International Conference on Mechanical, Industrial and Materials Engineering 2024 (ICMIME2024)
11-13 December, 2024, RUET, Rajshahi-6204, Bangladesh.

Paper ID: 340

Numerical and Experimental Investigation of a Wave Energy Converter Prototype to Generate Electricity

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Abstract

This study investigates the creation of a wave energy converter prototype, a point absorber variation that employs a permanent magnet linear generator. The goal is to determine the best buoy construction for effective energy conversion. SolidWorks and ansys are used to model and simulate multiple buoy designs, including tulip-shaped, spherical, and cylindrical. The results suggest that the tulip-shaped buoy is the most resilient, able to withstand the most stress. The prototype is tested in a wave generation facility, and the generator settings are optimised. The study investigates the relationship between wave height and power production, with experimental results indicating a minimum power of 0.324W for a 0.027m wave height and a maximum power of 51.63 W for a 0.232m wave height. These studies illustrate wave energy systems' real-world uses and feasibility in renewable energy generation.

Keywords: Wave energy; buoy; wave generator; PMLG; wave generator; simulation.

“1. Introduction”

Energy demand in wealthy countries is on the rise, with a projected 100% increase by 2040 compared to 2016 [1]. Renewable energy sources are becoming increasingly important due to the depletion of fossil fuels, environmental concerns, and safety measures [2]. Renewable energy is derived from natural resources that replenish themselves on a human timescale, including sunshine, wind, rain, tides, waves, and geothermal heat [3]. It requires no fuel and can be gathered throughout the year [4] [5]. Wave energy is a reliable renewable source since it occurs naturally in ponds, rivers, and oceans, independent of time or weather [4]. Wind energy is transferred to waves when the speed of the waves above the ocean surface is slower than that of the wind [7] [8]. Friction and pressure differences between upwind and water surface create shear stress in the water, leading to wave generation [9]. Wave energy generation can generate energy over a wide variety of parameters, including height, speed, water density, and wavelength [10]. Flow properties allow for large energy production at low wave speed, wavelength, and height. Hydroelectric energy generation is costly and can pose environmental risks, compared to other energy sources [11]. Solar and wind power are not a substantial contributor to overall energy projections due to their high costs and intermittent availability. Solar energy is weather-dependent, expensive, and requires a large area to generate power, leading to a decrease in production [12]. USA According to the U.S. Energy Information

Administration, Utility Scale Electricity Generation by energy source, 2019 (Source: Energy Information Administration) 17.5% of total energy was produced from renewable energy sources among which 37.71% was produced from hydropower as shown in Fig. 1. However, this data comprises marketed production solely. In the case of non-marketed energy production, some steps have been taken without the involvement of the government to fulfill the necessity of personal requirements [13]. Many research works have been conducted to produce wave energy and convert it to electricity along with some literature suggestions. Safian et al. [14] employed piezoelectric material to absorb vibrational energy from ocean waves' buoyancy force. Increasing the thickness of the piezoelectric material led to higher energy output with PZT-5H compared to PZT-5A under same conditions. The project was expected to generate 2.5 kWh monthly with 100 mechanisms. Here in Figure *1* we can see various types of wave energy converters

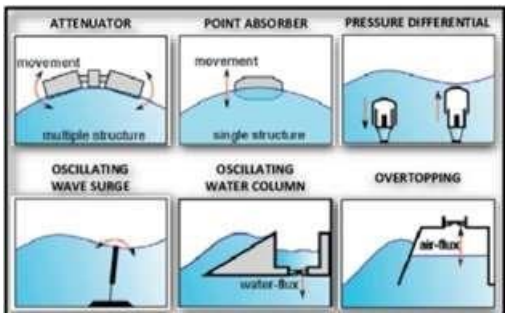


Figure 1: Types of wave energy converters

In contrast, Leijon et al. [15] investigated wave power utilisation utilising a linear generator on the seabed and a point-absorbing floating buoy. The buoy movement directly rotated the generator piston, which was counterbalanced by a spring. The main concern of this paper is to establish a cost-effective mechanism to harvest energy from waves using the buoyancy force of water in remote areas with the availability of water bodies. The most efficient float structure is designed and simulated before fabricating the experimental setup. This procedure does not require any advanced technology or huge initial investment and it offers the flexibility of materials and dimensions.

“2. Methodology”

“2.1 Materials”

Polyvinyl chloride rigid materials are resistant to corrosion, chemical degradation, abrasion, and weathering [6]. Additionally, it is affordable and lightweight. This material was chosen for the float design and simulation because to its qualities, including density, tensile strength, impact strength, Young's modulus, melting point, water absorption, specific heat, and heat transfer coefficient.

“2.2 Methodology”

In SolidWorks, we designed three different buoy shapes: a sphere, a cylinder, and a tulip shape, which is a mix of cylindrical and conical forms, as you can see in Figure *2*. The volume is set at 0.1131 m3, and every wall has a thickness of 0.04 m in all structures. This makes it easier to compare them, especially since they have a hollow inside. We're simulating these structures with the finite element method (FEM) to make sure the boundary conditions are the same in ANSYS (student version-16.0). Also, we looked into equivalent stress (Von-Misses) analysis and checked out the directional deformation analysis on these structures. Check out the simulation results in Figs. 3-4 for the three structures. It's worth noting that we did an equivalent stress analysis to determine the best geometry for the buoy structure. The idea is that a structure that experiences less stress is generally more efficient under the same load compared to others. The buoy structure experiences two main forces: gravitational force and buoyancy force, which actually work against each other. For the boundary conditions, we apply a load ranging from 0.05 MPa to 0.30 MPa to simulate the buoyancy force. This is done in six steps, all directed upwards on each structure.



Figure 2 Tulip, Cylindrical and Spherical Buoy

We keep the applied pressure within this range to make sure that the maximum stress stays within the elastic limit for each buoy. We noticed that the highest stress on the cylindrical buoy structure is 4.689 x 10^4 N/m2, which is actually lower than the ultimate strength of Polyvinyl chloride (PVC) rigid material, as illustrated in Fig. 4. On the other hand, the spherical buoy structure shows a deformation of 7.33 x 10^6 m, and the tulip-shaped structure has a deformation of 2.06 x 10^-6 m.

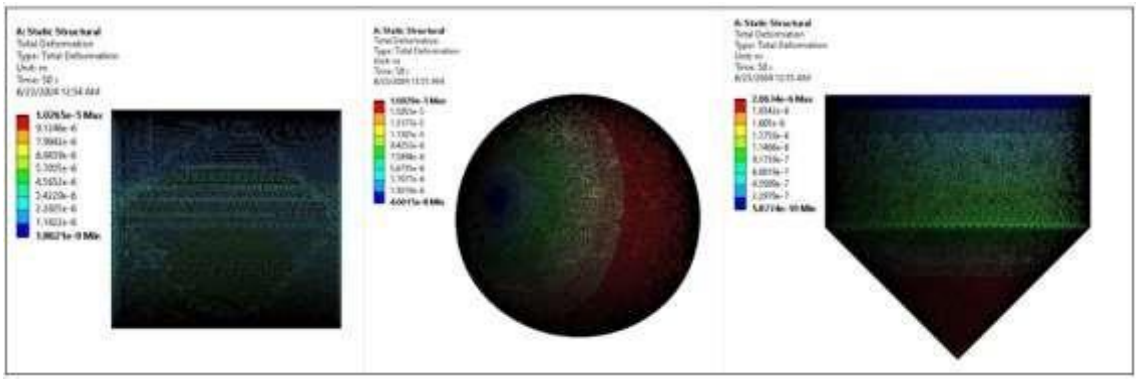


Figure 3:Deformation Analysis of Cylindrical, Spherical, Tulip and buoy.

It turns out that the stress for the spherical-shaped buoy is 8974.3 N/m2, while for the tulip-shaped buoy, it's 6974.3 N/m², as you can see in Fig 4 we also took a look at deformation analysis to see how much each buoy structure moved at its maximum displacement.

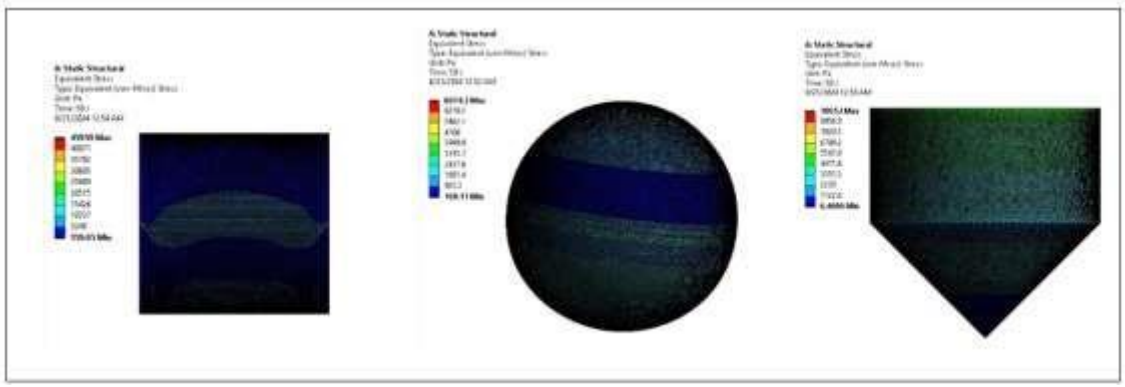


Figure 4:Stress analysis of cylindrical, Spherical and Tulip buoy

So, considering simulation results of total deformation and stress analysis we can conclude that Tulip shape buoy will be suitable for our experiment. Wave energy converter uses a buoy with a tulip-shaped design and works on the basis of electromagnetic induction. The apparatus is situated within a regulated wave production facility that allows for the manipulation of wave height and velocity. Upon activation of the wave creation system, waves travel through the facility, translating the buoy along its vertical axis as it tracks the crest and dip of the wave. Magnet with copper coils surrounding it is fastened to the buoy. The magnet in the coils goes up and down as the buoy responds to the waves.

$$\Phi_B = \iint_{\Sigma(t)} \mathbf{B}(t) \cdot \mathrm{d}\mathbf{A} \qquad \textbf{(1)}$$

Here Φ_B is flux density, $\mathbf{B}(t)$ is time variant magnetic field, dA is area vector. According to Faraday's Law of Electromagnetic Induction, this motion leads the magnet to cut through the magnetic flux lines, creating an electromotive force (EMF) in the copper coils.

$$\mathcal{E} = -N \frac{\mathrm{d}\Phi_B}{\mathrm{d}t} \qquad (2)$$

This wave energy converter works by using the motion of a buoy, which moves vertically with the rise an d fall of ocean waves. As the buoy travels, a permanent magnet inside a coil of wire moves up and down. This motion creates voltage in the coil by electromagnetic induction, in which the changing magnetic fiel d of the moving magnet generates electrical energy.The number of turns in the coil directly influences the magnitude of the induced voltage, with more turns resulting in a larger voltage. Furthermore, the height of the waves is important—larger waves generate greater movement of the buoy and magnet, resulting in more substantial changes in the magnetic field and, hence, a higher induced voltage. This device effectively transfers the mechanical energy of waves into electrical energy, making it a viable renewable energy solution.

“3. Experimental Setup”

In figure 5 we see the setup or wave generation facility includes

- Wave generator
- Wave Container

Utilising the kinetic and potential energy of ocean waves, a wave generator, also known as a wave energy converter (WEC), produces electricity. It’s length, width, depth are 5m,1.5m,1m accordingly. Generally, it functions by translating the wave's up-and-down motion into mechanical movement, which a generator uses to convert into electrical power.



Figure 5:Experimental Setup

Two-dimensional regular and irregular waves are considered propagating in the positive y-direction relative to x-y-z coordinate system. The water basin has a length of 15 m, a width of 5 m and a water depth of 0.65 m. The wave paddles are driven by a total of 15 hydraulic pistons moving in the horizontal direction only.

“4. Result and Discussion”

Figure 6 represents the relationship between the number of turns in a coil and voltage induced in the coil. From 0 to 900 turns, the voltage increases significantly, starting from 0 mV and reaching 1000 mV at 900 turns. This indicates that as the number of turns increases, the induced voltage also increases, which aligns with the principles of electromagnetic induction.

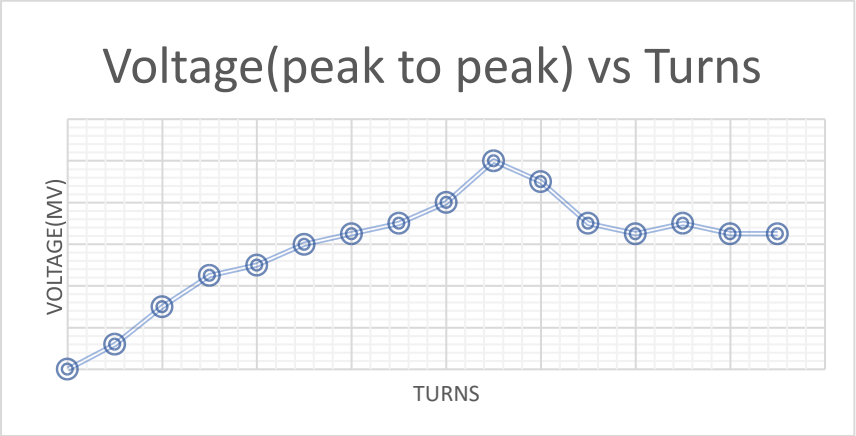


Figure 6:Voltage vs Turns

The maximum voltage of 1000 mV is reached at 900 turns. This suggests that this is the optimal number of turns for generating the highest voltage under the given conditions. The voltage begins to decline at 900 spins, reaching 1000 mV. At 1000 turns, it drops to 900 mV, and at 1100 turns, it drops even lower to 700 mV. This decrease suggests that, after a given number of turns, additional spins may not be able to generate voltage as effectively because of losses or saturation effect. Around 650 mV is where the voltage stabilises between 1300 and 1500 rotations. This suggests that the system might be approaching a limit at these higher turn counts, when more turns won't materially change the voltage output.

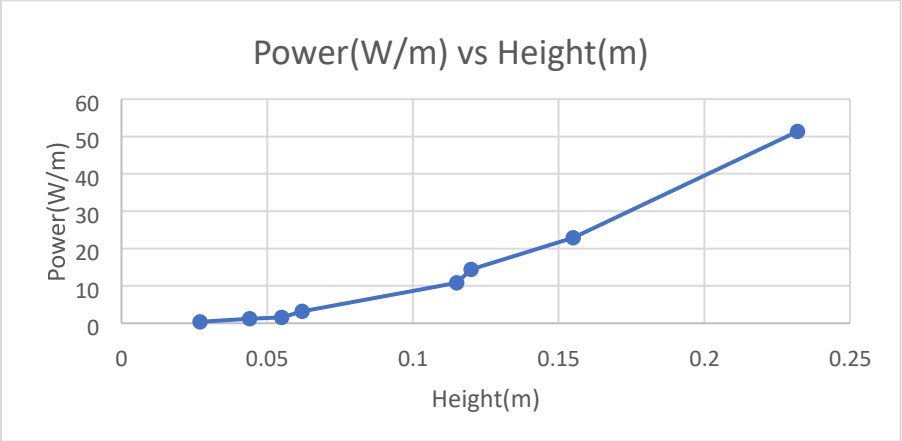


Figure 7:Power vs Height

According to figure 7 at an elevation of 0.027 meters, the power production is somewhat modest at 0.374 W/m². However, as the elevation increases to 0.155 meters, the power output significantly increases to 22.89 W/m². Further, this pattern persists, reaching its highest point at 0.232 meters with a substantial output of 51.36 W/m². The significant rise in power at specific elevations indicates that the wave energy converter is more efficient in harnessing energy from bigger waves, underscoring the significance of wave height in maximising energy generation in maritime settings.

“5. Conclusion”

A comprehensive investigation has led to the successful implementation of the given criterion for the linear generator. In this project, a compact wave energy converter will be integrated with a novel linear generator design to generate a highly efficient power output. This result shows that energy can be harvested from waves using this mechanism efficiently using buoyancy force solely. Different buoy structures are compared through the simulation by ANSYS to find out the most suitable geometry. Hence, the complete CAD model of the machine set-up is designed in SolidWorks with proper dimensions followed by the fabrication according to the designed. The materials of each part are chosen considering the aspects of weight, strength, durability, and availability. The data from the experiment clearly shows positive result in energy production. The Floating Buoy Technologies will serve as the operating system for the placement of the newly built linear generator, benefiting from its compact size, mobility, affordability, and high efficiency in power transmission. The finalised design characteristics for this project include a PMLG tubular type, air-cored stator, moving magnet, and radial topology with an axial magnet alignment. The

study investigates the relationship between wave height and power production, with experimental results indicating a minimum power of 0.324 W for a 0.027m wave height and a maximum of 51.63 W for a 0.232m wave height. The simulation and analysis have been conducted, and the design has been optimised to accomplish the given goal. Upon careful analysis of the design's performance, it is determined to be satisfactory in this pertinent field.

“6. Future Work”

The selected prototype can be similarly multiplied and optimized to maximize the performance of the linear generator. The format model has to be analyzed with the same finite factor analysis to find out about the power technology and model efficiency to be in contrast with current linear generators in market.

References

[1] T. B. Johansson, Renewable Energy: Sources for Fuels and Electricity, 1993.

[2] N. V. Viet, "A review on energy harvesting from ocean waves by piezoelectric technology".

[3] J. P. Painuly, "Barriers to renewable energy penetration: A framework for analysis," 2001.

[4] M. Leijon, "An electrical approach to wave energy conversion," 2006.

[5] E. M. a. O. McDoom, " Promoting Energy Efficiency and Renewble Energy: GEF climate change projects and impacts.," 2000.

[6] L. C. a. B. Kuźniewski, "An overview of methods for wave energy conversion," 2015. [7] A. R. P. B. Drew, "A review of wave energy converter technology," 2009.

[8] F. d. O. Falcão, "Wave energy utilization: A review of the technologies," 2010. [9]

J. F. a. J. Løvseth, "Ocean wave energy," 1991.

[10] R. Z. E. Al Shami, "“Point absorber wave energy harvesters: A review of recent developments,," 2019. [11]

C. N. a. A. Layeni, "Ocean wave energy An option for Nigerian power situation," 2013.

[12] Z. G. Yin, "“Experimental investigation on water exchange performance through a hollow buoy driven by wave overtopping," 2018.

[13] Safian, "Piezoelectric Energy Harvesting from Direct Buoyancy Force," 2018.

[14] Q. Q. H. He, "Numerical simulation of section systems in the Pelamis wave energy converter," 2010.

[15] M. A. Mueller, "Electrical generators for direct drive wave energy converters," 2002.

[16] R. K. Bansal, A Text Book of Fluid Mechanics and Hydraulic Machines, 20005.