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Resource-induced voltage flicker for wave energy converters – assessment tools

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Abstract: For wave energy converters, the input resource has a typical period of 5–20 s depending on the site location and dominant seastates. Wave energy converters generally produce mechanical power twice per wave cycle and therefore depending on the storage available, the electrical power output has half the period of the input resource. These regular power changes induce a voltage change at the point of connection (POC) which is proportional to the amplitude of the power change and at the same frequency. Therefore the coupling of the input resource to the output power of a wave energy converter will cause voltage flicker at the POC, which may exceed the permitted limits under specific conditions. This study establishes the nature of the flicker issue from wave energy converters. Some practical tools for the evaluation of flicker from a device are introduced. These tools are suitable for early stage flicker assessment to assist in the design process only. They are not meant of substitutes for existing codes and standards which are outlined in this study. This study concludes that wave energy converters may exceed flicker emission limits as a result of the coupling of the resource to the output power, and this may be particularly severe when connected to weak grids. Some potential strategies for overcoming this problem are presented also.

Nomenclature

P_{st}	short-term flicker – 10 min
P_{lt}	long-term flicker – 120 min
S	apparent power (VA)
P	active power (W)
Q	reactive power (VAr)
Z	impedance (Ω)
R	resistance (Ω)
X	reactance (Ω)
Ψ	impedance phase angle (°) – $\tan^{-1}(X/R)$
U_n	nominal system voltage (V)
U	voltage at point of connection (V)
ΔU	change in voltage at point of connection (V)
T_p	spectral peak wave period (s)
H_s	significant wave height (m)
S_n	nominal generator power (MVA)
S_k	short-circuit power (MVA) or fault level
I_k	short-circuit current (A) or fault current
$\cos\theta$	power factor
$c(\Psi k)$	flicker coefficient
POC	point of connection

1 Introduction

1.1 Flicker

Voltage flicker, or just flicker, refers to the subjective impression that is experienced by humans to changes occurring to the illumination intensity of light sources [1]. These changes are caused by rapid, regular changes to the voltage level of the electrical supply to the light source in question, typically an incandescent light bulb. It is the human element of flicker that makes it difficult to evaluate. Flicker may induce discomfort in the form of nausea, headaches, annoyance and distraction. In extreme cases, flicker may even induce epileptic fits.

The rapid voltage variations are caused by devices connected to the electrical system. These are mainly loads, but can also be caused by generators, particularly renewable generators. The voltage variations are caused by a fluctuation in the power consumed or generated by a load or generator, respectively, more severely for reactive power fluctuations. Therefore for a generator, the rapid, regular changes of the output power have the potential to manifest itself as a flicker problem.

Flicker is measured in flicker severity (unitless) and is normally given in short-term flicker, P_{st} and long-term flicker, P_{lt}. The weighted average flicker severity over 10 min is P_{st} and the cube root of the cubed average over 120 min is P_{lt} [2].

1.2 Grid code requirements

As the issue of flicker affects the customers, all electrical power system operators have limits for flicker within their respective grid codes. The limits are broadly similar across jurisdictions. The limits for flicker from the Irish and UK

grid codes are given in Tables 1 and 2 below along with those recommended in IEC 61000-3-7. They are separated into distribution connected (MV) and transmission connected (HV). Note that a limit of flicker severity of 1.0 means that it is at the level of disturbance (note: not everyone will perceive flicker at this level, but 50% based on controlled studies). There is some disparity between the distribution connected limits, with Irish limits being relatively low; however, the transmission connected limits are identical.

1.3 Voltage fluctuation calculation

The fluctuation in voltage across the electrical power system is caused by power flow (both active and reactive) within the system. In reality, as reactance is normally much larger than resistance within the power system reactive power flow creates much greater fluctuation in voltage than active power flow; however, this is not strictly true at 'weaker' parts of the network, where the network may be more resistive. For a generator connected to the grid, the amplitude of voltage fluctuation at its point of connection (POC) is caused by several factors [6] namely:

1. The amount of active and reactive power ($S = P + jQ$) to/from the generator.
2. The impedance ($Z = R + jX$) of the grid (sometimes given as a fault level or fault current) at the POC.
3. The impedance phase angle [the ratio of the resistance (R) to reactance (X) within the grid impedance, that is, $\tan^{-1}(X/R)$]. This is also referred to as the X/R ratio.

This is illustrated in Fig. 1.

There are a variety of possible methods for calculating voltage change at a node caused by a load or generator into that node. Voltage fluctuation (ΔU) calculations in this paper have been carried out according to (1) below. This equation is a simplified voltage fluctuation equation using an infinite bus circuit, but is shown in [7] to closely model a full load flow equation with minimal error. Therefore it is sufficiently accurate for this analysis

$$a = \frac{U_n^2}{2} - (RP + XQ)$$
$$b = (P^2 + Q^2) \times Z^2 \qquad (1)$$
$$\Delta U = \sqrt{a + \sqrt{a^2 - b}}$$

Table 1 Flicker severity limits for distribution (MV) connections

	Ireland [3]	UK [4]	IEC [5]
P_{st}	0.35	1.0	0.9
P_{lt}	0.35	0.8	0.7

Table 2 Flicker severity limits for transmission (HV) connections

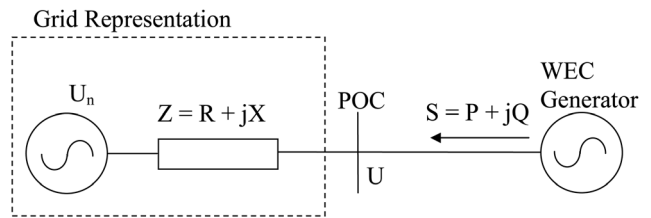|	Ireland [3]	UK [4]	IEC [5]
P_{st}	0.8	0.8	0.8
P_{lt}	0.6	0.6	0.6

Fig. 1 *Simple representation of generator connected to the grid*

2 Wave energy resource-induced flicker

2.1 Flicker curve

The flicker emission is unity (i.e. 1.0) when it is at the threshold of perception, that is, greater or equal than 1.0 means the flicker can be perceived (by the majority of people). The flicker emission unity threshold is shown in Fig. 2 at the 230 V level (for rectangular voltage changes). This shows the allowable percentage voltage fluctuation ($\Delta U/U$) at various frequencies. We can see from Fig. 2 that at 8.8 Hz the flicker unity threshold is very low at ~0.3% ($\Delta U/U$); however, it is over 1% for frequencies below 100 mHz and above ~20 Hz. The flicker curve given in Fig. 2 is taken from [8]; however, similar curves are also available from [4, 5, 9].

2.2 Voltage flicker emission from wave energy converters

The area of particular interest in the flicker curve for wave energy is at the frequency of the primary resource which is typically 0.05–0.2 Hz ($T_p = 5$–20 s). In actual fact, as the power output is only positive, the wave energy converter (WEC) will effectively 'half-wave rectify' the resource and so the frequency of the output power will be twice that of the primary resource. Therefore the area of interest will be 0.1–0.4 Hz. This range is highlighted in Fig. 2 and, as can be seen, the limit of voltage fluctuation ($\Delta U/U$) to give unity flicker emission in this range is ~0.85–1.3%.

Other sources of flicker could also be possible such as from potential switching operations (generators cutting in and out) and control system effects, but this paper is primarily focused on the 'resource induced' flicker concerns for wave energy converters.
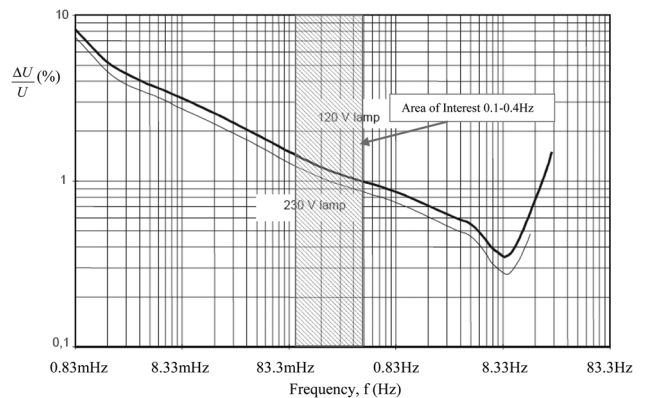

Fig. 2 *Voltage fluctuation corresponding to flicker emission unity threshold for 120 and 230 V lamp[4]*

3 Flicker assessment

3.1 Basic flicker assessment

In [4], a simple, first pass, assessment of potential flicker is given. This shows that the percentage voltage change for balanced three-phase systems can be defined as shown in the follwing

$$\Delta U(\%) = \frac{100 \times S_n}{S_k}\% \qquad (2)$$

Equation (2) gives the generator nominal power (in kVA) as a percentage of ten times the grid fault level (in MVA). This is useful for an initial assessment and as can be seen in the previous section if this value is >0.85–1.3% then it is obvious that the generator in question may exceed flicker limits. However, this simplified measure makes a number of assumptions, in particular about the grid conditions, which make it only useful as a first-pass, high-level calculation.

3.2 Flicker assessment charts

Flicker emission levels, given in P_{st} and P_{lt}, can be relatively difficult to calculate and for the purposes of developing WEC electrical systems it would be particularly beneficial to have a more accurate tool for first-pass analysis of the likely flicker issues associated with a particular technology.

As such flicker assessment charts have been developed here which will allow a quick but accurate assessment to be conducted. The following assumptions have been made in the development of the graphs:

1. The power output is assumed to be continuously oscillating, that is, with a fixed amplitude and frequency. This would not necessarily be the case in reality as the amplitude and period of the wave resource would change over time, but is considered a worst-case scenario.
2. The power oscillation is assumed to occur at the more flicker sensitive frequency in the 'resource induced' range, that is, 0.4 Hz – giving unity flicker at 0.85% $\Delta U/U$. This would not be the case in reality and so can be considered a worst-case scenario.
3. The power oscillation is assumed to be rectangular, which is the most severe, or worst, case. This would not be the case in reality and the fluctuating output power from a WEC would more likely be sinusoidal or triangular in shape;however these correction factors are not applied here.

Therefore the flicker assessment graphs have some safety factors inherently built in because of the use of worst-case scenarios.

For the avoidance of doubt, note that 'Lagging' power factor implies that the generator is exporting active power and reactive power. 'Leading' power factor implies that the generator is exporting active power, but importing reactive power. This is the normal convention for generators.

The following steps are required to utilise the graphs:

1. Grid fault level, S_k – This can be derived from the grid impedance, Z, or short-circuit current, I_k, also.
2. Grid X/R ratio, or impedance phase angle, ψ_k.
3. WEC max fluctuating power (ΔS_n). Note that this may be a percentage of the WEC nominal power, S_n, and may even be greater than the S_n (in the case of a power take off (PTO)

which absorbs power from the grid during the wave cycle, that is, complex conjugate control).
4. WEC output power factor (cos θ).
5. Site scatter diagram (optional).
6. P_{st} and P_{lt} limits in the jurisdiction.

All of these items are, however, not strictly necessary and some can be derived from guidance given in the International Electrotechnical Commission (IEC) standards, as outlined in the steps below.

The graphs work as with the following steps:

1. If known the $\Delta S_n/S_k$ ratio is calculated, that is, the ratio of the fluctuating generator power to the grid fault level. If the grid fault level is not known then it can be substituted for a 'typical' multiple of S_n (reference [10] recommends the range of 20–50).
2. The power factor (cos θ) is noted. If PF not known then it can be substituted for a typical case (0.95–1.0 lagging).
3. The P_{st} and P_{lt} applicable limits are noted. If not known, then these can be substituted for a typical value (0.8 would be prudent in most cases).
4. The X/R ratio is noted. If not known, then these can be substituted for a typical value (1–4 is prudent).
5. A suitable graph (given the P_{st} and P_{lt} limits) is chosen from Figs. 3 to 5 below and the intersection of $\Delta S_n/S_k$ and X/R is marked.
6. If that intersection 'lies above' the applicable power factor line, then there 'will be a potential issue with flicker' for the chosen configuration and a further, detailed, study is required. If that point 'lies below the line' then there will be 'no issue with flicker' for the chosen configuration, even in the worst-case scenario.

Two observations are immediately apparent from Figs. 3 to 5.

Firstly, the 0.95 lagging power factor curve allows much lower power fluctuation ($\Delta S_n/S_k$) than that for the unity power factor. This is due to the fact that the reactive current flows from generator to grid in this case and contributes to the voltage variation amplitude.

Secondly, there is a large peak around the X/R ratio of 4 for the 0.95 leading power factor curve. This allows much higher power fluctuation ($\Delta S_n/S_k$) than that for the unity power factor. This peak only occurs at low X/R ratios and from $X/R = 6$ onwards the 0.95 leading power factor allows lower power fluctuation than for the unity power factor. This is due to the fact that the reactive current flows from grid to
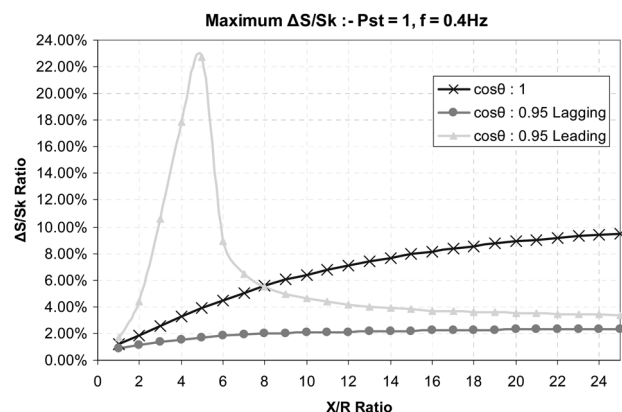

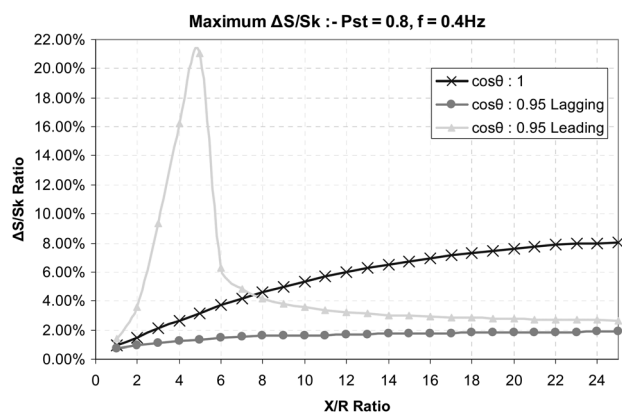**Fig. 3** *Maximum permissible $\Delta Sn/Sk$ for $P_{st} = 1.0$*

Fig. 4 *Maximum permissible ΔSn/Sk for P_st = 0.8*
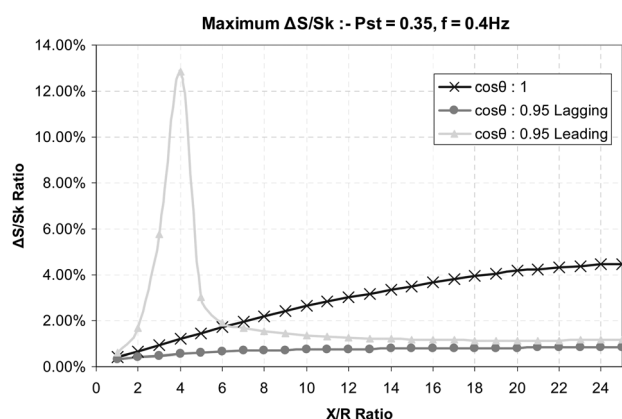
Table 3 Theoretical examples using flicker guidance curves

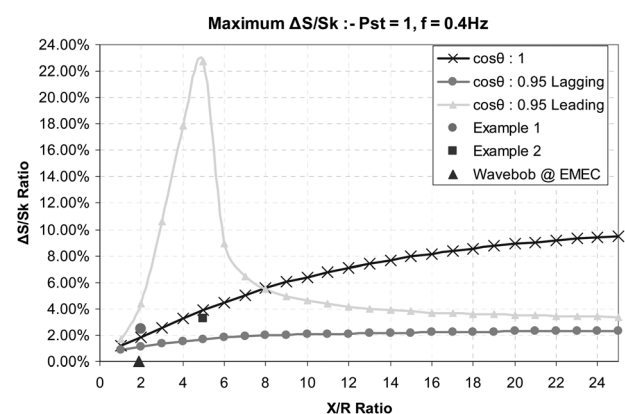|	Example 1	Example 2
grid fault level (S_k), MVA	40	30
WEC max fluctuating power (ΔS_n), MVA	1	1
$\Delta S_n/S_k$, %	2.5	3.3
P_{st} and P_{lt} limits in the jurisdiction	1.0	1.0
grid X/R ratio	2	5
WEC power factor (cos θ)	1	1
site scatter diagram	T_p min: 5 s	T_p min: 5 s
	yes	no
potential flicker issue	detailed study required	no flicker study required

Fig. 5 *Maximum permissible ΔSn/Sk for P_st = 0.35*

Fig. 6 *Example use of chart with points for examples 1 and 2 shown (Wavebob case study also shown – see Section 5.2)*

generator in this case. For low *X/R* ratios, this has the effect of cancelling out the voltage variation from the active power flow (from generator to grid). When the *X/R* ratio becomes larger, the reactive current causes the voltage to drop more than the active current causes it to rise and this means that the voltage dips to the point that it exceeds the flicker emission limit.

3.2.1 Examples of flicker assessment charts: Two theoretical examples using Fig. 3 are given below in Table 3 and illustrated in Fig. 6.

The examples shown above in Table 3 and Fig. 6 illustrate that even though the WEC in Example 2 is connected to a weaker grid, that is, one with a lower fault level, because it has a higher *X/R* ratio the same WEC fluctuating power, ΔS_n, can be connected to it without exceeding a P_{st} limit of 1.0. This is shown as the Example 1 point (red circle [colour online]) is shown above the 'cos θ: 1' line. Example 2 (purple square [colour online]) is shown below this line. Wavebob case study is also shown in Fig. 6 and is explained in Section 5.2.

3.3 Flicker measurement standards

Flicker is a known issue from a number of renewable generators and industry standards existing for the assessment of flicker. Notable power quality standards are IEC 61400-21 for wind energy [10] and IEC 62600-30, which is being developed by the IEC TC114 for wave and tidal devices.

It is not the authors intention to replace these standards. The tools given in this paper are meant to be practical, user friendly, tools which can be used at the design stage. The compliance with approved industry standards, such as the IEC standards mentioned above, will be a requirement of any device connecting to the network.

The above methods in Sections 4.1 and 4.2 can be seen as a preliminary, 'go/no-go', assessment. If these indicate that further analysis is required, then a full flicker assessment must be carried out in line with the industry standards.

The method of measurement of flicker for wind turbines is given in [10] and the design specification for a flickermeter is given in [2]. A flickermeter essentially filters the voltage magnitude profile to separate the frequency components which cause flicker. The flicker level is then quantified by means of a model of the human 'lamp–eye–brain' response. A block diagram of a flickermeter is shown below in Fig. 7.

The full flicker assessment method involves either measuring or simulating the power output from the WEC and calculating the resultant change in voltage at the POC. Once this is done, the voltage profile is fed through a flickermeter to give P_{st} and P_{lt} values.

4 Case study – Wavebob

A case study is undertaken to show the use of the flicker evaluation tools discussed in Section 4 and also to show, for an actual grid connected wave energy converter, the severity of the flicker for the entire scatter diagram. This
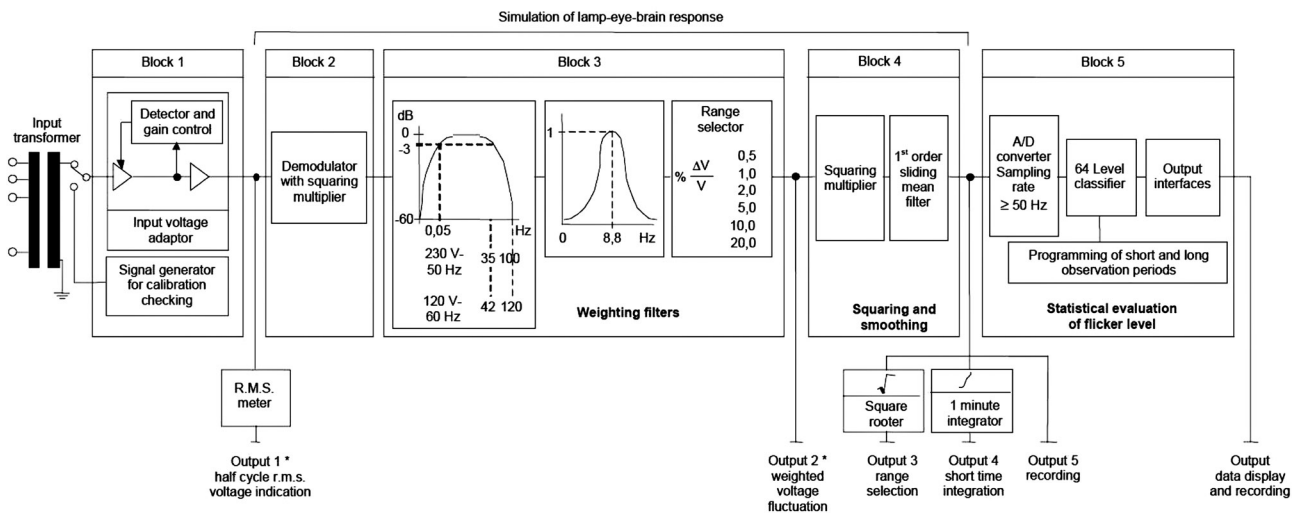
Fig. 7 *Block diagram of flickermeter from [2]*

will illustrate the seastates which induce the largest flicker emission levels.

The case study will involve the Wavebob WEC at the European Marine Energy Centre (EMEC) test site. The characteristics for the case study are given below in Table 4. These values are derived from the information provided by Wavebob and EMEC.

4.1 Basic flicker assessment

Using the equation given in Section 4.1, we calculated that the potential voltage variation $\Delta U/U$ is only 0.164%. This is below the level of any issue with flicker, 0.85%. Therefore from this basic assessment, we can say that the case study WEC will not present any issue with flicker.

4.2 Flicker evaluation charts

The relevant flicker evaluation chart is given in Fig. 3 where the P_{st} limit is 1.0 and is reproduced with the result in Fig. 6 in Section 4.2. The $\Delta S_n/S_k$ percentage in this case is 0.00164% and the X/R ratio is 1.87. This means that the intersection point for these values is below the line for 'cos $\theta = 1$'. Therefore, from the flicker evaluation charts, we can also say that the case study WEC will not present any issue with flicker. This is expected as the ratio of S_n/S_k is so small in this case study. Normally, this would indicate that no further assessment is required.

4.3 Full flicker assessment

No further assessment would normally be required for this case study which is because of the large S_k/S_n ratio and hence no flicker issue.

Table 4 Parameters for case study

Wavebob at EMEC	
$\Delta S_n/S_k$, %	0.00164
P_{st} and P_{lt} limits in the jurisdiction	1.0
grid X/R ratio	1.87
WEC power factor (cos θ)	1

However, in order to investigate the flicker emissions from the WEC further, a full assessment was carried out with the grid fault level/WEC rated power ratio (S_k/S_n) set to 1.0 and the X/R ratio set to 1.2 ($\psi_k = 50°$). This will give the 'flicker coefficient', $c(\Psi_k)$, for all the seastates at the site. The X/R ratio chosen as one of the several recommended X/R ratios given in [10].

The 'flicker coefficient', $c(\Psi_k)$, is a non-site specific (i.e. generic) value and can be divided by the actual S_k/S_n ratio for any site to give the actual P_{st} values, at the same impedance phase angle (Ψ_k), for that site.

The assessment was carried out using time domain simulations of the Wavebob WEC (un-tuned) at the EMEC test site. The original scatter from [11] is adapted to use custom intervals for H_s and T_p values, suitable for the Wavebob in-house simulations tools and is shown below in Fig. 8. This shows that the highest occurring seastates are at lower period (5.5–8.5 s).

A 10 min simulated power output time series from the device was evaluated and the $c(\Psi_k)$ calculated for each of the cells in the scatter diagram, that is, each seastate. The voltage variation was calculated using the same formula from [7] presented in Section 2.3 and the P_{st} value was calculated using an IEC flicker evaluation software program [12].

The flicker coefficient for the scatter diagram is presented in Fig. 9 below with the characteristics shown in Table 5.

What is shown in Fig. 9 is that the more severe flicker occurs at the lower period (higher frequency) seastates (<10 s). This is as expected as the flicker limits are lower for higher frequencies in the area of interest shown in Fig. 2. As the significant wave height, H_s, becomes larger and therefore the seastate contains more energy, the more severe flicker becomes more severe at higher period (low frequency) seastates. However, this is only to a point as the highest period (lowest frequency) seastates exhibit a drop off in the flicker severity, even for large H_s values.

In Fig. 9, the highest flicker coefficient is 33.34 ($H_s = 5.25$ and $T_p = 8.5$). For a P_{st} limit of 1, what can be inferred is that the Wavebob device will exceed the flicker limits for any grid fault level/WEC rated power ratio (S_k/S_n) of less than 33.34, given an X/R ratio of 1.2 ($\psi_k = 50°$) and power factor of 0.98 lagging. If we use this $c(\Psi_k)$ value for the EMEC case study shown in Table 4, we can see that the maximum

Hs [m]	Annual Occurrence % (Total = 100%)											
5.75					0.01	0.03	0.19	0.36	0.50	0.25	0.12	0.08
5.25				0.00	0.01	0.03	0.42	0.37	0.10	0.04	0.01	0.01
4.75				0.01	0.10	0.32	0.55	0.41	0.08	0.03	0.01	0.02
4.25			0.01	0.01	0.40	1.29	0.66	0.26	0.06	0.04	0.02	0.02
3.75			0.01	0.31	0.96	2.03	0.80	0.21	0.06	0.02	0.01	0.01
3.25		0.02	0.09	1.44	2.22	1.64	0.60	0.14	0.07	0.03	0.02	0.02
2.75		0.14	0.73	2.53	2.95	0.85	0.37	0.14	0.09	0.05	0.02	0.02
2.25	0.06	0.76	3.49	3.37	2.28	0.81	0.40	0.20	0.12	0.06	0.02	0.02
1.75	0.71	2.12	5.12	3.65	1.73	0.77	0.41	0.19	0.09	0.03	0.01	0.02
1.25	2.27	4.89	5.16	3.49	1.81	0.84	0.42	0.17	0.07	0.04	0.01	0.02
0.75	6.26	9.13	6.34	3.69	1.75	0.81	0.46	0.26	0.15	0.07	0.02	0.01
	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50
	Tp [s]											

Fig. 8 *Scatter diagram from EMEC adapted from [11]*

Hs (m)	Flicker Coefficient, $c(\psi_k)$											
5.75					31.86	29.78	23.4	19.31	14.85	13.02	8.58	7.17
5.25				33.34	30.56	25.03	21	16.46	12.78	9.84	8.49	6.72
4.75				30.98	26.17	20.88	18.79	15.08	10.46	8.96	7.25	5.93
4.25			29.96	27.07	22.45	21.23	15.62	11.69	8.54	7.21	5.32	4.17
3.75			26.63	24.41	18.72	15.29	13.11	8.82	8.8	5.89	4.83	3.42
3.25		28.19	23.27	19.13	15.55	13.25	8.87	6.89	5.4	4.01	2.96	2.6
2.75		20.82	18.48	16.48	10.71	8.74	7.35	5.14	3.94	3.31	2.65	1.74
2.25	14.55	15.79	15.1	11.28	9.17	5.04	4.58	3.72	2.63	2.26	1.83	1.48
1.75	10.7	12	8.29	6.58	4.87	3.43	2.95	2.12	1.77	1.29	0.92	0.87
1.25	6.28	6.66	5.44	3.96	2.6	2.17	1.7	1.06	1	0.65	0.64	0.45
0.75	2.73	2.22	2.03	1.43	1.06	0.97	0.48	0.4	0.34	0.26	0.25	0.23
	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50
	Tp (s)											

Fig. 9 $c(\Psi_k)$ *for Wavebob, $(\Psi_k = 50°)$*

Table 5 Parameters for $c(\psi_k)$ calculation

Wavebob at EMEC	
$\Delta S_n/S_k$	100% [make $\Delta S_n = S_k$ for $c(\Psi_k)$ calculation]
grid X/R ratio	1.2 ($\psi_k = 50°$)
WEC power factor (cos θ)	0.98 (lagging)

flicker emission, P_{st}, at EMEC for the Wavebob device would be 0.0546 ($c(\Psi_k)/(S_k/S_n) = 33.36/610$), for Ψ_k of 50°, which is well below the limit of 1.0. This verifies our initial assessments in Sections 5.1 and 5.2.

It should be noted that this simulation is a 'un-tuned' Wavebob WEC. The Wavebob WEC can be tuned with the opening, partial opening and closing of its submerged tank. With tuning, the response of the WEC could be reduced for higher seastates meaning a potential reduction in the maximum flicker coefficient witnessed.

For this worst-case cell ($H_s = 5.25$ and $T_p = 8.5$) other X/R ratios and power factors are evaluated. As per [10], a range of typical X/R ratios are evaluated, namely 0.57 ($\psi_k = 30°$), 1.2 ($\psi_k = 50°$), 2.7 ($\psi_k = 70°$) and 11.4 ($\psi_k = 85°$). Also a range of power factors are evaluated between 0.95 lagging and 0.95 leading. The results are plotted in Fig. 10 below.

Fig. 10 shows that the flicker coefficient becomes smaller as the X/R ratio becomes larger and also that as the power
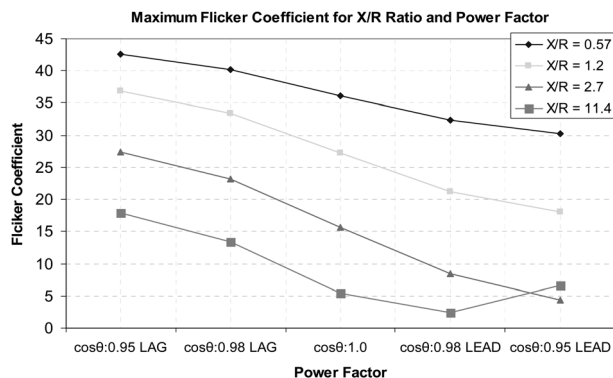

Fig. 10 *Wavebob C_f for various X/R ratios and power factors*

factor changes from lagging to leading the flicker coefficient also becomes smaller. This coincides with the results shown in the flicker evaluation charts in Figs. 3–5.

5 Cancellation effects for an array of devices

It has been demonstrated in this paper that WECs have the potential to cause 'resource induced' flicker. This raises the obvious question of whether there will be a cancellation

effect in an array of WECs which will mitigate this flicker emission.

This issue is well understood in wind farms [6] with an array cancellation factor generally being of the order of $n^{-1/2}$, where n is the number of wind turbines in the array. This means that a wind farm with ten turbines would have an equivalent flicker emission of 3.16 ($10^{-1/2}$) individual turbines and not 10, that is, there is a cancellation factor of 31.6%. As larger wind farms will be connected to stronger grid nodes with higher fault levels, this has the effect of lowering the flicker emissions from the array.

Interference and interaction of WECs in arrays is less well understood than for wind turbine arrays. Some work has been carried out on the potential of flicker cancellation from WEC arrays [13]; however the interference effects were simplified. Therefore it is difficult to currently predict what smoothing may occur. It can be stated that some smoothing is expected to occur, but, depending on the layout of the array and the seastate, there may be occasions where the fluctuating power of the WECs occur simultaneously which will reduce the cancellation factor.

It is likely that the cancellation factor for WEC arrays will be somewhere between $n^{-1/2}$ and 1 (i.e. no smoothing), depending on numerous factors in the configuration of the array.

6 Flicker mitigation methodologies

If the resource-induced flicker from a WEC exceeds the local emission limits, then there are several possibilities for overcoming this. Some of these have been discussed previously in [14].

6.1 Energy storage/smoothing

Obviously some sort of energy storage solution could be installed either on the WEC device itself or at the POC to smooth the power fluctuations and hence reduce flicker if necessary. There are several options available for energy storage. Mechanical storage solutions are available such as flywheels, hydraulic accumulators etc. Electrical storage solutions are also possible such as capacitors, battery energy storage etc.

The storage system will have to be fast acting and rated for the amplitude of the power fluctuation. It will also be subjected to multiple cycles during its lifetime. This solution will, however, mean additional costs and losses in the overall system which may be unacceptable.

6.2 Spatial configuration (cancellation effect)

As discussed in Section 6 when the cancellation effects in WEC arrays are better understood, it may be possible to reduce flicker by an appropriate spatial design of the array.

6.3 Control strategy

A control strategy could be implemented in certain situations which not only reduces power fluctuation from individual devices [15], but also changes the characteristic of individual devices in a WEC array to avoid a statistical summing of power fluctuations and maximise the flicker cancellation factor.

6.4 Reactive power compensation

Another possibility to counter a power fluctuations problem is the addition of a controlled reactive power device such as a static synchronous compensator (STATCOM) at the POC [16]. This will instantaneously control the import and export of reactive power (VARs) from/to the grid, and hence control the voltage level to be sufficiently smooth at the POC. Like the energy storage, this solution will mean additional costs and losses in the overall system which may be unacceptable.

6.5 Increasing short-circuit power

By reconfiguring the network at the POC or by reinforcing the network up to the POC, the fault level can be increased meaning that the power variations would not as severely affect the voltage. However, this is a costly method requiring new infrastructure.

7 Conclusions

Flicker is a power quality issue that any renewable power generator will need to consider. As the authors have shown it is particularly of interest in wave energy due to the fact that 'resource induced' flicker lies in the frequency range of the flicker curve.

As flicker evaluation can be complicated and specialised, the authors have presented a number of options for evaluating the flicker issue. These range from a preliminary calculation, the use of bespoke flicker assessment charts and a full flicker assessment. The simplicity of the flicker assessment charts should allow for any party to evaluate the potential flicker from a wave energy converter at a given site.

A case study was undertaken to show the use of the methods. However, the case study WEC was shown, with the flicker assessment graphs, to not have a flicker issue at the specified site. This is because of the very large S_k/S_n ratio.

The flicker coefficient was evaluated for the device and can be used to evaluate flicker at different sites in the future. This flicker coefficient showed that the 'resource induced' flicker is more apparent at lower period waves and particularly at high energy (high H_s), low period waves.

There are several possibilities for overcoming these flicker issues; however, these would all seem to have a cost or efficiency penalty on the overall system.

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