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Abstract—The inherently fluctuating nature of sea waves can be reflected to a significant extent in the power output of tidal turbines. However, these fluctuations can give rise to power quality issues such as flicker. Hence, it is important to assess the impact which tidal farms may have on their local network before such power plants are allowed to connect to the grid. This paper describes the influence of the wave climate on the short-term flicker level induced by a tidal farm on the point of common coupling. It analyses also under which conditions the tidal farm breaches the grid code requirements in terms of short-term flicker level.

Index Terms—tidal energy, flicker, wave, grid code

I. INTRODUCTION

Tidal turbines are now considered as sufficiently mature to be deployed in pre-commercial tidal farms [1]-[2]. So far, they have been tested in sheltered areas where the influence of sea waves on their power output could be considered as negligible [3]. Hence, wave-induced flicker generated by tidal turbines has not been analyzed experimentally, nor has it been studied numerically, despite the significant influence waves may have on the electrical power output of a tidal turbine [4]. This paper intends to fill this gap in simulating the flicker level generated by a tidal farm by means of numerical power system simulations.

II. MODELING

A. Tidal Turbine Characteristics

The characteristics of the tidal turbine considered in this study were extracted from [4] and are summarized in Table I. The turbine is equipped with a permanent magnet synchronous generator.

B. Modeling of the Horizontal Water Speed

The mechanical power extracted by a tidal turbine is calculated based on the horizontal component \( V \) of the water flow speed perpendicular to the rotation plane of its blades. This horizontal speed is composed of contributions from the tidal current and from the waves. It must be noted that interactions between these two phenomena may result in a significant increase of the mean wave height [5]. However, these interactions are still not fully understood. In addition, they are currently modeled for detailed turbine structural design analyses at a relatively basic level in the ideal case of monochromatic waves superimposed to a linear tidal current [6]. Hence, it was deemed reasonable for the power system simulations performed in this study not to model these interactions at a first stage in similar fashion to [4]. Consequently, the horizontal component \( V \) of the water flow speed at any point in space and time can be formulated as:

\[
V(x, y, z, t) = U_x(z, t) + U_w(x, y, z, t)
\]  

(1)

where \( x \) and \( z \) are the horizontal and the vertical axes respectively, \( t \) is the time, \( U_x \) and \( U_w \) are the speed contributions from the tidal current and from the waves respectively. The most unfavorable case of collinear speed contributions is considered here.

1) Tidal current contribution \( U_x \)

The tidal flow is considered as linear and perpendicular to the rotation plane (0yz) of the turbine blades. Hence, no turbulence effect is considered in this study. It is important to recall that, although this phenomenon may induce a significant level of flicker [3], the objective of this study consists in analyzing wave-induced flicker only.

The variation of the tidal flow speed \( U_x \) at the sea surface \( (z=0 \text{ m}) \) as a function of time is usually considered as sinusoidal for diurnal tides such as:

\[
U_x(t) = A_x \sin(2\pi f_d t + \phi_d)
\]  

(2)

where \( A_x \) is the tidal amplitude of horizontal speed, \( f_d \) is the tidal frequency, \( \phi_d \) is the phase angle.

The wave-induced component \( U_w \) is composed of several parameters such as the wave speed, the significant wave height, etc. The wave speed is calculated using the wave period, the water depth, and the wave direction. The significant wave height is calculated using the wave spectrum. The interactions between the tidal turbine and the waves are modelled using a linear wave theory and considering the wave-induced forces on the turbine blades.

The generator characteristics are also taken into account in the model. The generator is a permanent magnet synchronous generator and its parameters are summarized in Table II. The generator is modeled using a common coupling. It ana...
\[ U_t(0, t) = U_{t, \text{max}} \sin\left(\frac{2\pi t}{T_t}\right) \]  \hspace{1cm} (2)

where \( U_{t, \text{max}} \) is the maximum tidal current speed selected arbitrarily as equal to 3.5 m/s in this study. This value is typical of high speed tidal currents characterizing the areas where tidal farms are envisaged to be deployed. Term \( T_t \) is the tidal period almost equal to half a lunar day, i.e. 12h25 \( \approx \) 44,700 seconds. The variations of the tidal flow speed as a function of the water depth \( z \) (\( z < 0 \)) for a given time \( t_0 \), can be modeled as follows [7]:

\[ U_t(z, t_0) = U_t(0, t_0) \left(\frac{d+z}{d}\right)^{1/7} \]  \hspace{1cm} (3)

where \( d \) is the distance between the sea surface and the sea bottom which is equal to 35 m in this study. This water depth corresponds to this of the site selected for the Paimpol-Bréhat tidal farm in France [4]. In summary, the contribution in speed \( U_t \) from the tidal current can be expressed as:

\[ U_t(z, t) = U_{t, \text{max}} \sin\left(\frac{2\pi t}{T_t}\right) \left(\frac{d+z}{d}\right)^{1/7} \]  \hspace{1cm} (4)

2) Waves contribution \( U_w \)

Sea surface elevation is usually modeled using linear wave theory [8]. However, this theory is not valid for shallow to intermediate waters which are traditionally characterized by a water depth less than 50 m, as it is the case in this study. Stokes’ wave theory is the typical alternative for modeling non-linear waves in shallow to intermediate waters. The order of Stokes’ law must be selected based on the wave climate characteristics considered, i.e. the significant wave height \( H_s \) and the peak period \( T_p \), and on the water depth \( d \). The significant wave height \( H_s \) is the height of the one-third of the highest waves of a sea-state and the peak period \( T_p \) is the period corresponding to the frequency band \( \Delta f \) with the maximum value of spectral density in the non-directional wave spectrum \( S(f) \) characterizing a given sea-state. A classical Bretschneider spectrum was selected. It is defined as [8]:

\[ S(f) = \frac{5h^2}{16\pi^2f^5} e^{-\frac{5}{16\pi^2f}} \]  \hspace{1cm} (5)

In this study, the significant wave height range considered is \( 2 \text{ m} \leq H_s \leq 8 \text{ m} \) and the peak period range considered is \( 5 \text{ s} \leq T_p \leq 15 \text{ s} \). These values correspond to wave climates having low to high energy levels.

It appears clearly from Fig. 1 that the waves can be modelled as \( 2^{\text{nd}} \) order Stokes waves for the cases considered in this study. In the case of a monochromatic wave of height \( H \) and of period \( T \), the velocity potential \( \phi \) can thus be expressed as [10]:

\[ \phi = \frac{HL \sin \left( k(d + z) \right)}{2T \left( \frac{1}{sh(kd)} \right)} \sin(kx - \omega t) + \frac{3\pi^2 H^2 \sin \left( 2(kd + z) \right)}{16T \left( \frac{1}{sh^4(kd)} \right)} \sin(2(kx - \omega t)) \]  \hspace{1cm} (6)

where \( k \) is the wave number defined as \( k = \frac{2\pi}{L} = \omega / \sqrt{gd} \) [8] \( \omega \) the radian frequency defined as \( \omega = 2\pi f \). Hence, the contribution in speed \( U_w \) on the \( x \) (horizontal) axis from a single monochromatic wave can be calculated as:

\[ U_w(x, z, t) = \frac{\partial \phi}{\partial x} = \frac{\pi H \sin \left( k(d + z) \right)}{T \left( \frac{1}{sh(kd)} \right)} \cos(kx - \omega t) + \frac{3\pi^2 H^2 \sin \left( 2(kd + z) \right)}{4TL \left( \frac{1}{sh^4(kd)} \right)} \cos(2(kx - \omega t)) \]  \hspace{1cm} (7)

However, a sea-state is the sum of multiple waves of amplitude \( a_i \), of period \( T_i \) and of wave number \( k_i \). Hence, the total contribution in speed \( U_w \) of all the monochromatic waves is the sum of their individual contributions \( U_{w_i} \) such as:

\[ U_w(x, z, t) = \sum_i U_{w_i}(x, z, t) = \sum_i \frac{2\pi a_i \sin \left( k_i(d + z) \right)}{T_i \left( \frac{1}{sh(k_i d)} \right)} \cos(k_i x - \omega_i t) + \frac{3\pi^2 a_i^2 \sin \left( 2(k_i d + z) \right)}{T_i L_i \left( \frac{1}{sh^4(k_i d)} \right)} \cos(2(k_i x - \omega_i t)) \]  \hspace{1cm} (8)

The amplitudes \( a_i \) are calculated such as [8]:

\[ a_i = \sqrt{2S(f_i)\Delta f} \]  \hspace{1cm} (9)

3) Averaged water flow speed

As it will be explained in the next section, the mechanical power extracted by the tidal turbine depends on the cube of the water flow speed \( \overline{V(t)} \) averaged over the circular surface swept by the blades. This variable can be calculated as:

\[ \overline{V(t)} = \frac{\int_{-d_h-r}^{-d_h+r} V(x,z,t)2\sqrt{R^2-(d_h+z)^2}dz}{\pi R^2} \]  \hspace{1cm} (10)

Profiles for the average speed \( \overline{V(t)} \) were simulated for four values of the significant wave height \( H_s \): 2 m, 4 m, 6 m, 8 m,
and for four values of the peak period $T_p$: 5 s, 7 s, 9 s, 11 s, 13 s, 15 s.

C. Modeling of the Tidal Turbine

The mechanical power $P_{mec}$ extracted by the tidal turbine can be expressed as:

$$P_{mec}(t) = \frac{1}{2} \rho \pi R^2 C_p(V(t))^3$$  \hspace{1cm} (11)

where $\rho$ is the density of sea water equal to 1027 kg/L and $C_p$ is the power coefficient. The curve of the optimal power coefficient $C_p$ as a function of the tip speed ratio $\lambda$ considered in this study was extracted from [4] and is reproduced in Fig. 2. The tidal turbine is controlled in speed so that the power coefficient $C_p$ remains sufficiently close to its maximal value. The control system was developed under Matlab-Simulink and is shown in Fig. 3. The mechanical power $P_{mec}$ extracted by the tidal turbine is computed based on the rotor speed and on the $C_p-\lambda$ characteristic of the turbine in the “Power extraction” block. This block computes also the dynamic reference speed $\omega_{ref}(t)$ to maintain power coefficient $C_p$ close to its maximal value. The error between the dynamic reference speed $\omega_{ref}(t)$ and the rotor speed is transformed into phase voltages to be applied at the terminals of the turbine. The blocks “dq2abc” and “PWM inverter” were extracted from Simulink model “power_pmmotor.mdl” which simulates field-oriented control [11]. The $d-q$ axes inductances $L_d$ and $L_q$ are equal and the generator has permanent magnet excitation so the control of the electrical torque $T_e$ relies solely on the quadrature axis current $i_q$. The direct axis current $i_d$ is maintained at zero.

D. Modeling of the Tidal Farm

The electrical output $P_{tot}$ of an entire tidal farm composed of 20 turbines was simulated based on the addition of identical individual electrical power profiles $P_{e_n}$ (where $n$=[1, ..., 20]) each shifted by a random time delay $\delta_n$. The tidal turbines are assumed to be operated at unity power factor, thus leading to a farm nominal power $S_n$ equal to 20×1.5=30 MVA.

E. Modeling of the Electrical Network

The electrical network was modeled under power system simulator PowerFactory [12] as shown in Fig. 4. It is composed of (from right to left): a “static generator” built-in model outputting the electrical power output $P_{tot}$ of the tidal farm, a 0.4/10 kV transformer, a 1 km long submarine cable whose length was selected arbitrarily, a 0.1 MVA load (load 1), a 5 km long overhead line, a VAr compensator to maintain the power factor at the point of common coupling (PCC) at unity, a 20/38 kV transformer, a 2 MVA load (load 2) and finally a 15 $\Omega$ impedance in series with a constant 38 kV voltage source simulating the rest of the national grid. This model is inspired from a model already used in previous works [13] and representing the Irish marine energy test site, called AMETS, located off Belmullet [14]. Short-term flicker was evaluated by means of a flickermeter compliant with IEC standard 61000-4-15 [15].

III. RESULTS

A. Influence of the Wave Climate on the Flicker Level

1) Significant wave height $H_s$

Fig. 5 presents the flicker level $P_{fl}$ as a function of significant wave height $H_s$ for different impedance angles $\Psi_k$ and different peak periods $T_p$. It appears clearly that the significant wave height $H_s$ has a considerable influence on the flicker level $P_{fl}$. However, this influence is highly dependent on the impedance angle $\Psi_k$. This can be explained by means of the simple two-bus system shown in Fig. 6. The generator $G$ connected to Bus 1 injects a complex power $P + jQ$ (where $j$ is the imaginary unit) into the impedance

![Figure 3. Speed control system developed under Matlab-Simulink](image-url)
stage variations initially induced by active power consumption of the impedance is transferred to the series reactor, the 20/38 kV transformer and the 38 kV load. Hence, the amplitude of the voltage variations initially induced by the tidal farm decreases up to \( \Psi_k = 70^\circ \), thus resulting in a lower flicker level. However, the influence of the reactive power flow is predominant for \( \Psi_k = 85^\circ \), which leads to an increase of the voltage fluctuations amplitude, thus to a higher flicker level.

2) Peak period \( T_p \)

It can be observed from Fig. 5 that the peak period \( T_p \) has a non-negligible influence on the flicker level \( P_{st} \) than the significant wave height \( H_s \). However, as it can be observed in Fig. 6, there is no trivial relation between the flicker level \( P_{st} \) and the peak period \( T_p \). This was expected due to the low level of coupling between the speed fluctuations induced by the waves and the individual electrical power output \( P_t \) of each turbine due to their large inertia \( J \). In a previous work focusing on wave energy devices [16], it had been demonstrated that the flicker level induced by a wave farm including no means of storage could be reasonably well estimated by means of a sinusoidal voltage profile whose period was equal to the sea-state energy period (which is proportional to the peak period \( T_p \) used here). However, this method was no longer applicable in the case where a significant storage capacity was included in the wave farm. In similar fashion, the large inertia of tidal turbines acts as a storage means of considerable energy capacity.

B. Compliance of the tidal farm with flicker requirements

In order to maintain the quality of the electricity supplied to the customer, grid operators require that any grid-connected installation complies with a certain number of requirements, and among them flicker requirements. In most grid codes, flicker is required to be maintained under a maximal allowed limit at the PCC. Numerical values found in a number of national grid codes range between 0.35 and 1 for short-term flicker [13]. In order to perform an analysis independent of the short-circuit level \( S_k \) of the rest of the national grid, the flicker coefficient \( c_f(\Psi_k) \) was used. This coefficient is expressed as [17]:

\[
\Delta V = \frac{P_{eq}+Q_{eq}}{V_2} \quad (12)
\]

Hence, for sufficiently low impedance angles \( \Psi_k \) (i.e., resistive networks), the voltage deviation \( \Delta V \) is influenced mostly by the active power \( P \). On the contrary, for sufficiently high impedance angles \( \Psi_k \) (i.e., reactive networks), the influence of the reactive power \( Q \) dominates.

Figure 6. Simple two-bus system
For a given impedance angle \( \Psi_k \), the flicker coefficient \( c_f(\Psi_k) \) is constant. Fig. 8 shows the flicker coefficient \( c_f(\Psi_k) \) as a function of the significant wave height \( H_s \) for different impedance angles \( \Psi_k \). The minimum short-circuit level \( S_{k,\text{min}} \) for which the flicker level \( P_{st} \) remains below the maximum allowed flicker level limit \( P_{st,\text{max}} \) is calculated such as:

\[
S_{k,\text{min}} = \frac{c_f(\Psi_k) S_n}{P_{st,\text{max}}} \tag{14}
\]

Numerical values of the minimum short-circuit level \( S_{k,\text{min}} \) are shown on the right-hand side of Fig. 8. They correspond to the values of the flicker coefficient \( c_f(\Psi_k) \) indicated on the left-hand side axis of the graph. The values for \( S_{k,\text{min}} \) were calculated for each of the maximum allowed flicker limits considered in this study and equal to 0.35 and 1.0 respectively. It can be observed that the minimum short-circuit level \( S_{k,\text{min}} \) for which the flicker level \( P_{st} \) remains below unity is relatively close to the nominal power of the tidal farm. Considering that it is unlikely that a 30 MW tidal farm may be envisaged to be connected to such nodes due to power transmission capacity issues, the flicker level \( P_{st} \) can be considered as unlikely to exceed the most permissive limit. The same observations apply to most situations in the case of the most stringent flicker limit equal to 0.35. However, this limit may be exceeded in the rare cases meeting the three following conditions: 1) the tidal farm is connected to a node of relatively low short-circuit level in the range of approximately 50 MVA to 100 MVA, 2) the tidal farm is operated in high energetic wave conditions \( (H_s \geq 6 \text{ m}) \), which is quite unlikely, 3) the impedance angle \( \Psi_k \) of the grid node to which the tidal farm is connected is less than or equal to 50°, or equal to 85°. Hence, based on these observations, it can be concluded that the flicker level induced by a tidal farm on its local network is unlikely to exceed even the most stringent flicker limit. It is important to point out that the influence of no other storage means (e.g. batteries, supercapacitors) than the tidal turbine inertia was included in the model. However, this study has also shown that flicker could reach significant levels. This could contribute to make the total flicker level induced by the tidal farm and other installations connected to the same node exceed the maximum allowed limit in the case where the pre-connection flicker is already significantly high.

### IV. Conclusions

This paper has described the influence of sea waves on the quality of the electrical power output generated by a tidal farm in terms of short-term flicker level \( P_{st} \). First, the influence of the wave climate characteristics (significant wave height \( H_s \) and peak period \( T_p \)) on the flicker level \( P_{st} \) was studied. Then, the compliance of the tidal farm with the grid code requirements in terms of short-term flicker level was also analyzed in the second part of this paper. It was shown that the flicker level \( P_{st} \) induced by the tidal farm at the point of common coupling is unlikely to exceed even the most stringent limit found among a number of national grid codes. However, the flicker induced by the tidal farm reaches significant levels. Hence, in the case where the pre-connection flicker level is already significant, the grid connection of a tidal farm may lead the total flicker level at the point of common coupling to exceed the maximum allowed limit.

### REFERENCES


