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Design and Development of a Laboratory-Scale Wave Power Plant Using the Oscillating Water Column System

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ABSTRACT

Renewable energy is one of the strategies promoted by the government to enhance national energy resilience and reduce dependence on fossil fuels. As an archipelagic country, Indonesia has great potential in utilizing ocean energy, particularly wave energy. This study aims to design and construct a laboratory-scale wave power plant using the Oscillating Water Column (OWC) system and to analyze the electrical voltage generated by the turbine under various test conditions. The method used is an experimental laboratory approach, involving a system composed of an oscillation tank, a DC motor as the wave-generating mechanism, and a DC turbine as the generator, tested both with and without a boost converter. The artificial waves generated by the pushing mechanism produce air pressure in the chamber, which rotates the turbine to generate electrical voltage. The experimental results show that optimal performance occurs at a water height of 26 cm and a wave height of 2 cm, with a wave period of 0.502 seconds. The maximum voltage output produced by the turbine was 3 V when connected to a boost converter. These results indicate that the OWC system is capable of effectively converting wave energy into electrical energy in a laboratory-scale setting.

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1. INTRODUCTION

Renewable Energy is a governmental initiative aimed at increasing national electricity supply and reducing the use of fossil fuels [1][2][3]. One form of RE utilization is wave energy, derived from ocean water, which remains underutilized and relatively unknown by many stakeholders, including the Indonesian Ocean Energy Association [4]. Renewable Energy is considered an environmentally friendly and sustainable energy source, capable of ensuring long-term energy availability [5][6].

Ocean wave energy is fundamentally generated by the interaction between wind and the surface of the sea. Although the total energy potential of ocean waves is lower compared to solar energy, its main advantage lies in its high energy density, capable of producing power in the range of 2–3 kW/m² [7]. The wave formation process also involves resonance between vertical water pressure and small surface waves. This resonance is influenced by pressure differences caused by wind speeds being higher at the crest of the wave than at the trough, resulting in pressure gradients that contribute to increasing wave height. In general, wave height is influenced by three primary factors: wind speed, the duration of wind blowing, and the fetch (the stretch of open water over which the wind blows) [8 One method for utilizing wave energy as electrical energy is through the Oscillating Water Column (OWC)-based Wave Energy Power Plant (PLTGL). This technology harnesses wave motion to generate air pressure inside a chamber, which is then used to rotate a turbine for energy conversion. The efficiency of energy conversion using the OWC system is highly dependent on wave characteristics, equipment geometry, and the airflow channel design [9][10]. Wave Energy Converter (WEC) technologies such as OWC have been widely adopted in developed countries as part of future renewable energy solutions [11].

The first known attempt to harness ocean wave energy was recorded in 1799 by a person named Girard, although the patent was never developed into an energy conversion device. The first practical wave energy conversion device was created by Bochaux-Praceique to power household electrical appliances in his own home [12]. The development of wave energy prototypes is a crucial step for further analysis of power generation potential, particularly for implementation along Indonesia's coastlines, which have promising wave energy resources [13].

Based on previous research, an oscillation tank was designed with an upward conical shape to direct air pressure more efficiently in one direction toward the turbine. Testing of the device produced electrical energy of 0.06 V at a water level of 30 cm, a wave height of 1 cm, and a wave length of 66 cm. At a water level of 40 cm, with a wave height of 5 cm and wave length of 75 cm, the system generated 0.08 V. When tested at a water level of 45 cm and wave height of 6 cm with a wave length of 97 cm, the generated voltage returned to 0.06 V [14].

2. METHOD

2.1. Research Methodology

The method used in this research is an experimental method conducted at a laboratory scale, referring to the following research flowchart the following in Figure 1.

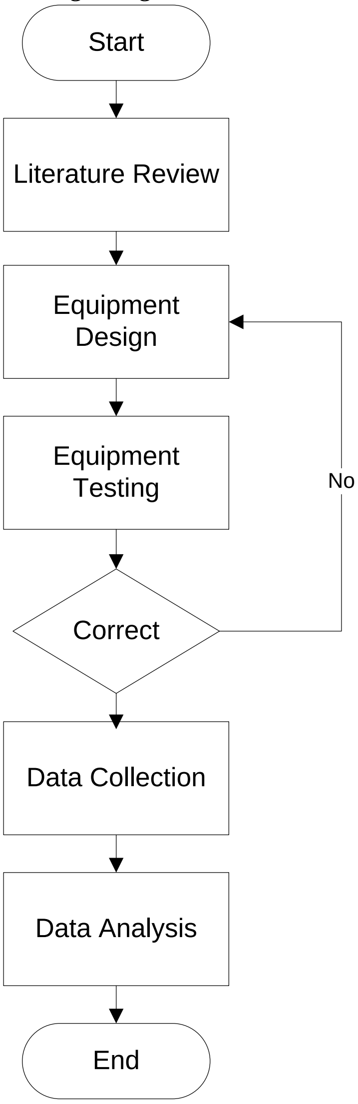

Figure 1. Research Flowchart

2.2. System Block Diagram

The following is the block diagram of the designed system, which consists of configurations both without and with a boost converter in Fugure 2.

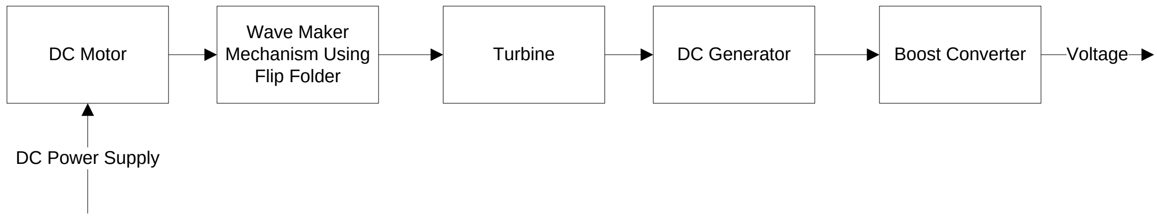

Figure 2. Block Diagram of The Designed System

In the system block diagram, the DC motor functions to drive the wave-generating mechanism using a flip folder. The artificial waves produced are directed into the Oscillating Water Column (OWC) system, where the rise and fall of the water surface inside the chamber cause air to be alternately compressed and drawn in. This airflow is then used to rotate the turbine. The turbine is connected to a DC generator, which converts mechanical energy into electrical energy. The output voltage from the generator is then amplified using a boost converter, resulting in a higher and more stable voltage output.

2.3. Oscillating Water Column System

The working principle of the Oscillating Water Column (OWC) system is to convert ocean wave energy into electrical energy based on the oscillation column mechanism. In this principle, incoming waves from the sea strike the OWC structure, which has an open-bottom column allowing seawater to enter the chamber [9].

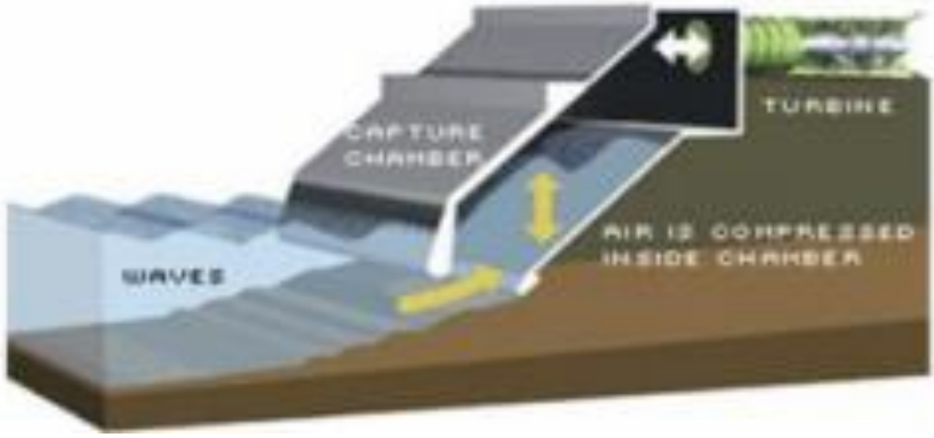

Figure 3. Oscillating Water Column System

2.4. Calculation Formulas

2.4.1. Converter Boost Converter Calculation

The working principle of a boost converter in increasing voltage is based on the charging and discharging process of the inductor and capacitor in the circuit scheme. The timing of this charging and discharging is controlled by the switching duration of the power switch, which is in turn determined by the duty cycle [15]. The relationship between the output voltage of the boost converter and the duty cycle is shown in equations (1) and (2) [16].

$$Vout = \frac{Vin}{1-D} \tag{1}$$

$$D = 1 - \frac{Vin}{Vout} \tag{2}$$

After determining the duty cycle at the boundary, the inductor resistance (RL) can be calculated using equation (3)$RL = \frac{2L}{(1-D)DT}$ (3)

With Imin = 0, equation (4) is obtained to calculate the inductor current as follows :

$$IL = \frac{Vo}{RL} \tag{4}$$

Thus, from the above equation, the maximum current (Imax) in the inductor can be determined using the following equation. (5)

$$Imax = 2 \times IL \tag{5}$$

Where :
Vin : Input voltage (V)
Vout : Output voltage (V)
D : Duty cycle
RL : Inductor resistance (Ω)
IL : Inductor current (I)
T : Period (s)

2.4.2. Wave Period Calculation

In the analysis of ocean wave period, wave length and speed are important factors, as shown in equation (6) [4]:

$$\mathrm{T} = 3{,}55\sqrt{\mathrm{H}} \tag{6}$$

Where :

T : Wave period (s)
H : Wave height (m)

2.4.3. Wave Length Calculation

After estimating the wave period from the previous analysis, the wave length and wave speed can then be calculated using equation (7) [17]

$$\lambda = 5{,}12 \times T^2 \tag{7}$$

Where :

T : Periode (s)
5,12 : Constanta

2.4.4. Wave Speed Calculation

Once the wave period and wave length are known, the wave speed can be calculated using equation (8)$\mathrm{V} = \frac{\lambda}{\mathrm{T}}$ (8)

Where :
V : Wave speed (m/s)
T : Period (s)
λ : Wave length (m)

2.4.5. Wave Power Potential Calculation

The next step in the analysis is to calculate the wave power potential that can be converted into electrical energy using equation (9) [18]

$$\mathrm{Pw} = 0{,}195 \times w.\rho.g.H^2.T \tag{9}$$

Where :

0,195 : Constanta
w : OWC chamber width (0.5 m)
ρ : Sea water density (1025 kg/m³)
g : Gravitational acceleration (9.81 m/s²)

H : Wave height (m)
T : Periods (s)

3. RESULTS AND DISCUSSION

Figure 3 presents the design sketch and the construction outcome of the laboratory-scale wave power plant. Following the construction, a series of tests were carried out using various components to assess the performance of the designed system

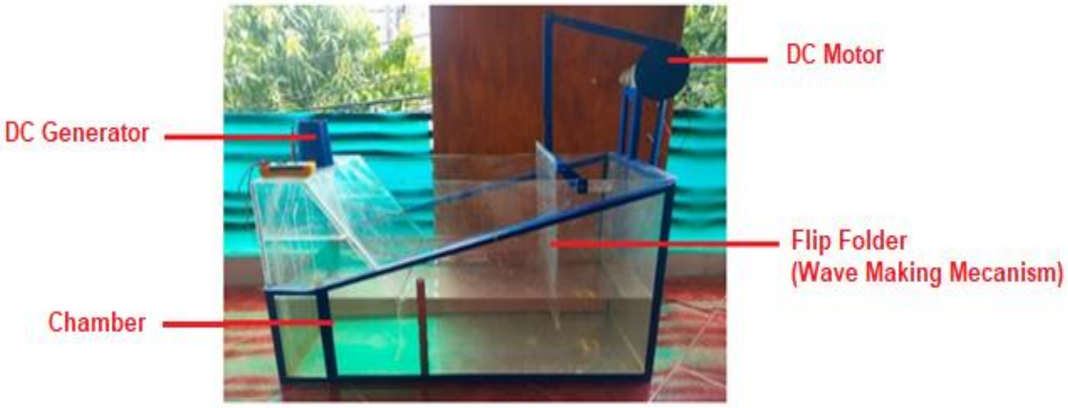

Figure 3. Laboratory-Scale Wave Power Plant Design Result

3.1. Calculation of Wave Length, Wave Period, and Wave Speed

The data in Table 1 shows the results of the wave length, wave period, and wave speed calculations at water heights of 26 cm and 27 cm.

Table 1. Wave Length, Wave Period, and Wave Speed Calculation Data

	Water Height 26 cm			Water Height 27 cm		
No.	Wave Length (m)	Wave Period (s)	Wave Speed (m/s)	Wave Length (m)	Wave Period (s)	Wave Speed (m/s)
1	0,814	0,159	5,119	0,129	0,159	0,811
2	0,322	0,251	1,283	0,323	0,251	1,286
3	0,645	0,355	1,817	0,645	0,355	1,818
4	1,29	0,502	2,569	1,29	0,502	2,569
5	1,363	0,561	2,429	1,29	0,502	2,569
6	0,968	0,435	2,225	0,968	0,435	2,225
7	1,29	0,502	2,569	0,968	0,435	2,225
8	1,29	0,502	2,569	0,645	0,355	1,818

3.2. Wave Power Potential Calculation

Tables 2 and 3 show the calculated wave power potential that can be generated to drive the turbine and produce voltage output

Table 2. Relationship Between Wave Power Potential and Turbine Voltage at 26 cm Water Height

Water Height 26 cm						
	Without Boost Converter			Boost Converter		
No.	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)
1	0,159	0,000623	0,01	0,159	0,000623	0,01
2	0,251	0,00615	0,01	0,251	0,00615	0,01

Water Height 26 cm						
	Without Boost Converter			Boost Converter		
No.	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)
3	0,355	0,0348	0,03	0,355	0,0348	0,03
4	0,502	0,1968	2,93	0,502	0,1968	3,00
5	0,561	0,3437	1,95	0,561	0,3437	2,34
6	0,435	0,0959	2,42	0,435	0,0959	2,85
7	0,502	0,1968	1,18	0,502	0,1968	1,22
8	0,502	0,1968	1,67	0,502	0,1968	1,8

Based on Table 2, the results show the calculated wave power potential used to drive the turbine and generate voltage output. At a wave period of 0.502 seconds, the wave power potential was 0.1968 watts, and the turbine produced voltages of 2.93 V and 3 V when operated without and with a boost converter, respectively.

Table 3. Relationship Between Wave Power Potential and Turbine Voltage at 27 cm Water Height

Water Height 27 cm						
	Without Boost Converter			Boost Converter		
No.	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)	Wave Period (s)	Wave Power Potential (Watt)	Turbine Voltage (V)
1	0,159	0,000623	0,01	0,159	0,000623	0,04
2	0,251	0,00615	0,01	0,251	0,00615	0,03
3	0,355	0,0348	0,01	0,355	0,0348	0,03
4	0,502	0,1968	2,69	0,502	0,1968	2,75
5	0,502	0,1968	1,1	0,502	0,1968	1,72
6	0,435	0,0959	2,24	0,435	0,0959	2,8
7	0,435	0,0959	1,27	0,435	0,0959	1,5
8	0,355	0,0348	1,42	0,355	0,0348	1,61

Based on Table 3, the results show the calculated wave power potential used to drive the turbine and generate voltage output. At a wave period of 0.502 seconds, the wave power potential was 0.1968 watts, and the turbine produced a voltage of 2.69 V. Meanwhile, at a wave period of 0.435 seconds with a wave power potential of 0.0959 watts, the turbine produced a voltage of 2.8 V—both values measured with and without the use of a boost converter.

4. KESIMPULAN

Based on the tests conducted on the design and construction of a laboratory-scale wave power generation system using the Oscillating Water Column (OWC) method, it was found that the system's performance is significantly influenced by variations in wave height, water level, and wave period. Under conditions without the use of a boost converter—where the wave height was 2 cm, the water level was 26 cm, and the wave period was 0.502 seconds—the turbine produced a voltage of 2.93 V. When the water level was increased to 27 cm with other parameters unchanged, the output voltage decreased to 2.69 V. In contrast, when the system operated with a boost converter under the same wave conditions (2 cm wave height, 26 cm water level, 0.502-second period), the turbine produced a higher voltage of 3 V. Additionally, under a wave height of 1.5 cm, water level of 27 cm, and wave period of 0.435 seconds, the generated voltage was 2.8 V. These results demonstrate that the laboratory-scale OWC system effectively converts wave energy into electrical energy, with its performance varying according to the wave parameters.

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