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Numerical Simulation Of An Electrical Generator For Sea Wave Energy

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***Abstract*—This paper presents some results of research and experiment of an electrical generator device for sea wave energy. The device is fabricated on the basis of the results of analysis, and numerical simulation of the operation of device. The device works in the vertical direction of sea waves and is fixed on the sea floor. The buoy of device floats on the sea surface and transfers the energy of sea waves to the electrical generator. The operating output power of the device is stable at 200 W during experiment. The output voltage of device is 220 VAC with frequency 50 Hz and is a pure sine wave. These results show that our device is reasonable for harvesting energy in Vietnam's sea condition.**

Keywords— Renewable energy, wave energy, electrical generator, power conversion.

I. INTRODUCTION

World energy consumption has been increased dramatically since 1950, the received energy from fossil fuels will become gradually exhausted and so alternative, renewable, and clean energy sources need to be explored to enable a diverse energy resource plan. It is interesting that oceans cover more than 2/3 on the entire of the Earth's surface. The large resources found in the oceans can be regenerated and used without environmental pollution. The resources of ocean include wave energy, current energy, tide energy, thermal energy, and so on. In over the world, especially in modern industrial countries, the research and fabrication of the electrical generators for sea wave energy source have been carried out for decades. The received electrical energy source from wave energy conversion has met some demands of society. Up to now, the electrical generators for sea wave energy have been investigated and fabricated in many countries, for example, Australia, Britain, China, Denmark, Ireland, Italy, Japan, Portugal, Spain, Sweden, South Korea, the United States [1]. The device models are categorized into two major types, the device fixed on the bottom of the sea (seabed) and the floating device on the sea [1-14]. The detailed researches of each type will be analyzed as below.

The electrical generator devices fixed on the bottom of the sea usually use the linear generators. For this type of device, the buoy of device floats on the sea surface to receive the energy from sea waves, it is directly connected via a rope to a permanent magnet linear generator placed on the seabed where it is less exposed to storms. To get the energy conversion, springs are attached between the alternator and the device foundation to pull the alternator downwards in wave troughs. When the buoy is reciprocated, a permanent magnetized translator gets vertical direction motion in the generator and the voltage is induced in the stator winding. Because the reciprocating motion is correlated with the sea wave motion, the voltage produced by the converter possesses irregular amplitude and frequency properties. The output voltage must be stabilized before connecting to the external loads or the power grid systems. The power of several devices is about 10 kW [1-9]. In a detailed review paper on the linear generator and related modern devices [10], Ekstrom et al. have categorized, described and compared different generators for wave energy converters based on technologies of electrical damping circuits and techniques of power output optimization.

The electrical generator devices floating on the sea surface consist of the two main types, a horizontal-floating type and a vertical-floating type. The horizontal-floating device can be mentioned here, such as a pelamis device that it looks like a snack. The structure of pelamis composes of four cylindrical sections linked by hinged joints, and aligned with the wave direction. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three industrial electrical generators. The power of this device is about 750 kW [1,4,14]. The vertical-floating electrical generator device consists of an oscillating upper part (the floater) and a bottom-fixed lower part (the basement) with the fixed installed linear generator. The floater is pushed down under a wave crest and moves up under a wave trough. This motion makes the generator work to generate the electric power about 10÷80 kW [1,4,11-14].

In Vietnam, several research institutions have fabricated electrical generators for sea wave energy. In Ref. [15], the researchers have calculated device models with industrial generating motors installed on fixed frame structures, and the buoy of device floating on the sea surface. The hydraulic driver system will transmit the obtained sea wave energy from the buoy to the generating motor. In Ref. [16,17], Ba, Anh and Ngoc have fabricated linear electrical generators that operate and float on the sea surface in vertical direction. The incipient experimental output voltage on load is received about 1 V. Another detailed research on the fabrication of the electrical generator from sea wave energy is done by Anh and Hai [18]. The authors have calculated a linear model of buoy motion to determine device's power, and measured the operating test of device during experiment at sea.

To reduce the influence of sea storms on the device operating at sea, we have build an electrical generator model with a generator part fixed on the bottom of sea with small and medium power (Fig. 1). The device works in the vertical direction, and the buoy of device floats on sea's surface. When sea waves act on the buoy, it will transmit sea wave energy to a generating motor through a rope in the vertical direction and a rotational mechanical structure system [18]. In this paper, we calculate the motion of buoy associated with piston-rack using a nonlinear model for a spring force component that links a piston-rack to the foundation of device [see Eq. (1)]. The fabricated device uses a type of industrial three-phase generating motor and a high performance 12 VDC voltage stabilizer with the input voltage received from the three-phase generating motor [19], and fabricate a block DC-AC inverter to generate the output voltage at 220 VAC frequency 50 Hz and pure sine wave [20, 21]. The electrical generator model has an advantage that it may be not much affected by sea storms impacts because the generator part is fixed on the seabed. Moreover, the device can be used for signal buoys of seaway and can supply the electrical power for use at island sea regions.

II. MODELLING OF THE ELECTRICAL GENERATOR

The electrical generator device is fabricated for converting sea wave energy to electrical energy. This requires a system that can convert the vertical slow motion of buoy to a high speed rotating motion at the input of generating motor. The main structures of device include a circular cylinder-shaped buoy, a rope, a piston-rack, a gearbox, a generating motor, a block of 12 VDC voltage stabilizer, a DC-AC inverter and a protection system with the generating voltage being 220 VAC frequency 50 Hz and pure sine wave, as shown in Fig. 1. The governing equation of buoy associated with piston-rack, as shown in Fig. 1, can be written as follows:

$$m\frac{d^2z}{dt^2}=\rho g S_b(z_s-z)-mg-\gamma\frac{dz}{dt}-k_L(z-z_0)-k_N(z-z_0)^3, \quad (1)$$

where m is total mass of the buoy and the piston-rack, $z= z(t)$ is the vertical coordinate describing the position of the buoy at time t; ρ is the water density, g is the acceleration of gravity, S_b is the bottom area of the buoy, z_s is the vertical coordinate describing the height of sea wave from the seabed; the damping constant γ is the sum of the fluid damping, γ_f, and the electrical generator damping, γ_{eg}, i.e. $\gamma=\gamma_f+\gamma_{eg}$; k_L is the linear spring coefficient, k_N is the nonlinear spring coefficient, z_0 is the rest position.

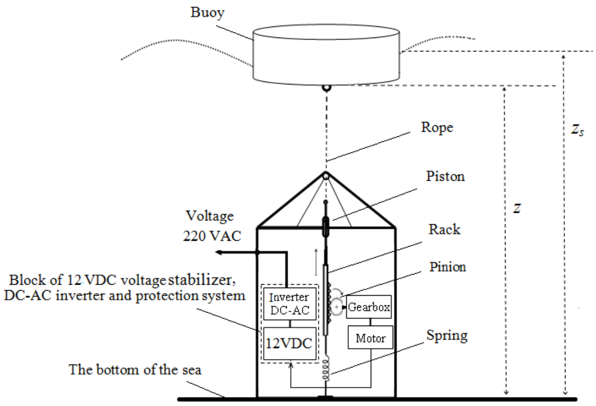


Figure 1. The schematic illustration of an electrical generator for sea wave energy

The average of the power P_{gm} extracted from the wave by the converter taken over the time interval [0,t] is given by [2],

$$P_{gm}=\frac{1}{t}\int_0^t \gamma\,\dot{z}^2 dt. \quad (2)$$

Eq. (1) will be solved to find optimal parameters for the purpose of designing and fabrication of the electrical generator. The numerical simulation calculations for the present device are carried out with parameters ρ=1020 kg/m^3, g=9.81 m/s^2, m=27 kg, S_b=0.5024 m^2, k_L=2100 N/m, k_N=630 N/m^3, z_0=5.5 m, γ_{eg}=3400 Ns/m. The damping coefficient of fluid, γ_f, is assumed to be very small in comparison with the electrical generator damping γ_{eg} [22], and can be neglected. In this study, the sea waves can be modeled as a harmonic fluctuation in both of the first- and second-order waves about the rest position z_0. The main parameters of sea wave are used for calculation with the wave amplitude being 0.5 m and the primary angular frequency being 1.472 rad/s (i.e. the real sea wave angular frequency arises primarily in the experiment of device at the sea site).

A. *Case of the first-order wave*

In practice, sea waves are complicated and have random nature in which they can be considered as a combination of an infinite number of waves with different frequencies and amplitudes. The change of sea waves in both frequency and amplitude will affect to the operation of device system when the device is placed at sea. In this subsection, for simplicity, the sea wave can be modeled as a harmonic fluctuation of the first-order wave about the rest position z_0

$$z_s = A\sin(\omega t)+z_0, \quad (3)$$

where A and ω are the wave amplitude (distance between crest and the mean sea level) and wave angular frequency, respectively.

Substituting Eq. (3) into Eqs. (1), (2) and then solving for z in numerical simulation, we obtain results of the buoy oscillation in time, oscillation amplitude of buoy, phase orbit of buoy motion, and power P_{gm} of device from sea wave energy. Fig. (2) illustrates the displacement of buoy and the sea wave elevation in time.

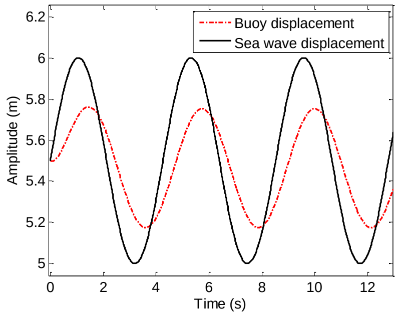


Figure 2. The displacement of buoy and the sea wave elevation level versus time

In Fig. 2, it is observed that the oscillating buoy is delayed in phase compared with the sea wave about 33.6^0. The sea wave amplitude is 0.5 m, and the received buoy oscillation amplitude is 0.261 m. The Fig. 3 shows the power curve P_{gm} [see Eq. (2)] depending on the angular frequency of sea wave. The received power of device increases in the angular frequency range from 0 to 16.17 rad/s, and reduces in the angular frequency range greater than 16.17 rad/s. The maximum power of device is 929.99 W at the angular frequency 16.17 rad/s.

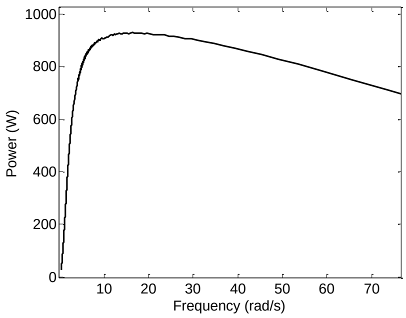


Figure 3. The power of the electrical generator versus frequency

The Fig. 4 illustrates the relationship between velocity and displacement. It is showed that the phase orbit of buoy motion is stable and approaches to a limit cycle around the 5.5 m rest position.

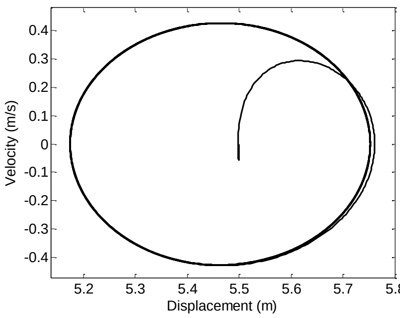


Figure 4. The phase orbit of buoy motion

B. Case of the second-order wave

In the present case, we consider the motion of the sea wave using Stokes's second-order theory in which the sea elevation level is given by [23]:

$$z_S = A\sin(\omega t) + \frac{A^2 k\cosh(kz_0)}{4\sinh^3(kz_0)}[2+\cosh(2kz_0)]\sin(2\omega t) + z_0, \qquad (4)$$

where A *is* the first-order wave amplitude, ω *is* the wave angular frequency, and k is a wave number that is given by the following formula [23,24]:

$$k = \frac{2\pi}{L}, \qquad (5)$$

where the wavelength L is determined by the following characteristic equation [24]

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi z_0}{L}\right), \qquad (6)$$

where T is the sea wave period.

The substitution of Eq. (4) into Eq. (1) leads to a nonlinear differential equation with the external second-order harmonic wave loading as follows

$$m\frac{d^2z}{dt^2} + \gamma\frac{dz}{dt} + \rho g S_b(z-z_0) + k_L(z-z_0) + k_N(z-z_0)^3 = -mg + \rho g S_b\left\{A\sin(\omega t) + \frac{A^2 k\cosh(kz_0)}{4\sinh^3(kz_0)}[2+\cosh(2kz_0)]\sin(2\omega t)\right\} \qquad (7)$$

Eq. (7) can be solved numerically to obtain the response $z = z(t)$. Using Runge-Kuttta algorithm, we get the evolution of response in time as presented in Fig. 5. The obtained calculation data of $z(t)$ are employed for computing the power P_{gm} in Eq. (2). The Fig. 5 illustrates the displacement of buoy and the sea wave elevation level in time.

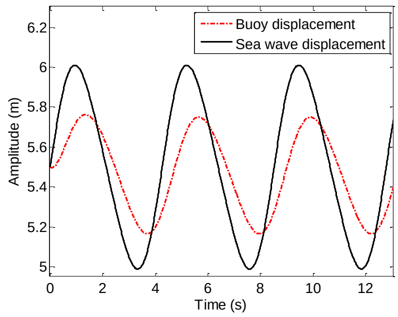


Figure 5. The displacement of buoy and the sea wave elevation level versus time

In Fig. 5, the influence of the second-order frequency component on system is evident. In this case the maximum of total sea wave amplitude is 0.51 m, and the received maximum oscillation amplitude of buoy is 0.262 m. Fig. 6 shows the numerical simulation result of power P_{gm} in angular frequency ω. The received power value of device increases in the angular frequency range from 0 to 16.71 rad/s, and reduces with frequency greater than 16.71 rad/s. The maximum power of device is 939.58 W at the angular frequency 16.71 rad/s. On the other hand, with the sea wave frequency range received from the sea survey data in the place of installation of the operating device, and the received numerical simulation power graph in Fig. 6, we can predict the output electric power of the electrical generator when it operates at the sea.

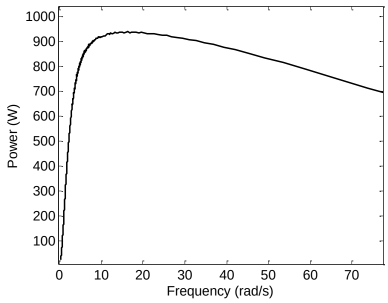


Figure 6. The power of the electrical generator versus frequency

The Fig. 7 illustrates the relationship between velocity and displacement of the buoy motion in the case of the second-order wave. It shows that the phase orbit of buoy motion is stable and varies in the frequency components of the second-order sea wave.

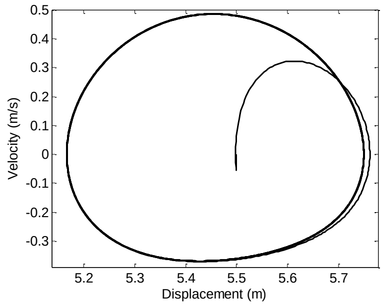


Figure 7. The phase orbit of buoy motion

C. Model evaluation

From the received results in the first- and second-order wave cases, we found that the operation of the electrical generator is affected considerably by the amplitude and frequency of the sea waves. Fig. 8 shows the motions of sea wave elevation depending on the first- and second-order wave input functions.

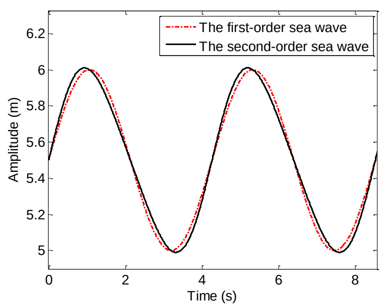


Figure 8. The sea wave elevation level in the first- and second-order wave functions versus time

Here, the received power value of device from the second- is greater from the first-order wave energy. The behavior of power characteristic curves of device in frequency is similar (see Figs. 3 and 6). In the case of the second-order wave function, we found that the phase orbit of buoy motion is stable and close to the real motion of buoy. Fig. 9 shows the power characteristic curves of device depending on the amplitude of the first- and second-order sea wave input functions.

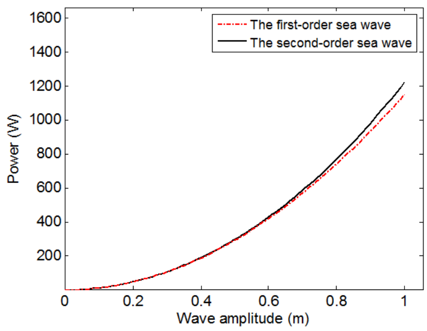


Figure 9. The power characteristic curves versus sea wave amplitude

In Fig. 9, at small sea wave amplitude values, for example amplitude $A \le 0.3m$, the difference between received power values of device in two cases is very small. For sea waves having large amplitude, the received power values in two cases are quite different. For the second-order sea wave with the high wave amplitude, the power of device is quite large. At the sea wave angular frequency 1.472 rad/s and amplitude 0.5 m, the received power P_{gm} values of device from the first- and second-order sea wave functions are 292.7 W, and 295.8 W, respectively. In case of 1 m sea wave amplitude, the power value corresponding to the second-order wave is about 6.36% larger than that of the first-order wave. These power values will be compared with the received experiment results at the sea in the next section. Our present calculation exhibits that, in the case of the second-order wave function, the received power value is consistent with the practical operation of device.

III. EXPERIMENT RESULTS

The electrical generator device for sea wave energy has operated for a long time in the Hon Dau sea, Haiphong province, Vietnam. At the experiment site, the sea wave amplitude is about 0.4÷0.5 m, and the sea wave angular frequency arises primarily about 1.472 rad/s. The measurement results received from the electrical generator during experiment are shown in Table I. The equipments are used to measure and analyze voltage and current as Picoscope USB oscilloscope 2204A of England, Gwinstek digital clamp meter of Taiwan, Kyoritsu digital clamp meter of Japan, voltage meter Sanwa CD800a of Japan, and voltage meter Klein tools MM2000 of America.

In Table I, we use normal loads with a 40 W incandescent lamp and two 100 W incandescent lamps. The quantities U_{DC} and I_{DC} are voltage and current received at the output of the 12 VDC voltage stabilizer, and are also input data of the DC-AC inverter. U_{AC} and I_{AC} are voltage, current received at the output of the DC-AC inverter and protection system. The performance of the DC-AC inverter is 84.30%, and determined from the voltage and current at the input and output through the experimental measurement data in Table I.

TABLE I. MEASUREMANT RESULTS RECEIVED FROM INPUT AND OUTPUT OF DC-AC INVERTER OF DEVICE

Load power *P (W)*	Voltage U_{DC} *(VDC)*	Current I_{DC} *(A)*	Voltage U_{AC} *(VAC)*	Current I_{AC} *(A)*
100	12	9.92	224	0.45
140	12	13.47	223	0.61
200	12	20.33	223	0.92

The measured values in Table I show that the output power of the electrical generator is operated stably at 200 W load during the experiment. Fig. 10 shows the voltage and current characteristic curves versus output loads at the experiment site.

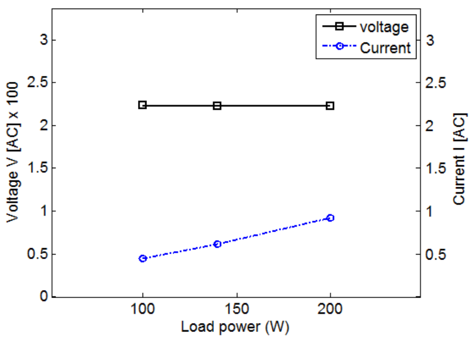
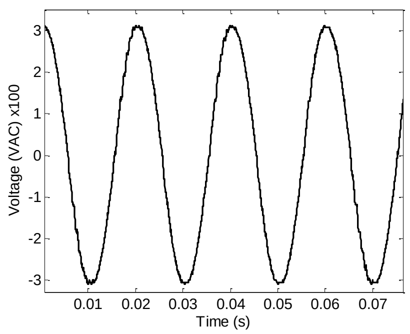
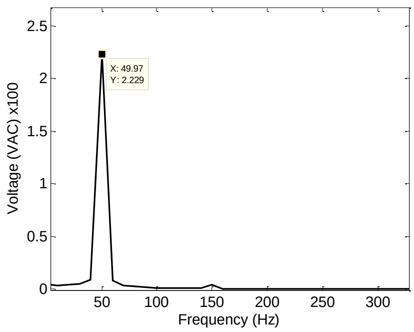


Figure 10. The voltage and current characteristic curves versus output loads

In our experiment, we use the Picoscope USB oscilloscope 2204A and the software of signal processing to analyze the output voltage obtained from the electrical generator. In Fig. 11, it is observed that the output voltage wave on the 200 W load in time and in frequency is received at 220 VAC ± 1.515% frequency 50 Hz ± 0.06% and is a pure sine wave.



a. Output load voltage versus time



b. Spectrum of output load voltage

Figure 11. The output voltage wave on the 200 W load of the electrical generator for sea wave energy

From the results of the numerical simulation of power and the received experimental test data at the sea site, if the sea wave is determined as the second-order wave function with the amplitude is 0.5 m and the primary angular frequency is 1,472 rad/s, the efficiency of the electrical generator is determined from the calculated power P_{gm} and the received experimental electric power P_{out} as follows

$$\eta = \frac{P_{out}}{P_{gm}} = \frac{200}{295.8} 100\% = 67.61\% \quad (8)$$

Fig. 12 demonstrates several pictures of experiment field of the electrical generator for sea wave energy in the Hon Dau sea, Haiphong province, Vietnam.

a. Uploading experiment device components onto the HQ1788 Ship

b. Experimental preparation

c. Buoy of device

d. *Testing power of device on loads*

e. Analysis of output voltage and power

Figure 12. The experiment process and data measurement of the electrical generator on the sea site

IV. CONCLUSIONS

Sea waves occur naturally, and are non-polluting source of power generation. The research and fabrication of a device for converting sea wave energy into electrical energy are needed. In this paper, we present some numerical simulation and experiment results of the operation of the electrical generator device with the first- and second-order sea wave input functions. Our fabricated device works in the vertical direction of sea wave. The generator part is fixed on the seabed where it is less exposed to storms as it operates at the sea. The output power of the electrical generator is operated stably at 200 W load during experiment at the Hon Dau sea, Haiphong province, Vietnam. In the framework of experimental study, the received average performance of the DC-AC inverter from 12 VDC voltage to 220 VAC voltage is about 84.30%. The output voltage of this device is received at 220 VAC frequency 50 Hz and is a pure sine wave. The operating efficiency of the electrical generator reaches about 67.61%. We realize that the study and fabrication model is reasonable and efficient.

For the obtained output electric power of the electrical generator, the device can be used for the signal buoy of the seaway. Moreover, at the top of buoy of device has a signal lamp and a 30 W solar panel. The solar panel is also extra energy source to assure that the signal lamp always operates for the time at which the sea is calm. The received experiment results have also been used for analyzing the system model in order to improve the device, for enhancing power and efficiency of the electrical generator to meet the needs of the electrical energy at island sea regions.

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