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On optimizing the wave energy converters configuration in a farm

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Abstract

In this paper a finite arrays of bottom hinged flap-type wave energy converters are modeled using a numerical approach. The converters are similar to the ones from Aquamarine Power, which is called *Oyster* and we use ANSYS-AQWA as a software for numerical simulation. The goal of this study is to optimize the annual energy absorption of a farm depending on the lateral and vertical spacing between converters based on a wave-spectrum case study. By design of some tests, the ability of ANSYS-AQWA is probed for modeling the hydrodynamic interactions of wave energy converters (WEC) in a farm. In order to obtain the acceptable results from the tests and validate the software abilities, three different layouts are presented for the farm. The performances of converters are studied in each layout and later on the layout with appropriate spacing and power-take-off systems (PTO) is chosen in order to maximize the farm annual energy absorption. Our results show that variation in the lateral spacing (perpendicular to the wave direction) of the converters changes the energy absorption slightly and the shape of energy diagram and its peak period remain the same. However, changing the vertical spacing (parallel to the wave direction) of the converters dramatically affects the energy absorption as well as the peak period of energy diagram.

Keywords: *Wave farm; Wave energy converters; ANSYS-AQWA; Wave-body interaction.*

1. Introduction

Increasing energy demand due to Earth population increase, lack of conventional energy sources and worldwide interest toward the green life, lead governments to spend significant amount of time and funding to find a reliable source of green energy. Therefore, new methods of exploring energy from natural sources have been widely investigated and studied recently. On the other hand, these studies mostly focused on wind and solar energies, while wave energy research is in its infancy. Due to the high density of seawater, the WEC has more energy absorption in comparison to wind or solar energy converters with the same size. However, commercialization of wave energy systems requires that the converters install together in large numbers and create a WEC farm. Note that due to lack of enough space near shore-line areas, the converters cannot be installed in such a distance with no effects on each other performance. The interaction between vortex shedding from the converters can cause positive or negative effects on each other performance, saying that a device in the farm may produce more or less amount of energy in comparison to that of the isolated one. Therefore, the study of this phenomenon is one of the most important issues for maximizing the energy absorption in WEC farms. In this paper, we present parametric investigations on bottom-hinged flap type converters similar to the commercial one, which is called Oyster. This kind of converter has a thin submerge rectangle flap hinged to seabed with a joint and stands in front of incoming waves and oscillates across the joint (see figure 1).

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Siddorn and Taylor [1] proposed an analytical approach to calculate the radiation and diffraction for the farm of cylinder-shape converters and compared the amount of energy absorption of a converter in the farm with a single isolated one. Babarit [2] investigated the impact of separating distance between two different kinds of heave and surge interacting wave energy converters. This author also showed that the alteration of the energy absorption due to wave interaction effects, decreases with the square root of the converters spacing distance. Pecher et al. [3] experimentally investigated the effects of wave period and direction on a pair of semi-submerged oscillating wave surge converters. Wolgamot [4] calculated the interaction factor between three-member arrays of WEC using the boundary element method and studied how converters affect each other. Furthermore, the directional analysis was carried out to find the effects of incoming wave direction on energy absorption and interaction factors. In 2013, Renzi et al. [5] showed that an array of flap-type converters is able to exploit the resonance of the system transverse modes resonance of the system transverse modes". in order to capture higher amount of energy. They used inviscid potential-flow model to obtain new expressions of the reflection, transmission and radiation coefficient for the farm of converters. In another work by Renzi et al. in 2013 [6], the semi-analytical and fully numerical models were proposed to investigate hydrodynamic parameters such as water velocity and the effects of nearby converters on the energy absorption in the array of WEC. Furthermore, in 2014 Renzi et al. [7] studied WEC farms with a large number of converters for various configurations. The effects of converters arrangement and the spacing between the flaps were investigated extensively and finally the most efficient layout was discovered to increase energy absorption of WEC array.

In 2012, Bhinder et al. [8] used the linear potential theory as well as the computational fluid dynamics (CFD) to study the effect of viscosity on annual power production. They also conducted a sensitive analysis on a range of the drag coefficient to maximize the power take off for a WEC system. Later on, in 2015, Schmitt and Elsaesser [9] used OpenFOAM CFD toolbox to assess the applicability of Reynolds-Averaged Navier-Stokes (RANS) method on simulation of flap type wave energy converters. They compared the numerical results with an experimental model of WEC and found a good agreement between them. In 2016, Tom et al. [11] introduced new types of wave surge energy converters, which have flexible attributes. These WECs can match their hydrodynamic characteristics with different sea states to maximize their power capture. The flexible converters are able to drastically increase the power take off and decrease the structure loads on the seabed supports. Recently, Kumawat et al. [10] used the three-dimensional boundary element method to assess the effect of multiple configuration on the total energy absorption of a WEC farm. They arranged the converters in two shapes of wedge and rectangular to absorb the maximum energy. In addition, they conducted another parametric study to evaluate the effect of incoming wave angle on the power capture. In the same year, Zhong and Yeung [12] studied a semi-analytical method to assess the surface-wave interactions among an array of wave-energy converters and investigated the effects of WEC numbers, their spacing, and the layout geometry on power extraction from the farm.

Due to difficulty in analytical and experimental modeling of WEC farm, we exploit computational fluid dynamic methods for this study and use ANSYS-AQWA as a modeling software. In this paper, at first, some tests are designed to evaluate the software's ability to model the WEC farm. Later on, we study the converters performance for different layouts, spacing and PTO systems to maximize the farm annual energy absorption. The PTO system is assigned to the bottom joint of the converter, which contains a spring and a damper. The application of this PTO system was studied extensively in one of the author's previous work [13].

2. Theory

In several different modeling sets, we apply hydrodynamic forces on the converters center of mass and then calculate its final displacement. Incident waves are applied in two different types: regular and irregular waves. Note that the fluid is assumed to be invicid and incompressible; and furthermore, the wave height and converters displacements are small compared to the wavelength.

We calculate hydrodynamic coefficients and wave exciting floater forces using a standard 3D linear radiation-diffraction flat panel method applied in the form of the commercial ANSYS-AQWA package. This method assumes that the flow satisfies the Laplace equation in the fluid domain and a linear boundary value problem is formulated for the fluid-solid interactions in incident harmonic waves [14]. Furthermore, Green's theorem is used to derive integral equations with unknown velocity potential on the body surface. The solution is found in the frequency domain, which is the set of some velocity-time diagrams. Afterwards, the absorbed energy by WEC can be calculated based on the velocity-time diagrams and the joint damping. By finding the absorbed energy for each device in the farm, group performance can be evaluated for its characteristics. The farm interaction factor q is one of the prevalent methods in evaluating the group performance, defined as:

$$q = \frac{P_{N,max}}{N\,P_{1,max}} \tag{1}$$

where $P_{N,\max}$ is the absorbed energy by N converters in the most efficient condition; and $P_{1,\max}$ is the absorbed energy by a single isolated device in its optimum performance condition.

3. Software ability tests

Validation of the software performance in modeling of a single wave energy converter has been widely investigated in one of the author's previous work [13]. In this paper, we design new sets of tests to investigate the software ability in modeling of wave energy converters in a farm and the effect of their oscillation on surrounding waves.

3.1. Test 1

In first test, we model the water surface in a steady state condition without any incoming waves. A horizontal external force is applied to the converter at the beginning of the test then the converter starts to swing freely across the joint and we record the fluctuations at the water surface. Figure 1 shows the water cross-section and the waves created by the converter oscillation, which is due to the applied force.

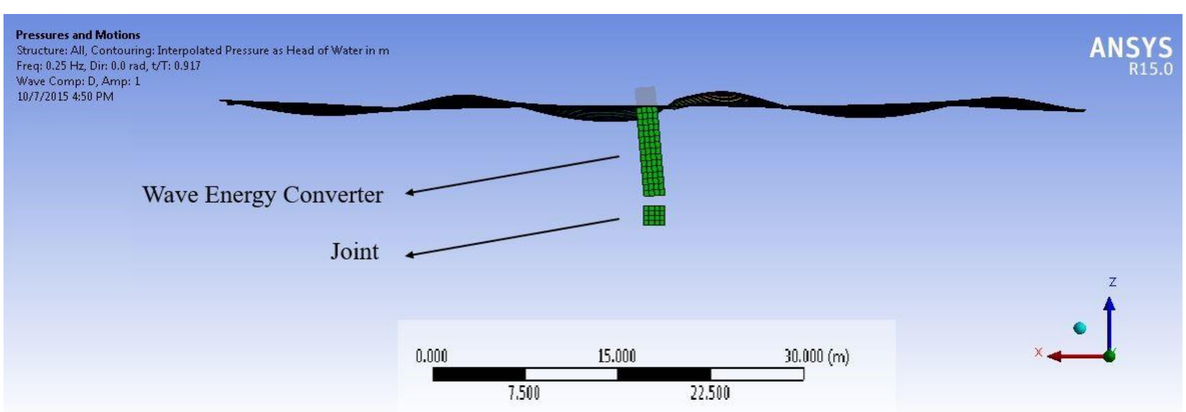

Figure 1. The water cross-section and the waves created by the converter oscillation.

3.2. Test 2

In the second test, a large solid wall (rectangular box in figure 2) is modeled in the middle of the sea, facing a regular wave, which is parallel to the positive *x* direction. The purpose of this test is to evaluate the ability of the software in modeling of diffraction and reflection phenomena. We record the fluctuations in the water surface around the solid wall. As shown in figure 2, there are two types of change in wave heights in the surrounding of the wall. At the downstream (back of the wall), the waves heights decreases as we get to the middle of the plane (see the area close to the black wall bisector shown in figure 2), while this trend is quite opposite for the other side of wall, that is saying the waves height is higher close to the bisector. Needless to say, at the upstream side of the wall, reflection is the main reason for larger wave heights, while wave collision with the wall results in energy decay and smaller wave heights at the downstream. Note that, the water surface height variation along the plane sides (parallel to *x* axis) is the reason to confirm the effect of diffraction phenomenon in the model.

We should mention that, the incident wave has the height of 1 m, while the color bar in figure 2 shows that water surface height could increase up to 30% in some locations. This results in increasing WEC displacement and rotational velocity, which in their turn lead to higher energy absorption in WEC farm. In other words, armed with an efficient spacing between converters, we can maximize the WEC farm performance exploiting from the phenomenon explained above.

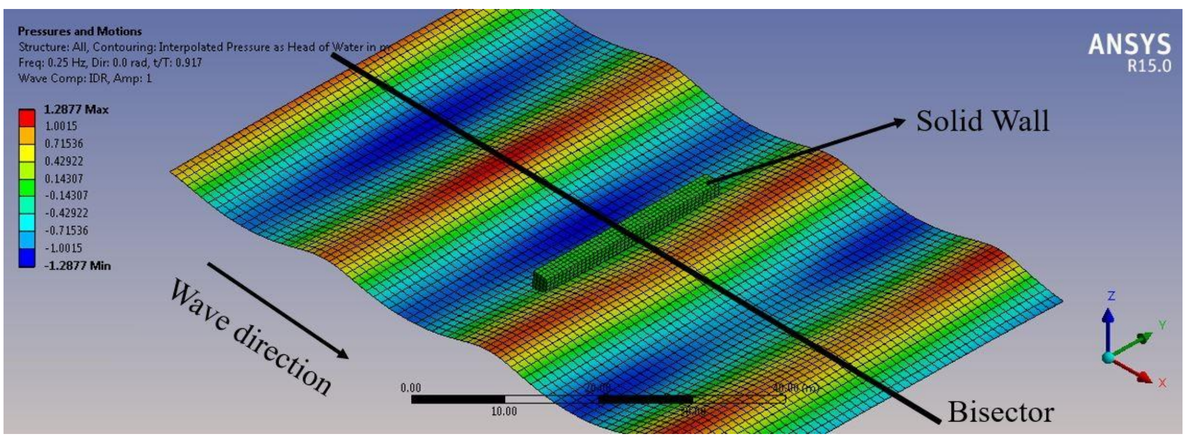

Figure 2. Wave height around a solid wall. Color bar shows the water elevation.

3.3. Test 3

In the final test, two converters with the same size and natural frequency are placed far from each other parallel to incident wave direction (positive *x*-axis). As shown in figure 3, a large rigid wall is placed in front of the converter 1. The purpose of this test is to investigate the effects of an obstacle in front of the converter on the amount of energy absorption. In this test, the large wall plays the obstacle role, while in the real condition, front line converters in the farm are the obstacle for the back-line ones. In addition, by modeling the converter 2 far from the first one and the wall (see figure 3), wave energy recovery can be investigated as well. Figure 3 shows that the wave energy decays after hitting the wall and then recovers (the wave height increases) before reaching the second converter.

The results obtained from the above tests show that the software has the primary capabilities for modeling of the WEC farm. In the next part, the energy absorption from an array of WEC will be investigated by modeling of limited number of devices placed next to each other.

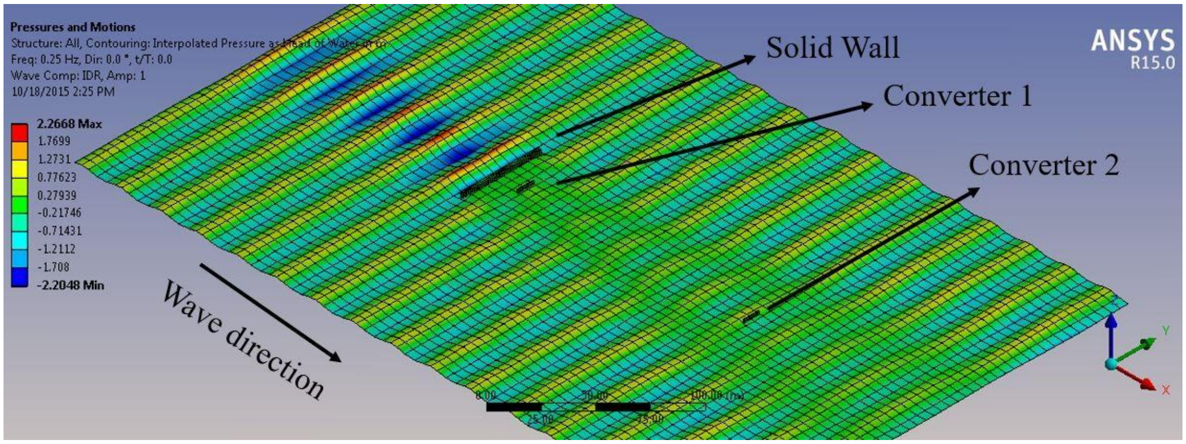

Figure 3: Water surface with solid wall and two converters. Color bar shows the water elevation.

4. Analysis of array of WECs

4.1. Design of farms

In this section, we model a WEC farm with five converters and in three different layouts as shown in figure 4. In the first stage, regular waves with 1 m height and different periods are projected to the farm and the absorbed energy is recorded for each converter with different wave periods. In order to get insight to the effects of the farm converters on each other, the performance of an isolated converter is analyzed and compared with that of the one located in a farm. Note that all converters considered here have 26 m width, 13 m height and locate in water depth of 13.5 m. The bottom of each converter has 0.5 m displacement across the seabed to satisfy software modeling discrepancies.

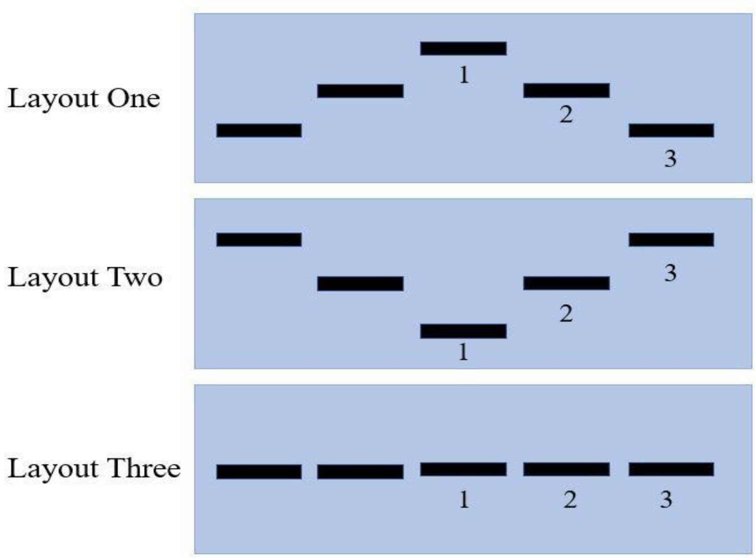

Figure 4. The schematic of five converters in three different layouts.

According to the results of the designed tests in §3, the rate of wave height variation is high close to the oscillating converters. Therefore, the main focus of this study is to investigate the effects of spacing between converters on the total energy absorption in a WEC farm. As shown in figure 5, b and d are the lateral and vertical spacing between the converters respectively. Note that several different spacing values for b and d are considered for each of the three layouts presented in figure 4. The spacing in both *x* and *y* directions (the lateral and vertical spacing respectively) change from 0 to 25 m with intervals of 5 m and this trend is repeated for every layout.

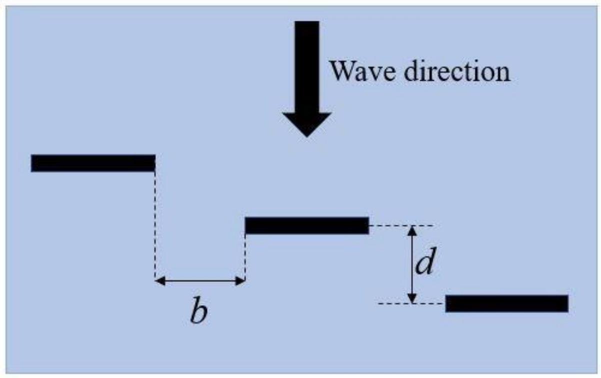

Figure 5. The schematic lateral and vertical converters spacing *b* and *d* respectively.

4.2. Effects of spacing between converters on the energy absorption

4.2.1. Lateral spacing

By fixing the vertical spacing at *d* = 20 m and varying the lateral spacing *b* from 10 m to 25 m with 5 m interval, the absorbed energy (or power) is recorded as a function of incoming wave period in the layout one (see figure 4). Figure 6 shows the results of this test while figure 4 illustrates the schematic shape of layout 1 along with converters label. The curves in figure 6(a-d) show that change in lateral spacing *b*, while the vertical spacing *d* is kept fixed, only results in a slight change in the energy absorption (power). However, the parabolic shape of the curves is almost the same and the power diagrams peak (for each converter) happens at almost the same wave periods.

According to these results, the change in the amount of energy absorption (power) is not predictable and do not follow any order, meaning that it is not monotonic as *b* increases (see figure 6(a-d)). This unpredictable phenomenon is also common in other cases with different values of *d*.

4.2.2. Vertical spacing

In this section, the lateral spacing *b*, is set to zero and the vertical spacing *d*, changes from 10m to 25m by interval of 5m in the layout one (see figure 4). Figure 7 shows the energy absorption or power as a function of the wave period for the front, middle and rear lines of converters (the solid, dash and dotted curves respectively), labeled as 1, 2 and 3 respectively, in figure 4, with parameters values mentioned earlier (*b* = 0, *d* = 10, 15, 20 and 25m). Our results here demonstrate that the change in the vertical spacing *d*, sharply changes the trend of the energy absorption or power in the farm in terms of diagrams peak location, number of peaks and the total amount of energy absorption. As shown in figure 7(a), the maximum peak for the front converter or converter 1 (labeled 1 in figure 4) happens when the wave period is about 9 sec, while the smaller peak happens around the wave period of 5 sec (see the solid line in figure 7(a)). By increasing the vertical spacing *d*, the amplitude of energy absorption around the higher wave period peak (which happens around wave period 9 sec) does not change a lot but will fade at *d* = 25 m, while the amplitude of lower wave period peak increases and the peak moves to the right (solid lines in figure 7(a-d)). This trend shows that, by increasing the vertical spacing *d* from 10 to 25 m, the second peak becomes closer to the lower wave periods, which shows effect of reflected and intensified waves from another device of the farm. In other words, increasing the distance between converters along the wave direction, increases the group effect in the farm. Our results here collectively confirm that increasing the vertical spacing *d* intensifies the effects of diffraction and reflection phenomenons, which in its turn can prove the existence of the second peak on the curves. Note that if *d* increases more (for example 35 m), the group effect start decreasing, the diagram only has one peak and the energy absorption-wave period becomes closer to an isolated converter performance in terms of value and location of the peak (the results are not shown here).

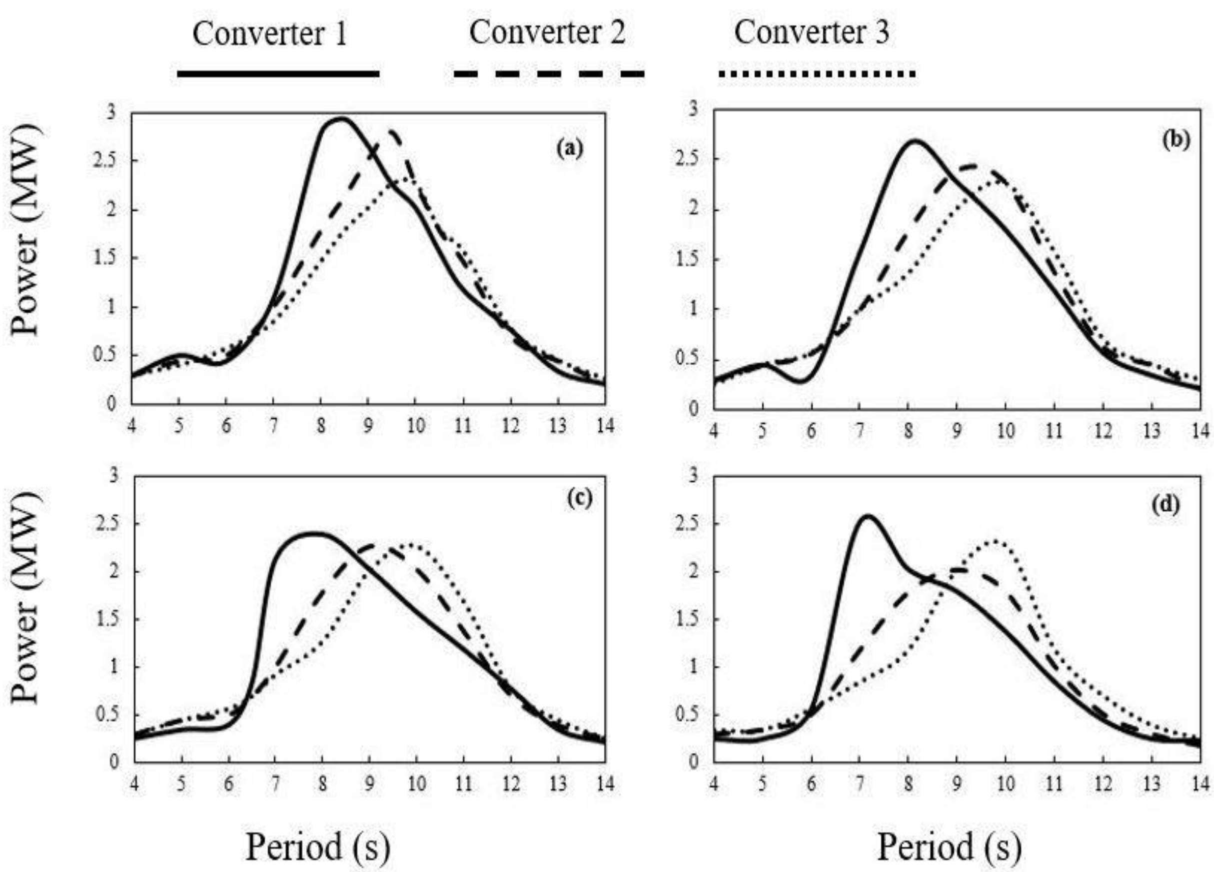

Figure 6. Energy absorption or power (the *y* axis) versus the wave period (the *x* axis) for the front, middle and rear lines of converters (the solid, dash and dotted curves respectively) for several values of the vertical spacing *d*. In (a), (b), (c) and (d) the vertical spacing *d* is 10, 15, 20 and 25 respectively.

As explained earlier, the general trend of the absorbed energy-wave period graphs can be predicted roughly, but it is still impossible to find it exactly. Needless to say there are lots of other factors that play important roles in the farm energy absorption such as incoming waves amplitude and period, reflected waves from each converter in the group, diffracted waves from each device in the group and finally created waves due to oscillation of the converters. Therefore, the purpose of this paper is to present the ideal layout and spacing between converters using a comprehensive parametric study by modeling the large number of cases and calculate energy absorption in each layout configuration.

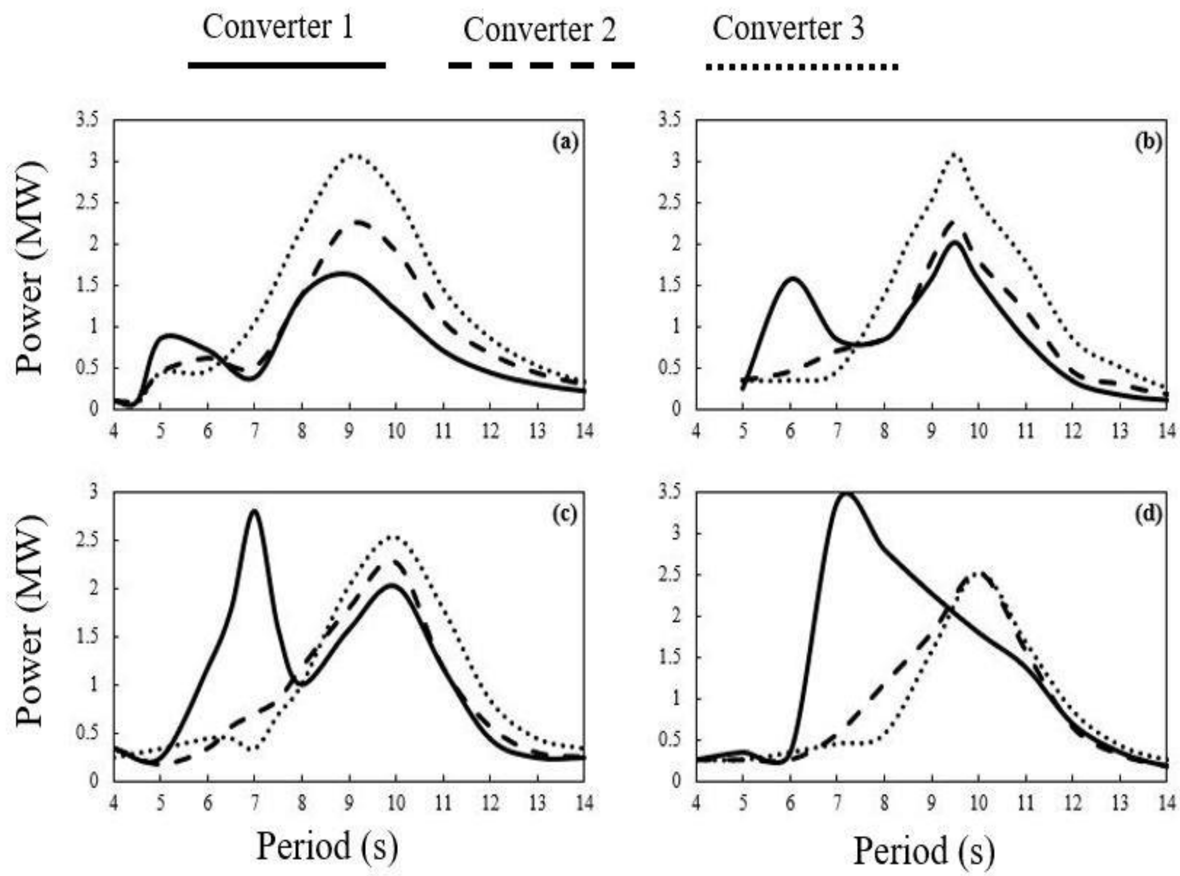

Figure 7. Energy absorption or power (the *y*-axis) versus the wave period (the *x*-axis) for the front, middle and rear lines of converters (the solid, dash and dotted curves respectively), labeled as 1, 2 and 3 respectively in figure 4, for several values of the vertical spacing *d*. In (a), (b), (c) and (d) the vertical spacing *d* is 10, 15, 20 and 25 m respectively, with lateral spacing *b* = 0.

5. Assessment of a farm performance for the wave-rose of Persian Gulf

The installation point of converters farm is located at the east of the Persian Gulf and south of the Hormuz Island with coordinates of (27.143479, 56.653061) and the depth of 13.5 m which is presented in figure 8. In addition, figure 9 shows the sites wave-rose obtained from the field study at the location. Recommended dimensions for the converters are 20 m length, 0.5 m width and 12 m height with 0.5 m displacement between the bottom of the converter and the seabed. Device power take off system is modeled by a torsional spring to create oscillating motion as well as a damper to control the increasing device motion in near-resonant conditions. In an earlier work [13], stiffness and damping of PTO system and the direction of a single converter were optimized by maximizing the energy absorption in the device. In this work, by applying the same characteristics to every device in the new WEC farm, spacing between converters is optimized in order to increase the farm performance.

Figure 8. The converters farms location at the east of the Persian Gulf and south of the Hormuz Island with coordinates of (27.143479, 56.653061) and depth of 13.5 m.

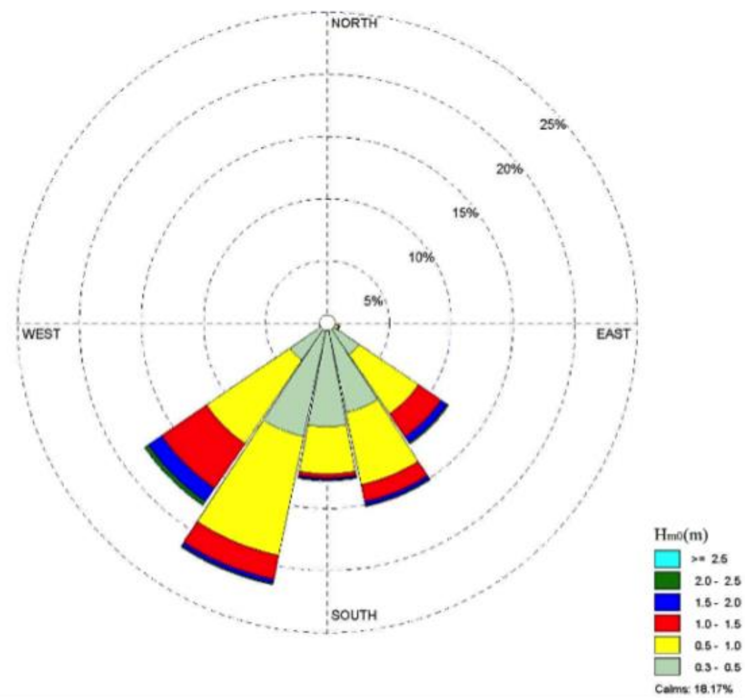

Figure 9. Wave-rose of incoming waves at the installation location shown in figure 8. The color bar shows the significant wave heights and each diagram section is the percentage of occurrence for each wave heights in the corresponding direction.

In order to calculate the energy absorption of the converters, we divide the wave-rose into 21 separated wave spectrum (total wave-rose sections, see figure 9) with specific directions, wave periods, significant wave heights and probability of occurrences. Then each of the extracted spectrum is projected to the farm and the converters oscillating motion is recorded for 500 sec. The absorbed energy of the farm for each spectrum E_k, $1 \leq k \leq 21$, is calculated by averaging the square of each converter rotational velocity in 500 sec as shown below.

$$E_k = \sum_{n=0}^{5000} \frac{c\, V_{k,n}^2}{500 \times 10}, \quad 1 \leq k \leq 21 \tag{2}$$

In this equation, c is the converters damping and $V_{k,n}$ is the converter rotational velocity at timestep n for the wave spectrum k, $1 \leq k \leq 21$. The time-step is 0.1 sec during all modeling phases. By dividing the summation of energy absorption from each spectrum by the total probability of occurrence (100), the annual energy absorption from the farm E_{total}, can be calculated as

$$E_{total} = \frac{E_1 + E_2 \ldots . + E_{21}}{100} \tag{3}$$

This calculation is repeated for every single layout (shown in figure 4) and spacing to find the most efficient configuration for the WEC farm in order to maximize the annual absorbed energy. The results are shown in §5.1–5.3.

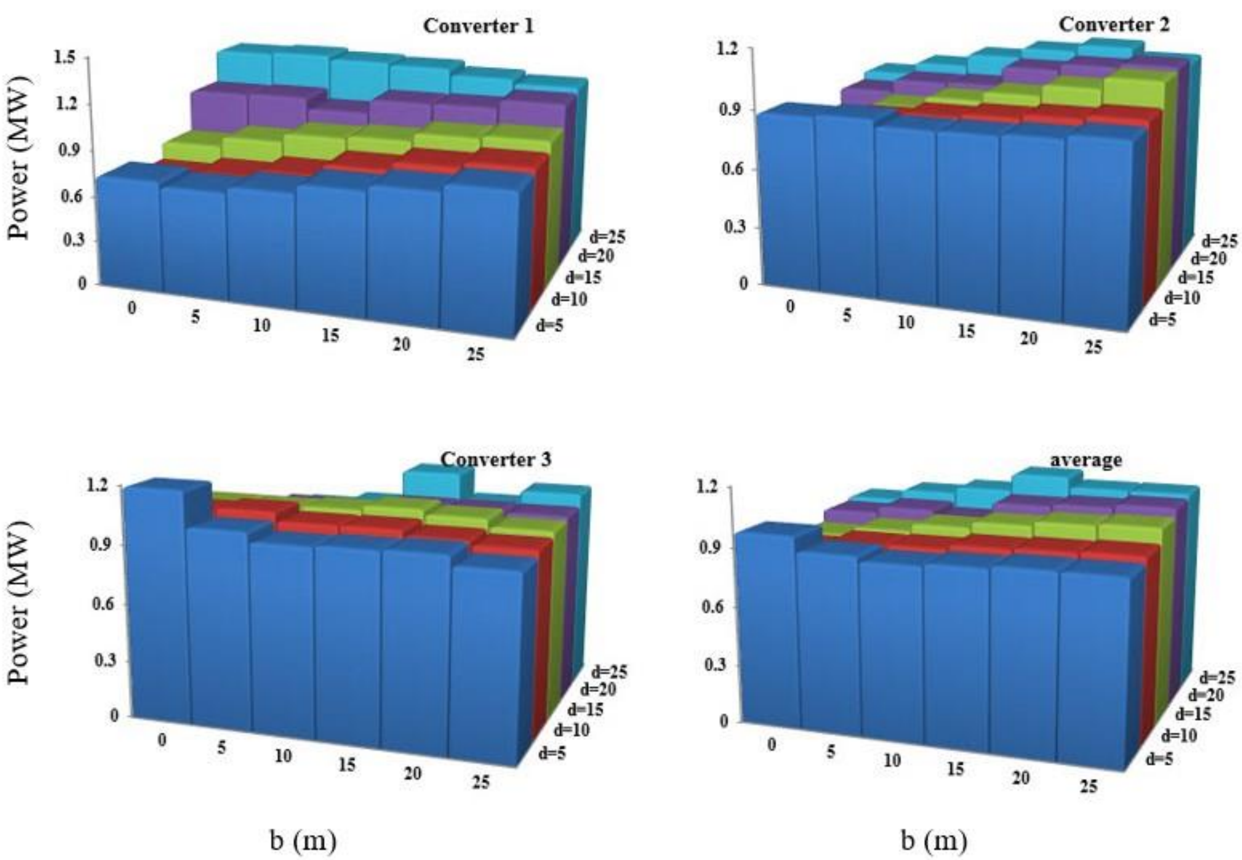

Figure 10. (a), (b) and (c) are the 3-D energy absorption diagrams for each converter (the installation location shown in figure 8) and (d) is the average absorbed energy for layout 1 shown in figure 4 versus different lateral (b) and vertical (d) spacing.

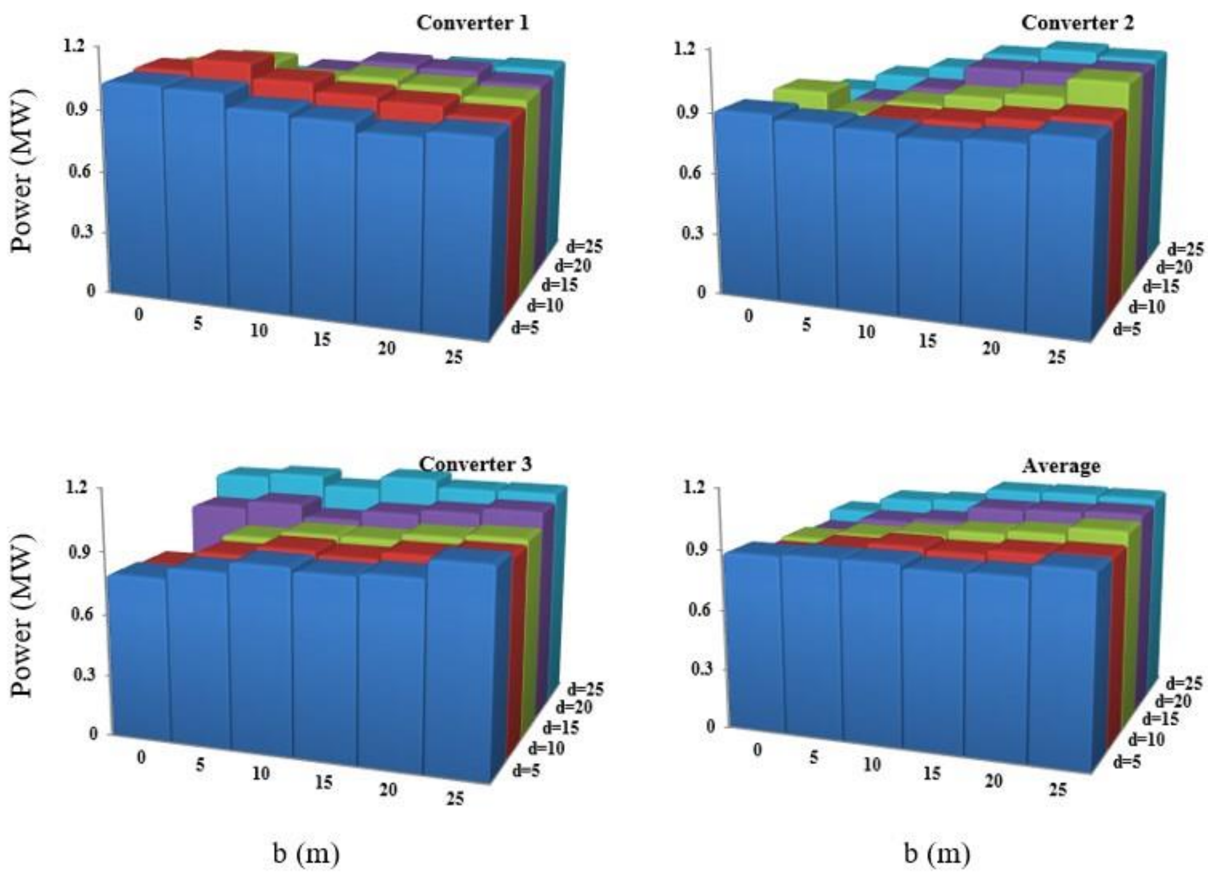

Figure 11. (a), (b) and (c) are the 3-D energy absorption diagrams for each converter (the installation location shown in figure 8) and (d) is the average absorbed energy for layout 2 shown in figure 4 versus different lateral (*b*) and vertical (*d*) spacing.

5.1. Layout one

In this subsection, we model the converters farm with the first layout configuration as presented in figure 4. Different spacing between the converters are investigated to find the most efficient spacing for the maximum absorbing energy. Figure 5.1(a) demonstrates the energy absorption for the front line converter (converter 1). As shown here, increasing the vertical spacing *d*, increases the energy absorption in converter 1. This is mainly because of the fact that as *d* increases, the group effect will increase too and generally for this layout configuration, front line converters will benefit from the effect of other converters.

The energy absorption for the middle converter (converter 2, see figure 4) is shown in figure 5.1(b). Here, the energy absorption in converter 2 increases with the lateral spacing *b*. Note that, increasing the lateral spacing between converters will help the middle lane converters to exploit more from the incident waves.

Figure 5.1(c) shows the energy absorption for the converter 3 shown in figure 4. Here, as the vertical spacing *d* varies the trend is opposite of what we found for converter 1, which may stem from that the group effect is destructive for the last line converters for most of times.

Finally, the average energy absorption of the farm is presented in figure 5.1(d), showing that the layout with the lateral and vertical spacing b = 15 m and d = 25 m respectively, is the most efficient configuration in terms of achieving the maximum energy for the layout 1 shown in figure 4.

5.2. Layout two

The layout 2 of converters configuration is shown in 4. Note that all reasoning and and explanations given for the layout 1 earlier in §5.1, can be applied for this layout as well. As the vertical spacing d increases, the performance of the first line converters (converter 3) increases and vice versa. In addition, the energy absorption for converter 2, in most cases, increases by increasing the lateral spacing b. Note that figure 5.3(d) shows with the lateral and vertical spacing b = 20 m and d = 25 m the annual energy absorption for layout 2, achieves its maximum.

5.3. Layout three

In the layout 3, the converters are installed next to each other in a horizontal line (here the vertical spacing d = 0). Figure 4 shows the shape of the layout and the converters labels. The lateral spacing b varies from 5 m to 25 m and the energy absorption was calculated for each converter in different spacing. Figure 12 shows the absorbed energy versus the lateral spacing b for all converters. Our results here show that, there exists a minimum energy absorption around b = 15 m, while the highest performance can be achieved at a smaller spacing.

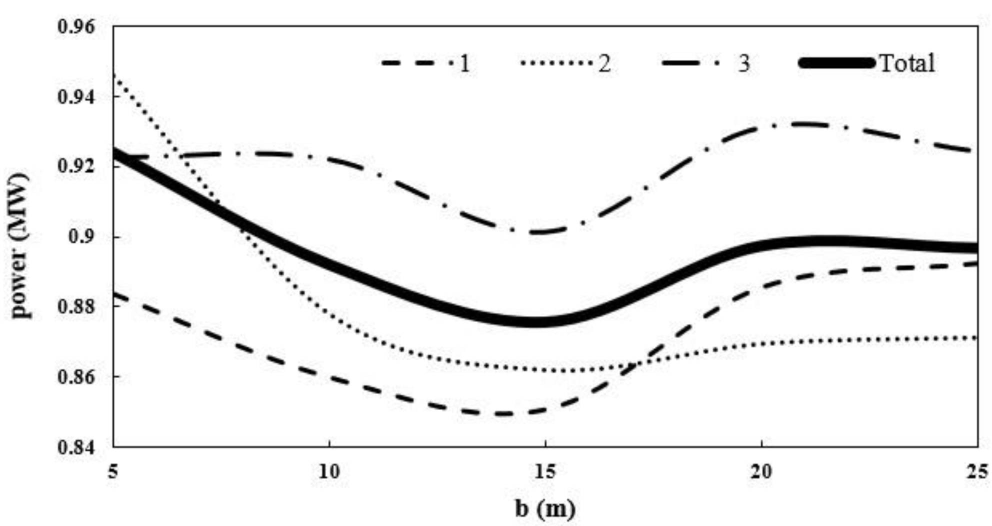

Figure 12. Energy absorption for each converter and the total average absorbed energy (labeled "Total" in the legend) versus the lateral spacing b for layout 3 shown in figure 4.

5.4. Comparison of the layout and the solo device performances

We model a single converter in an isolated condition to assess the performance of the converters in the farm. The solo converter has the exact same characteristics of the converters used in the farm. In addition, the same wave spectrum is projected to the isolated converter and absorbed energy from the converter is recorded. The amount of the absorbed energy from each layout in their most efficient spacing is divided into the number of converters in the farm. The results are the index to evaluate the farm performance in comparison to a solo converter.

Table 1 shows the layout 1 and 2 both have a constructive attitude in the WEC farm and absorb more amounts of energy compare to the solo device, while layout 3 has a destructive attitude and the average absorbed energy of converters in the farm is less than the one by the solo converter. Furthermore, the layout 1 is the most efficient layout configuration due to absorbed energy ratio.

Table 1. The ratio of energy absorption from each layout compare to the isolated converter.

	Absorbed energy for each layout in their most efficient spacing (MW)	Ratio of absorbed energy from the group converter to the isolated converter
Isolated converter	0.98	1
Layout 1	1.18	1.2
Layout 2	1.07	1.09
Layout 3	0.92	0.94

6. Conclusions

In a WEC farm variation in the lateral spacing *b*, slightly changes the amount of energy absorption by saving the absorption trend. While changing the vertical spacing between converters *d*, will sharply change the amount of energy absorption, shape of energy diagram and peak periods. In addition, changing the vertical spacing relocates the peak of the energy diagram or even creates a second peak. We have found that increasing the vertical spacing will increase the group interaction effect in the WEC farm, saying that the constructive and destructive effects on the front and the rear lines converters respectively, both increase with *d*.

In general, the energy absorption versus period curves for different values of the vertical spacing *d*, demonstrate almost parabolic shapes. This shows that the maximum interaction between converters occur in a certain spacing and by increasing or decreasing this displacement the interaction factor will decrease. In our case study the peak of interaction factor happens in $d = 25$ m. Result of this study shows that average absorbed energy from the WEC farm in layouts one and two are respectively 18 and 7 percent more than absorbed energy by the solo converter and these two layouts have constructive effect on the farm energy absorption. While layout three has destructive effect by 8% decrease on energy absorption compared to an isolated device.

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