Power Smoothing by Aggregation of Wave Energy Converters for Minimizing Electrical Energy Storage Requirements

M. Molinas¹, O. Skjervheim¹, B. Sørby², P. Andreasen¹, S. Lundberg³, T. Undeland²

¹ Department of Electric Power Engineering, Norwegian University of Science and Technology
O.S. Bragstad plass 2E 7491 Trondheim, Norway
E-mail: marta.molinas@elkraft.ntnu.no

² Department of Mathematics and Technology, Norwegian University of Life Sciences
P.O. Box 5003, NO-1432 Aas, Norway
E-mail: bsorby@gmail.com

³ Department of Electrical Engineering, Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
E-mail: stefan.lundberg@chalmers.se

Abstract

The degree of reduction of required electrical energy storage for smoothing the power output in a wave farm is investigated by considering spatial power smoothing by a particular choice of aggregation of wave energy converters (WEC). Several possible arrays are analyzed considering that no energy storage is provided locally at each WEC unit and that all energy storage required will be electrical and provided at the point of connection to the electrical network. This paper focuses on a case study of direct drive WEC for near shore devices and the power output data implemented in the study derives from a linear hydrodynamic model developed in Matlab with input forces obtained by solving the radiation problem with the finite element simulation tool Comsol. The results from simulations indicate that there is a significant smoothing effect for sinusoidal waves and quite a good short term smoothing effect is achieved in an irregular sea.

Keywords: power smoothing, near shore devices, spatial averaging effect, electrical energy storage

Nomenclature

\( \lambda \) = wave length of sinusoidal wave
\( T \) = period of a sinusoidal wave
\( H \) = height of a sinusoidal wave
\( x \) = distance from WECs to the wave front
\( n \) = number of WEC units
\( t_s \) = time shift
\( d_s \) = distance between rows in a WEC
\( T_z \) = statistical wave period
\( H_s \) = significant wave height
\( T_o \) = eigen period of WEC

Introduction

Ocean waves harbour and transport energy of widely variable and unpredictable nature. Short and long term fluctuation of extractable power from waves can pose serious concerns when it comes to deliver this power to the electrical network. When large scale integration of wave power is being considered, energy storage becomes then the key to widespread acceptability on a utility system.

For a single WEC the variation of the power output can be quite large, since without any means of energy storage, the instantaneous power absorption goes from zero to maximum output within seconds. If several WECs are connected together in a wave farm, this variation will be reduced although it may still be a challenge for the power quality. A study shows that for a farm with 64 uncorrelated devices in a typical sea state, the power variation is 3.6 to 1 [1].

Depending on the power take off system, energy storage could be implemented in different stages of the conversion chain. It is recognized that energy storage in the first stages of energy conversion will reduce the stresses and required ratings of components in the subsequent conversion stages. However, when the WEC unit is not provided with energy storage, a centralized electrical energy storage unit at the point of connection with the electrical network should be considered. It is then desirable to be able to minimize the storage requirement of such centralized unit.

In order to reduce the required rating of electrical energy storage for direct drive wave energy converters, a first smoothing by spatial aggregation of several WEC units is considered and proposed in this paper. The principle of spatial averaging is based on a well known trigonometric principle that can be implemented in a very simple way by spacing the WECs in a specific manner in the sea with respect to the wave front. This generalized approach of spatial arrangement of WEC units will have as a result the effect of averaging the fluctuating power extracted from the wave energy converters, assuming purely sinusoidal waves. A few references can be found in the literature regarding spatial arrangement of WECs for maximizing the power extraction of an array or for smoothing the power to be...
delivered to the network [2-4]. With the purpose of demonstrating this principle, a particular concept of wave energy converter is chosen and analyzed [5]. These WECs are placed in an array as shown in Fig. 1, in which the distance $x$ between WECs is calculated according to the proposed principle. Each WEC consists of a semi submerged platform with 21 eggs (point absorbers) that are moving in heave by the exciting force of the waves. The power extraction of one egg is first obtained by using a linear hydrodynamic model of one egg developed in Matlab. This is then extended to 21 eggs that are part of the platform, as shown in Fig. 2, and the total power of the platform is calculated by phase shifting the power obtained for one egg according to the phase displacement introduced by the distance between eggs with respect to the wave length. To demonstrate the principle, 7 platforms are first studied. An assumption made in this study is that the platform itself is not moving by the influence of the waves and therefore in a strict sense the platform is composed by a cluster of 21 eggs moving in heave by the influence of the waves.

1 The Principle of the Spatial Averaging

An investigation of the power averaging principle is done by a simulation study in which two possible arrays are considered:

- A random array of 7 platforms. If platforms are randomly spaced, this aggregation will be stochastic.
- A specific array of 7 platforms with a spacing between platforms given by the principle that adding up sinusoidal signals with the same frequency displaced by $360/n$ will give as a result a constant value that corresponds to the average value of the given signal. Applied to the extracted power from each platform, the implementation of this principle will give as a result the average value of the power obtained by each platform. In other words, this method consists on a spatial averaging on the sea of the power extracted from the waves.

Figure 1: Array of several platforms to compose a wave farm based on the principle of spatial averaging delivered to the network [2-4]. With the purpose of demonstrating this principle, a particular concept of wave energy converter is chosen and analyzed [5]. These WECs are placed in an array as shown in Fig. 1, in which the distance $x$ between WECs is calculated according to the proposed principle. Each WEC consists of a semi submerged platform with 21 eggs (point absorbers) that are moving in heave by the exciting force of the waves. The power extraction of one egg is first obtained by using a linear hydrodynamic model of one egg developed in Matlab. This is then extended to 21 eggs that are part of the platform, as shown in Fig. 2, and the total power of the platform is calculated by phase shifting the power obtained for one egg according to the phase displacement introduced by the distance between eggs with respect to the wave length. To demonstrate the principle, 7 platforms are first studied. An assumption made in this study is that the platform itself is not moving by the influence of the waves and therefore in a strict sense the platform is composed by a cluster of 21 eggs moving in heave by the influence of the waves.

Figure 2: Geometry of the platform under study: 21 eggs distributed in 5 rows

The approach will consist on achieving power smoothing by phase displacing the output power of each platform by siting the platforms with a separation between each other given by:

$$x = \frac{\lambda}{n} \quad (1)$$

Where $\lambda$ is the wave length and can be estimated by using the relation

$$\lambda = \frac{2\pi g}{\omega^2} \quad (2)$$

where $\omega$ is the wave frequency, $n$ is the number of platforms in the farm and $g$ is the acceleration of gravity. Figure 1 shows an array example for smoothing the total output power. Figure 2 shows the chosen platform under consideration for demonstration of the principle. This consideration is done assuming that that each platform output power is sinusoidal (assuming that passive loading is performed on eggs of each platform, the power output can be approximated by a sine wave) and that the angle of incidence does not considerably change for each platform.

Figure 3: Illustration of the egg used in the WEC system of this paper
That means that perfect smoothing will only be achieved under certain particular conditions such as constant wave directionality (which is likely to happen near shore), sinusoidal waves and stiff position of the platforms.

2 Simulation Model of WEC

The WEC units under study in this paper consist on a platform with 21 eggs or point absorbers as shown in Fig. 2. Eggs are placed on 5 rows. The distances between the rows are assumed to be 8 m and the platform is assumed to be 40x40 m. The power production from one egg is used for the calculation of the power production of one platform. First, the power production for each row is calculated by multiplying the power production of one egg by the numbers of eggs in the row and time shifting to compensate for the time it takes for the wave to propagate through the platform. The total power production for the platform is calculated by adding up the power from the rows. The time shift between rows can be approximated as:

\[ t_i = \frac{2\pi d_i}{gT} \]  

(3)

All power conversions are assumed to be loss-less. The above assumption does not take into consideration the attenuation effect of adjacent rows.

The egg analyzed in this paper is shown in Fig. 3. Hydrodynamics effects of adjacent eggs in a platform are neglected in this study.

In the following sections the principle described here will be tested under two types of waves. The first one with a purely theoretical meaning will be the platform being excited by sinusoidal waves and it will serve to prove the principle. The second one, a more practical case, will be the platform being excited by irregular waves and the main purpose will be to observe the degree of smoothing that can be expected by implementing the approach proposed in this paper under real sea conditions.

3 WEC Excited by Sinusoidal Waves

Based on the model described previously, the power of one platform is calculated using the power of one egg obtained by simulations with the Matlab linear hydrodynamic model. Sinusoidal wave parameters chosen for the study are given in Table 1. Then, the proposed principle is implemented by siting the 7 platforms in the sea with a distance between each other corresponding to equation (1).

<table>
<thead>
<tr>
<th>GEOMETRY OF THE EGG AND WAVE TYPES</th>
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<tbody>
<tr>
<td>Egg: cylindrical body with hemispherical base</td>
</tr>
<tr>
<td>Mass: 3000 Kg</td>
</tr>
<tr>
<td>Submerged part: 18 cm</td>
</tr>
<tr>
<td>Eigen period: ( T_o = 2.27 \text{ s} )</td>
</tr>
<tr>
<td>Sinusoidal Wave</td>
</tr>
<tr>
<td>( T = 7.5 \text{ sec.} )</td>
</tr>
<tr>
<td>( H = 2 \text{ m} )</td>
</tr>
<tr>
<td>Irregular Wave</td>
</tr>
<tr>
<td>Pierson-Moskowitz wave</td>
</tr>
<tr>
<td>( T_p = 7.5 \text{ sec.} )</td>
</tr>
<tr>
<td>( H_s = 2.5 \text{ m} )</td>
</tr>
</tbody>
</table>

Figure 4: Power extraction from each row of the platform and total power of the platform for the case of passive loading

Figure 5: Power extraction from each row of the platform and total power of the platform for the case of latching control

Figure 6: Spatial averaging with 7 platforms for passive loading and latching control (incoming wave \( T = 7.5 \text{ seconds} \), design wave \( T = 7.5 \text{ seconds} \))
The fluctuation of power for each row in the platform and of case of passive loading being implemented. Figure 5 shows power of a single platform operating on its own, for the each row in the platform and the fluctuation of the total platforms in the first row and the remaining 3 on a second row separated by a distance corresponding to half of the wave length gives as a result peak to peak power variation of 1400 kW). In short, according to the simulation results portrayed in Fig. 6 the need for electrical energy storage is considerably reduced compared to a random array.

A sensitivity case is presented in Fig. 7. The sensitivity of the proposed array is investigated for the case in which the platform is excited by a different wave frequency from that used to determine the distance between platforms in the array. In order to test the sensitivity of the array configuration with a fixed distance based on the design wave frequency, a different incoming wave frequency was tested by simulations (T=5 seconds) and the results are observed in Fig. 7. It is clear that the smoothing effect is reduced because the distance of the array was selected based on a wave length corresponding to T=7.5 seconds. However, the oscillation is not as pronounced for the passive loading as for the latching control. These results suggests that there would still be a possibility of having a smoothing approach for several wave frequencies based on a more sophisticated dispatching approach of the right platform that corresponds to the incoming wave frequency (moving platforms).

In general, the results of the simulations done indicate that aggregation of multiple units based on the proposed principle will lead to some power smoothing even for non perfect sinusoidal wave forms as can be seen in the example of Figs. 6 and 7. This gives room for investigating the performance of the proposed principle in the case of a random sea, considering that an irregular wave will be composed by the superposition of several sinusoidal waves of similar periods. Considering that the period of the wave front varies typically in the order of 6 to 10 seconds, it may be appropriate to design the spacing of platforms according to the same principle applied to sinusoidal waves to reduce power fluctuation considerably even for irregular waves.

4 WEC Excited by Irregular Waves

Once the principle of spatial averaging has been demonstrated for the case of sinusoidal waves, it is necessary to investigate how the principle will apply in a random sea. In order to test the principle of the array of platforms in a random sea the Pierson-Moskowitz spectrum is used to represent the random sea, with significant wave height $H_s=2.5\text{m}$ and peak period $T_p=7.5\text{s}$. Dimensions, geometry, and irregular wave parameters are given in Table 1. Excitation forces originated by irregular waves are generated for each of the 7 platforms by phase shifting according to the distance between platforms given by the principle proposed in this paper. This distance is kept the same as in the example with sinusoidal waves because the frequency spectrum is selected so that the peak corresponds to a $T_p$ with a period equal to the one of the sinusoidal wave. Once the irregular waves are generated for each platform, the power absorption by each platform is obtained by first calculating the excitation forces corresponding to these irregular waves and then running the simulation in Matlab to obtain the extracted power. This is done 7 times for each platform. To obtain the total power of

![Figure 7: Sensitivity of spatial averaging with 7 platforms for passive loading and latching control (incoming wave T=5 seconds, design wave T=7.5 seconds)](image)

**Table 1: Geometry of buoy and wave types**

Figure 4 shows the fluctuation of power that applies to each row in the platform and the fluctuation of the total power of a single platform operating on its own, for the case of passive loading being implemented. Figure 5 shows the fluctuation of power for each row in the platform and of the platform total power for the case of latching control being implemented. Considering the implementation of passive loading and observing that the total power of a platform resembles closely a sinusoidal wave, the principle proposed in this paper is then implemented. Figure 6 illustrates the result of implementing the proposed spatial averaging principle. The power of each of the 7 platforms is shown by the upper lines and the averaged power is shown in the lower lines for passive loading and latching control. The negative sign is the convention for generated power. The results shown are for a limitation on average power of each egg to 31 kW and for peak power to 110 kW. This limitation represents the ratings of the electrical generator and of the power electronics converter respectively. A more advanced electrical model that will include the electrical machine and the power electronics in detail is being developed and the results obtained with such model will be compared with the ones presented here in a further stage of this investigation.

The simulation results verify that there is a significant averaging effect for the two possible control strategies: passive loading and latching control. Observing Fig. 6, there is remarkable smoothing effect for the case of passive loading (variations peak to peak of 100 kW) while more fluctuations are observed for the case of latching control but with the additional advantage of 1000 kW of extra power extraction. The random array (placing the 7 platforms in one row) gives a variation of peak to peak power of 3000 kW. If another array is used (placing 4 platforms in the first row and the remaining 3 on a second
Also in this case a sensitivity analysis is performed to test the principle when another wave group (different from the wave period $T_p$ used for determining the spacing between platforms) hits the platforms. This wave group is generated using a wave spectrum in which the peak corresponds to a $T_p = 5s$. The result of this case is illustrated in Fig. 9 and we can observe that the deviation from the ideal case is not that significant as the deviation observed in the previous figure. Considering that the variation of sea states frequencies is not that wide, we can conclude that the sensitivity of the approach is good and the averaging technique promises to be robust.

The smoothing effect observed is on the short term (the order of a wave period). These short term fluctuations can be the cause of quality problems in the power delivered to the electric network. Voltage flicker could be one of the most fastidious effects to be observed in the network. Without local or centralized energy storage, this problem can be significantly reduced by the implementation of the principle of spatial averaging. As observed in Fig. 8, the peak power is also reduced although fundamentally the long term fluctuations remain.

5 Discussion

This paper proposes a spatial averaging principle very simple to implement for smoothing of the extracted wave farm power. For calculating the total power extracted by a platform, a simple phase shifting approach was implemented. By doing this, the hydrodynamic effects of eggs close to each other are being neglected. Based on observation of the simulation results it is clear that the arrangement of eggs in the platform itself could be optimized utilizing the same principle of spatial averaging presented here for the arrangement of platforms in the sea. This will probably give a smoother power output of each platform and therefore a much better smoothing could be achieved with the farm array. In order to have a more accurate model of the extractable power under this type of platforms it is necessary to take into account the hydrodynamic interferences between adjacent eggs and observe the influence this will have in the extractable power. This will be part of further investigation [6]. As a preliminary conclusion it could be said that after the smoothing effect less electrical energy storage (to compensate for a peak to peak power of 100 kW compared to total production of 4000 kW) with a centralized energy storage device will be needed for compensation at the point of interconnection with the electrical network. Further improvement of the technique can be done (with a sophisticated sequence for dispatching platforms) to minimize the need of electrical energy storage in a random sea. The averaging effect treated in this paper for power smoothing is valid only for short term smoothing. In real sea conditions, there will be large fluctuations in the long term and different approaches can be exploited to cope with this. One could be the geographical smoothing based on the same principle by coordinating the dispatching of wave farms at different sea states. Another approach could be by complementing the time delay between wind and wave as discussed in [7]. In terms of electrical energy storage, as
presented in [8-9], there are several alternatives to be discussed and the one that suits the direct drive power take off system could be the flywheel for each WEC unit as a local energy storage solution. Another one, could be a STATCOM with energy storage in the DC link such as super capacitors as one centralized energy storage solution which will also provide voltage smoothing and stability support to the network [10]

References


