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Wave farm flicker severity: Comparative analysis and solutions

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ABSTRACT

This paper proposes a flicker severity study for Wave Energy Converter farms. The flicker severity is introduced and the reason why it is an important constraint for a wave farm is explained. A new representation called intrinsic flicker severity is introduced which describes the flicker severity independently of the grid. The influence of device type, its control and the sea-state on average production, flicker severity and on the ratio between flicker and production are studied with three types of devices: an Oscillating Water Column and two Direct Wave Energy Converters (two point absorbers: a Heaving Buoy and the SEAREV). The influence of the size and the placement of each unit in the wave farm is presented with a farm-unit flicker ratio, compared with the square-root of unit hypothesis (noise behavior), as a function of wave direction by taking into account wave direction dispersion. Finally, solutions are presented to reduce the flicker produced to comply with grid code requirements in order to allow grid integration of wave farms.

1. Introduction

Integration to the grid is one of the keys to commercializing Wave Energy Converters (WECs) [1,2]. However, some WEC technologies produce power that fluctuates at the rate of ocean waves. Some of them have intrinsic energy storage from the pneumatic or hydraulic chain, but can still have other issues, like efficiency and reliability.

When the produced power fluctuates at frequencies between 5 mHz and 33 Hz, the induced rms-voltage fluctuations can cause power quality problems at the grid connection point. WECs have been identified as particularly susceptible to induce flicker [3–6]. The combination of the weak grid (which could be the case with an island or a near-shore distribution grid) and production fluctuations can cause flicker non-compliance, relative to the grid code requirements. In order to analyze this issue, a new representation called intrinsic flicker is proposed in order to represent the results under several conditions; such as grid characteristics and reactive power injection.

Wave farm flicker severity depends on several influences; device type, different controls, sea-states, sizes of farms and architecture of farm. A comparison of different device types is proposed here: oscillating water column (OWC), heaving buoy, and the SEAREV [7] (see Fig. 1). Some studies has already been made on the flicker severity, but are often limited: Ref. [5,8] are interested in one device type (OWC) and one control strategy for one sea-state for a 22 and 6 units wave farm respectively, with investigation of only two wave directions. In Ref. [9], one type of device (OWC) is investigated with two different controls for several sea-states and different wave farm sizes but does not investigate architecture and wave direction. Ref. [10] discusses one device type (Wavebob) and one control with just one unit.

This work will focus on relative small farms (5–20 MW) connected to a medium voltage distribution grid (1–50 kV).

Section 2 introduces the flicker constraint, and proposes a definition for an intrinsic flicker severity, that allows a generalization of the results for all grid characteristics at the PCC (Point of Common Coupling) and grid codes. Section 3 presents the model used for the three different devices and their control. Then, in Section 4 the different influences are presented with flicker-production ratio and farm-unit flicker ratio in order to compare different cases. The classical hypothesis used in wind energy [11] that states this ratio must be near $\sqrt{N}$ (that is that each unit is considered as an independent noise source) will be compared to the results. Finally, Section 5 proposes solutions to reduce flicker to

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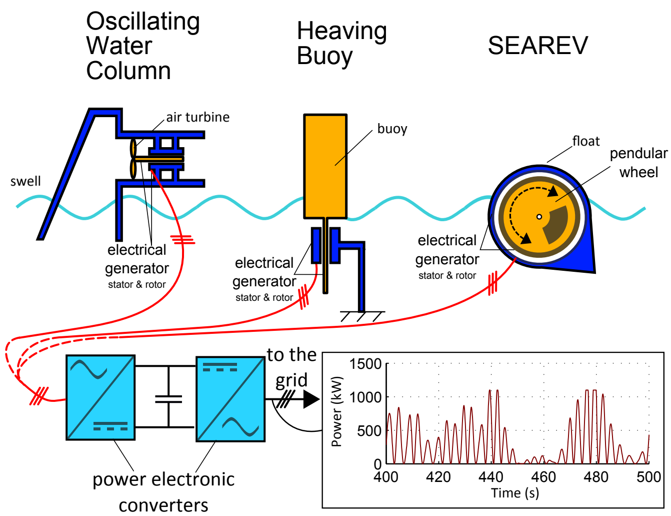

Fig. 1. Three types of Wave Energy Converter with a strong pulsating power production used for this study: an Oscillating Water Column, a Heaving Buoy and the SEAREV.

allow grid integration of wave farms.

2. Flicker and flickermeter

2.1. Flicker definition and standards

To enable grid integration, energy producers must meet some constraints on the quality of injected energy. The limitation of voltage fluctuations (flicker) is a critical constraint for WECs. Power-line flicker is a visible change in brightness of a light source due to rapid fluctuations in the power supply voltage. These fluctuations are caused by variations in either active or reactive power to the network [12]. Beyond a certain amplitude, these rapid fluctuations (in a range from 5 mHz to 33 Hz) may cause humans to suffer from fatigue, irritability and epilepsy but can also cause premature aging of electrical devices [13]. So these fluctuations are constrained by flicker standards to keep them limited (see Fig. 2).

Two flicker severities are typically used in grid codes:

- The short-term flicker severity P_{st} is measured over a 10-min period,
- The long-term flicker severity P_{lt} is measured over 2 h.

Flicker measurement with a flickermeter is defined in the IEC

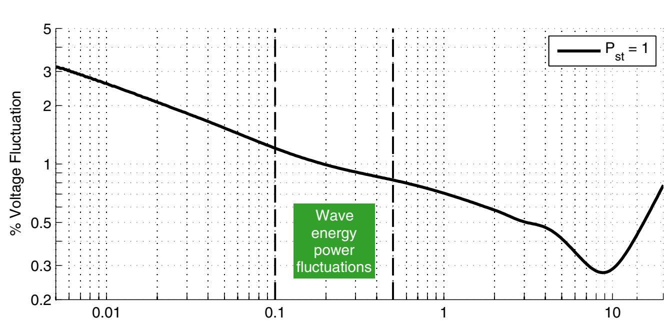

Fig. 2. Flicker constraint: $P_{st} = 1$ curve for regular rectangular voltage changes according to the IEC 61000-4-15 Standard. The zone above the curve corresponds to irritation for the consumer. Wave power fluctuations typically fall between 0.1 and 0.5 Hz.

61000-4-15 Standard [12]. Three blocks constitutes a flickermeter:

- The first process is a demodulation process that involves squaring and filtering the input voltage profile in order to compute rms-voltage waveform.
- This waveform then goes through the simulation filters which have a maximum value at 8.8 Hz that simulates the lamp to eye response, whilst a squaring operation and a sliding mean filter simulate the non-linear memory process in the eye and brain.
- The extent to which flicker is annoying to the observer depends on its level and its rate of occurrence. This is carried-out by a distribution which relates to the proportion of time each particular level of flicker is exceeded. After 10 min of data accumulation, key levels are taken from this distribution to compute the short-term flicker severity P_{st}.

A flickermeter installed in Matlab is used [14]. Further details on the use of this flickermeter can be found in Ref. [15]. The short-term flicker $P_{st}(\Delta V(t)/V)$ is used in the following as a function of a 10-min temporal profile $\Delta V(t)/V$ and similarly the long-term flicker $P_{lt}(\Delta V(t)/V)$ as a function of a 2-h temporal profile $\Delta V(t)/V$.

The long term flicker severity P_{lt} is simply calculated with twelve consecutives values of the short term flicker severity P_{sti}:

$$P_{lt} = \left(\frac{1}{12}\sum_{i=1}^{12} P_{sti}^3\right)^{1/3} \tag{1}$$

By definition, a flicker severity equal to 1 for the P_{st} corresponds to the acceptable limits that the electricity distribution must provide to its customers and the limit for P_{lt} is 0.8.

2.2. Flicker emission limits

To ensure these levels, the distributor system operator requires consumers and producers to limit their individual flicker contribution to lower levels (due to pollution aggregation).

$$P_{st} \le P_{st\ max} \tag{2}$$

$$P_{lt} \le P_{lt\ max} \tag{3}$$

Table 1 gives the individual flicker severity limits according to the IEC standard [16] and some grid codes. These limits consider only the effect of the producer (or consumer) at its PCC, because the producer (or consumer) can only be responsible for maintaining his emissions. The utility is responsible for the overall control of disturbance within the electrical grid, and we want to consider here only the wave farm responsibility.

The wave elevation considered in this study is poly-chromatic and is described with different sea-states (each one described by its spectrum defined with its significant height and its peak period). If this phenomenon is stationary for a duration of around 2 h, a

Table 1
Individual flicker severities limits (Medium Voltage).

	$P_{st\ max}$	$P_{lt\ max}$
IEC 61000-3-7 [16]	0.35[a]	0.25[a]
France [17]	0.35	0.25
Ireland (Wind/wave) [18]	0.35	0.35
United-Kingdom [19]	0.50[a]	N/A
Denmark (Wind) [20]	0.30[d]	0.50[b]/0.35[c]/0.20[d]

[a] Basic limits, further explanations in 5.1.
[b] $U_n \le 35$ kV.
[c] $35\ kV < U_n \le 100$ kV.
[d] $U_n > 100$ kV.