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Design, Development and Experimentation of Deep Ocean Wave Energy Converter System

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Abstract

Energy from ocean waves remains largely an untapped resource. This is also highly consistent in comparison to other alternate sources of energy such as wind and solar. Present study deals with the design and development of innovative wave energy converter (WEC) that uses a buoy-type point absorber. The device is proposed to be mounted on an offshore platform and be used to produce electric output for meeting the operational energy demands, partially. The device employs lever arm and gear boxes to obtain the mechanical work from the heave energy of the floating buoy. Subsequently, electric energy is generated from the mechanical work harnessed from the waves by deploying a generator. Design Failure Mode and Effect Analysis is carried out on system to identify effects of failure modes.

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Keywords : renewable energy; wave energy; point absorber; wave power; energy converter

1. Introduction

Existing traditional methods of energy production are contributing to serious environmental problems. There is an urgent need for pollution-free green power generation and hence the focus of present research and development in renewable energy is redirected towards viable and sustainable energy resources. Compared to other forms of alternate sources of energy, wave energy is more consistent and predictable [1]. Energy density is the highest amongst the renewable energy sources [2-3]. Ocean wave power can be converted into electrical energy by different methods [4-7] namely: (i) Oscillating water columns [8-9]; (ii) Oscillating bodies [10-11]; and (iii)Overtopping devices [12]. In the resent study, point absorber is used to harness wave power [13-17].

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2. Methodology

Fig.1 shows the experimental setup of the proposed device. Horizontal cylindrical buoy (1) with an extended fin is connected to an oscillating lever arm (2) through the connector. This buoy is used for capturing wave energy in the heave mode. In order to convert the reciprocating vertical motion of the buoy to rotary motion, unidirectional gear assembly (4) is deployed. A flywheel (7) is also used to rectify the discontinuous flow of power. A permanent magnet DC generator (6) is used to generate electric power by the principle of electromagnetic induction. Effective mass of the buoy is reduced when the approaching waves passes, due to the increase in the surrounding water level. The lever arm becomes unbalanced between its two ends. Due to the imbalance created, counter weights (5) pull the buoy, which oscillates the arm in one direction. Similarly, the arm oscillates in the other direction when the wave trough approaches the buoy. In this manner, displacement of the buoy is converted into an alternative rotation by the oscillating lever arm. Unidirectional rotation of low speed and high torque is converted to high speed rotation with a step-up gearbox (3). Stepped up rotary output is coupled with the shaft of the permanent magnet generator through a flywheel to produce electric energy. Load is connected across the generator, which identifies the presence when the bulb glows. Power analyzer is deployed to detect the electric power across the load. A rpm sensor is used to measure the rpm generated by the set up.

Fig.1. Experimental setup of the proposed device

3. Conceptual design

Experimental investigations are carried out on the scaled model of the proposed device in the random wave cum current flume at Dept. of Ocean Engineering, IIT Madras, India. Horizontal cylindrical buoy is used with an extended fin to capture the incident wave energy in the heave direction. An oscillating lever arm, consisting of a straight frame pivoted at its middle is employed. Buoy is attached to one end while a counter-mass assembly is attached to the other. Gear box is used to convert bi-directional motion of the alternatively rotating arm of the shaft into continuous unidirectional rotary motion. The step-up gear box used in the design is capable of increasing the rpm of the input shaft. The lever arm stalls at its positive and negative extreme positions when it oscillates due to the buoy's interaction with the approaching waves; hence power generation at these extreme positions is not successful. A flywheel is used for enabling a continuous flow of power. Table 1 shows the summary of design parameters of the components of the proposed system.

Table 1. Summary of design parameters of the components

Wave flume	Buoy	Lever arm	Gear box	Flywheel	DC Generator
Flume Width: 2m Flume length: 40m Water depth: 1m Maximum wave period: 3s Maximum wave height: 30cm	Material: Mild steel Buoy length: 1.6m Buoy diameter: 0.8m Buoy weight: 65kg Fin length: 0.5m	Material: steel Arm length: 2.7m Counter weight: 45kg	Input gear module: 2.5 mm Gear face width: 25mm UD gearbox speed ratio: 9 Step-up gearbox speed ratio: 12	Flywheel Mass: 16kg Material: steel Diameter: 300mm Face Width: 25mm Maximum RPM estimated: 600	Rated power: 0.25KW Rated Current: 8A Rated voltage: 24V Speed: 600r/min Connection: PMDC

4. Failure Mode and Effect Analysis (FMEA) of proposed Deep Ocean Wave Energy Converter System

The proposed system is also investigated for potential failure in operation using design FMEA. This is a systematic tool for identifying the effects of a potential failure (or) the product [18]. Design FMEA is most effective when applied before the design of the product is released [19]. Three major variables namely: (1) Severity, S; (2) Occurrence, O; and (3) Detection, D, used in the study are rated on a 10 point scale. Severity is a rating that corresponds to the seriousness of an effect of a potential failure. Rating of severity as 1 means no effect and 10 means most hazardous. Occurrence rating corresponds to the rate at which a cause and its failure will occur in the design life of the overall system. Rating of occurrence as 1 means that the failure is unlikely and that of 10 means it is certain. Detection rating corresponds to the probability that the detection methods or existing control mechanisms will detect the potential failure even before it occurs. Rating of detection as 1 implies that the existing controls will detect the failure and that of 10 implies that it is certain that controls will not detect the failures. Product of the above three variables gives the Risk Priority Number (RPN), which is useful in identifying the critical components according to the order of Risk. The detailed FMEA report of the proposed device is shown in Table 2.

Table 2. Detailed failure mode and effects analysis worksheet of the Deep Ocean Wave Energy Converter

component	Function or process	Failure Mode	Effects	S	O	Cause of failure	Controls	D	RPN	Recommend-ed Action
Buoy	Gives displacement in heave motion	Does not give desired displacement & force	Power at low voltage / no power generated	4	3	Faulty design or less wave energy	Check buoy design & wave energy properly	7	84	Rigorous testing in lab as well as in wave basin
Lever arm	Converts displacement into oscillatory motion	Seizes during oscillation/ pivot pin breaks	less power output or no power output	4	3	Rusting/ wave of high amplitude	galvanization & balancing with counter weight	6	72	Routine maintenance & testing to find counter weight
Uni-directional gear box	Bi-directional rotation into unidirectional rotation	Broken tooth	no power output	3	3	wear or manufacturing faults	Check design and lubricate properly	6	54	Rigorous testing in lab

Step-up gearbox	Increases the speed of rotation	Broken tooth	no power output	2	3	Wear or manufacturing faults	Check design and lubricate properly	6	36	Rigorous testing in lab
Bearings	Helps in running the device smoothly	Damaged ball	Efficiency gets reduced	3	2	Manufacturing faults	Check design properly	6	36	Rigorous testing in lab
Shaft	Mechanical component for transmitting torque and rotation	Shaft breakage	no power output	3	2	Excessive torque/ Inadequate lubrication/ corrosion	Check design, lubrication & galvanization	5	30	Routine maintenance
Nutts & Bolts	Holds components together	Fracture	detached components	3	2	Rusting or excessive loading	galvanization	5	30	Routine maintenance
Flywheel	Reduces the fluctuation in power output	Does not reduce fluctuation in power output properly	Less smooth power output	2	2	Poor design	Check design properly	6	24	Redesign flywheel according to power to be transmitted
Electrical generator	Transforms rotational kinetic energy into electrical energy	Faulty armature wiring	less power or no power generated	2	2	Manufacturing faults	Check wirings properly	6	24	Proper inspection required
Bulbs	Loads the electrical system	Bulb burns out	No electrical power detection	1	2	Over-voltage or voltage fluctuations	Check for rated power	5	10	Replace after the incident

5. Results

A 1:6 scaled model of the proposed wave energy converter is designed, fabricated and tested in 2m deep wave flume at Indian Institute of Technology Madras, India. Buoy of length 1.6 m and weight 165 kg is used for the experimental analysis. Counter weight of 45 kg is used to activate the reciprocating motion of the rotating arm. An 8-pole permanent magnet DC generator unit is used as the electricity generating unit and electrical bulbs are used as loading units. Generated electrical power is recorded using a power analyzer. The device's responses for varying parameters are presented. Fig. 2 shows the comparison of mechanical power output for different wave heights and buoy position (0^0, 16^0, 32^0 and 48^0) with respect to the wave approach angle, respectively. Plots are drawn for comparing the electrical power output of the system for varying lengths of the lever arm of 1 m and 1.7 m under the wave height and period of (0.3m, 3s); results are shown in Fig. 3. While Fig.4 shows the average mechanical power produced for different angles of rotations of the buoy for 0.30m wave height, 3s wave period and 1.7m arm length, Table 3 shows the wave power, mechanical power and the efficiency of the system for different cases considered for the present study. The device shows a maximum efficiency of 23.47% at 32^0 angle of rotation of the buoy for 1.7 m arm length.

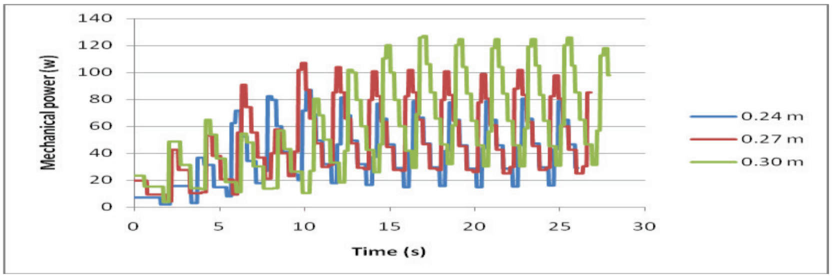

Fig. 2.Variation of mechanical power output for different wave heights

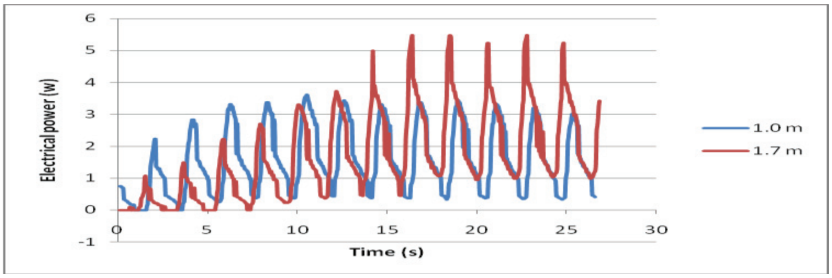

Fig. 3. Variation of electrical power for lever arms

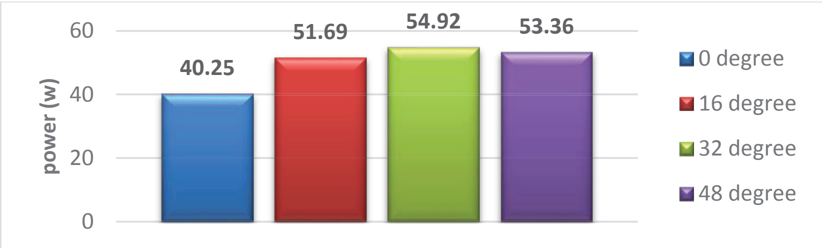

Fig. 4. Variation of mechanical power for angles of rotation of the buoy

Table 3. Wave power, mechanical power and efficiency for angles of rotation of the buoy

Angle of rotation of the buoy (°)	Wave amplitude(m)	Time period (s)	Lever arm length (m)	Wave power (W)	Mechanical power (W)	Efficiency (%)
0 °	0.24	3	1.0	165.08	15.07	9.13
	0.24	3	1.7	165.08	31.98	19.37
	0.27	3	1.0	208.93	22.63	10.83
	0.27	3	1.7	208.93	41.11	19.68
	0.30	3	1.0	257.94	33.52	13.00
	0.30	3	1.7	257.94	40.25	15.61
16 °	0.24	3	1.0	165.08	28.63	17.34
	0.24	3	1.7	165.08	31.38	19.01
	0.27	3	1.0	208.93	33.37	15.97
	0.27	3	1.7	208.93	46.58	22.29
	0.30	3	1.0	257.94	43.32	16.80
	0.30	3	1.7	257.94	51.69	20.04
32°	0.24	3	1.0	165.08	25.26	15.30
	0.24	**3**	**1.7**	**165.08**	**38.74**	**23.47**
	0.27	3	1.0	208.93	29.62	14.18
	0.27	3	1.7	208.93	48.39	23.16
	0.30	3	1.0	257.94	40.64	15.75
	0.30	3	1.7	257.94	49.14	19.05

48 °	0.24	3	1.0	165.08	16.22	9.82
	0.24	3	1.7	165.08	37.31	22.60
	0.27	3	1.0	208.93	22.38	10.71
	0.27	3	1.7	208.93	39.86	19.08
	0.30	3	1.0	257.94	34.51	13.38
	0.30	3	1.7	257.94	53.36	20.69

6. Conclusions

Experimental investigations of scaled model of the proposed wave energy converter device are carried out for different wave height, period and lever arm length; angle of the buoy with respect to the wave approach angle are also varied during the study. Mechanical and electrical outputs of the system are recorded for different wave heights varying from 0.24-0.30 m and with the time period of 3 s. It is seen that there is an increase in the power output for increase in wave heights. It also seen that the output is maximum for the lever arm of 1.7m. Proposed device produces maximum average power at 32^0compared to other degrees of rotation. Maximum mechanical power produced by the system is about 127.08 watts, as measured on the scaled model. Overall, mechanical efficiency of the device is determined as 23.47%. Design FMEA shows floating buoy as the most vulnerable part with the RPN of 84. Recommended actions focus on the rigorous testing of the buoy in lab for robust design of the buoy.

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