

Smart System for Generating green electricity from Wave energy using a laboratory model

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ABSTRACT

Wave energy converters are a promising and important technology for diversifying renewable energy sources and reducing dependence on fossil fuels. Although many converter designs have been proposed, nevertheless, buoyancy-based systems that collect wave energy using several horizontal turbines have not received much attention. This paper presents physical model experiment to converted wave energy to electrical power through a buoyancy-driven mechanism. The experiments were carried out in a recirculating open channel flume located at the Hydraulics Engineering Laboratory, Higher Institute of Engineering in El Shorouk City. The physical model consists of a horizontal rectangular buoy fixed with three turbines on its front and three turbines on its back. The maximum electrical power produced in full-scale tests that was obtained experimentally. The devices demonstrated the ability to produce energy at a water depth of 6.00 m, a wave height of 2.42 m, a frequency of 0.78 Hz, and wave energy equal 7181.4 Joule/m². It was discovered that buoyancy with three horizontal turbines mechanism performed best buoyancy than three vertical turbines. These findings advance the continuous evolution of effective, economical wave energy conversion technologies.

Keywords: write up to Wave energy converters; Power take-off; Renewable energy; Regular wave; Sonic wave sensor XB; Energy conversion efficiency; Experimental setup

I. INTRODUCTION

Temperature variations lead to wind generation. This leads to the movement of water on the surface of the sea and form waves, which move towards the shore and the advantage of these waves that they carry amounts of kinetic energy and keep them throughout the journey towards the beach. The kinetic energy of the sea waves is harnessed to mechanical works such as electricity generation. Over the past decades, numerous varieties of WECs have been created, including oscillating water columns, overtopping devices, and oscillating body systems. Practical experimental investigations concentrating on straightforward, affordable, and highly efficient WEC designs that can be adjusted to various marine situations are still required despite a great deal of study. Specifically, not enough research has been done on how buoy direction and turbine configuration affect energy extraction efficiency and system stability. This study aims to experimentally evaluate a newly developed horizontal buoy-type WEC equipped with multiple turbines, intended to enhance system balance and energy conversion efficiency. A thorough analysis of current wave energy converter research is given in the section that follows, emphasizing the devices' limitations, energy capture methods, and working principles.

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Bouhrim et al. (2024) highlighted that resource characterization relies on multiple approaches, including in situ measurements, satellite altimetry, reanalysis datasets, and spectral wave modeling. Alva et al., (2023) evaluated the impact of varying power take-off (PTO) system adaptability levels on dense wave energy converter (WEC) array power absorption. Point absorber WECs frequently employ hydraulic PTO systems, which can be modified to include accumulators and regulating valves. Various control techniques can be used to maximize the systems' performance Guo B et al., (2022). Yasser et al., (2022) investigated experimental model based on the vertical movement of the waves. Three floating pontoons with a breakwater function were combined to create a hybrid system in by Peng et al., (2021). To investigate the hydrodynamic behavior of the system under typical wave conditions, experimental tests were conducted in a wave flume. The findings demonstrated that the output stability and energy conversion efficiency are highly influenced by the pontoons' design, particularly their draft arrangement and spacing. Furthermore, power fluctuations were lessened by incorporating the pontoons into a breakwater construction. A mechanical PTO system for a rolling-type wave energy converter was presented by Jiang et al. (2020). It uses a planetary gear train and two counter-rotating flywheels to transform bidirectional rolling motion into stable unidirectional rotation. According to experimental results, the new PTO produced a reliable and low-maintenance substitute for hydraulic systems, with steady voltage and power fluctuations below 8% and a maximum mechanical efficiency of 50% at a speed increaser ratio of 13. Tay, (2020) proposed an integrated multi-raft wave energy converter coupled with a floating breakwater (IMR-WEC). Yasser, (2019) presented physical models to convert wave energy to electrical power. And each model work as a floating breakwater to dissipate the wave energy and leading to minimum transmitted wave energy. The IMR-WEC allows wave energy to be converted into electricity while also safeguarding the coast from erosion caused by wave impact. Ashlin et al., (2018) investigated in an experimental study the effect of various spacing between arrays of oscillating water column (OWC) devices incorporated with offshore-detached breakwater on their hydrodynamic performance. Wan et al., (2017) proposed one improved kind of pendulum wave energy converter (PWEC) to lower costs, which integrates a pendulum, two side-walls, and a slope to concentrate wave power to climb up and drive the floating pendulum to rotate upward. Masjono Muchtar et al. (2016) presented physical model experiment of wave energy converter based on the water mass vertical movement to be converted into renewable energy. Wassim Chehaze et al. (2016) presented wave Roller Device for Power Generation. Erik Lejerskog et al. (2015) presented Experimental results on power absorption from a wave energy converter at the Lysekil wave energy research site. Developing wave energy in Mediterranean Sea: pest analysis and examination of other non-technological barriers to the implementation and sustainable development of wave energy was studied by E. Papadopoulos and C. Synolakis (2013). A review of wave energy converter technology presented by B. Drew, A R Plummer, and MN Sahinkaya (2009).

II. MATERIALS AND METHODS

Wave flume

The experimental tests were performed in a 0.50 m wide, 0.60 m deep and 12.00 m length wave flume at the Hydraulics and water Engineering Laboratory, The higher Institute of Engineering in El Shorouk Academy. A piston-type unidirectional wave maker was installed at one end of the wave channel, and a wave absorber was located at the other end to reduce wave reflection as shown in Figure 1. Sonic Wave Sensor XB was employed to measure the wave height and wave period. To guarantee precise, non-contact readings of the wave motion, the sensor was securely placed at a height of at least one meter above the free sea surface. Figure 2 depicts the sensor's appearance. The experimental test flume is based on a 1:20 scale models.

Physical model

A pontoon waves energy converter (WEC)-type floating breakwater; the physical model consists of a horizontal rectangular buoy fixed with three turbines on its front and three turbines on its back. The rectangular buoy is made of plastic, compressed by air, and surrounded by a group of wooden panels. Its dimensions are 36.00 cm wide, 44.00 cm long, and 20.00 cm height. The turbine used in this device has four blades mounted on a horizontal axis connected to a generator, and there are curved blades on the edge of the wheel. The experiments on this model are divided

into two stages. In the first stage located at the front of the buoy, there are three vertical turbines perpendicular to the direction of the wave. One turbine is fixed in the middle of the buoy, while the other two are fixed 5.00 cm from the edges, as shown in Figure 3. The back of the buoy there are three horizontal turbines surrounded by plastic sides parallel to the surface of the water, as shown in Figure 4.

The second stage, the three vertical turbines fixed on the buoy back and three horizontal turbines surrounded by plastic sides. Through the vertical movement of the wave moving up and down, the action of the blades rotates, and the generator converts the rotation to electricity. Figure 5 shows the elevation and location of the device. A series of flume experiments were carried out at 0.24 m of water depth. The dimensions of the water wave state and the floating buoyancy with three Turbine device parameters are shown in Table (1) and Table (2)

The turbines used in this device have four blades each fitted to a rotating shaft connected to the generator. Through the vertical motion of the wave, the action of the blades rotates, making the axis rotate and thus rotating the generator. The generator converts the rotation to electric power. The resulting DC is suitable for power circuits that normally use batteries. The height of the wave, wave period, water depth, the buoy weight, and the location of the turbine were the only dependent variables in this suggested converter.



Figure 1 wave flume

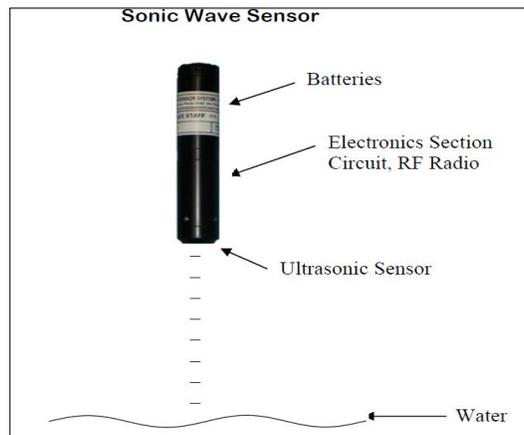


Figure 2 The Ocean Sensor Systems wireless Sonic XB

TABLE 1 Dimensions of the physical model of Floating buoyancy in 1:20 scale and its equivalent in nature.

Parameter	Unit	Experimental	Full scale
Length of buoyancy (L_b)	m	0.34 (m)	6.8
Width of buoyancy (B_b)	m	0.36	7.2
Height of buoyancy (H_b)	m	0.23	4.6
The weight of the buoy (W_b)	kg	5.00 and 9.00	10 and 18

TABLE 2 Floating buoyancy with three turbines test

Parameter	Range
Water depth (d_w)	0.24 (m)
Wave height (h_w)	0.09, 0.08, 0.075, 0.056, 0.039 and 0.031(m)
Wave period (T)	1.28, 1.46, 1.76, 2.09, 2.5 and 2.86 (s)
Wave length (L)	2.55, 3.35, 4.86, 6.68 (m)
The weight of the buoy (W_b)	5.00 and 9.00 (kg)



Figure 3 A buoyancy with three vertical turbines



Figure 4 A buoyancy with three horizontal turbines

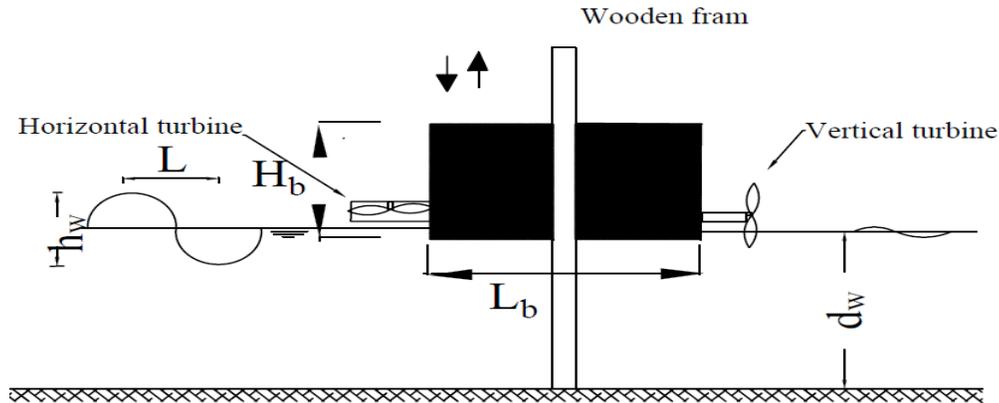


Figure 5 Definition sketch for the experimental Floating buoyancy with three Turbine (vertical and horizontal)

III. RESULTS AND DISCUSSION

Effect of wave steepness (h_w/L) on generation electrical power.

The performance of a floating buoy with three turbines on generated electrical power was investigated experimentally under regular waves. The floating buoyancy device was tested on two different weights (W_b) = 5 kg and 9 kg at a constant water depth of 0.24 m and six different wave heights and wave lengths to obtain six wave steepness ($h_w/L = 0.038, 0.026, 0.015, 0.009, 0.005, \text{ and } 0.0031$). The study was conducted on the turbines in two cases: first if they were vertical and second if they were horizontal surrounded by plastic sides.

In the first case, experiments on the floating buoy with three vertical turbines are divided into two stages; the first stage when the turbines are at the front of the buoy and the second stage

when the turbines are at the back of the buoy. **Error! Reference source not found.** shows the relation between ratio of (P_c/P_w) and wave steepness (h_w/L) for a buoy with three vertical turbines. Testing of this case showed that it could extract much electric power from waves by increasing wave steepness (h_w/L). The bigger buoy weight gets, the less efficient it becomes at harvesting electric power. The buoy with 5kg weight generates electric power of 0.037 watt, followed by (W_b) equal 9.00 kg generating 0.033 watt at (h_w/L) = 0.051 when the vertical turbines are placed at the front. When the vertical turbines were installed at the back of the buoy, (W_b) equal 5.00 kg weight generated electric power of 0.0301 watt, followed by (W_b) equal 9 kg generated 0.0272 watt at (h_w/L) = 0.051. From the graph, the turbines placed at the front of the buoy are more efficient than those placed at the back of the buoy.

In the second case, experiments on the floating buoy with three horizontal turbines surrounded by vertical plastic sides are divided into two stages, the first stage when the turbines are in front of the buoy and the second stage when the turbines are at the back of the buoy. **Error! Reference**

source not found. presents the relation between electric power and wave steepness (h_w/L) for a buoy with three horizontal turbines at two different (W_b). According to the graph, the horizontal turbines placed at the front of the buoy are more efficient than those placed at the back of the buoy. The result also showed the bigger buoy weight has lowered the efficiency of harvesting electric power. At $(h_w/L) = 0.051$, the buoy with a weight of 5.00 kg generated 0.076 watt when the horizontal turbines were placed at the front and 0.064 watt when the turbines were at the back of the buoy, while the buoy with a weight of 9 kg generated 0.069 watt and 0.0555 watt when the horizontal turbines were placed at the front and the back of the buoy, respectively.

Effect of frequency on generation electric power.

Error! Reference source not found. shows the electric power verses frequency graph for a buoy with three vertical turbines. The amount of electricity generated was increasing with increased frequency. When the vertical turbines were placed at the front of the buoy with a 5.00 kg weight, the maximum electrical power was generated from this device, which is equal to 0.034 watt at the highest value of the frequency, 0.78 Hz. Therefore, the power generation rate was proportional to frequency, as larger waves at a higher frequency thus induce a larger motion of the buoy. Shorter period waves have higher wave heights and move faster. Generally, large waves are more powerful.

From **Error! Reference source not found.**, the electric power verses frequency graph for a buoy with three horizontal turbines is shown. It can be shown that increasing frequency leads to an increase in the generation of electricity. When the horizontal turbines were placed at the front of the buoy with a 5 kg weight, the maximum electrical power was generated from this device, which was equal to 0.0763 watts at the highest value of the frequency, 0.78 Hz. Therefore, the power generation rate is proportional to the frequency.

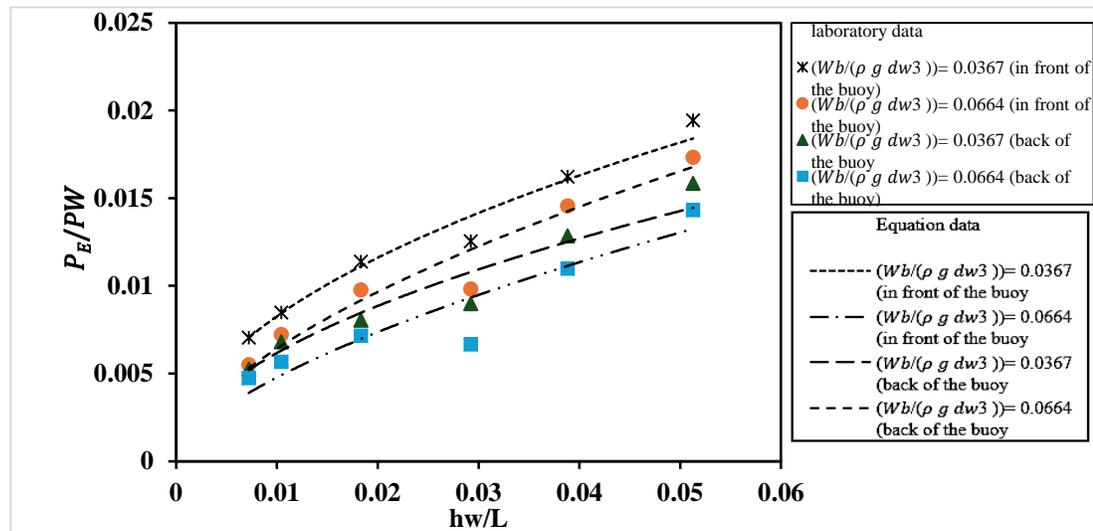


Figure 6 P_E/P_W verses wave steepness for buoy with vertical turbine at different buoyance weight

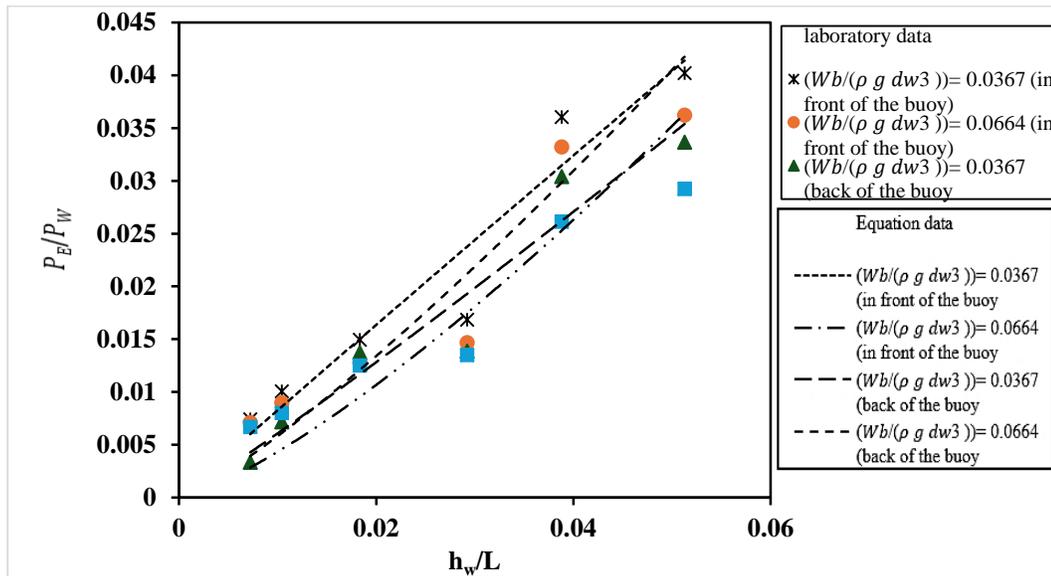


Figure 7 P_E/P_W versus wave steepness for buoy with horizontal turbine at different buoyance weight

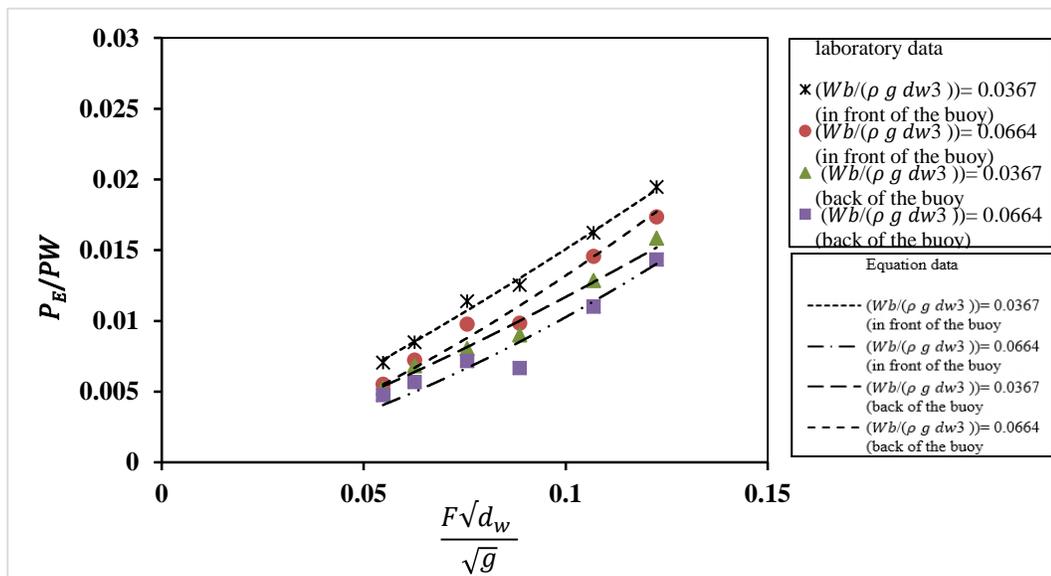


Figure 8 Relation between P_E/P_W and frequency for buoy with vertical turbine

Where: P_E is electric power, P_W is wave power, F is wave frequency, d_w is water depth, g is gravitational acceleration and W_b is weight of buoyancy.

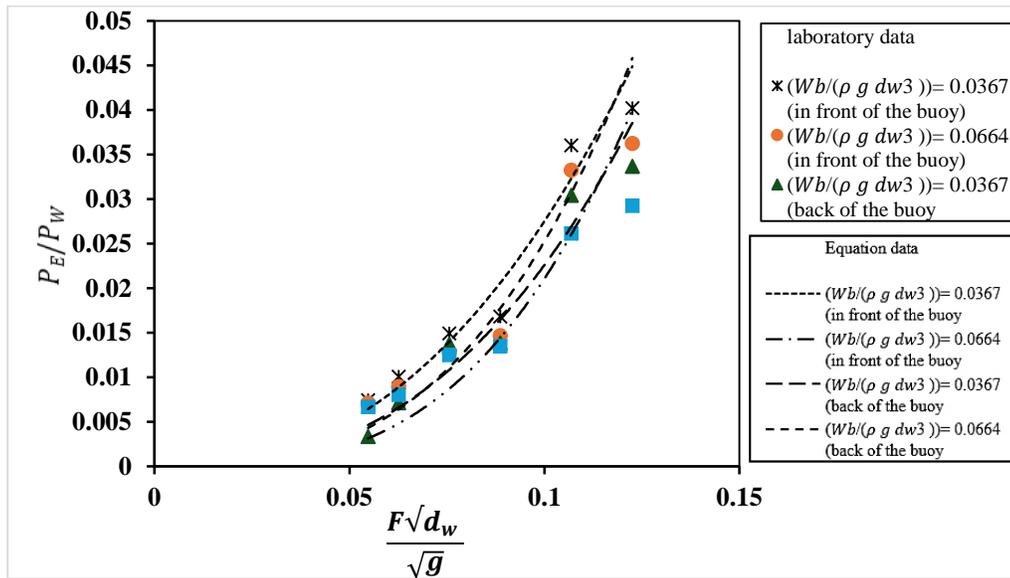


Figure 9 Relation between P_E/P_W and frequency for buoy with horizontal turbine.



Figure 10 The vertical motion of the rectangular buoy with three vertical turbines.

The vertical motion of the rectangular buoy with three vertical turbines moves up and down with the motion of the waves (**Error! Reference source not found.**). As the wave crest approaches, the buoy starts to move up (**Error! Reference source not found.** - a). the wave crest pushes the buoy up when it strikes it (Figure 10 - b). When the wave crest travels away and the trough approaches, the water level drops and the buoy moves down (Figure 10 - c), and the wave cycle repeats. During both the upwards and downward movement, the action of the blades rotates, the generator converts the rotation to electricity.

The vertical movement of the rectangular buoy with the three horizontal turbines moves with the movement of the waves up and down. As the wave crest approaches, the buoy starts to move up (Figure 10 - e). When the wave crest strikes the buoy, it moves up and the turbine blades rotate clockwise (Figure 10 - f). When the wave crest travels away and the trough approaches, the water level drops, the buoy moves down, and the turbine blades rotate counterclockwise (Figure 10 - g), and the wave cycle repeats. During both the upwards and downward movements, the action of the blades rotates, and the generator converts the rotation to electricity.

Error! Reference source not found. presents the relation between relative electric power and h_w/d_w for three vertical turbines and three horizontal turbines surrounded by vertical plastic sides when the turbines are in front of the buoy and at the back of the buoy. It is clear that the performance of vertical and horizontal turbines was better in generating power when the turbines were placed in front of the buoy compared to any other position. This is because the energy of the waves facing the front of the buoy was great. Some wave energy was lost at the back of the buoy due to waves impinging on the device. It was found that the values of electrical energy generated by the horizontal turbines surrounded by vertical sides were larger than those from the vertical turbines. The highest electrical energy generated by the horizontal turbines surrounded by vertical sides equals 1.7 times that from the vertical turbines at a wave period of 1.28 sec, 0.24 m water depth, the buoy weight equals 5 kg and $(h_w/d_w)=0.4$.

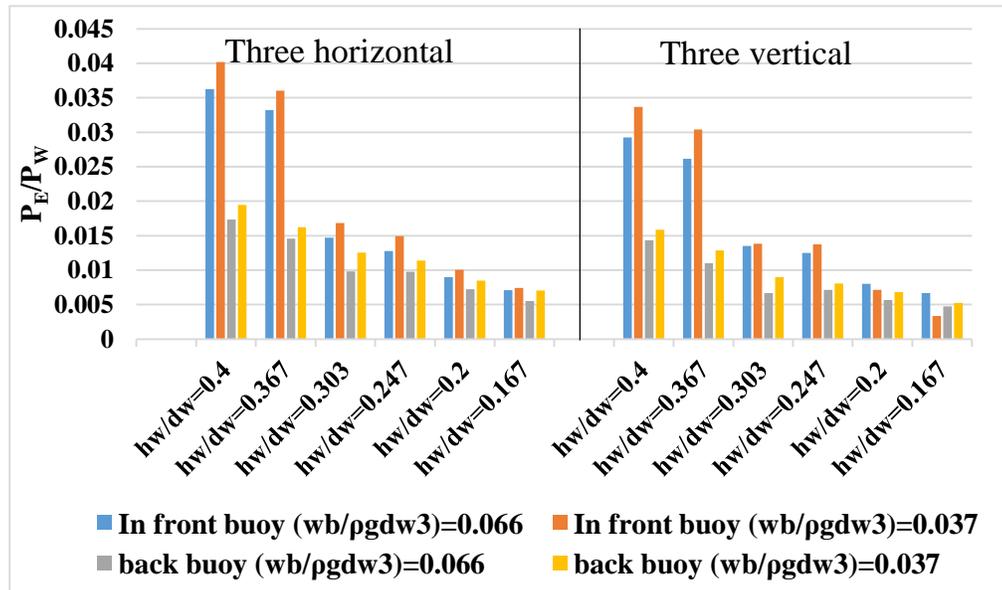


Figure 11 The relation between electric power and h_w/d_w for each vertical and horizontal turbines

Empirical equation for maximum electrical power output

A multiple linear regression analysis is used to connect the relative electrical power output with other independent parameters in order to produce empirical equations for calculating the maximum electrical power generated by a floating buoy with four dynamos. The correlation coefficients and stander errors of Eq. (1) are (98.66 %, 0.0006), for Eq. (2) are (94.48 %, 0.001),

for Eq. (3) (93.98 %, 0.0036), and for Eq. (4) are (95.10 %, 0.0027). **Error! Reference source not found.** compares the measured data to the anticipated data.

Three vertical turbine in front of the buoy

$$P_E/P_W = -0.0073 - 0.247 \left(\frac{h_w}{L}\right) + 0.336 \left(\frac{F\sqrt{d_w}}{\sqrt{g}}\right) - 0.0616 \left(\frac{W_b}{\rho g d_w^3}\right) \dots\dots\dots(1)$$

Three vertical turbine back front of the buoy

$$P_E/P_W = -0.0034 - 0.0907 \left(\frac{h_w}{L}\right) + 0.2015 \left(\frac{F\sqrt{d_w}}{\sqrt{g}}\right) - 0.0466 \left(\frac{W_b}{\rho g d_w^3}\right) \dots\dots\dots(2)$$

Three horizontal turbine in front of the buoy

$$P_E/P_W = -0.048 - 0.999 \left(\frac{h_w}{L}\right) + 1.1432 \left(\frac{F\sqrt{d_w}}{\sqrt{g}}\right) - 0.071 \left(\frac{W_b}{\rho g d_w^3}\right) \dots\dots\dots(3)$$

Three horizontal turbine back front of the buoy

$$P_E/P_W = -0.0472 - 1.026 \left(\frac{h_w}{L}\right) + 1.086 \left(\frac{F\sqrt{d_w}}{\sqrt{g}}\right) - 0.047 \left(\frac{W_b}{\rho g d_w^3}\right) \dots\dots\dots(4)$$

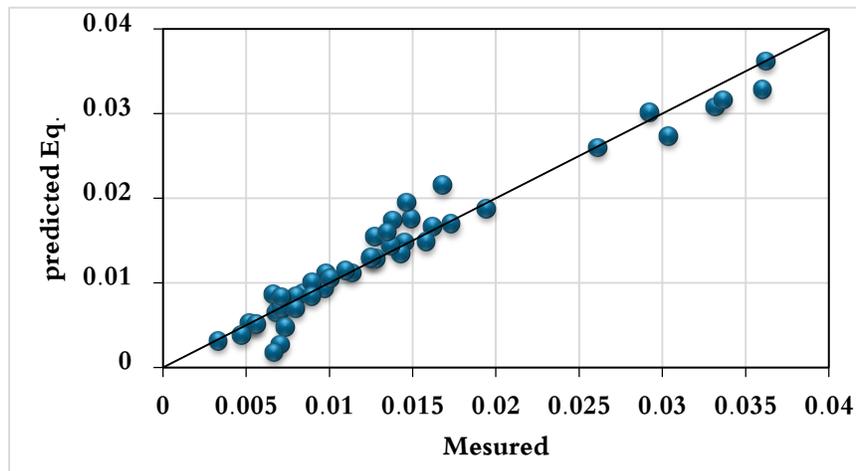


Figure 12 predicted data verses experimental data

IV. CONCLUSION

The main conclusions from floating buoy with three turbines as follows:

The buoy with 5.00 kg weight has a generating electricity of 0.228 Watt, followed by (W_b) equal 9.00 kg generated 0.19 watts at (h_w/L) = 0.038 and when the horizontal turbines placed at the front. The highest electrical energy generated by the horizontal turbines surrounded by vertical sides equal 1.7 times that from the vertical turbines at wave period equal 1.28 sec, 0.24 m water depth, the buoy weight equal 5.00 kg and (h_w/L)= 0.038. It is clear that the performance of vertical and horizontal turbines is better in generating power when the turbines are placed in the front of the buoy compared to the other position.

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