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Article

Simulation and review of a small-scale device for wave energy conversion

Simulación y revisión de un dispositivo de pequeña escala para la conversión de energía del oleaje

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Abstract

The exploration and analysis of wave energy potential in some Mexican coastal nodes is complemented by this work, shich presents an electromagnetic analysis and simulation of the transducer device for converting wave energy into electricity. The device developed for this purpose is the permanent magnet linear electric generator (LEG). The wave energy potential obtained in a preliminary work at various points in Mexican coastal waters provides a precedent for the design of this device.

The application of linear generators to obtain electrical energy from alternative sources of energy is a topic that is increasingly of interest for the progress of new distributed generation system. Therefore, in addition to determining the energy potential through electromagnetic simulation, this work also analyzes the performance and energy quality supplied by a linear generator. The simulation developed in this work is based on the displacement spectrum, and is a function of the significant wave height and its periodicity in the Mexican coastal points analyzed in the preliminary work. This study also contributes to both the design and development for micro-generation systems based on wave power, widening the range of electric power converters to assist in the energy control and quality of these linear generator devices.

Keywords: Wave energy, wave energy conversion, linear generator, micro-grids, energy sustainability.

Resumen

La exploración y análisis del potencial energético undimotriz en la costa mexicana se complementa en este trabajo exponiendo el análisis y simulación electromagnética del dispositivo transductor para la conversión de energía del oleaje en electricidad; un dispositivo que se desarrolla para este propósito es el generador eléctrico lineal (GEL) de imanes permanentes. El potencial energético del oleaje en diversos puntos en aguas costeras mexicanas obtenido en un trabajo preliminar proporciona un panorama precedente para el diseño de estos dispositivos. La utilización de generadores eléctricos lineales para conseguir energía eléctrica por fuentes alternas de energía es una temática que cada vez toma mayor fuerza para el progreso de nuevos sistemas de generación distribuida (micro-redes), por lo que este trabajo además de determinar el potencial energético a través de la simulación electromagnética del dispositivo, analiza el rendimiento y calidad energética proporcionada por GEL; el análisis de simulación desarrollado en este trabajo se fundamenta en la obtención del espectro de desplazamiento en función de la altura significativa de las olas y su periodicidad en los puntos costeros mexicanos analizados en el trabajo preliminar. Este trabajo contribuye para el diseño y desarrollo de dispositivos enfocados a micro-generación por undimotriz y abre el abanico para el modelado y desarrollo de convertidores de electrónica de potencia para ayudar en el control y calidad energética de estos dispositivos generadores eléctricos lineales.

Palabras clave: conversión de energía por oleaje, energía undimotriz, generador eléctrico lineal, micro-redes, sustentabilidad energética.

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Introduction

The Mexican electric power industry is currently undergoing some indispensable and necessary changes in the way it distributes energy. It also aims to harness its energy resources in a rational, sustainable, and efficient manner for social and economic benefits. The national goals are to provide energy to all communities in the country, with competitive prices and quality. Distributed generation (microgrids) is a viable option for the energy industry to implement. At present there are designs and developments of wind and photovoltaic generation, however Mexico is still lagging in research and devices that use new energy alternatives. Therefore, this paper focuses on the design, analysis, and research related to the performance of the linear electric generator, which is used in the conversion of wave energy into electrical energy. As an overview of the energy performance and quality provided by a LEG for harnessing wave energy, this will help with the design of a wave energy microgrid, in order to use its energy optimally and efficiently. With micro-generation, the opportunity is created to develop new energy conversion devices capable of using alternative and sustainable energies, such is the case of the LEG, developed and tested for ocean wave energy (Vining, Lipo, & Venkataramanan, 2011; Viola, Trapanese, & Franzitta, 2014). In addition, the LEG has been used in electric generation by means of internal combustion pistons (Wang & Howe, 2005; Wang, West, Howe, Zelaya-de-la-Parra, & Arshad, 2007) and for hybrid vehicles (Rinderknecht, & Herzog, 2010). The LEG design was reviewed by Danielsson, Eriksson and Leijon (Danielsson, Eriksson, & Leijon, 2006), where this device was described and having been developed in order to be coupled to a wave energy conversion system (WEC), using a buoy (Polinder, Damen, & Gardner, 2005) and a submerged air filling chamber, known as Archimedes Wave Swing (AWS). In Mexico, there are reports of the results from tests of a hydro-generator called Impulsa, for use with marine currents (López-González, Silva-Casarín, & Mendoza-Baldwin, 2011).

With the WEC system, the waves have uneven and irregular movements, which affect the voltage and power output of the LEG. With the objective of optimizing the output power (De-la-Villa-Jaen, García-Santana, & Montoya-Andrade, 2014) present a control method. With this background and with the exploration of the energy potential developed in the preliminary work, there is an interest in developing and investigating the energy performance and quality provided by an LEG when implemented by a WEC system in coastal points of Mexico. The study carried out by this work aims to identify the energy performance and quality provided by a WEC system through electromagnetic simulation and experimentation with a small-scale prototype. This provides a basis to establish efficient mathematical models for studies of power flows in micro-generation systems using the WEC system, and helps with the specification of electronic power components that guarantee the LEG's energy stability and quality in a WEC system.

General design of the linear electric generator

The linear electric generator used in this work has a tubular (cylindrical) design, defined in this way for its ease in the electromagnetic simulation —both two-dimensional (2D) and three-dimensional (3D). In general, the designed LEG has four elements to be dimensioned in our design process: 1) stator, which hosts the induced magnetic flux; 2) actuator, a piece that captures the axial movement of the wave; 3) permanent magnets, which are parts that provide the magnetic power needed to induce voltage; 4) windings, which is where the electromotive force (or induced voltage) is induced. The windings considered for the LEG were simulated for both a single-phase and three-phase voltages, the latter making the LEG more compact than the single-phase type. The windings are formed with donut-type coils connected in series. The design process is iterative, as shown in the flow chart in Figure 1.

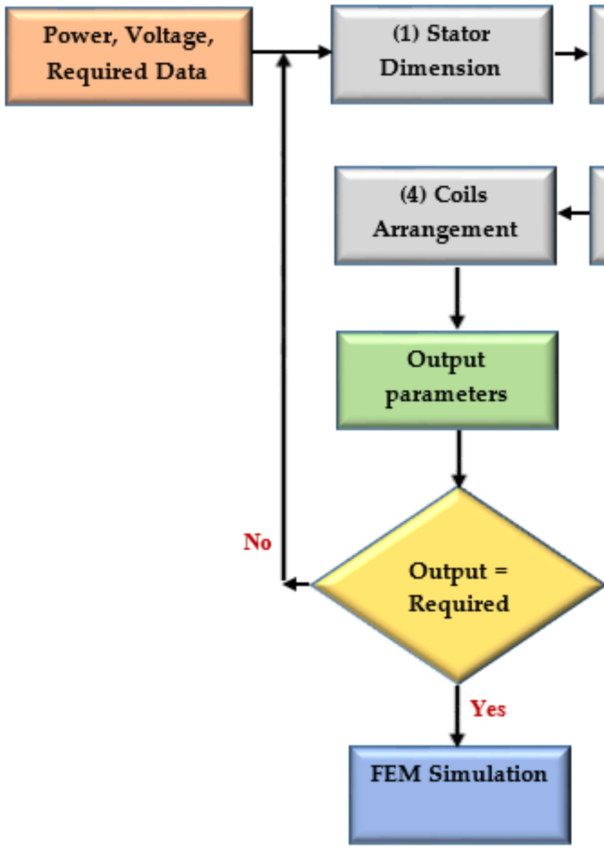


Figure 1. Flow diagram with the design process used for the LEG.

In the initial stage of the process, the input variables are introduced: power desired, voltage generated, and the stroke and average speed with which the magnets will move. For our work, the stroke depends on the significant height (*Hs*) of the average wave, which was determined in the coastal points analyzed in the preliminary work. The average speed depends of the swell period (T_Z). The next thing is to determine the dimensions of the stator part, where the drivers needed to generate the voltage are located. It is possible to determine the surface dimensions of the stator by means of:

$$A_s = \frac{\sqrt{2}P_{in}}{B_m J_m v_m r_m} \tag{1}$$

where A_s is the dimension of the stator surface, given in m^2, and since the device is tubular, A_s is the surface of the cylinder given by $\pi \cdot D_s \cdot L_s$; and where D_s refers to the diameter of the stator (m) and L_s is its axial length (m); P_{in} is the desired power rate (watts); B_m is the average magnetic flux density in the stator and whose unit is the Tesla (*T*); J_m (ampere/m^2) is the current density in the stator; r_m (m) the stator radial thickness; and v_m (m/s) is the axial speed of the magnets.

We proceed to calculate the actuator part, the piece in axial movement. Here, the diameter of the arrow and its necessary length are calculated according to the number of magnets required to be attached to it.

The determination of the dimensions of the actuator can be summarized by:

$$A_a = \frac{A_g B_g}{2B_a} = \frac{\tau \pi D_g B_g}{2B_a} \qquad (2)$$

where A_a (m^2) is the cross-section of the arrow where the magnets will be mounted, with which it is possible to obtain their diameter D_a (m); A_g (m^2) is the cross-section of the air gap cylinder, which is given by $\tau \cdot \pi \cdot D_g$, τ being (m) the pole pitch and D_g (m) the average diameter of the air gap circumference; B_g (T) is the magnetic flux density in the air gap, B_a (T) is the magnetic flux density in the arrow or actuator. The permanent magnets used are Neodymium grade N40 to N52. According to magnets manufacturers, the residual magnetic field density, *Br*, of this quality magnet is roughly 1.25 T for N40 and 1.43 T for N52 (Magnetika Saiffe, 2017). The magnets considered have a ring shape when used with a magnetic direction perpendicular to the ring faces, but also our design process contemplates magnets that are sectorized (to form a ring) when a radial magnetic direction is required. The width or axial thickness of the ring magnet is given by the pole pitch, τ, and the selected number of magnets.

The required number of turns is then determined, as well as the dimensions of the windings based on the caliber of the conductor. The calculation of the coil is based on the number of turns of the stator, *Ns,* needed to generate the desired voltage, V_{gen} (V). The calculation of the number of laps is determined by:

$$N_s = \frac{\sqrt{2}\, V_{gen}}{B_m A_s v_m} \qquad (3)$$

With the dimensioning of the four entities of the generator, it will be possible to estimate the losses, and with that calculate the machine efficiency percentage, $\%\,\eta$, with:

$$\%\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}} \tag{4}$$

where P_{losses} (watts) represents the losses of the machine in the stator conductors due to the current and losses by currents induced in the stator and actuator. The force (*N*) for the generation is determined by:

$$F_{gen} = \frac{\frac{P_{in}}{\eta} - P_{mec}}{v_m} \tag{5}$$

P_{mec} are the mechanical losses due to friction in the supports of the arrow. For simplicity in the design of the generator, these losses were considered negligible.

The comparison stage consists of checking the output variables of the voltage generated, the stroke, and the output power. If these do not comply with the input values, a new process is started by calculating a new stator, actuator, and coil dimensions until satisfying the values required by the input. When this is met, it is validated by means of electromagnetic simulation with the finite element method (FEM). A prototype with a small power of 100 W, 50V single-phase was developed, which allowed us to validate the design and expand the knowledge for the possible manufacture of a prototype with greater power. The geometric model of the LEG is shown in Figure 2, which shows: the elements it contains; the stator, formed by sweet iron discs with a relative permeability, μr, of approximately 4 000; the windings, manufactured with copper conductors. For the actuator, the same stator material was used (black iron), and the mounted magnets were neodymium.

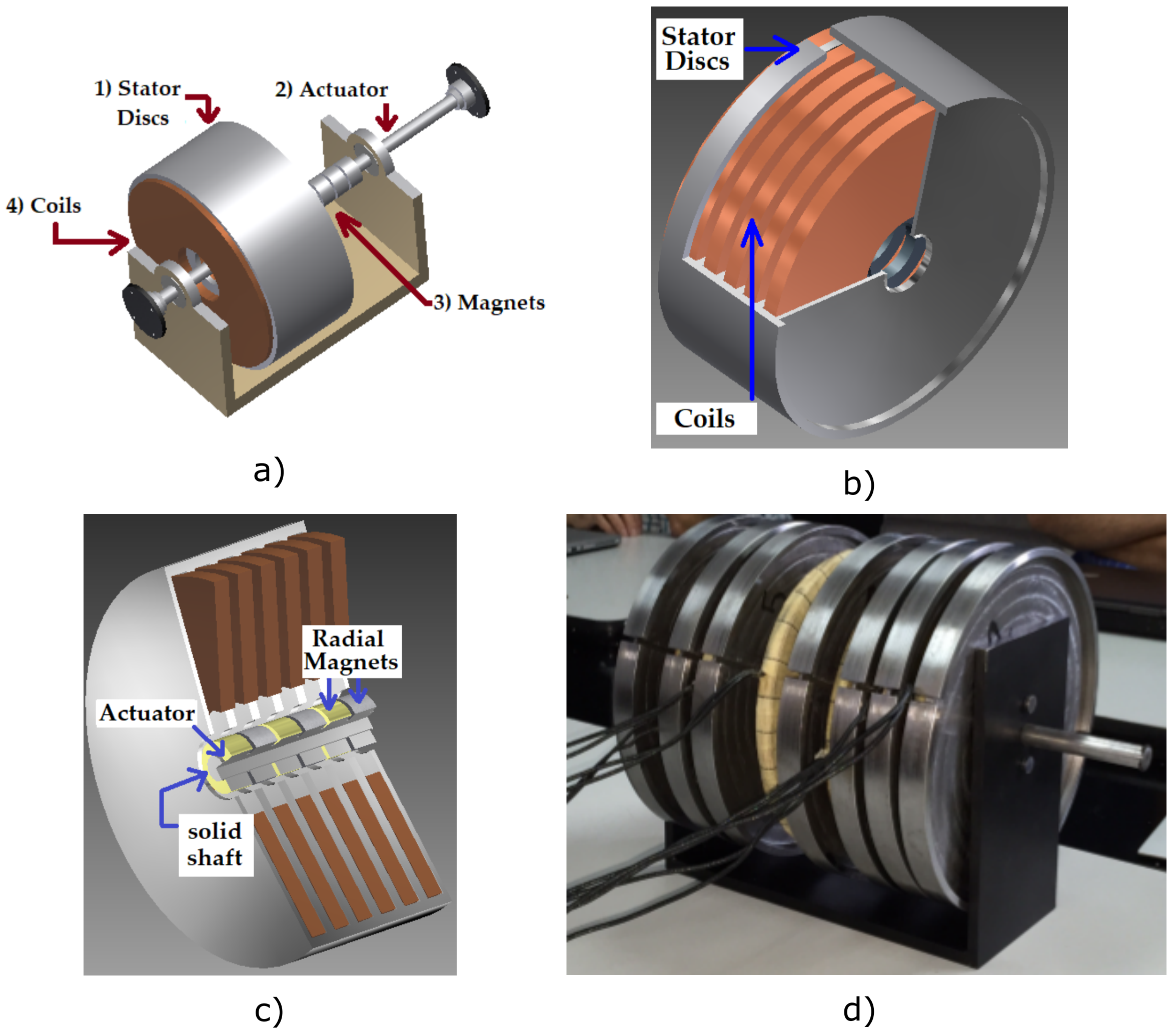


Figure 2. Diagram of the analyzed and simulated LEG: a) main components; b) interior of the stator; c) interior of the actuator; d) actual assembly of a 100W LEG prototype for experimentation.

Dynamics of the movement of the ocean waves used for generation

Ocean wave energy is a very attractive alternative energy for distributed generation in Mexican coasts. According to the preliminary work, the use of LEG seems to be the most convenient way to use this source of energy. The general scheme for wavelength micro-generation is shown in Figure 3, where it is possible to note two components: 1) the WEC unit, which contains a buoy element that is the translator of the wave energy and is coupled to the axis of the LEG; and 2) the power stability and control unit, which is used to store and attenuate power fluctuations at the LEG output. This unit contains the electronic power and control components needed to obtain stable power transmission to the network or local load. In the WEC system, the upward and downward movement of the wave is absorbed by the buoy, creating mechanical energy that will be converted into electricity by the LEG. Thus, the characteristic of the wave greatly influences the design of the LEG. In this work, the characteristic of the wave was obtained from the data provided by the preliminary work (González, Hernández, & Barrios, 2017).

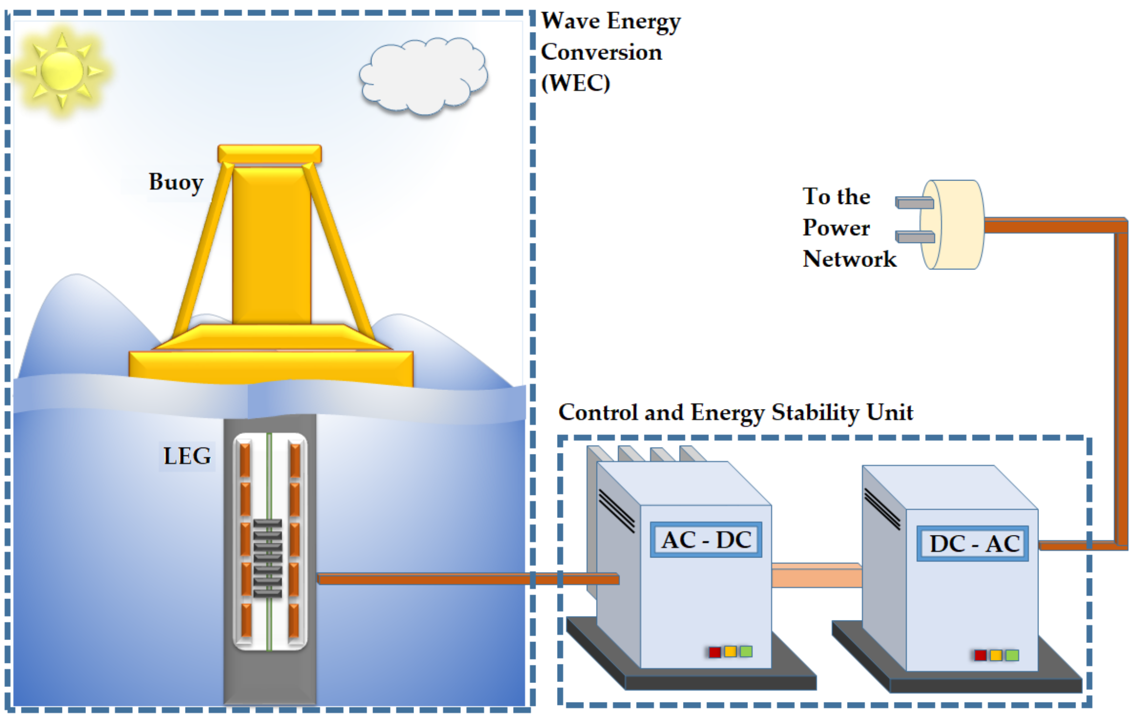


Figure 3. General scheme of the distributed generation system for the use of wave energy using a LEG.

A floating asymmetric body, such as a buoy, can have different movements, or degrees of freedom (see Figure 4). There are six, and are described as follows (González *et al*., 2017): 1) translation on the *x*-axis (surge), which indicates the positive forward advance of the body; 2) translation on the *y*-axis (sway), which indicates lateral displacement, which is considered positive and to the left; 3) translation on the *z*-axis (heave), which indicates body height (positive upwards); 4) rotation on the *x*-axis (roll), indicating lateral body swing, positive is to sink the right side of the body; 5) rotation on the *y*-axis (pitch), indicating vertical pitch, positive is to sink the front part of the body; rotation on the *z*-axis (yaw), indicating the horizontal pitch of the body, positive is to turn left.

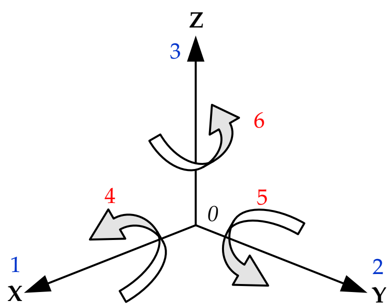


Figure 4. Six degrees of freedom of a floating body (González *et al.*, 2017).

The dynamics of the movement of the movable part of the LEG can be determined by the equation that governs the movement of the WEC. For simplicity, a single degree of freedom in the buoy was considered. This means only vertical movement $y(t)$ and ascending and descending. Therefore, by applying Newton's second law in this direction, the equation that governs the movement can be written as:

$$m\ddot{y}(t) = f_h(t) + f_m(t) \tag{6}$$

where f_h represents the hydrostatic forces of the wave and f_m represents all the mechanical forces of the system present in WEC, considering all the components of forces present in the system:

$$f_h(t) = f_e(t) - \left(A\ddot{y}(t) + B\dot{y}(t)\right) - \rho g S y(t) \tag{7a}$$

$$f_m(t) = -Ky(t) - C\dot{y}(t) \tag{7b}$$

it is possible to summarize (6) as:

$$(m + A)\ddot{y} + (B + C)\dot{y} + (\rho g S + K)y = f_e(t) \tag{8}$$

The equation of motion in the Laplace domain is:

$$X(s) = \frac{F_e(s)}{(m + A)s^2 + (B + C)s + (\rho g S + K)} \quad (9)$$

where f_e is the force of excitation of the wave (the profile of a regular wave is a simple sinusoidal function for regular waves); m is the mass of the buoy plus the mass of the actuator, A, of the LEG; B is the damping coefficient, which depends on the buoy's body and the wave frequency (a regular Mexican wave in coastal areas has typical periods of 3 to 10 s) since the design of the LEG involves considering movements of the actuator with low frequencies (less than 0.3 Hz); C is known as the load coefficient and is the energy conversion capacity; K represents the spring constant; $\rho g S$ is the hydrostatic force of the buoy, which depends on the density of the water, ρ, acceleration due to gravity, g, and the cross-section of the buoy, S. It is recommended to (Shi, Cao, Liu, & Qu, 2016; Ekstrom, Ekergard, & Leijon, 2015) for more details on obtaining and solving the buoy's movement and the LEG's piston.

The wave dynamics, $f_e(t)$, are considered for the simulation with a sinusoidal wave profile for a regular wave. In the case of an irregular wave, it is based on distortion models obtained from the spectrum proposed by Pierson and Moskowitz (Pierson & Moskowitz, 1964). In order to have a more realistic simulation with the data obtained for the significant height and periodicity of the wave in the different points of the Mexican coast, a distortion model was obtained that enables emulating the wave dynamics. This model is composed of the sum of Fourier terms:

$$\begin{aligned} x(t) = Hs[A_0 + A_1\cos(w\cdot t) + B_1\sin(w\cdot t) + \cdots \\ A_2\cos(2\cdot w\cdot t) + B_2\sin(2\cdot w\cdot t) + A_3\cos(3\cdot w\cdot t) + B_3\sin(3\cdot w\cdot t) + \cdots \\ A_4\cos(4\cdot w\cdot t) + B_4\sin(4\cdot w\cdot t) + A_5\cos(5\cdot w\cdot t) + B_5\sin(5\cdot w\cdot t)] \end{aligned} \quad (10)$$

where the values of A_0 to A_5 and B_1 to B_5 denote the amplitude of the function. This means that the effective value of the function will be at the desired significant height, Hs. Table 1 summarizes the values used for these constants (10). It also contains the parameter, w, that denotes the average frequency of the wave, which is a function of the periodicity, T_z, and can be calculated by:

$$w = \frac{2\pi}{5T_z} \quad (11)$$

Table 1. Values for the simulation of the displacement of the designed LEG.

Constants		
	Ai	*Bi*
i = 0	0.0049	------
i = 1	- 0.0161	- 0.0156
i = 2	- 0.0206	- 0.0400
i = 3	0.0237	- 0.1679
i = 4	- 0.0705	- 0.0552
i = 5	0.7530	0.5812

Most of the points analyzed in the coast of Mexico have a single model, given by (10), which characterizes them, since each point has its own waves and periodicity characteristics (see Table 2). In this work, (10) represents a model of the average displacement of the LEG's actuator during a full day. Simulating a full day (86 400 s) in FEM is inconvenient due to the expense and computational time, and because model (10) is a continuous and repetitive series, with a random amplitude, so that the simulation of 10 min (600 s) could be considered as representative. For the simulation study developed in this work, the electromagnetic design of the LEG considered the node that resulted in the highest prediction of energy potential, which was the Guerrero node, Llano Real (Latitude 17 ° N, Longitude 110 ° 30 ' W).The node with the lowest potential value, corresponded to the Champoton node, Campeche (Latitude 19 ° 30 ' N, Longitude 91 ° 30 ' W). For each of the nodes analyzed, it was necessary to customize the design. So in this preliminary estimation and simulation stage, it would be inconvenient to design each of the generators. For this reason, only the node with the highest estimated power and the lowest node were considered. Table 3 presents the summary, with the values of

Hs and *Tz* for these nodes. The profile of the movement obtained for the simulation of the displacement of the piston in the WEC system in these two nodes is shown in Figure 5. As can be seen, there are more waves in Champoton than in the Real Llano node, but with a lower significant height, which has an exceptional effect on the movement of the piston with magnets inside the LEG, affecting the extraction of power.

Table 2. Values obtained for significant height, Hs, and periodicity, T_Z.

Geographic information			***Hs* (m) Annual average**	**T_Z (s) Annual average**
#	**Zone**	**Nearest town**		
1	Nayarit	San Blas	0.532	10.139
2		San Francisco	0.724	10.281
3	Colima	Peña Blanca	1.119	10.282
4		San Juan de Alima	1.273	10.313
5	Guerrero	Barra de Potosí	1.238	10.272
6		Llano real	1.233	10.311
7		Copala	1.160	10.271
8	Oaxaca	Santa María Chicometepec	1.239	10.302
9		San Mateo del Mar	1.321	8.834
10		Aguachil	1.235	9.578
11	Chiapas	Tonalá	0.982	10.089
12		Pijijiapan	1.015	10.141
13		La Encrucijada	1.166	10.134
14		Tapachula	1.229	10.164
15	Campeche	Campeche	0.498	2.959
16		Champotón	0.598	3.225
17			0.419	2.741
18		Carmen	0.483	3.288
19			0.696	3.644
20			0.723	3.568
21	Veracruz	San Andrés Tuxtla	0.724	4.234
22		Lechuguillas	0.797	4.43
23		Papantla	0.803	4.464
24		Tuxpan	0.917	4.445

25		Ensenada de Mangles	0.905	4.501

Table 3. Values for significant wave height, periodicity, and estimated power for two nodes.

Llano Real, Guerrero													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual aver.**
Hs (m)	0.83	0.95	1.22	1.38	1.43	1.37	1.45	1.36	1.43	1.32	1.10	0.96	1.23
T_Z **(s)**	9.49	10.05	10.69	10.76	10.61	10.18	10.74	9.94	10.40	10.59	10.11	10.18	10.31
Pm (kW)	408	537	919	1151	1230	1163	1284	1137	1175	1093	722	547	947
Champotón													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual aver.**
Hs (m)	0.40	0.41	0.43	0.47	0.46	0.42	0.46	0.44	0.37	0.40	0.39	0.39	0.42
T_Z **(s)**	2.90	2.86	2.77	2.60	2.66	2.57	2.44	2.59	2.84	2.83	2.98	2.86	2.74
Pm (kW)	2	1	1	2	2	1	1	1	1	1	1	1	1.25

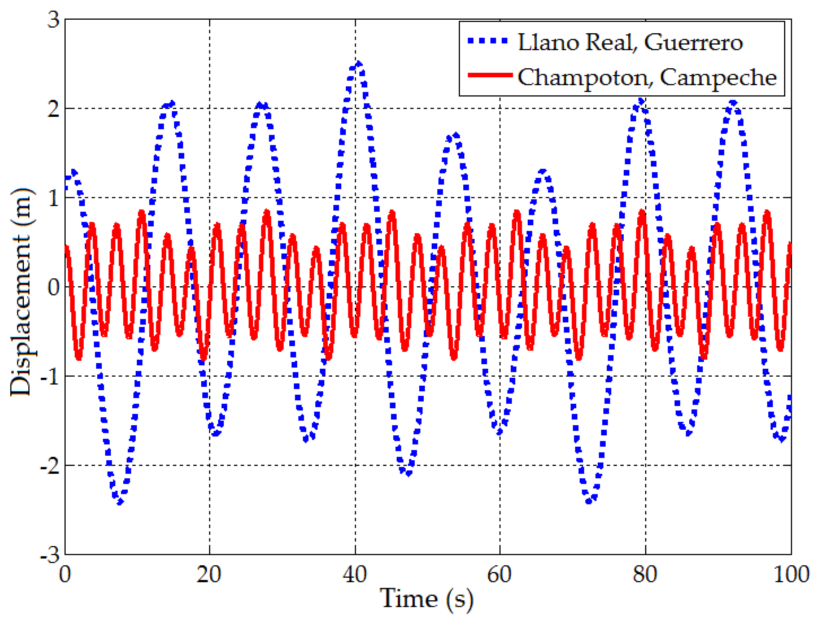


Figure 5. Spectra obtained for simulating the displacement in the WEC with expected waves at Champotón, Campeche, and Llano Real, Guerrero.

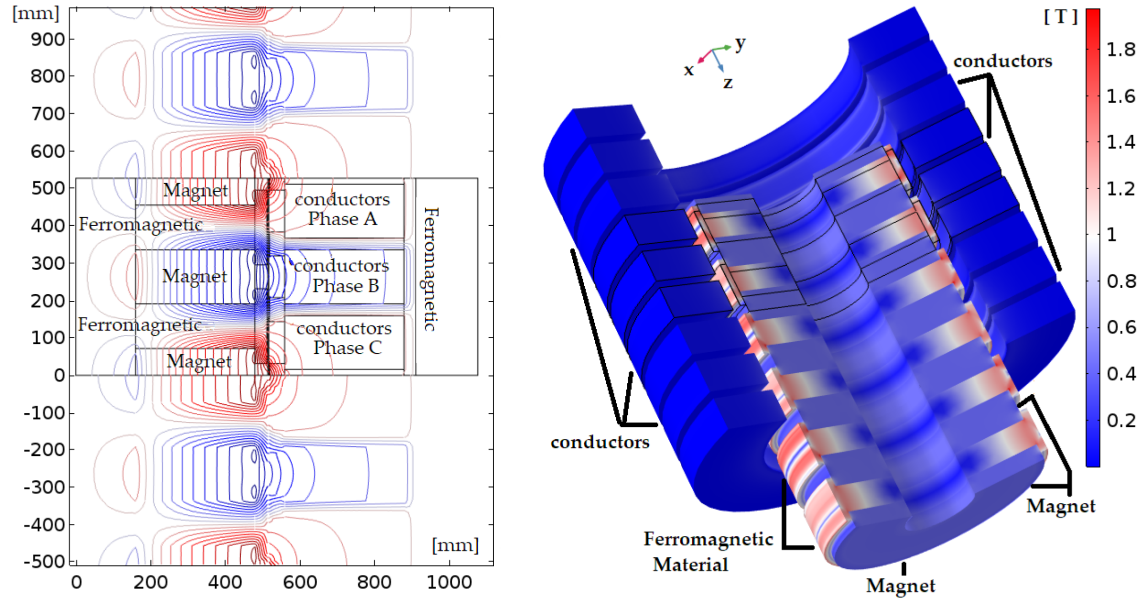
Simulations with FEM and evaluation of results

To extract the power from the LEG by means of electromagnetic simulation, LEG designs were developed to be used in the WEC system with two nodes on the Mexican coast. Table 3 contains the average *Hs* and T_Z values needed for the design of the LEG, at the two selected nodes. The Llano Real node has an estimated average power of 947 kW while the Champoton node is roughly 1.25 kW. There is a great power difference between both, since the Llano Real node has a depth of 295 m and Champoton is only 11 m deep, and the energy conversion capacity of the rigid body (buoy) depends on the depth (the greater the depth the greater the capacity to absorb the energy through the buoy).

A 5 kW LEG was designed for the Champoton node and a 100 kW for the Llano Real node, considering the possibility of having 10 units with the same capacity.

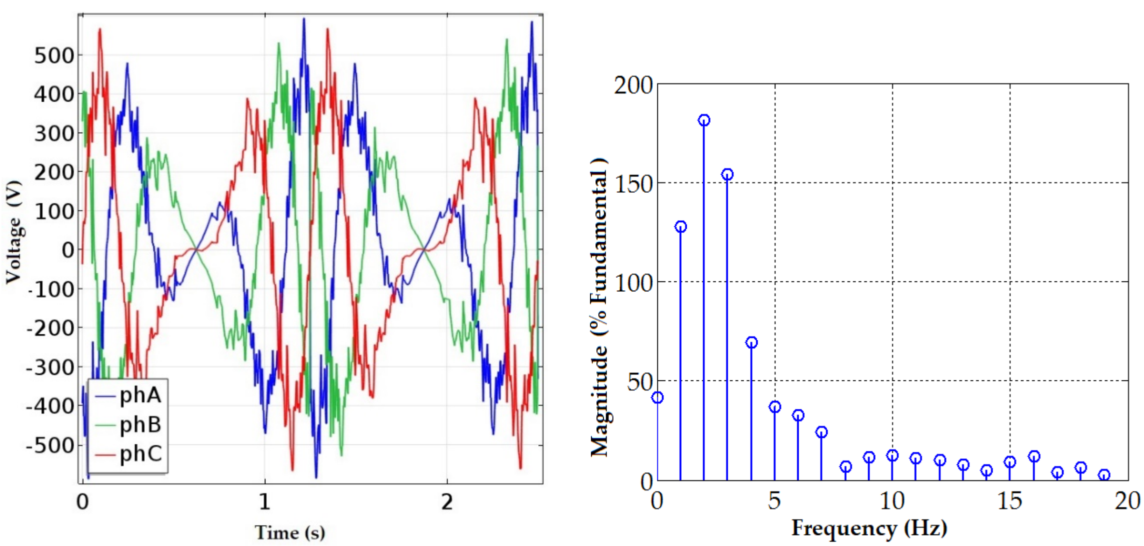
The simulation of the LEG with FEM was done in an asymmetric module because the device is tubular. Using this module saves time and computational memory. It also provides a 3D panorama of the magnetic flux density inside the device. The stroke or displacement of the piston with the magnets is a function of the significant height of the wave, and the time it takes the piston with magnets to travel a cycle is given by the periodicity of the wave.

Figure 6a shows the magnetic flux lines in a cross-section of the device. Figure 6b presents the 3D magnetic flux density inside the device. The voltage generation that is sought with this design is 240 V rms (or effective value). If the waves were regular, a sinusoidal voltage would be expected, but because the waves are irregular and are given by the proposed displacement spectrum (10), a distorted voltage (harmonics) is obtained (see Figure 7a).



a) b)

Figure 6. The electromagnetic simulation of the LEG: a) magnetic flux lines and b) magnetic flow density inside the LEG.



a) b)

Figure 7. a) Voltage of 240 Vrms generated in the simulated LEG for the Champoton node; b) frequency spectrum generated to obtain the *THD* of the voltage signal.

Results of the energy quality delivered by the LEG

To analyze and evaluate the quality of energy supplied by the LEG, the voltage signal generated is used, with which the total harmonic distortion, *THD*, is calculated. This parameter measures the number of harmonics of the output signal, and is given by:

$$THD = \frac{\sum Potencias\ de\ los\ armónicos}{Potencia\ Fundamental} \qquad (12)$$

The THD was calculated using the Fast Fourier Transform (FFT) method, which determines the frequency spectrum of the harmonics of the signal analyzed (Figure 7b).

The *THD* of the voltage obtained for the Champoton node was 47.96%. This means that almost 48% of the estimated output power of the LEG will be wasted by unwanted frequencies (distortion), partly caused by the irregularity of the wave movement, and possibly because of the LEG design itself.

For the Real Flat node, the *THD* of the obtained voltage corresponded to 55.39%, which means an output power of only 44.61% of the expected power. This may imply that at lower frequencies or higher periodicities (f = $1/T_Z$), the expected energy output signal will present more distortion.

Conclusions

With the future goal of developing a micro-generation system (distributed generation) that uses alternative sources of energy, a small-scale prototype was studied and simulated to identify the energy performance and quality provided by a wave energy conversion system (WEC). In González *et al.* (2017), the nodes or locations of buoys with oceanographic data were established, and with those, the average energy potential was determined, as well as two important parameters (*Hs* and T_Z) in order to develop the electromagnetic simulation of the converter unit (linear electric generator, LEG) with waves having a single degree of freedom. This simulation required a model of the irregular wave spectrum, in order to complete the electromagnetic simulation and thereby obtain results related to the energy efficiency of the WEC system. The findings of the electromagnetic simulation identified that, due to the irregularity of the wave, the useful power was close to 50% of the desired power. This means that the LEG must be resized to obtain the estimated energy power, based on methods where the periodicity and height of the wave are considered constant during a whole month or year. The proposed irregular wave model must be improved in order to obtain evaluations that are as close as possible to reality. Furthermore, this work contributes to knowledge about the design and development of devices used for micro-generation with ocean wave energy. It also presents an overview of the energy potential, in order to provide continuity in this research and have new energy alternatives for the country.

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