Experimental Verification for Generating Characteristics of Double-Sided Permanent Magnet Linear Synchronous Generator for Ocean Wave Energy Converter

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Abstract

In this paper, we present an experimental verification of the performance evaluation system of a double-sided permanent magnet linear synchronous generators (PMLSG). The core technical field of PM wave power generation system is the re-search field which concentrates on the optimum design of electromagnetic circuit of PMSG, characteristic analysis technology, power generation performance analysis technology, loss analysis and performance evaluation technology. Until recently, research on this has been actively conducted, but there is no research on power generation analysis in which a wave generator and buoy are linked. In addition, it generally deals with verification under regular wave conditions. Therefore, in this study, the PMLSG of the performance evaluation system predicted buoy's motion to derive the area generating optimal power generation for regular and irregular wave conditions.

I. INTRODUCTION

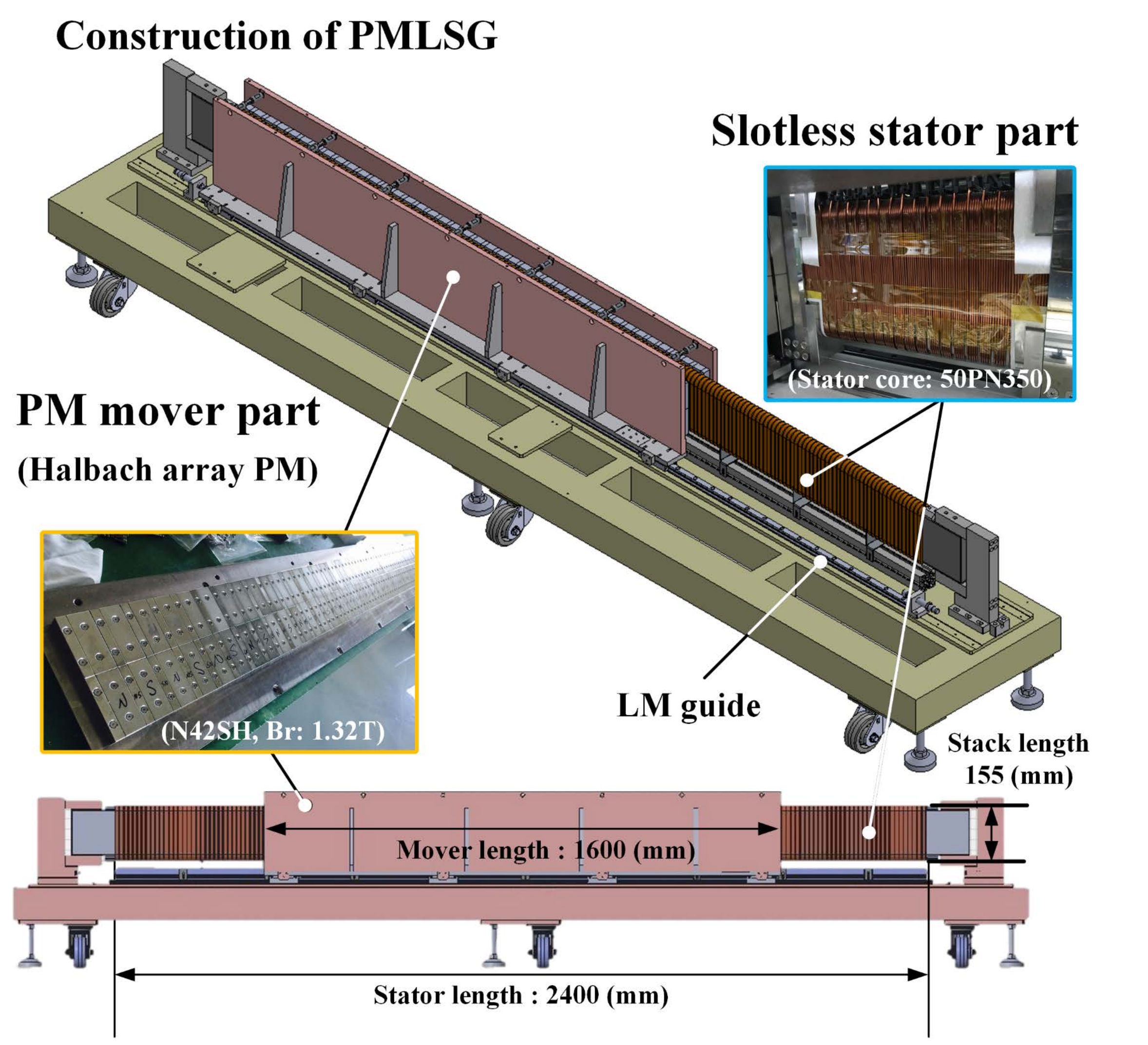

Fig.1. Structure of slotless stator double-sided Halbach array PMLSG for performance evaluation system.

TABLE I. Design specifications for manufactured PM linear generator with Halbach magnet array mover and slotless stator structure

Parameter	Value	Parameter	Value
Stator length	2400	Mover core thickness	15
Mover length	1600	Pole pitch	40
Pole number	40	Pole pitch (vertical)	28
Coil number	180	Pole pitch (horizontal)	12
Stack length (Stator)	135	Diameter of tapped hole	4.5
Stack length (Mover)	155	Turns per coil	5
Stator core thickness	30	Coils per phase	60
Coil thickness	4	Coil spec. (square type)	4×2
Air gap thickness	7	Material of core	50PN350
PM thickness	20	Material of PM	N42SH

- ✓ In this study, we performed various performance evaluation using the model designed in reference [3], and the components of the system for performance evaluation are shown in Fig. 1.
- ✓ This system implemented oscillating bodies wave energy converter and is floating type considering buoy motion by wave energy.
- ✓ In the case of waves, there are regular and irregular waves and there has been little research on power generation analysis assuming a wave energy converter combined with a buoy.
- ✓ Therefore, when wave energy converter and buoy interlocked, generation performance evaluation was performed considering buoy motion and power take-off (PTO) damping was considered for buoy motion.

II. PERFORMANCE EVALUATION SYSTEM

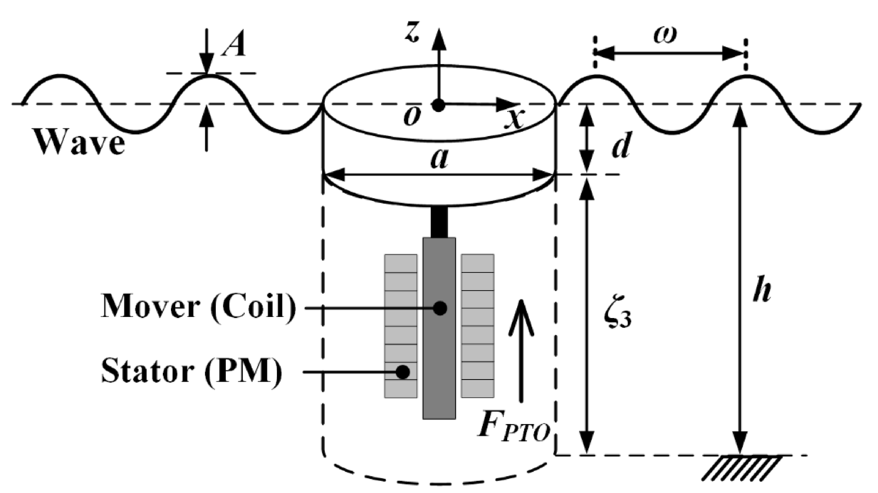

Fig. 2. Heaving motion of buoy coupled with PMLSG for ocean wave energy harvester.

- ✓ Fig. 2 shows the wave energy converter system of buoy coupled with PMLSG.
- ✓ The buoy's kinetic energy due to waves corresponding to the generator's input speed is changed using power take-off (PTO) damping.
- ✓ Furthermore, it is assumed that the power extracted through buoy's motion considering PTO damping is the same as the input power of the generator.

- ✓ Heave motion of buoy coupled with PMLSG can be defined by using linear potential theory and its displacement and power can be obtained.
- ✓ In addition, using Newton's second law, the equilibrium between the inertia of the structure and the external forces can be written as follows:

$$m_b\ddot{\zeta}_3(t) = F_r(t) + F_h(t) + F_{exc}(t) + F_{PTO}(t) \quad (1)$$

- ✓ where m_b and ζ_3 are the mass of the buoy and second time derivation of the heave motion, respectively. In addition, F_r, F_h, F_{exc} and F_{PTO} are the radiation force, hydrostatic force, wave exciting force and PTO inertial force, respectively.
- ✓ Therefore, the time-averaged extraction power with the PTO damping coefficient is given by Eq. (2), which is equal to the input power of the generator.

$$\underbrace{\bar{P} = A^2\left(\frac{1}{2}c_{pto}\omega^2\left|\frac{\zeta}{A}\right|^2\right)}_{Buoy\ Extracted\ Power} = \underbrace{P_{in}}_{Generator\ Input\ Power} \quad (2)$$

- ✓ Here, c_{PTO} and ω are the PTO damping coefficient and undamped natural frequency, respectively.

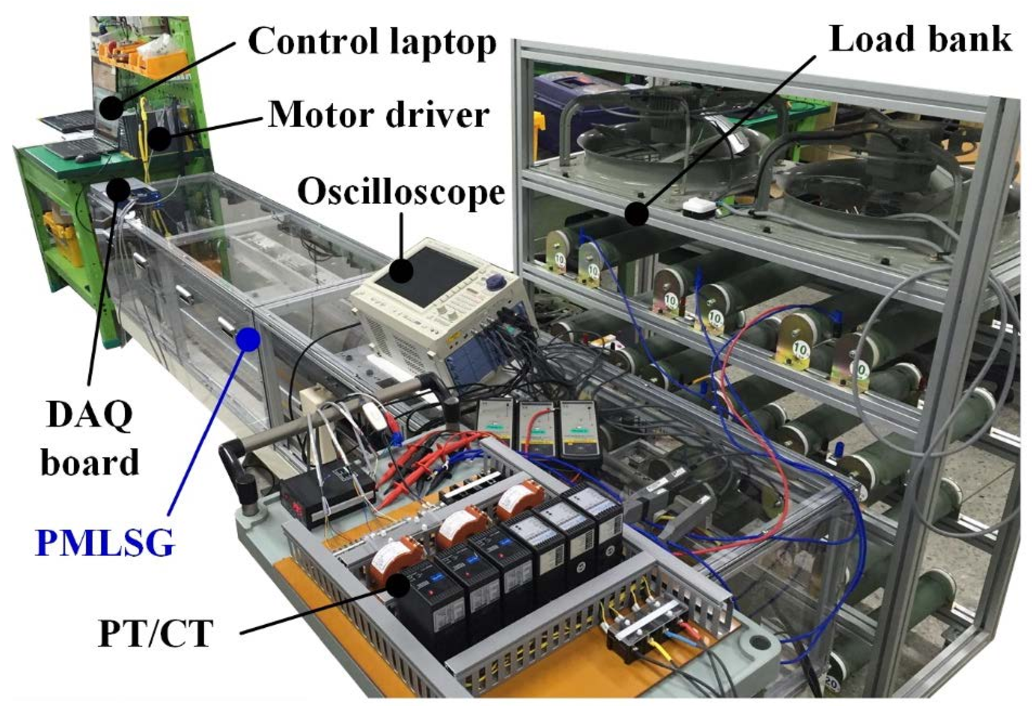

Fig. 3. PMLSG performance evaluation system experimental set.

- ✓ Fig. 3 shows the performance evaluation system and the performance evaluation system can be used to simulate the velocities of regular and irregular waves.
- ✓ The rated power and speed of the generator are 10 kW and 1.8 m/s.
- ✓ Fig. 4 (a) shows the experimental results according to the velocity at a load resistance of 2Ω for evaluation of the generating performance.
- ✓ The experimental results for all six velocity conditions (based on the results in Fig. 4) are shown in Fig. 4 (b) and (c) in comparison with the equivalent circuit method.

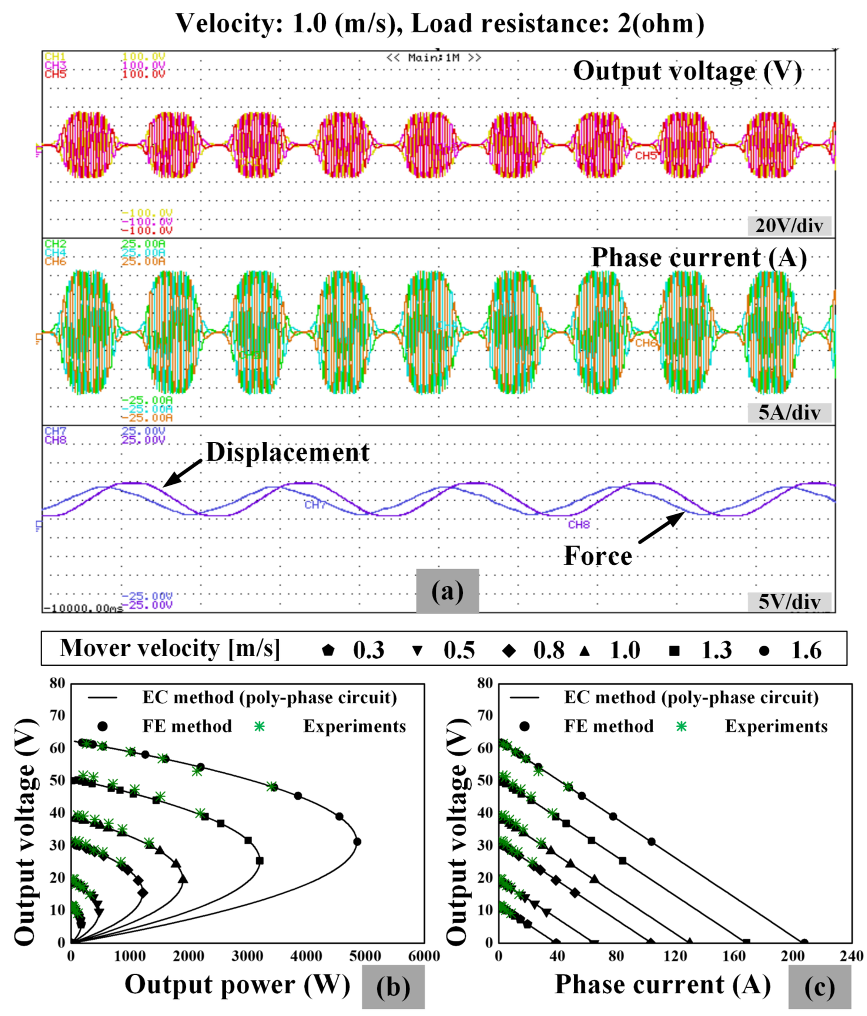

Fig. 4. Generating performance characteristics according to load and velocity: (a) experimental measurement results, (b) power, (c) current and voltage.

- ✓ From the generator's point of view, the mechanical input power and electrical output power are calculated by using (3) and (4), respectively.

$$P_{in} = F_{in} \cdot V_s \quad (3)$$

$$P_{out} = 3V_{out}I_{out}\cos\theta \quad (4)$$

- ✓ Moreover, Eqs. (6) and (7) represent the efficiency (η) and power losses (P_{loss}) of the wave energy converter, respectively.

$$\eta = \frac{3V_{out}I_{out}\cos\theta}{F_{in}V_s} \quad (5)$$

$$P_{loss} = F_{in}V_s - 3V_{out}I_{out}\cos\theta \quad (6)$$

- ✓ Then, (7) and (8) can be obtained by using (3) to (6).

$$P_{emloss} = P_{loss} - P_{m.loss} \quad (7)$$

$$\eta_{em} = \frac{3V_{out}I_{out}\cos\theta}{3V_{out}I_{out}\cos\theta + P_{emloss}} \quad (8)$$

- ✓ Here, the mechanical and electrical parameters V_s, F_{in}, P_{in}, P_{out}, V_{out}, and I_{out} of the performance evaluation system represent the velocity, force, input power, output power, output voltage, and phase current, respectively.

III. CHARACTERISTICS UNDER OCEAN WAVE CONDITIONS

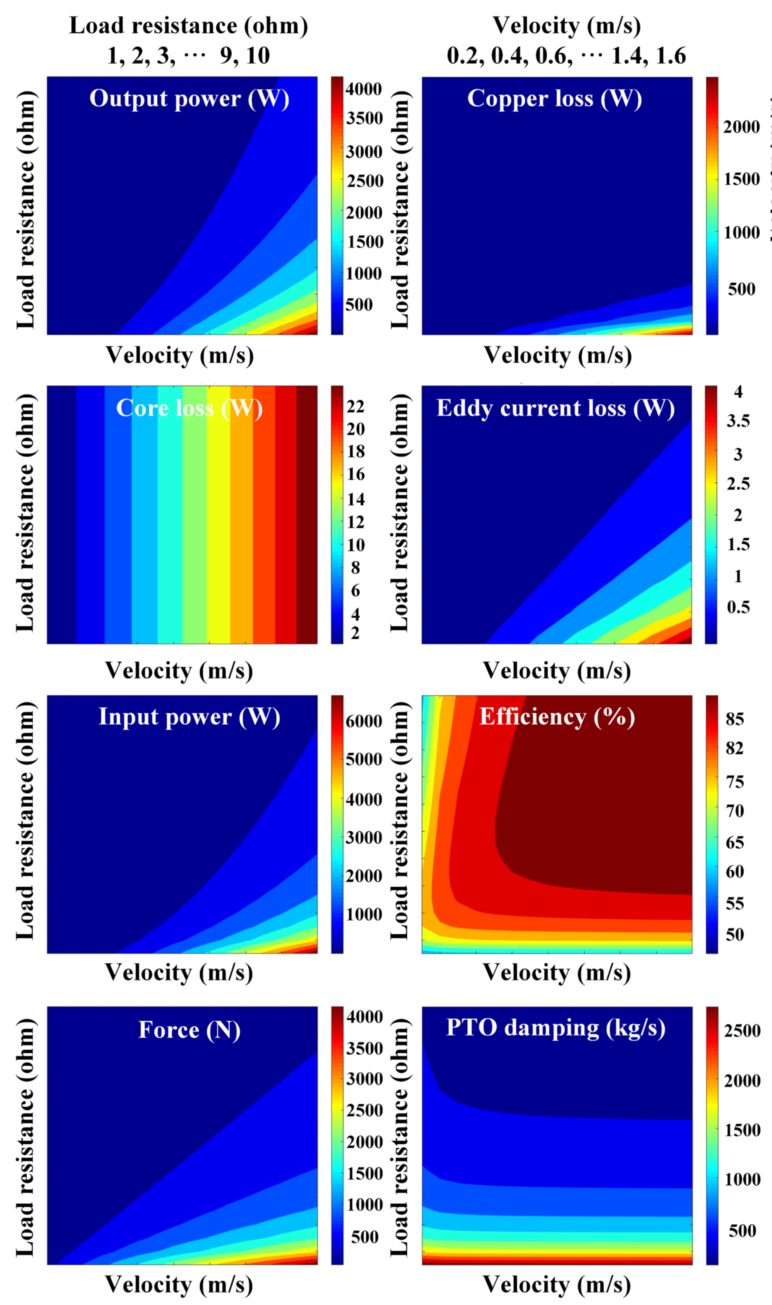

Fig. 5. Performance and PTO damping characteristics of manufactured PM linear generator according to the load and velocity.

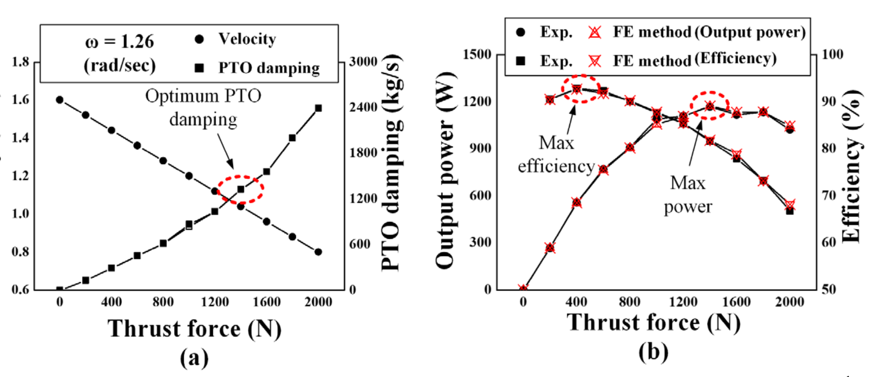

Fig. 6. (a) PTO damping, (b) output power and efficiency.

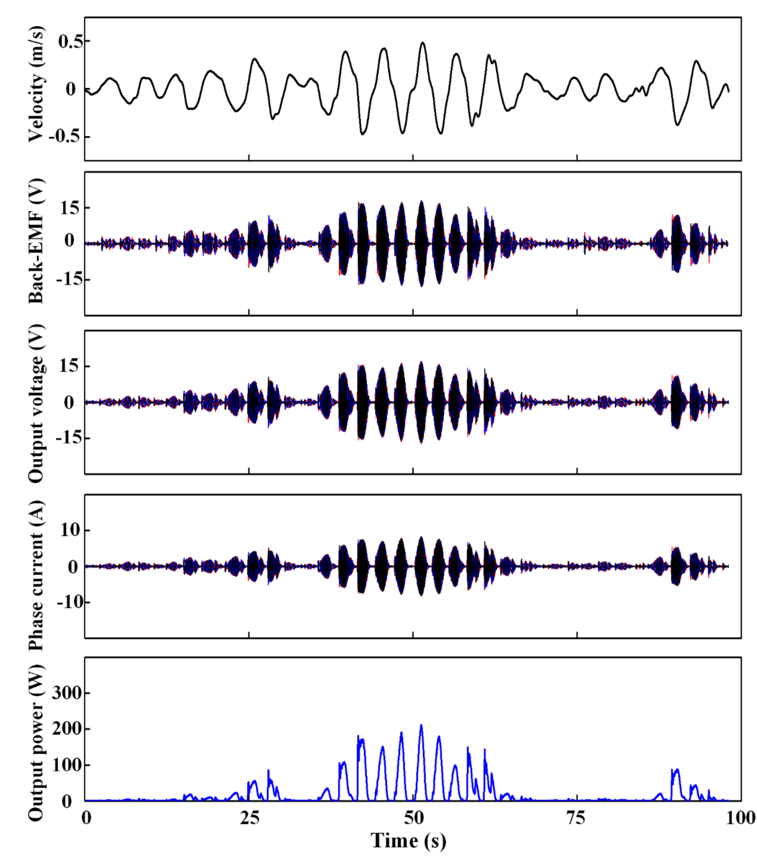

Fig. 7. Performance characteristics of the manufactured PMLSG according to irregular velocity condition

TABLE II. Measurement results for two conditions for irregular velocity

	Case 1	Case 2	Case 3	Case 4
Max Velocity [m/s]	0.477	0.549	0.5	0.636
Back-EMF [V]	17.9	20.8	19.2	24.2
Output voltage [V]	17.02	18.77	18.1	21.7
Phase Current [A]	8.1	8.94	8.55	10.34
Output Power [W]	211.4	252	238	336

- ✓ Fig 6 shows the generating characteristics of PM linear genera-tor according to variation of PTO damping coefficient in condition of wave frequency 1.2rad/s and exciting force 4000N of the buoy.
- ✓ Fig. 6 (a) shows the variation of velocity by the buoy coupled with the PM linear generator, and the variation of velocity is effected to PTO damping coefficient of PM linear generator.
- ✓ Fig. 6 (b) shows the power performance and generating efficiency according to conditions of velocity.
- ✓ Here, the value of max power is 1170W and the point of optimum PTO damping coefficient is 1324kg/s, respectively.
- ✓ Fig. 7 shows the experimental results of cases: no-load and with a load (at a load resistance of 2Ω) and we experimented with 4 cases in total. Simulations of the irregular velocity conditions used irregular wave energy and buoy motion equations.
- ✓ Here, the irregular velocity of the buoy modeling result is entered into the manufactured setup through a monitoring sys-tem that calculates the velocity according to the displacement of the PMLSG. the results are presented in Table II.

IV. CONCLUSION

PMLSG performance evaluation is a very important step to ensure efficient use of energy. However, ocean waves consist mainly of irregular waves. Hence, in this study, a performance evaluation system is constructed for regular and irregular wave conditions considering PTO damping, which is an important factor in calculating the input power of a generator. In general, performance evaluation has been conducted in regular wave conditions where PTO damping is not considered. As a result, the model can predict the PMLSG input conditions for various wave conditions and verify its performance under these conditions. Therefore, the results of this study can be useful for ocean wave energy-harvesting systems and for designing and analyzing a system with variable velocity and loads for various applications, as well as for marine energy generation.