technologie).

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Contents

Renewable Energy (RE)

Modeling and Analyze of an Energy Recovery System (ERS) to Transform of Sea Waves Kinetic Energy into Electrical Energy

Bachir Ouartal and Mustapha Zaouia

Abstract In order to transform the mechanical energy into the electrical one rotary electric generators are the principal electromechanical devices which are used, but in some particular cases linear generators are more indicated for this task. Linear machines have significant advantages, such as simplicity of construction and a high efficiency compared to rotary machines. To achieve high efficiency, permanent magnet (PM) tubular topologies are particularly interesting among the different types of linear machines. Also, tubular linear machines have an advantage over flat linear machines because they produce high thrust due to the absence of normal forces. This work presents the magneto-hydrodynamic modeling of a sea wave energy converter. The devise is named Energy Recovery System (ERS). The magnetic field in the generator is calculated by means of finite element method and the set of mechanical equations is solved numerically on Matlab. The results are mainly the speed, the displacement and the distribution of the magnetic induction as well as the induced electromotive force.

Keywords Tubular linear generator · Sea wave · 3D finite element · Energy recovery system

1 Introduction

In our days, different types of wave energy conversion devices are used. The two well-known concepts are the IPS buoy [1, 2] and the Aqua-Bouy [3]. These devices require a whole intermediate mechanical system to transform the kinetic energy of the buoy into the one which is compatible with the generator. However, the complexity

B. Ouartal (✉) · M. Zaouia
LATAGE Laboratory, Mouloud Mammeri University of Tizi-Ouzou, B.P17 RP, 15000 Tizi-Ouzou, Algeria
e-mail: bachir.ouartel@ummto.dz

M. Zaouia
e-mail: mustapha.zaouia@ummto.dz

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of the structure increases mechanical losses and it is makes difficult the modelling of the whole system. Moreover, the combination of the different components pose reliability problems when operating in extreme conditions of the marine environment and this is the biggest obstacle to manufacture a wave energy converter under real field conditions [4, 5]. Several electromechanical devices for converting wave energy using a linear generator have been presented and describe in [6, 7] particularly, the one using a permanent magnets three-phase synchronous linear generator [8]. This structure has the advantage of being simple, without many intermediate structures and less losses of mechanical energy. In this study, a wave energy converter consisting of a buoy connected directly to a linear permanent magnet generator is studied. The generator is modeled using the 3D finite element method and the mechanical equations are solved numerically on Matlab.

2 Description of the ERS and Sea Wave Model

The concept and operation of the device are described in Fig. 1. The piston is covered with rows of permanent magnets of alternating polarity. The rows of magnets are separated by aluminum spacers. The stator is made of electrical non-oriented steel laminations and insulated copper conductors. The conductors are wound into slots in the stator steel and form closed loops or coils. When the buoy oscillates in swell mode under the forces of the waves, it causes the piston to move relative to the stator. The reciprocating movements of the piston induce currents in the stator winding. The current in turn affects the piston with a magnetic force opposite to the direction of motion. The oscillating model of the device is shown in Fig. 1.

3 Electromagnetic–Mechanical Modeling

3.1 Electromagnetic Model

The formulation $\overrightarrow{T} - \psi$, describes the distribution of the electromagnetic field by the use of the electric vector potential $\overrightarrow{T}$ and the magnetic scalar potential ψ [8, 9]. This formulation has the advantage of allowing a reduction in the computational cost by reducing the degrees of freedom from three to one in all the non-conductive zones [10]. The electromagnetic formulation which is used for the modeling of the device is the formulation $\overrightarrow{T} - \psi$: The general equation is given as follows:

$$\vec{\nabla} \wedge \left(\frac{1}{\sigma}\vec{\nabla} \wedge \vec{T}\right) - \nabla \wedge \left(\frac{1}{\sigma}\vec{\nabla}\vec{T}\right) + \mu\frac{d}{dt}\left(\vec{T} - \vec{\nabla}\psi\right) = 0 \quad (1)$$

In ferromagnetic areas:

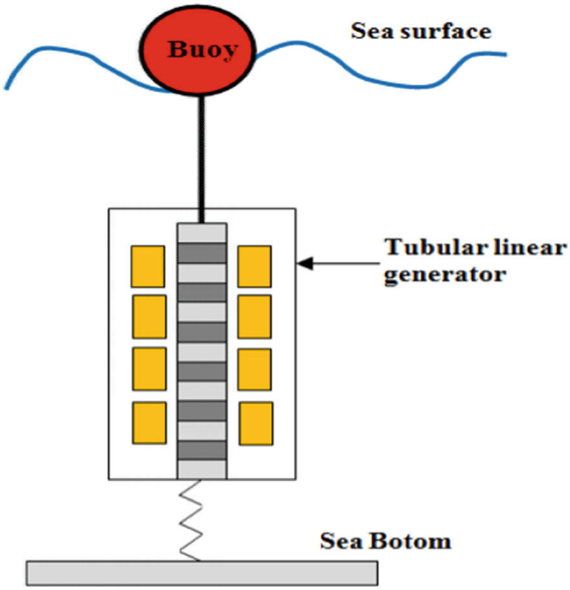

Fig. 1 Wave energy converter system (ERS)

$$\vec{H} = \vec{T} - \vec{\nabla}\psi \tag{2}$$

In the air zone:

$$\vec{H} = -\vec{\nabla}\psi \tag{3}$$

In the area containing permanent magnets:

$$\vec{H} = H_c + \left(\vec{T} - \vec{\nabla}\psi\right) \tag{4}$$

With

$\overrightarrow{T}$ Magnetic vector potential,
ψ Magnetic scalar potential,
$\overrightarrow{H}$ Magnetic field,
H_c Coercive field,
σ Electrical conductivity,
μ Magnetic permeability.

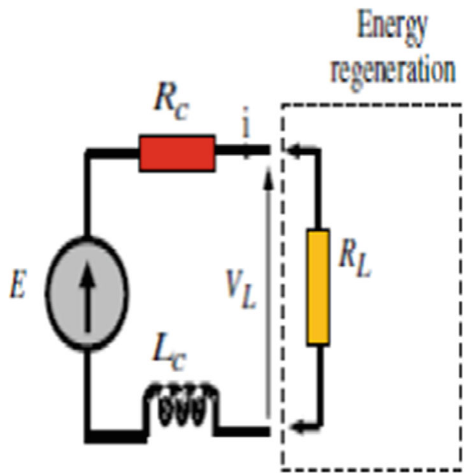

Fig. 2 Wave energy converter electrical circuit model

3.2 Electrical Circuit Model of the Electromagnetic Device

The equivalent electrical circuit of the electromagnetic generator is shown in Fig. 2, where R_{coil} and L_{coil} are the resistance and inductance of the coil, and R_{load} as the external resistance characterising the energy regeneration [11].

The electrical load connected to the generator determines the relationship between the circuit current and the induced electromotive force e when the $\boldsymbol{R_{load}}$, the circuit Eq. (5):

$$E = (R_{coil} + R_{load})i + L_{coil}\frac{di}{dt} \tag{5}$$

Neglecting the coil's inductance, the maximum power loss is obtained when the regenerative energy is zero $R_{load} = 0$ i.e. the stator coils are short circuited. In addition, the maximum power regeneration occurs as the external resistance is set equal to the internal resistance. The power is given by the following equation:

$$P = \frac{E^2}{R_{coil} + R_{load}} \tag{6}$$

4 Mechanical Model

- **Hydrodynamic equation**

It is assumed that the wave which moves from left to right towards the positive x therefore the free surface profile is given by [13]:

$$y(x, t) = A\cos(kx - \omega t) \tag{7}$$

where: A: the amplitude of the waves, k the spatial frequency, ω the temporal pulsation and t the time. Spatial frequency is related to wave length and temporal frequency is related to wave period.

The hydrodynamic formulation can be expressed by Eq. (8):

$$\ddot{z} = \frac{1}{m + \xi}(-\lambda\dot{z} - Kz(t) - F_{em} + F_{ex}) \tag{8}$$

With

- m the dry mass of the buoy,
- ξ The added mass,
- λ The radiation damping term,
- K the hydrostatic stiffness
- $\ddot{z}$ the acceleration of the floating buoy,
- $\dot{z}$ represents the velocity of the floating buoy,
- z represents the position of the center of gravity of the float along the axis (o, z),
- F_{ex} the forces of excitation, the forces linked to the converter are noted F_{em}.

To analyze and study of our system constituted by permanent magnet linear generator ERS and wave sea model, the 3D finite element method is used and Matlab software to solving the mechanical equations. The 3D finite element analysis is carried out to analyze the permanent magnet generator. The permanent magnets used are of NdFeB type with axially magnetized. Figure 3 shows the geometrical of a tubular permanent magnet linear generator ERS. The dimensions and characteristics are given by Table 1 [12].

Figure 4 shows the mesh diagram of the generator. The meshing process plays an essential role to obtain good results. The magnetic flux density and magnetic field strength is analyzed; Fig. 5 presents the isometric view of the PM tubular linear generator (ERS).

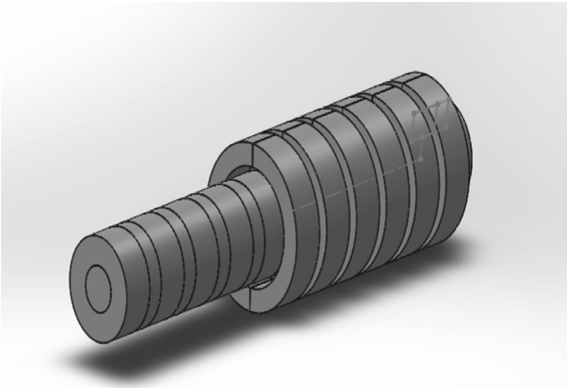

Fig. 3 Geometrical of a tubular permanent magnet linear generator (ERS)

Table 1 Dimensions and characteristics of the ERS

Components	Parameter	Value (mm)
Number of phases	Φ	3
Pole pitch	τ	15
PM width	τ_m	10
Steel pole width	τ_s	5
PM inner radius	R_{im}	10
PM outer radius	R_{om}	22.5
Air-gap length	δ	3.3
Coil inner radius	R_{ic}	25.8
Coil outer radius	R_{oc}	33.4
Mover length	l_m	180
Stator length	ls	390
Number of turns per slot	n_c	220 turns

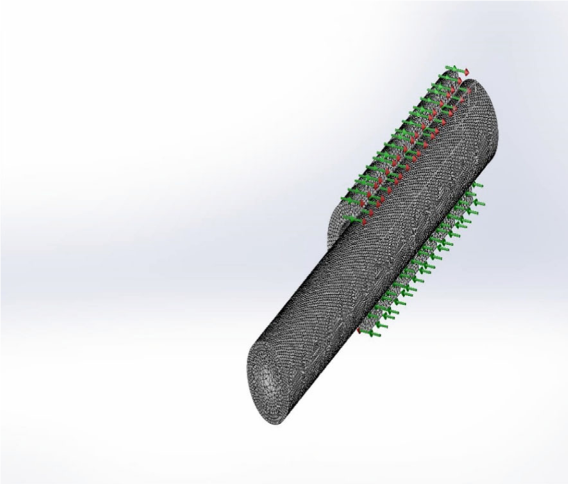

Fig. 4 3D finite element mesh of PMTLG

Figure 6 shows respectively the free surface elevation, and Fig. 7, the speed and displacement of the floating buoy.

Figures 8 and 9 are shown respectively the variation of magnetic flux densities due to magnetic excitation and the magnetic field strength of the tubular linear permanent magnet generator.

The induced electromotive force as a function of time EMF in the linear generator It is calculated using Eq. (5), this force is related to the wave speed and the

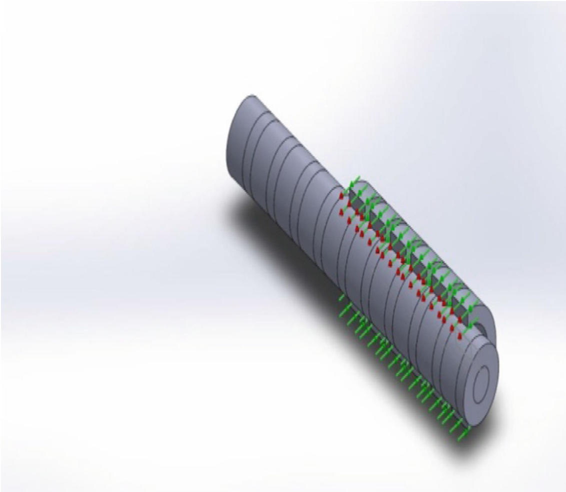

Fig. 5 Isometric view of PMTLG

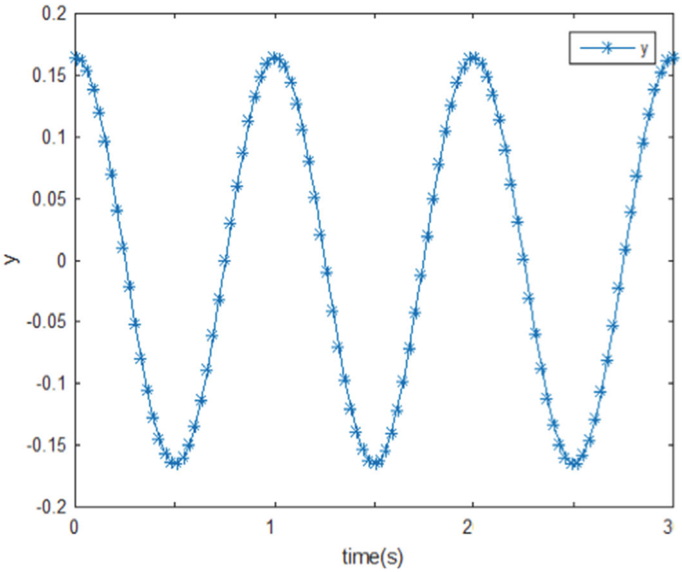

Fig. 6 Free surface elevation

displacement, when the displacement is large the electromotive force induced EMF is increased, if the displacement is small the induced EMF has a modest value see Fig. 10. The induced electromotive force EMF also depends on the relative speed between the coil and the translator, as the translator moves back and forth along the vertical or 'z' direction, the magnetic field varies, while the stator is stationary.

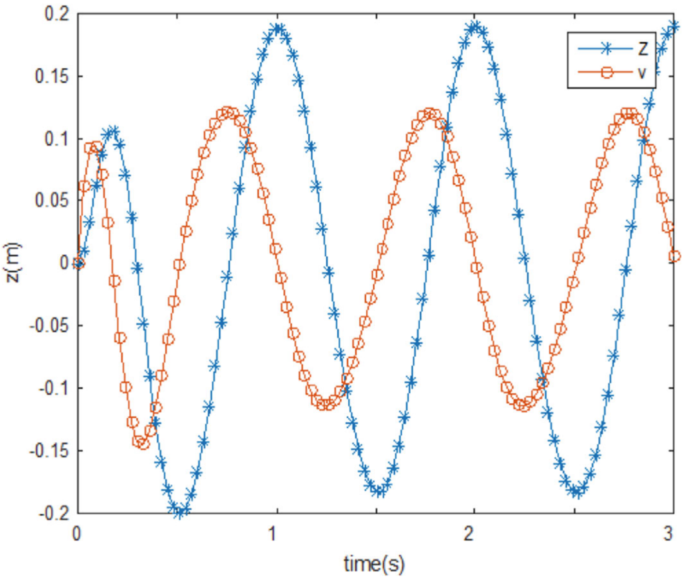

Fig. 7 Velocity and displacement

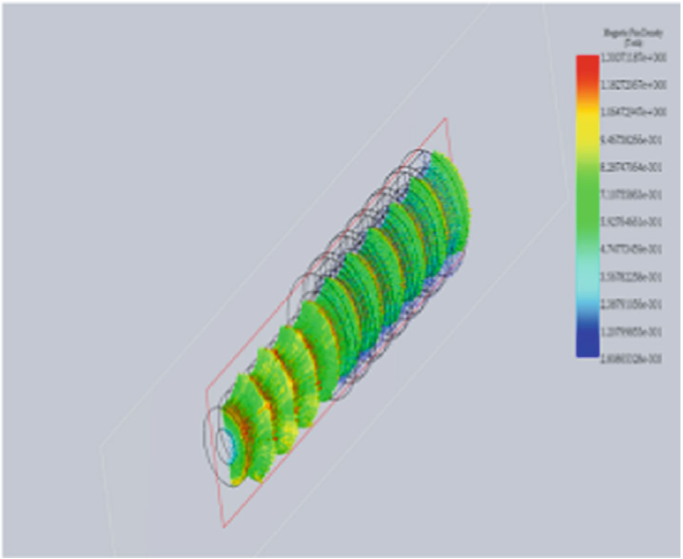

Fig. 8 Distribution of the magnetic flux density

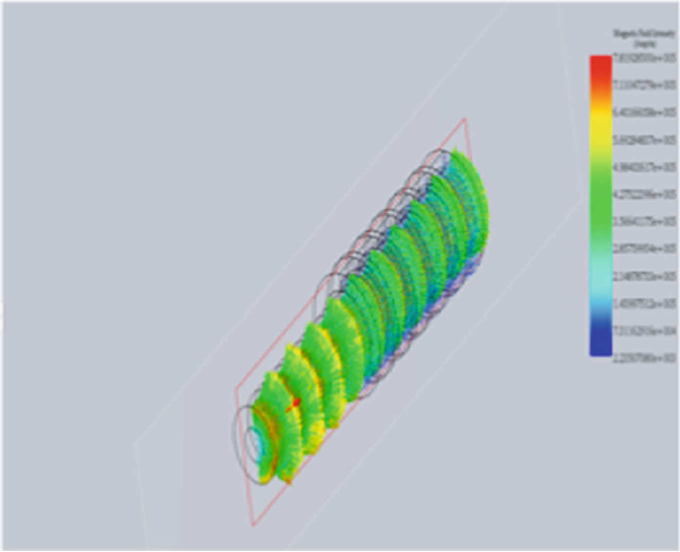

Fig. 9 Distribution of the magnetic field

Therefore, according to Faraday's law, the induced EMF induced EMF increases as the speed increases; the calculated magnitude of the total induced EMF is 9.93 V. The electrical output power obtained as a function of time is given by Fig. 11. It is calculated using Eq. (6) governing the equivalent electrical circuit given in Fig. 2. The peak value of the electrical power is 16.89 W. The obtained results can be merged with many adaptive techniques in control theory (see [14–44]).

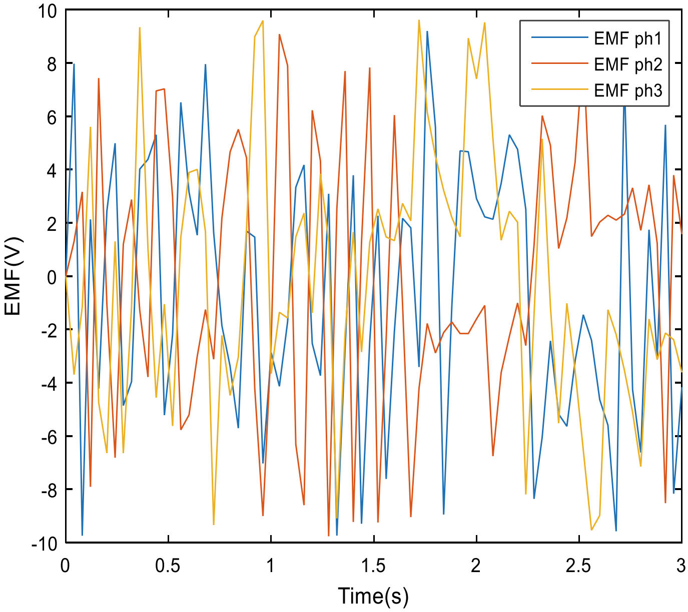

Fig. 10 Induced electromotive force

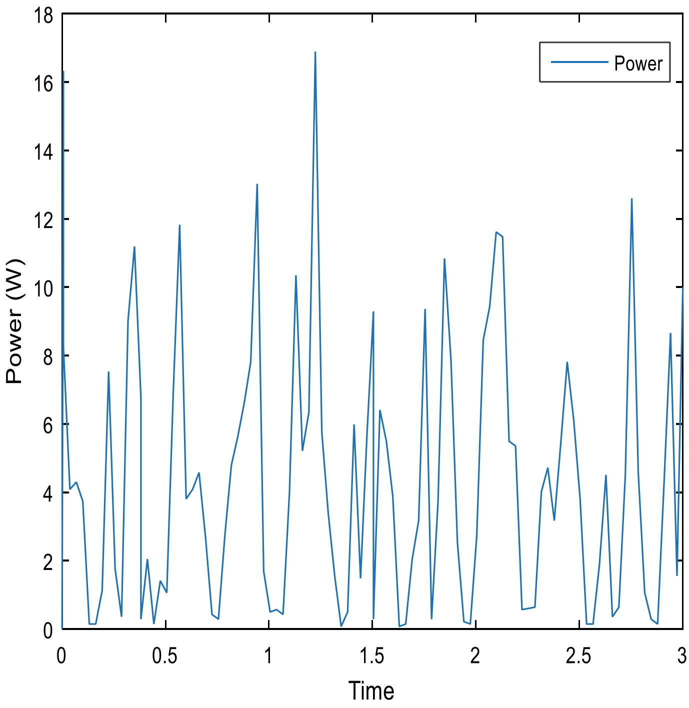

Fig. 11 Power in linear generator

5 Conclusion

In this work, we presented a modeling of a linear permanent magnet generator ERS as well as a hydrodynamic modeling of the wave-buoy system. We have also presented a simple configuration comprising a buoy directly connected to a linear permanent magnet generator ERS which is allowed to couple the two mechanical-electromagnetic phenomena. The first phenomenon describes the movement of the buoy was solved numerically under Matlab environment and the second describes the electromagnetic formulation using Maxwell's equations and solving using 3D finite element. The mechanical-electromagnetic coupling was simulated. The results presented are mainly the 3D finite element mesh, a view of the generator with the arrangement of the permanent magnets, the mapping of the magnetic induction in the generator and the force density distribution and velocity and displacement of the floating buoy. The Induced electromotive force obtained from the three phases and Maximum output electrical power versus time is also presented.

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