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# Influence of the wave dispersion phenomenon on the flicker generated by a wave farm

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**Abstract**— The inherently fluctuating nature of waves may be reflected to some extent in the power output of wave energy converters (WECs). These fluctuations can induce voltage fluctuations which can potentially generate flicker. Hence, wave farm managers will be required to demonstrate that their farm is compliant with grid codes and similar regulations, in order to be granted grid connection. This is usually performed through grid impact assessment studies by means of numerical power system simulators. However, in many studies, the electrical power output of a wave farm is calculated as the sum of identical power profiles corresponding to a single WEC, each shifted by a random time delay. Hence, this approach does not take into account the wave dispersion phenomenon. A comparative study was performed, and is presented in this paper, for assessing the validity of neglecting the influence of this phenomenon on flicker. This study is expected to contribute in defining the required level of hydrodynamic detail necessary for simulating the output power of a wave farm when it is to be used for flicker analyses.

**Keywords**—Flicker, aggregation effect, hydrodynamic modelling, time delay-based approach

## I. INTRODUCTION

The inherently fluctuating nature of waves may be reflected to some extent in the power output of wave energy converters (WECs). These fluctuations can induce voltage fluctuations which can potentially generate flicker [1]-[7]. Hence, wave farm managers will be required to demonstrate that their farm is compliant with grid codes and similar regulations, in order to be granted grid connection. This is usually performed through grid impact assessment studies by means of numerical power system simulators such as DIgSILENT PowerFactory [8], PSS@E [9], etc. Hence, numerical models of the considered WEC(s) are necessary.

These models can be based on experimental data in the form of electrical power output time series [10] or on so-called “wave-to-wire” models which compute this type of data

from the (usually simulated) sea surface elevation. A significant number of such “wave-to-wire” models have been developed, as reviewed in [11]. However, few of them have considered arrays of WECs as described in [12]. Regarding these latter, different approaches have been used. The most comprehensive approach consists in simulating the sea surface elevation at each node of the wave farm where a WEC is located, taking into account the wave dispersion phenomenon, as well as the hydrodynamic interactions between WECs due to radiation and diffraction. Using this approach is very heavy from a computational perspective and should be restricted to simulating the output power of a wave farm whose WECs are closely located. In the case where the WECs are sufficiently far away from each other so that their hydrodynamic interactions can be considered as negligible, a second approach should be used which consists in calculating the sea surface elevation at each node of the wave farm where a WEC is located without taking into account the radiation and diffraction due to the neighbouring WECs. Finally, a third simplified approach has been widely used in the electrical engineering community in flicker studies focussing on wave farms. This approach consists in calculating the output power of an entire farm based on the power profile of a single WEC. This power profile serves as a reference to which a random time delay is applied for each WEC in order to model the device aggregation effect [1]-[7], which will be described in Section C.2. The computational effort regarding this latter approach is extremely light with respect to the other two approaches. However, questions remain concerning its physical validity, as this approach does not take into account the wave dispersion phenomenon.

The objective of this paper is to tackle this question by comparing the flicker level obtained from the second and the third approaches described in this section. Sufficiently distantly located WECs will be considered in order to neglect the inter-WECs hydrodynamic interactions. The farm output

power is then injected in a local electrical grid model developed under PowerFactory to compute the corresponding voltage profile at the Point of Common Coupling (PCC). This voltage profile serves as input to a flickermeter from which the associated short-term flicker level is computed. The modelling hypotheses will be described in Section II and the results in Section III. In Section IV, the conclusions will be detailed.

The results of the comparative study will contribute in defining the required level of hydrodynamic detail necessary for simulating the output power of a wave farm when it is to be used for flicker analyses.

## II. MODELLING HYPOTHESES

### A. Hydrodynamic simulation

The hydrodynamic model is based on linear wave theory and simulates wave field from a superposition of Airy waves obtained through discretising a JONSWAP spectrum and using random phases. Contrary to the time delay-based method, the wave dispersion phenomenon is taken into account here.

By discretising the wave spectrum  $S(\omega)$  using  $n$  regularly spaced frequency components, the amplitude of each elementary wave component is given by [13] as:

$$a(\omega_i) = a_i = \sqrt{2S(\omega_i)\delta\omega} \quad (1)$$

Each wave component then represents a complex elementary free surface elevation at horizontal position  $(x, y)$  and time  $t$ :

$$\tilde{\eta}_i(x, y, t) = a_i e^{j[k_i(x \cos \bar{\theta} + y \sin \bar{\theta}) - \omega_i t + \varphi_i]} \quad (2)$$

where  $\bar{\theta}$  is the mean wave direction of the mono-directional wave field,  $\varphi_i \in [0, 2\pi]$  is the random phase of the  $i^{\text{th}}$  wave component chosen at wave field initialisation and  $k_i$  is the wave number, which is solution of the dispersion relation given by

$$\omega_i^2 = gk_i \tanh k_i h \quad (3)$$

with  $h$  being the mean water depth at position  $(x, y)$ . If the water depth can be considered as infinite, the relation degenerates to  $\omega_i^2 = gk_i$ . Summing the  $n$  contributions gives the free surface elevation:

$$\eta(x, y, t) = \text{Re} \left\{ \sum_{i=1}^n \tilde{\eta}_i(x, y, t) \right\} \quad (4)$$

This linear wave field modelling is then integrated into a linear framework for wave structure interactions that relies on hydrodynamics coefficients obtained from the linear potential flow theory. Note that in this study, no hydrodynamic interactions between the scattered wave fields are taken into account so that only coefficients for one isolated body are to

be calculated using the seakeeping software NEMOH [14] which is based on the Boundary Element Method (BEM).

The time domain linear excitation force applying to a body having position  $(x, y)$  is then obtained by the superposition of the excitation generated by each wave component as:

$$F_{ex}(x, y, t) = \text{Re} \left\{ \sum_{i=1}^n \tilde{F}_{ex}(\omega_i) \tilde{\eta}_i(x, y, t) \right\} \quad (5)$$

Sea-states were simulated for significant heights equal to 1 m and 3 m, as well as for peak periods equal to 7 s, 9 s, 10 s and 12 s.

### B. Wave device

The wave farm is composed of identical heaving buoys controlled passively and described in a previous paper [15]. As the focus of this paper is on the comparison of two methods for modelling the device aggregation effect on flicker, a simple, passive control strategy was adopted for the WEC. It consists of the application of a constant damping factor as a function of the sea-state characteristics (significant wave height  $H_s$  and  $T_p$ ). This damping factor is optimised with respect to a given sea-state during a preliminary offline study. For the sake of realism, levelling is applied on the power take-off (PTO) force, which is limited to 1 MN, and on the output electrical power, which is limited to 1 MW. Each WEC is connected to the offshore grid through a fully rated back-to-back power electronic converter.

### C. Wave farm

#### 1) Wave farm layout

The wave farm considered in this study is considered to be composed of 24 of the devices described in the previous section. All these devices are deemed identical in terms of hydromechanical and electro-mechanical properties. They are placed at a distance  $d$  of each other, on 3 rows and 8 columns facing the incoming waves, as shown in Fig. 1. The inter-WEC distance  $d$  is supposed to be sufficient so that the hydrodynamic interactions between the devices can be considered as negligible. In this research work, it was assumed equal to 600 m in the full hydrodynamic approach, while it is made approximately equal to 600 m in the time-delay based approach, as it will be described in Section C.4 [16].

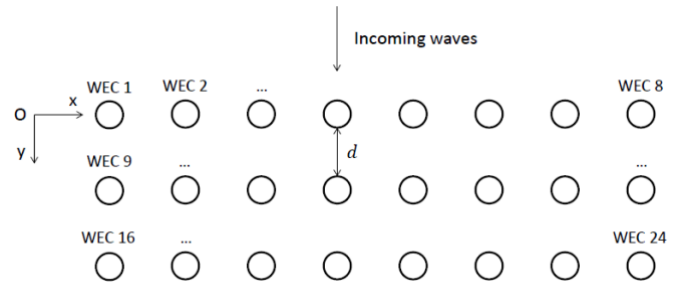


Fig. 1 Wave farm spatial layout

## 2) Introduction to the two approaches studied here

The wave farm power output is computed as the sum of the power output of all the WECs composing the farm. As the temporal profile of the sea surface elevation at a given node in the wave farm is not expected to be identical to this corresponding to another node, it is not expected either that two power output temporal profiles from two different WECs could be identical. Hence, the power output of a wave farm cannot be computed as the product of the power output of a single device times the number of WECs composing the farm. Also, the fact that different WECs achieve peak power at different times leads to a reduced peak-to-average ratio of the wave farm power output compared to that of a single device. This is illustrated in Fig. 2 which shows the temporal power output profile for a single WEC and for the wave farm composed of 24 devices normalised by their respective average value. While the peak-to-average ratio is equal to 3.6 for the single WEC (even though its power output is limited to 1 MW), it is equal to 1.9 for the wave farm. This decrease in the peak-to-average ratio implies that the temporal power output profile is “smoother” in the case of a wave farm than in the case of a single WEC which is usually referred to as the device aggregation effect. The objective of this paper was to determine whether a full hydrodynamic simulation was required to model this effect on flicker, or whether a simplified, time delay-based method was sufficient. These two approaches are described in the next sections.

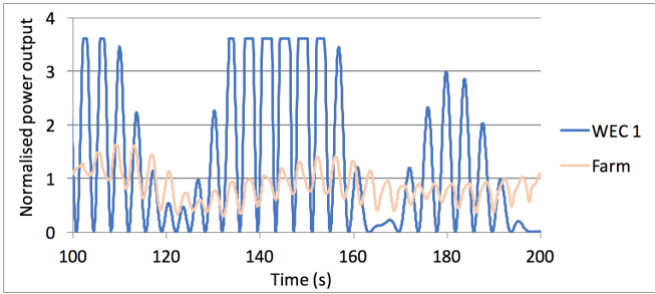


Fig. 2 Temporal power output profile (over 100s) for a single WEC (blue) and for the wave farm composed of 24 devices (pink) for significant wave height  $H_s=3$  m and peak period  $T_p=7$  s. The profiles are normalised with respect to their average value.

### 2.1) Full hydrodynamic simulation

In this approach, the wave excitation force at each node of the wave farm where a WEC is located is computed by means of the code described in Section A. Then, the power output of each WEC is computed based on its corresponding excitation force temporal profile. Hence, the power output  $P_{farm}$  of the wave farm corresponds to the algebraic sum of the power output  $P_{WECi}$  of each WEC  $i$ , such as:

$$P_{farm}(t) = \sum_{i=1}^{24} P_{WECi}(t) \quad (7)$$

### 2.2) Time delay-based method

The time delay-based method requires only a single power output temporal profile  $P_{WEC1}$  of a single WEC, to which different uniformly distributed random time delays  $\Delta t_i$  are applied to represent the power output of the other devices composing the farm. Hence, the wave farm output power can be expressed as:

$$P_{farm}(t) = \sum_{i=1}^{24} P_{WEC1}(t + \Delta t_i) \quad (8)$$

where  $\Delta t_i$  models the fictive propagation of a wave group whose envelope characteristics are independent of the travelled distance. This means that the wave dispersion phenomenon is not taken into account here. This physical effect implies that in dispersive media such as water, the travel speed of a sine wave is linked to its frequency through the dispersion relationship which, for deep water waves, can be expressed as [17]:

$$\omega^2 = gk \quad (9)$$

as mentioned earlier. Term  $\Delta t_i$  is assumed equal to:

$$\Delta t_i = \frac{d_{td}}{v_g} = \frac{4\pi d_{td}}{gT_p} \quad (10)$$

where  $d_{td}$  is distance between a reference WEC (whose time delay is equal to zero) and given WEC  $i$ , and  $v_g$  is the group speed which is defined as equal to  $gT_p/4\pi$  here, where  $g=9.81$  m.s<sup>-2</sup> is the gravity of Earth. Given that the incoming waves are simulated as mono-directional waves, the distance  $d_{td}$  taken into account here is equal to the distance along the axis parallel to the wave front propagation direction. In the full hydrodynamic approach, the distance between the WECs was assumed to be equal to a fixed distance  $d=600$  m. However, if this constant distance were used in the time delay-based approach (i.e.  $d_{td} = d$ ), given that the excitation force temporal profile is similar for all WECs, then all the devices located on a given row of the wave farm would present the same power output at any time  $t$ , thus resulting in coincident power profiles for 8 WECs, which is unrealistic. Hence, in order to avoid this situation, an additional uniformly distributed random distance  $d_{rand}$ , arbitrarily selected as ranging between -50 m and +50 m (in order to represent WECs linear drift), is added to the fixed inter-WEC distance  $d$  such as:

$$d_{td} = d + d_{rand} \text{ where } d_{rand} \in [-50; 50] \text{ m} \quad (11)$$

Ten time delay sets were used in this study.

#### D. Electrical grid

An electrical grid model was developed under the power system simulator PowerFactory and is shown in Fig. 3. This model is inspired from the Atlantic Marine Energy Test Site (AMETS) [18] located off Belmullet, Ireland for the onshore local grid part. It is composed of a 10/20 kV transformer whose impedance is equal to  $2 \cdot 10^{-4} + j0.06$  pu (where  $j$  is the imaginary unit) and of a 0.1 MW load representing the onshore substation connected to the rest of the national network through a 5 km-long overhead line of impedance  $0.09 + j0.3$   $\Omega$ /km. On the 20 kV bus (which is the Point of Common Coupling (PCC)), a VAr compensator maintains power factor at unity. Then, a 20/38 kV transformer (of impedance equal to  $2 \cdot 10^{-4} + j0.06$  pu) connects to the farm to the local (national) grid where a 2 MW load (representing the consumption of a local town) is also connected. The rest of the national grid is modelled by means of a 38 kV voltage source in series with an impedance. This impedance magnitude is selected to be equal to  $Z=20$   $\Omega$  (i.e. equal to a short-circuit level of 72 MVA), and its angle is selected to be equal to  $30^\circ$ , which corresponds to a “weak grid” and constitutes thus a worst case scenario in which relatively high flicker levels can be expected.

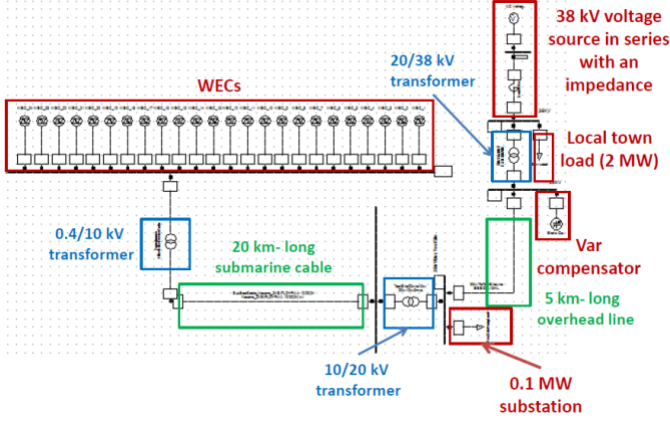


Fig. 3 Electrical grid model developed under DIgSILENT PowerFactory

The offshore grid is composed of a 20 km-long submarine cable of series impedance equal to  $0.07 + j0.11$   $\Omega$ /km and capacitance equal to  $0.31$   $\mu$ F/km, as described in [19]. The cable distance was selected according to the values observed for two planned or already existing wave energy test sites [18], [20]. The offshore network is also composed of a 0.4/10 kV transformer (of impedance equal to  $2 \cdot 10^{-4} + j0.06$  pu) and of 24 wave devices. The influence on the study results of the internal network between the WECs and the 0.4/10 kV transformer was deemed negligible and was therefore not included in the model.

### III. RESULTS

#### A. Flicker level with respect to time delays

As mentioned earlier, ten different time delay sets were used in the time delay-based approach. The corresponding

minimum, maximum, and average short-term flicker levels  $P_{st}$  are shown in Table I and Table II for the two significant wave heights considered here ( $H_s=1$  m and  $H_s=3$  m). The standard deviation, also shown in these tables, indicates that for most cases the deviation from the average value is relatively small, compared to the allowed flicker limits which range usually between 0.35 and 1 [21]. However, some higher values of the standard deviation indicate that the time delay set can have a non-negligible influence on flicker, and that it is therefore important to average the flicker level corresponding to several time delay sets in order to obtain a reasonable estimation of the flicker which would have been obtained through the more realistic, full hydrodynamic approach.

Table I  
Short-term flicker levels  $P_{st}$  for the ten time delay sets ( $H_s=1$  m)

		Peak period $T_p$ (s)			
		7	9	10	12
Short-term flicker level $P_{st}$	Average	0.09	0.40	0.50	0.76
	Standard deviation	0.04	0.12	0.14	0.16
	Minimum	0.04	0.26	0.31	0.60
	Maximum	0.14	0.68	0.84	1.14

Table II  
Short-term flicker levels  $P_{st}$  for the ten time delay sets ( $H_s=3$  m)

		Peak period $T_p$ (s)			
		7	9	10	12
Short-term flicker level $P_{st}$	Average	0.63	0.80	0.96	0.83
	Standard deviation	0.12	0.09	0.21	0.10
	Minimum	0.43	0.67	0.73	0.73
	Maximum	0.80	0.94	1.40	1.09

As the average flicker level is mostly representative of the order of magnitude of the flicker level corresponding to the 10 different time delay sets, it will be used for the comparative study between the time delay-based approach and the full hydrodynamic approach, as described in the following section.

#### B. Comparison of the two approaches

It is shown in Fig. 4 that both approaches generate similar results with a difference which is generally negligible in comparison with the usual maximum allowed flicker limits ranging between 0.35 and 1. This observation applies to both the low-energy and the mild sea-states ( $H_s=1$  m and  $H_s=3$  m respectively).

Hence, it can be concluded that the flicker level generated by a wave energy farm can be estimated with a relatively high level of accuracy in most cases by means of the average flicker level corresponding to several time delay sets (here, ten time delay sets were used). In other words, this means flicker



can be estimated from a single WEC power output, without further requirement for modelling the hydrodynamic conditions at each node in the farm where a WEC is expected to be located. This means also, in physical terms, that the wave dispersion phenomenon can usually be considered as negligible when it comes to flicker studies under the conditions considered in this study.

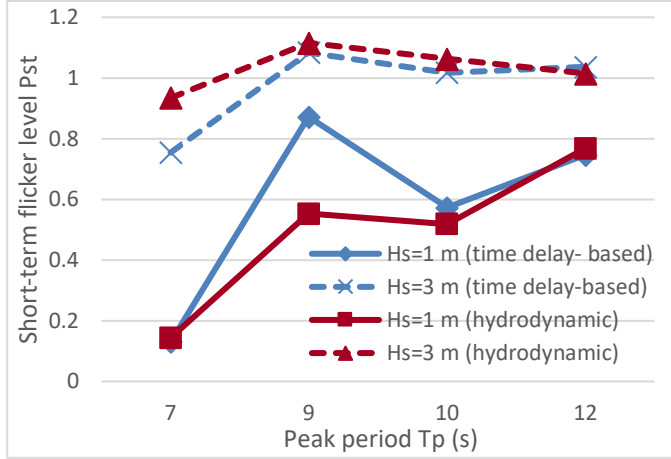


Fig. 4 Short-term flicker level  $P_{st}$  as a function of the sea-state peak period  $T_p$  for  $H_s=1$  m and  $H_s=3$  m, and for the two considered approaches

#### IV. CONCLUSIONS

This paper has described a comparative study between a time delay-based approach and a more realistic, full hydrodynamic approach for determining the flicker level generated by a wave farm composed of 24 devices. The results have shown that in most cases, using the average flicker level corresponding to 10 different time delay sets leads to a negligible error compared to the full hydrodynamic approach. This means that the wave dispersion phenomenon has a limited impact on flicker. However, some non-negligible values for the flicker level error in some rare cases suggest that the time delay-based approach should be restricted to estimating flicker at a first stage before more refined studies based on the full hydrodynamic approach are conducted. Future work will focus on the comparative analysis, in terms of flicker level, between the two approaches described in this paper and a more comprehensive hydrodynamic approach including the hydrodynamic interactions between WECs. It will also investigate the influence of several parameters such as inter-WEC distance, WEC spatial arrangement, device number, etc.

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