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Voltage Flicker Evaluation for Wave Energy Converters – Assessment Guidelines

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Abstract

Voltage flicker is a power quality problem caused by regularly oscillating active and reactive power either from a load or generator. The regular power oscillations induce a voltage change at the grid connection which is proportional to the amplitude of the power oscillation and at the same frequency. The impedance of the grid (grid strength) at the point of connection is a factor in the amplitude of the voltage oscillation.

The frequency band of interest for flicker evaluation is from 0.01-20Hz, and is most severe at 8.8Hz. The frequency of the primary resource for wave energy converters lies within this range. Therefore the coupling of the input resource to the output power of a wave energy converter will cause voltage flicker at the point of connection. This is particularly true for 'direct drive' wave energy converters.

This paper serves to establish the flicker effects of wave energy converters on the grid voltage. The paper outlines some working guidelines for the evaluation of flicker from a device. The paper concludes that wave energy converters may exceed flicker emission limits, particularly in weak grid areas and suggests some strategies for overcoming this problem.

Keywords: Wave Energy Converters, Power Quality, Flicker, Resource..

1. Introduction

Power quality refers to the maintenance of voltage, current and frequency of electrical power supply to the customer within accepted norms and limits. Power quality includes issues such as harmonic distortion, voltage and current imbalances, transients, and frequency variations among many other issues. One of these issues is flicker, which is a voltage quality problem, and is discussed in relation to Wave Energy Converters (WECs) in this paper. Voltage flicker is differentiated from steady state voltage variation which allows a much larger deviation in voltage levels. Voltage flicker limits, depending on the frequency of the oscillation, will permit a much smaller level of deviation in voltage levels.

Voltage flicker, or simply flicker, refers to the subjective impression that is experienced by humans to changes occurring to the illumination intensity of light sources [1] be it a light bulb, television or other electrically powered light source. These changes are caused by rapid, regular changes to the voltage level of the electrical supply to the light source in question. 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 can 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. The voltage fluctuations are caused by a fluctuation in the load power consumed or the generator power exported, especially for reactive power fluctuations. Therefore, for a generator, the rapid oscillation of the output power has the potential to manifest itself as a flicker problem.

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

1.1 Grid Code Requirements

As the issue of flicker affects customers all power system operators have limits for flicker within their own grid codes. The limits are broadly similar across jurisdictions, however can be relatively strict in smaller electrical systems such as Ireland. The limits for flicker from the Irish and UK grid codes are given in Table 1 & 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 threshold of perceptibility (Note: not everyone will perceive the flicker at this level, just a majority based on laboratory studies). There is some disparity between the distribution connected limits, with Irish limits being relatively low; however the transmission connected limits are identical.

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

Table 1: Flicker Severity Limits for Distribution (MV) Connections

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

Table 2: Flicker Severity Limits for Transmission (HV) Connections

2. Wave Energy Resource Induced Flicker

The flicker emission is unity (i.e. 1.0) when it is at the threshold of perception, i.e. greater or equal than 1.0 means the flicker can be perceived (by a majority). The flicker emission unity threshold is shown in Fig. 1 at the 230V level (for rectangular voltage changes). This shows the allowable percentage voltage fluctuation ($\Delta V/V$) at various frequencies. We can see from Fig. 1 that at 8.8Hz the flicker unity threshold is very low at 0.3% however it is over 1% for frequencies below 100mHz and above approx 20Hz. The flicker curve given in Fig. 1 is taken from [6]; however similar curves are also available from [4, 5 & 7]
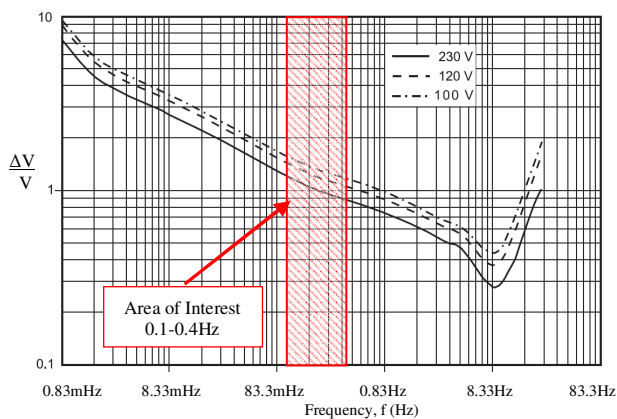

Figure 1: Voltage Fluctuation corresponding to flicker emission unity threshold [6]

The area of particular interest in the flicker curve for wave energy is at the frequency of the primary resource which is typically 0.05-0.2Hz (i.e. Tp: 5-20 seconds). In actual fact, as the power output is only positive, the 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 0.1-0.4Hz.** This range is highlighted in Fig. 1 and, as can be seen, the limit of voltage fluctuation ($\Delta V/V$) 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 we are primarily focussing on the 'resource induced' flicker concerns for Wave Energy Converters

3. Flicker Assessment

3.1 Basic Flicker Assessment

In [3] a preliminary, first pass, assessment of potential flicker is given. This shows that the percentage voltage change for balanced 3-phase systems can be defined as

$$\frac{\Delta V}{V}(\%) = \frac{S_n}{10 \times S_k}\% ,$$

Where: S_n is the generator rated power (in kVA) and S_k is the grid short circuit power (in MVA).

This method is useful for an initial assessment. As outlined in the previous section if $\Delta V/V$ is greater than 0.85-1.3% it implies that the generator in question may cause a flicker problem. However this simplified method makes a number of assumptions, in particular about the grid conditions and frequency of power oscillation, which make it only useful as a first pass, preliminary 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 preliminary analysis of the likely flicker issues associated with a specific technology.

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

1. The oscillating power is assumed to be continuous with a fixed amplitude and frequency. This would not 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 most flicker sensitive frequency in the "resource induced" range, i.e. 0.4Hz – giving unity flicker at 0.85% $\Delta V/V$. This would not be the case in reality and so can be considered a worst case scenario.
3. The oscillating power is assumed to be rectangular, which is the most severe, or worst, case. This would not be the case in reality and the actual oscillating 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 due to the use of worst case scenarios.

For the avoidance of doubt note that 'Lagging' power factor implies that the generator is exporting real power and reactive power. 'Leading' power factor implies that the generator is exporting real power but

importing reactive power. This is the normal convention for generators.

Voltage fluctuation ($\Delta V/V$) calculations in this section and the next section have been carried out according to the equation given below. This equation is a simplified voltage fluctuation equation using an infinite bus circuit but is shown in [8] to closely model a full load flow equation with minimal error. Therefore it is sufficiently accurate for our analysis.

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

The following information is ideally required to utilise the graphs;

1. Grid Fault Level (S_k) – This can be derived from the grid impedance or short circuit current.
2. Grid X/R Ratio or impedance phase angle (ψ_k). This is the ratio of the reactance to resistance in the grid impedance.
3. WEC Max Oscillating Power (ΔS_n). Note that this may be a percentage of the WEC rating or may even be more than the WEC rating (in the case of a PTO which absorbs power from the grid during the wave cycle, i.e. complex conjugate control)
4. WEC Output Power Factor ($\cos\theta$)
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 IEC standards, as outlined in the steps below.

The following steps and examples detail the methodology for using the graphs:

1. If known the $\Delta S_n/S_k$ ratio is calculated, i.e. the ratio of the oscillating 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 ([9] recommends the range of 20-50)
2. The Power Factor ($\cos\theta$) 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. 2-4 below and the intersection of $\Delta S_n \backslash S_k$ & 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

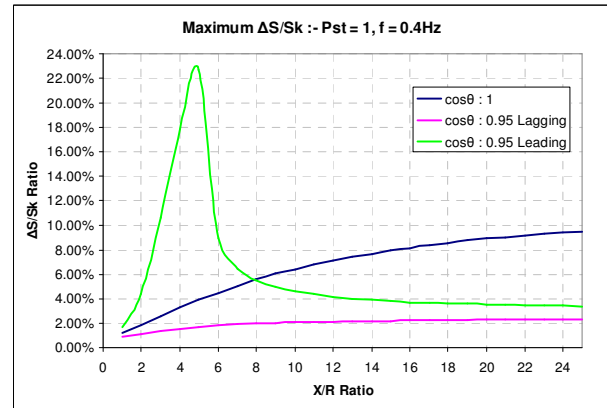

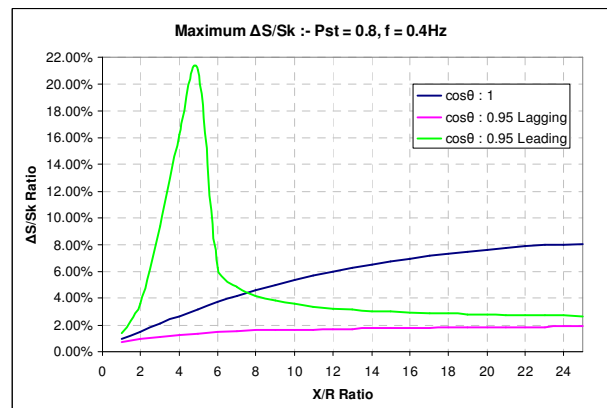**Figure 2:** Maximum Permissible $\Delta S_n/S_k$ for $P_{st} = 1.0$

Figure 3: Maximum Permissible $\Delta S_n/S_k$ for $P_{st} = 0.8$
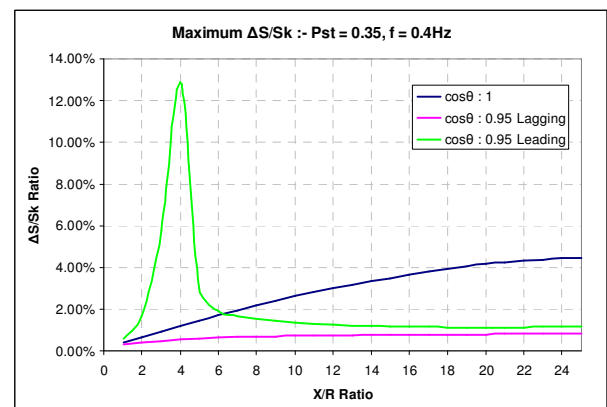

Figure 4: Maximum Permissible $\Delta S_n/S_k$ for $P_{st} = 0.35$

Two observations are immediately apparent from Figs. 2-4 above.

Firstly the 0.95 lagging power factor curve allows much lower power oscillation ($\Delta S_n/S_k$) than that for

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 oscillation ($\Delta S_n/S_k$) than that for 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 oscillation than for unity power factor. This is due to the fact that the reactive current flows from grid to 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.

Two theoretical examples using Fig. 2 are given below in Table 3 and illustrated in Fig 5.

	Example 1	Example 2
Grid Fault Level (S_k)	40MVA	30MVA
WEC Max Oscillating Power (ΔS_n)	1MVA	1MVA
$\Delta S_n/S_k$	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 (cosθ)	1.0	1.0
Site Scatter Diagram	Tp min: 5 seconds	Tp min: 5 seconds
Potential Flicker Issue	Yes. Detailed Study Required	No. No Flicker Study Required

Table 3: Theoretical examples using flicker assessment graphs.
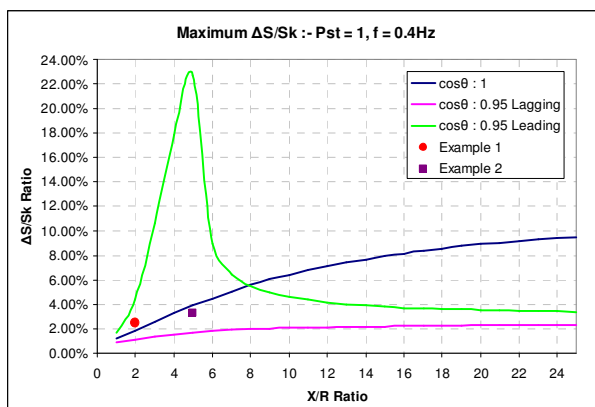
Figure 5: Reproduction of Fig. 2 with Example 1 & 2 shown

The examples shown above in Table 3 and Fig. 5 illustrate that even though the WEC in Example 2 is connected to a weaker grid, i.e. one with a lower short circuit power, because it has a higher X/R ratio the same WEC Oscillating 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) is shown above the "cosθ : 1" line. Example 2 (purple square) is shown below this line.

3.3 Full Flicker Assessment

The above methods in 3.1 and 3.2 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.

The method of measurement of flicker for wind turbines is given in [9] and the design specification for a flickermeter is given in [2]. A flickermeter essentially filters the voltage to separate the high 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 flicker meter is shown below in Fig. 6.
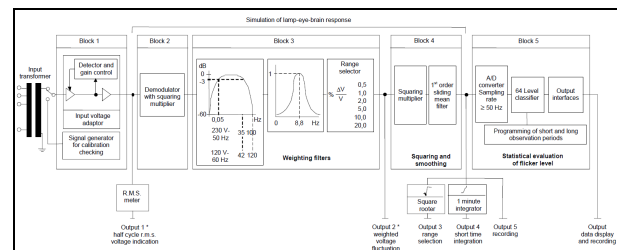
Figure 6: Block Diagram of Flickermeter from [2]

Also worth noting are the developing IEC standards under TC114 (IEC 62600-30 (ANW)) which will detail power quality requirements for wave and tidal energy converters.

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 point of connection. Once this is done the voltage profile is fed through a flicker meter to give P_{st} and P_{lt} values.

4. Case Study

A case study is undertaken to show the use of the flicker evaluation tools discussed in Section 3 and also to show, for an actual wave energy converter output, where in the scatter diagram the flicker is most severe.

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 information provided by Wavebob and EMEC.

	Wavebob @ EMEC
Grid Fault Level/WEC Rated Power Ratio, S_k/S_n	610
P_{st} and P_{lt} limits in the jurisdiction	1.0
Grid X/R Ratio	1.87 ($\psi_k = 68.7°$)
WEC Power Factor ($\cos\theta$)	1.0

Table 4: Characteristics for Case Study

The three methods outlined in Section 3 will be used to evaluate any potential flicker issues with this case study.

4.1 Basic Flicker Assessment

Using the equation given in 3.1 we calculated that the potential voltage variation ΔV 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. 2 where the P_{st} limit is 1.0. 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. Normally this would indicate that no further assessment is required.

4.2 Full Flicker Assessment

No further assessment would normally be required for this case study which is due to the large S_k/S_n ratio.

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_f, for all the seastates at the site. The X/R Ratio chosen as one of several recommended X/R ratios given in [9].

The 'flicker coefficient', C_f, is a non site specific value and can be divided by the actual S_k/S_n ratio for any site to give the actual P_{st} values 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 [10] is adapted to use custom intervals for Hs and Tp values, suitable for the Wavebob in-house simulations tools and is shown below in Fig. 7. This shows that the highest occurring seastates are at lower period (5.5-8.5 seconds)

Annual Occurrence % (Total = 100%)

Hs [m]	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50
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
								Tp [s]				

Figure 7: Scatter Diagram for EMEC test site adapted from [10]

A 10 minute simulated power output time series from the device was evaluated and the P_{st} calculated for each of the cells in the scatter diagram, i.e. each seastate. The voltage variation was calculated using the same formula from [8] presented in the previous section and the P_{st} value was calculated using an IEC flicker evaluation programme [11]

The flicker coefficient for the scatter diagram is presented in Fig. 8 below with the characteristics shown in Table 5.

	Wavebob @ EMEC
Grid Fault Level/WEC Rated Power Ratio, S_k/S_n	1 (flicker coefficient)
P_{st} and P_{lt} limits in the jurisdiction	1.0
Grid X/R Ratio	1.2 ($\psi_k = 50°$)
WEC Power Factor	0.98 (lagging)

Table 5: Characteristics for C_f Calculation

Flicker Coefficient, Cf

Hs (m)	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50
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
								Tp (s)				

Figure 8: C_f for Wavebob at EMEC

What is shown in Fig. 8 is that the more severe flicker occurs at the lower period (higher frequency) seastates. This is as expected as the flicker limits are lower for higher frequencies in the area of interest shown in Fig. 1. As the significant wave height, Hs, becomes larger and therefore the seastate contains more energy the more severe flicker becomes evident at even high period (low frequency) seastates. However this is only to a point as the much higher period (lower frequency) sea states exhibit a drop off in flicker severity, even for large Hs values.

In Fig. 8 the highest flicker coefficient is 33.34(Hs = 5.25, Tp = 8.5). As the P_{st} limit is 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. This is only for an X/R ratio of 1.2 and power factor of 0.98. If we use this C_f value for the EMEC case study shown in Table

4 we can see that the maximum flicker emission, P_{st}, at EMEC for the Wavebob device would be 0.0546 (C_f / (S_k/S_n) 33.36/610), which is well below the limit of 1.0. This verifies our initial assessments in 4.1 and 4.2

It should be noted that this simulation is an '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 (Hs = 5.25, Tp = 8.5) other X/R ratios and power factors are evaluated. As per [9] a range of typical X/R Ratios are evaluated, namely 0.57 (ψ_k = 30°), 1.2 (ψ_k = 50°), 2.7 (ψ_k = 70°), and 11.4 (ψ_k = 85°). Also a range of power factors are evaluated between 0.95 lagging and 0.95 leading. The results are plotted in Fig. 8 below.

Fig. 9 shows that the flicker coefficient becomes smaller as the X/R ratio becomes larger and that as the power 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. 2-4.
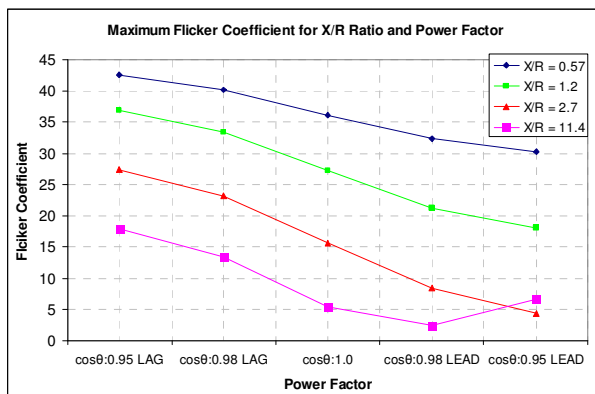
Figure 9: C_f for various X/R Ratios and Power Factors

5.   Cancellation for an Array of Devices

It has been demonstrated 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 [12] 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 10 turbines would have an equivalent flicker emissions of 3.16 ($10^{-1/2}$) individual turbines and not 10. 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. Therefore it is difficult to currently predict what

smoothing may occur. It can be stated that some smoothing may occur but, depending on the layout of the array and the seastate, there may be occasions where the oscillating 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*, depending on numerous factors in the configuration of the array.

6.   Flicker Mitigation Methods

If the resourced induced flicker from a WEC exceeds the local limits then there are several possibilities for overcoming this. Some of these have been discussed previously in [13].

1.   Energy Storage/Smoothing:

Obviously some sort of energy storage solution could be installed either on the WEC device itself or at the point of connection (POC) to smooth the power oscillations. 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 oscillation. 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.

2.   Spatial Configuration (cancellation effect)

As discussed in Section 5 when the cancellation effects in WEC arrays are better understood, it may be possible to reduce flicker by and appropriate spatial design of the array.

3.   Control Strategy

A control strategy could be implemented in certain situations which not only reduces power fluctuation from individual devices [14] 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.

4.   Reactive Power Compensation

Another possibility to counter a power fluctuations problem is the addition of a controlled reactive power device such as a STATCOM at the POC [15]. 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.

5.   Increasing Short Circuit Power

By reconfiguring the network at the POC or by the 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 graphs, and a full flicker assessment. The simplicity of the flicker assessment graphs 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 due to 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 Hs), 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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