Integrated Dynamic Modeling of a Point Absorber Wave Energy Converter in Regular and Irregular Waves

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***Abstract*—Wave energy offers the highest energy density when compared to other renewable energy resources, and its energy potentials are huge. Different technologies such as point absorbers are been developed to capture the wave power. Vigorous testing, evaluation procedures, and assessments of the device performances under different wave conditions are critically important. In this paper, an integrated dynamic model of a point absorber wave energy converter is developed to evaluate its dynamic behavior. The hydrodynamic and hydrostatic parameters of the system are discussed. A direct drive linear generator power take-off is considered. A phase control strategy is used to maximize the power extracted by the generator and stored in a battery. The simulation results under regular and irregular waves are presented to illustrate the overall performances of the system.**

I. Introduction

Ocean covers about three quarters of the world, and one tenth percent of energy that can be harnessed from the it is equivalent to five times word energy demand. Also, fifty percent of the world's electricity consumption can be covered by wave energy alone [1]. Currently, seldom exploited energy source is ocean waves. Varieties of wave energy devices that are able to transform the motion of the waves into electricity have been developed [2], [3]. The ocean provides an untapped energy resources with high power density which is also predictable, environmentally friendly, and widely available source of renewable energy [4]. Wave energy conversion is being investigated in part of of the world, particularly in the member States of the European Union, Canada, China, and USA [5]. In spite of the fact that the first patent certificate on wave energy conversion was issued in the 17th century, intensive research and development study of wave energy conversion began after the dramatic increase in oil prices in 1970s [6]. In the past decade, there has been a resurgent interest in wave energy around the world. Energy companies have been highly involved in the development of new wave energy schemes such as the Pelamis, the Archimedes Wave Swing, and the Wave Dragon [7], [8], [9].

The technology that captures the energy within the waves and transforms it to electricity is called Wave Energy Converters (WEC). This transformation may have multiple energy conversion stages. Mainly, the initial conversion stage in most devices is the conversion into kinetic or potential energy. Subsequently, a power take-off (PTO) mechanism converts the kinetic or potential energy into electrical energy [10]. Power electronic converters can be used to rectify or invert the electrical energy [11]. Compare to wind turbine technology, there are multifarious categories of wave energy technologies used to harvest energy from the ocean waves. Such as, Oscillating water columns, point absorbers, attenuators, and over-toppings. Over the last two decades extensive research has been done in developing WECs by research institutes and government - sponsored programs [12], [13], [14].

To develop a WEC system that can withstand the harsh environment of the ocean, hydrodynamic assessments of the device performance are critically important. The performance and evaluation of the systems are often based on the sinusoidal assumption of the incident waves [15]. However, this method may not be used to verify the performance of an actual system, since in reality ocean waves are irregular. Moreover, the feasibility of control strategies implemented under such system becomes unreliable. Hence, It is necessary to develop a detailed model that considers the hydrodynamic and hydrostatic parameters of the WEC system.

This paper presents a detailed dynamic modeling of a point absorber wave energy converter, with a direct drive linear generator Power-take-Off (PTO) using regular and irregular wave input. Section II and section III describes the hydrodynamic model and the electrical model of the WEC system, respectively. The simulation results are illustrated in section IV, with conclusion being drawn in section V.

II. Hydrodynamic system model

A single body point absorber wave energy converter oscillating in heave motion, shown in Fig. 1. The system consist of a buoy, a cylindrical spar, and a PTO mechanism. Energy is extracted from the relative motion of the buoy, through the PTO mechanism, a direct drive permanent magnet linear generator (DDPMLG). The modeling and analysis of WEC is primarily calculating the solution for its dynamic equations

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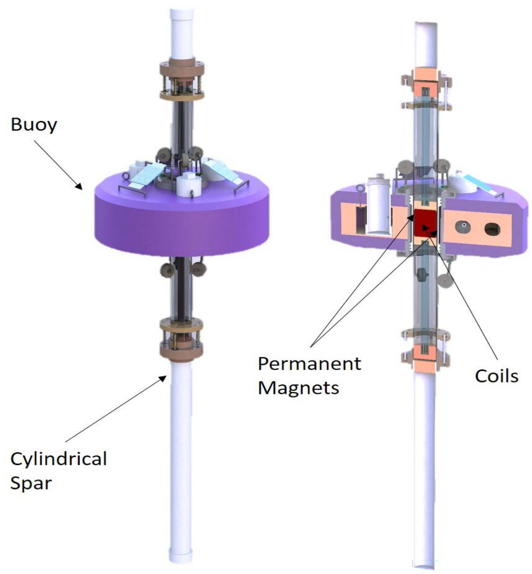

Fig. 1. Single Body Point Absorber WEC

which describes the body motion, following the Newton's second law with a single degree of freedom. The dynamic equation [16] is.

$$M\dot{v} = f_m(t) + f_r(t) + f_d(t) + f_b(t) + f_{gen}(t) + f_e(t) + f_v(t) \tag{1}$$

where M is the mass of the buoy and v is the heaving velocity. $f_e(t)$ is the excitation force which is the sum of pressure forces on the body surface due to incident and diffraction waves, and $f_gen(t)$ is the force produce by the PTO. Hydrostatic and hydrodynamic forces due to the motion of the WEC body in water includes diffraction force $f_d(t)$, wave radiation force $f_r(t)$, viscous force $f_v(t)$, and buoyancy force $f_b(t)$.

The wave radiation force $f_r(t)$, which occurs due to the radiated wave resulting from the WEC motion, can be express by the linear convolution of the radiation impulse response function $k(t)$ with the WEC's oscillation velocity $v(t)$, as shown in equation 2. The added mass A_∞ at infinite wave frequency represents the inertia of the surrounding fluid, which is added to the device thereby increasing its inertia.

$$f_r(t) = -\int_0^t h_r(\tau)v(t-\tau)d\tau - A_\infty \dot{v(t)} \tag{2}$$

$$f_b(t) = -\rho g S \int_0^t v(\tau)d\tau = -K_b x(t) \tag{3}$$

Equation 3 is the buoyancy force $f_b(t)$ that models the hydrostatic force, related to the WEC'S displacement through a hydrostatic stiffness constant K_b. The force $f_b(t)$ depends on the water density ρ, acceleration due to gravity g, and cross sectional surface area S of the device. Excluding the mooring and viscous forces, the above equations resulted in the commonly used Cummin's equation [17].

$$(M + A_\infty)\dot{v(t)} = -\int_0^t h_r(\tau)v(t-\tau)d\tau - K_b x(t) + f_{gen}(t) + f_e(t) + f_d(t) \tag{4}$$

III. Electrical system model

As shown in Fig. 2, the electrical system is formed by three main subsystems connected in cascade, which consists of the generator, the power electronic converters and the battery energy storage. The PTO mechanism is a DDPMLG, which is similar in principle to the direct drive in wind energy technology. Where the moving part of the generator is directly coupled to the energy absorbing part. The translator consists of a set of Neodymium-Iron-boron permanent magnets with alternating polarity, directly coupled to the heaving buoy, with the stator (spar) moored to the ocean bed. The DDPMLG is design to take advantage of the slow movement of the ocean waves that is transferred to it through the heaving buoy. It operates under variable speeds depending on the conditions of the sea waves. In a 3-phase permanent magnet linear generator the coils are displaced horizontally by a third of the magnetic wave length [18]. The 3-phase induced EMFs are given by

$$e_A = \hat{V}cos(\frac{2\pi}{\lambda}x)cos(\omega(t)) \tag{5}$$

$$e_B = \hat{V}cos(\frac{2\pi}{\lambda}x - \frac{2\pi}{3})cos(\omega(t)) \tag{6}$$

$$e_C = \hat{V}cos(\frac{2\pi}{\lambda}x + \frac{2\pi}{3})cos(\omega(t)) \tag{7}$$

The parameters used to model the linear generator can be found in [19]. Dq transformation is used to transform the EMF from abc coordinate into dq coordinate. The dq-model equations are expressed as follows

$$V_d = R_s i_d + \frac{d\lambda}{d(t)} - \omega_t \lambda_q \tag{8}$$

$$V_q = R_s i_q + \frac{d\lambda}{d(t)} - \omega_t \lambda_d \tag{9}$$

where

$$\lambda_d = L_s i_d + \lambda_{pm} \tag{10}$$

$$\lambda_q = L_s i_q \tag{11}$$

and

$$\omega_t = \frac{\pi v}{\tau} \tag{12}$$

where ω_t is the translator velocity in radian per second. V_d, V_q, i_d, i_q, λ_d, and λ_q are the terminal voltage induced, stator winding current, and flux linkage components in the dq reference frame. R_s and L_s are the stator resistance and inductance, and λ_{pm} is the flux linkage of the stator winding due to permanent magnet.

The reciprocating motion of the WEC causes the variable frequency and amplitude in the electrical output of the linear generator. Hence, a power conversion system is required. Fig.

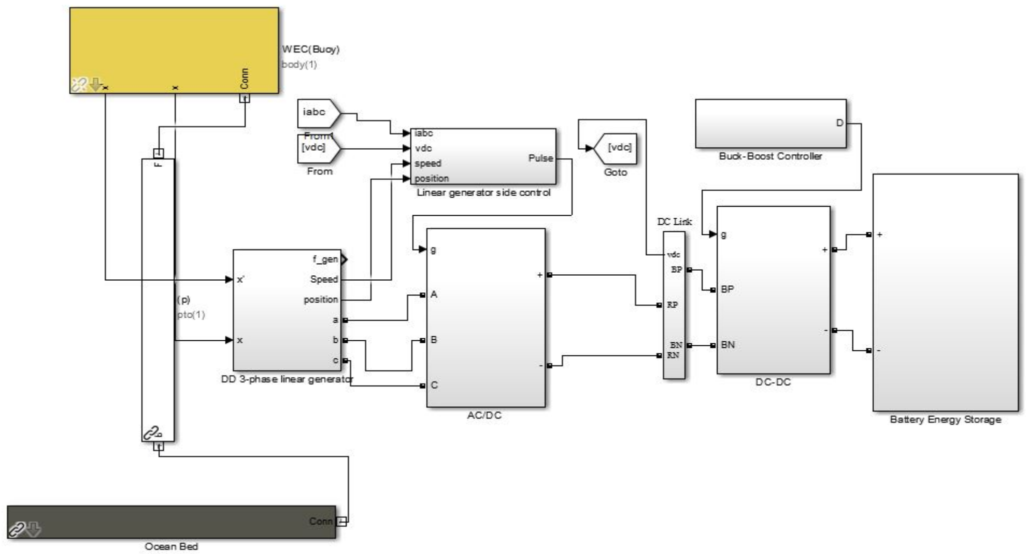

Fig. 2. Integrated WEC system model

TABLE I
SIMULATION PARAMETERS

Wave height	2.5m
Wave time period	8s
Buoy mass	50Kg
Rated voltage	150V
Rated current	25A
Rated power	3kVA
Air-gap length	1mm
Pole pitch	6.5mm
PM coercivity	940kA/m
PM remanence	1.2T
Phase number	3
Phase winding resistance	2.1Ω
Phase winding inductance	74.2mH

2 shows the linear generator connected to a AC/DC rectifier and a DC-DC buck-boost converter. The power extracted is stored in a battery energy storage. To maximize the generated power output, a well-known phase control strategy [20] commonly applied to point absorber WEC is considered. The translator position is used as a reference to the i_q current to control the DDPMLG reaction force. The generator force equation is given as

$$f_{gen}(t) = \frac{3\pi\lambda_{pm}}{2\tau_p} i_q(t) \tag{13}$$

Then, the power at the generator input can be written as

$$P_{gen} = f_{gen}(t)v(t) \tag{14}$$

IV. SIMULATION RESULTS

In this paper, a wave energy converter modeling toolbox called WEC-Sim is used to solve the Cummin's equation in equation 4. The WEC-Sim developed by National Renewable Energy Laboratory and Sandia National Laboratories, uses MATLAB® Sim-Mechanics as the multi-body dynamic solver to solve the system dynamics of the WEC. It provides a more realistic approach to determine the validity of a WEC design. Especially, a real sea-state performance is the determining criterion to validate a solution. The hydrodynamic parameters of the WEC and forces such as h_r and f_e are numerically calculated using WAMIT® program, a BIEM methods which performs the calculations in the frequency-domain.

In order to evaluate the performance of the WEC system model shown in Fig 2, Simulations are implemented in MATLAB® Simulink with the WEC-SIM toolbox, using design parameters listed in table I. Each simulation was performed for the same time series and are described under regular and irregular wave conditions.

A. Regular Waves

The wave force and motion characteristics of the WEC system in regular waves were studied. Simulations were run with regular wave height of 2.5 meters and a time period of 8s. Fig. 3 shows the device responses, its velocity and position. The phase voltage and current wave forms at no load conditions are presented in Fig. 4 and Fig. 5. Note that in Fig. 11 the wave excitation force is in phase with the motion of the buoy, indicating that the phase control strategy has been achieved. This allow maximum power to be extracted by the generator.

B. Irregular waves

It is essential to analyze the behavior and performance of the WEC device on a more realistic conditions, such as when

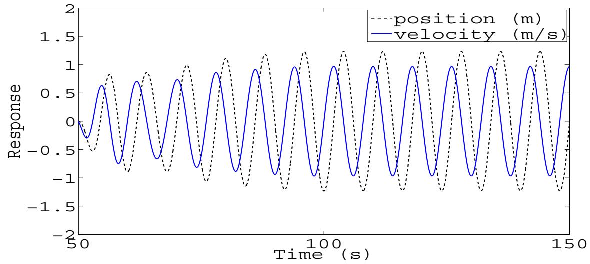

Fig. 3. WEC position and velocity in regular waves

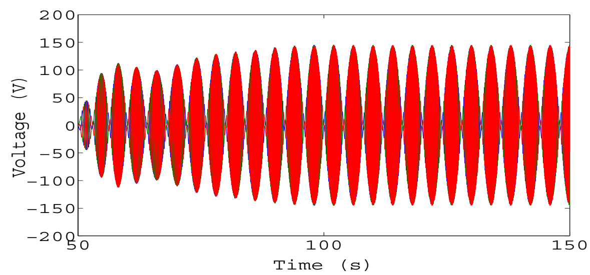

Fig. 4. 3-phase Induced EMF of the linear generator in regular waves

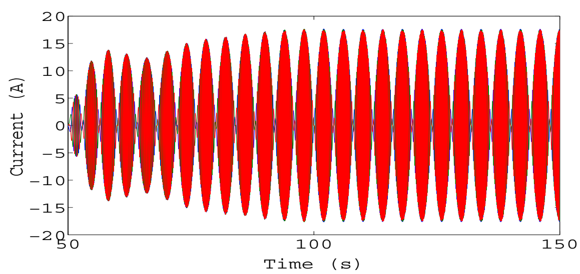

Fig. 5. 3-phase current of the linear generator in regular waves

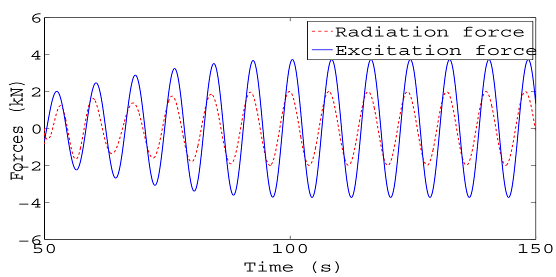

Fig. 6. Radiation and Excitation Forces in regular waves

it is subject to irregular incident waves. Fig. 8 and Fig. 9 Shows forces and the response of the device. The frequency fluctuations are larger than that of regular waves. It can be noted that the fluctuation directly influence the electrical power output of the device. The 3-phase voltage and current of the generator increases linearly with the translator speed, as shown in Fig. 10 and Fig. 11, respectively. Under this conditions the

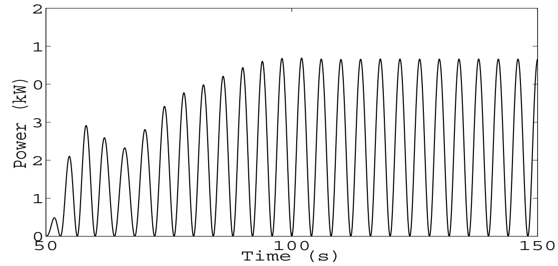

Fig. 7. Generator instantaneous power in regular waves

power converters must be able to track the changes in the frequency to extract maximum power. The rating of the Linear generator and the power electronics equipment should also be taken into consideration when designing a control strategy for the WEC. Parameters such as the peak-to-average power ratio is used to rate the power electronic inverters. In the power output shown in Fig. 12, the peak-to-average power ratio of the WEC system is higher than that in Fig 7. The power electronic converters would have to be considerably overrated for such system.

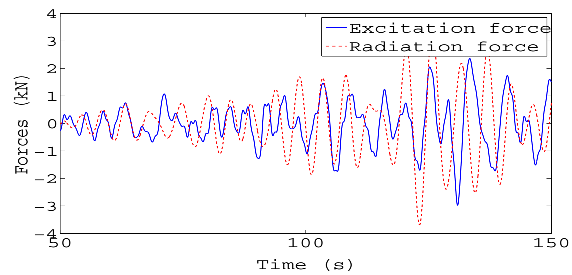

Fig. 8. Radiation and Excitation Forces in irregular waves

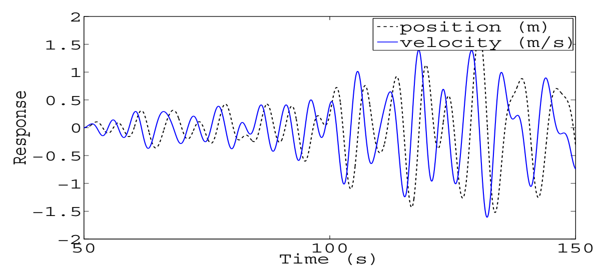

Fig. 9. WEC position and velocity in irregular waves

V. Conclusion

A detailed dynamic simulation model of a direct drive point absorber WEC has been evaluated for different wave conditions. The results illustrate the performance of the device in regular and irregular wave conditions. It has been shown that in actual application the frequency of oscillation of the WEC system will varies rapidly. The results are useful to

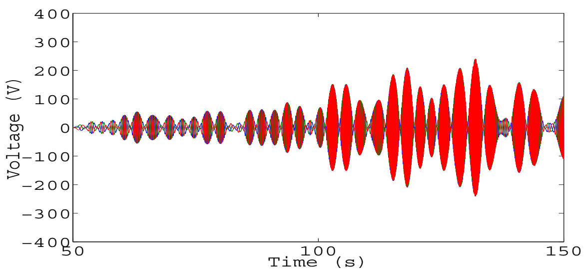

Fig. 10. 3-phase Induced EMF of the linear generator in irregular waves

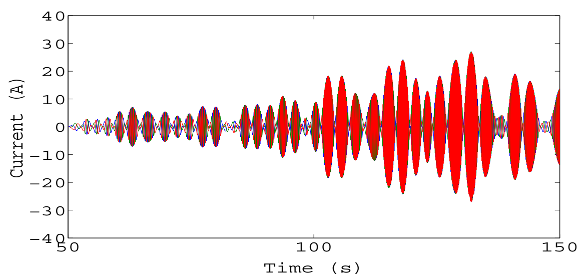

Fig. 11. 3-phase current of the linear generator in irregular waves

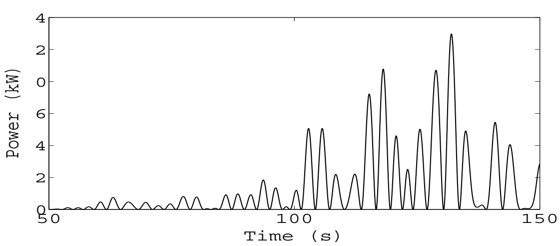

Fig. 12. Generator instantaneous power' in irregular waves

address design issues, verify the sensitivity of the WEC system parameters, and to develop control strategies to improve the system performance and reliability.

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