Renewable Energy 58 (2013) 68–78

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Review

On the park effect in arrays of oscillating wave energy converters

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ARTICLE INFO

Article history:
Received 25 July 2012
Accepted 7 March 2013
Available online 1 April 2013

Keywords:
Wave energy converter
Array
Power absorption
Wave interactions
Park effect

ABSTRACT

This paper aims to provide guidelines for designing the layout of arrays of oscillating Wave Energy Converters (WECs) based on a review of the literature of wave interactions and park effect in WEC arrays that has been published over the past 30 years.

First, the fundamentals of wave energy absorption by oscillating bodies are summarised, and the principal differences between the park effect in arrays of wave energy converters and wind turbines are highlighted. Then, the numerical approaches commonly used to deal with WEC arrays are outlined briefly and their limitations are discussed. It is argued that, at present, only Boundary Element Methods (BEM) are capable of the appropriate analysis. Finally, previous work on wave interactions and park effect in WEC arrays is reviewed. Similar trends are found in these studies, which allow conclusions to be drawn regarding the significance of the park effect as a function of the number of WECs in the array and their spacing. Based on these conclusions, the following tentative guidelines are proposed:

For small arrays of conventional devices (fewer than 10 devices of typical dimension 10–20 m) with usual layouts (regular or shifted grids with separating distance of order 100–200 m), the park effect appears to be negligible. For larger arrays (more than 10 devices), a negative park effect seems to be increasingly important with increasing number of rows (the lines of WECs perpendicular to the incident wave direction). Therefore, the number of rows should remain as small as possible, with a separating distance as large as possible. For arrays of non-conventional WECs (WECs of typical dimensions much larger than 10–20 m), no information has been found. However, trends similar to the previous cases could be expected, provided that aspect ratios are maintained.

1. Introduction

By definition, any renewable energy converter absorbs a certain amount of the energy resource. Therefore, the total available resource is reduced for other energy converters located nearby. In consequence, the total power from an array of N energy converters is less than N times the power of one isolated unit. This is called the park effect.

The park effect is well known in the wind turbine industry. Studies have shown that the park effect decreases as a function of increasing distance between the wind turbines. This has resulted in guidelines for the longitudinal and lateral distances between wind turbines.

There is also a park effect in wave energy conversion, which must be taken into account when designing an array of Wave Energy Converters (WECs). In contrast to the wind industry, there are no guidelines at present for their separating distance, although a large number of studies dealing with arrays of WECs has been published over the past 30 years. By reviewing this literature, the aim of the present paper is to provide a summary of the current knowledge on the park effect in arrays of WECs and to provide guidelines for its mitigation.

First, the fundamentals of wave energy absorption by oscillating bodies are summarised, and the principal differences between the park effect in arrays of wave energy converters and wind turbines are highlighted. Then, the numerical approaches commonly used to deal with WEC arrays are outlined briefly and their limitations are discussed. It is argued that, at present, only Boundary Element Methods (BEM) are capable of the appropriate analysis. Finally, previous work on wave interactions and park effect in WEC arrays is reviewed. Similar trends are found in these studies, which allow conclusions to be drawn regarding the significance of the park effect as a function of the number of WECs in the array and their spacing. Based on these conclusions, tentative guidelines are proposed for the design of the layout of WEC arrays to mitigate the park effect.

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0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.03.008

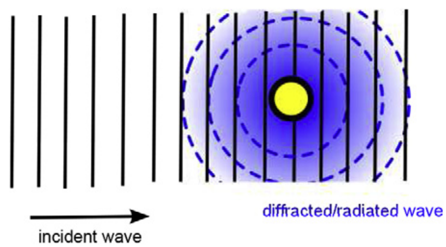

Fig. 1. Schematic of the wave pattern around an oscillating moving structure with incident waves.

2. Wave interactions in arrays of wave energy converters

2.1. Radiated/diffracted wave field around an oscillating structure

To understand the park effect in arrays of wave energy converters, it is necessary to understand the physical process of how a wave energy converter interacts and absorbs energy from the incident wave field.

The fundamental idea is that a fixed or moving structure in an incident wave field will give rise to additional wave systems known as diffracted or radiated waves (Fig. 1).[1] They are governed by the same set of equations as the incident wave (Laplace equation in the fluid domain plus boundary conditions, in particular free surface conditions). They carry energy in the same way as the incident wave.

However, there is an important difference between the diffracted/radiated wave and the incident wave. An incident wave is a plane wave propagating in only one direction, whereas a diffracted/radiated wave propagates in every direction from the source point (i.e. the oscillating structure). This is important to note because it means that one effect of the wave–structure interaction is to redistribute part of the incident energy, which had been propagating in a single direction, in all other directions. Therefore, the overall wave field is perturbed everywhere around the structure, and not only at the back (front and back being defined respectively to the direction of propagation of the incident wave).

2.2. Wave energy absorption as an interference

The principle of energy conservation implies that the energy in the diffracted/radiated wave is derived from the incident wave. This means that the phase in the diffracted/radiated wave is such that the incident wave is partly cancelled in some directions (which means that some energy is taken out), and partly increased in other directions (where some part of the energy is reemitted).

In the case of a WEC, in addition to energy being transferred from the incident wave to the diffracted/radiated wave, some of it is absorbed in what is referred to as a Power Take Off (PTO). In contrast to the case of zero wave energy absorption, effect of the PTO is observed as a change in the phase of the radiated wave, corresponding to an increase in incident wave cancellation and/or a decrease in incident wave amplification. Thus, by considering the total balance of energy, one would observe that some energy is missing in the fluid domain. This corresponds to the energy that has been absorbed by the WEC. This is explained by Ref. [1]:

"The physical law of conservation of energy requires that the energy-extracting device must interact with the waves such as to reduce the amount of wave energy that is otherwise present in the sea." or by Ref. [2]:

"To absorb energy from an incident wave, the radiated waves emitted from the surface(s) of an oscillating system must destructively interfere with the incident wave."

2.3. A fundamental difference to wind energy: "wake" is meaningless for WECs

A fundamental difference between wind energy and WECs is that in the latter, the perturbation of the wave field (diffracted/radiated wave) is observed not only at the back, but at every location around the structure (Fig. 2).

In the case of wind energy, one can define the wake as the downstream region where the wind speed is modified. Only wind turbines located behind other wind turbines are affected. Conversely, wind turbines in the front of the wind farm are not affected by the wake of wind turbines located downstream.

In the case of wave energy, it is not appropriate to talk about wake because, as discussed above, the wave field is modified in every direction from the source. Therefore, every single WEC in the array interacts with all the others, whatever their locations. In particular, WECs located in the front row of the array (the ones which meet the incident wave first) are affected by WECs behind them. Their response to the waves (and thus their energy absorption) is different with and without the WECs behind. Indeed, several authors [3–5] have observed that the modification of the energy absorption due to the park effect could be of higher significance for the WEC in front than for the WEC behind. In several cases, it has been reported that the energy absorption is actually *increased* for the front row by the presence of a row behind. However, one should note that these reported increases are small (a few percent).

Therefore, it appears that, *a priori*, a WEC array must be considered as a whole when assessing the park effect.

2.4. Decay of wave interaction with distance

It follows from energy conservation that the energy in a radiated/diffracted wave propagating in direction θ decreases with increasing distance to the source. This has two remarkable consequences:

- It implies that if two WEC units are sufficiently far from each other, wave interaction effects can be neglected.
- Even directly behind a WEC, the unperturbed wave energy flux is recovered with distance: at large distances from the WEC, the wave energy resource is similar to what it would have been in the absence of the WEC.

In both cases, full recovery of the wave energy flux is achieved only when the distance reaches a sufficient magnitude, which is directly related to the intensity of the diffracted/radiated wave. One can expect that for bigger WECs, the perturbation will be stronger, and hence that larger distances will be required.

3. Usual numerical approaches to deal with the park effect of WECs

This section provides an overview of the available numerical tools. For a more comprehensive review of the strengths and weaknesses of these tools, see Ref. [6].

[1] Usually, linear theory is used to model wave–structure interaction. Thus, it is possible to separate the effects by applying the superposition principle. The diffracted wave corresponds with the waves generated by the fixed structure in response to the incident waves. The radiated wave corresponds with the waves generated by the moving structure in still water. The solution of the complete problem (moving structure in waves) is obtained by superimposing diffracted wave + radiated wave + incident wave.