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# Case studies on the benefits of energy storage for power quality enhancement: oscillating water column arrays

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## Abstract

This paper presents case studies investigating the benefits of short term energy storage for wave farms connected to electrical networks having different grid strengths. The first network model represents the Atlantic Marine Energy Test Site (AMETS) of the Republic of Ireland, located at a significant wave resource but connected to a relatively weak network. The second network represents the Biscay Marine Energy Platform (BIMEP) test site, located off the Basque Country coast in Spain, which is connected to a relatively strong network. The case study utilises scaled real oscillating water column (OWC) device test data from the FP7 CORES project, and is intended to be a companion paper to a corresponding set of case studies performed with a point absorber farm, thus addressing two of the main wave energy technology types in the two papers. The paper investigates the impact of storage on voltage fluctuation, flicker, and power output profile.

**Keywords:** Power quality, oscillating water column, grid integration, energy storage.

## 1. Introduction

The significant power fluctuations associated with wave energy converters are an issue of concern for grid operators specifically in relation to power quality. Large changes in power over relatively short periods of time can cause voltage and frequency issues in regional networks, particularly at distribution level where grid impedance is higher.

Power quality standards are in existence for grid connected wind turbines [1] which address such issues as voltage flicker, power ramp rates and voltage transients. These are still under development for ocean

energy, but it is likely that similar limits will be imposed.

Short term energy storage can contribute to the enhancement of power quality for wave farm power outputs by mitigating the power fluctuations associated with many device technologies. Moreover, by reducing the amplitude of power peaks, the required rating for components such as cables and transformers may also be reduced, potentially reducing capital expenditure.

This paper investigates the benefits of short term energy storage on the power quality of an OWC-based wave farm when connected to two electrical networks of different strength or impedance. A companion paper performs similar case studies utilising a point absorber-based array.

## 2. Description of Case Studies

In this section, the case studies are described in detail.

### 2.1 Resource

A comprehensive resource characterisation of the AMETS test site is provided in [2] indicating that the majority of energy production sea states at AMETS fall within the ranges of 1.5m and 7m significant wave height and 7s-14s peak wave period, although storm wave conditions up to 10m wave height can be experienced. Both sites are open Atlantic sites and approximately similar conditions prevail at the BIMEP site as described in [3]. The case studies are simulated in the following seaway conditions for both sites:

Sea State	H <sub>s</sub> (m)	T <sub>p</sub> (s)
Low energy	1.3	13.8
Medium energy	2.4	11.0
High energy	5.7	16.5

**Table 1: Sea State Summary**

These sea conditions are selected as a reasonable cross-section of wave height and period, and also linked to available data in the context of this particular case study.

## 2.2 Test Sites

### AMETS

The AMETS test site is located off the north-west coast of Ireland. It is still under development and it is envisaged that this site will be used by developers for the final stages of device testing prior to commercial deployment. The grid model used in the current study for the test site is based on cabling design studies performed in conjunction with ESBI in the context of the grid connection application and is shown in Figure 1. The conceptual wave farm consists of two clusters each including up to 11 generators. The clusters are connected to the shore by two ac subsea feeder cables each, one being 6.5 km long, the other being 16 km long. Each feeder cable is connected to an offshore 0.4 kV/10 kV transformer. The cluster located at a 6.5 km distance from the shore is referred to as Cluster 1, whereas the other cluster (16 km from the shore) is referred to as Cluster 2 as shown. Each cluster consists of two radial feeders (Feeder 1 and Feeder 2) to which wave energy converters are connected. An onshore substation steps the voltage up to 20 kV. Then, the wave farm is connected to the rest of the national network of Ireland by a 5-km long, 20 kV overhead line. The on-shore VAR compensation system is designed to maintain the power factor at the PCC between 0.92 and 0.95 lagging as specified by the network code[4] of the distribution system operator (DSO), ESB. In this case study, a constant 0.93 lagging power factor was applied

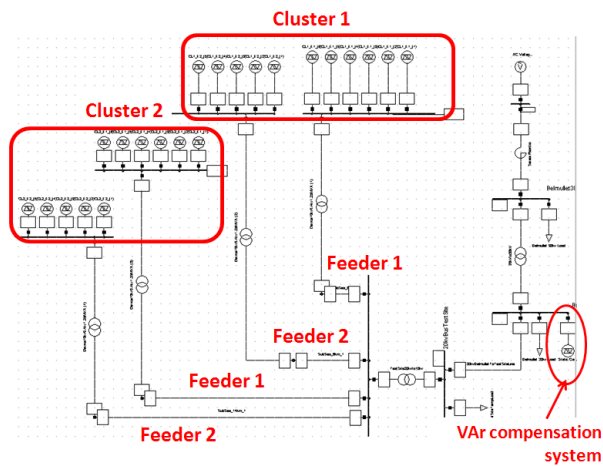


Figure 1: AMETS grid model

The rest of the national network is modelled by a 20kV/38 kV transformer connected to a fixed voltage source in series with a reactor. The impedance of this reactor represents the short-circuit impedance at this node, which was estimated to be equal to 22.8  $\Omega$  based on the EirGrid Transmission Forecast Statement [5]. This corresponds to a short-circuit power of 63MVA.

### BIMEP

The BIMEP (Biscay Marine Energy Platform) is an offshore facility for research, demonstration and operation of real-scale WECs on the open sea. It is

located in Northern Spain, South East of the Bay of Biscay, and it is expected to be in operation in 2013-2014. The facility comprises 4 offshore berths, rated at 5MW each, and composed of subsea cables of different lengths. Once onshore, the subsea cables are replaced by four identical land cables up to the substation. The substation consists of two 13.2/132 kV transformers, used for the wave farm connection to the PCC.

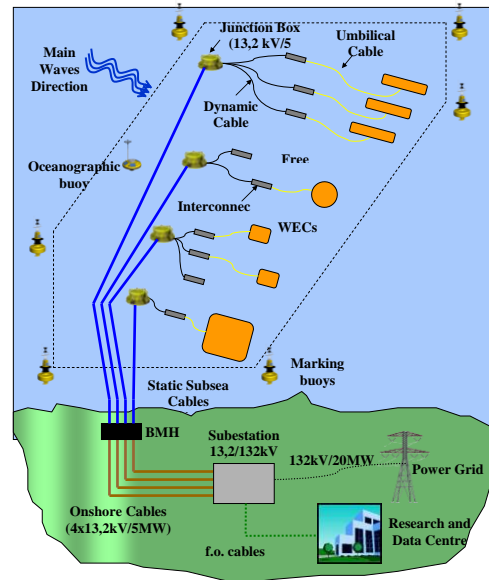


Figure 2: Bimep architecture

Each WEC (Wave Energy Converter) is connected to shore through an offshore cable. The model of each WEC includes a generator and a 0.69kV/13.2 kV transformer. Figure 2 shows the grid model for BIMEP.

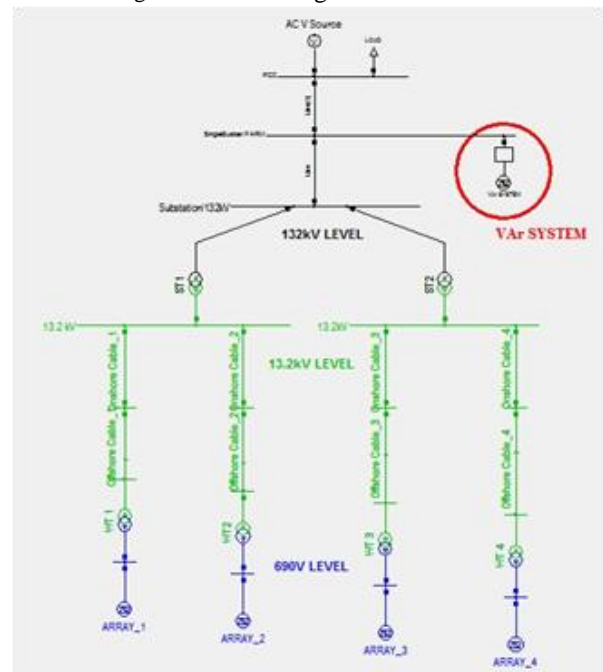


Figure 3: BIMEP grid model

The PCC is modelled considering its  $S_{sc}$  (short-circuit power) given by the DSO (Distributed System

Operator) as 4550 MVA. There is a static VAR compensator connected at the PCC in order to keep the power factor equal to unity.

### 2.3 WECs

Each wave energy converter is modelled by means of a DIGSILENT built-in “Static Generator” model, representing a generator connected to the grid via fully-rated back-to-back PWM converters. The electrical power output of each generator was modelled using an experimental power time series from the CORES project. CORES stands for “Components for Ocean Renewable Energy Systems”. It is an FP7 European collaborative research project focusing on the development of new concepts and components for power-take-off, control, moorings, risers, data acquisition and instrumentation for floating wave devices [6].

The project itself was based on a floating OWC-type system. The project began in April 2008 and ended in December 2011. The quarter-scale OWC prototype used in the project was deployed offshore from March to May 2011. Figure 4 shows the OWC deployed offshore.



**Figure 4:** Oscillating water column deployed in CORES

An important outcome of the project has been a considerable volume of time series data of electrical parameters at a resolution of 0.1 s. This can be scaled and used directly for grid impact studies, as in this case. In order to reflect the output of the farm in an appropriate manner, the power output time series from the CORES device must be scaled to full scale power level, and modified for each device to reflect the impact of spacing and aggregation. This process is described in [7] and involves the following steps:

1. Scale power data to full scale.
2. Introduce time delay shifting to represent spacing of devices within a cluster.
3. Introduce further time delay shifting to represent spacing of the two clusters.

### 2.4 Energy Storage

In this study, energy storage is assumed to be applied to the combined output of the entire at the shore side substation. It is modelled in a simplified manner as a first order low-pass filter with a variable time

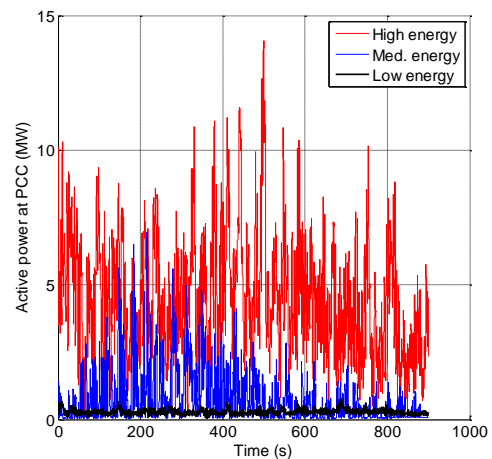
constant. In this manner, varying levels of energy storage can be represented in a generic way at this stage, without requiring specific detail on the exact implementation of the storage technology. The options considered correspond to a power smoothing on a time scale of 5 s, 25 s and 50 s respectively. These values are selected to correspond to a range of a real energy storage options from hydraulic accumulators to flywheel inertia to seawater reservoirs, as outlined in [8].

## 3. Results and Outputs

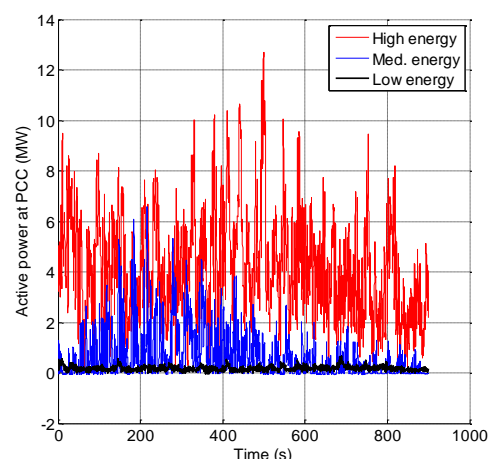
Results for power fluctuation, voltage fluctuation, flicker and contingency are given in the following sections.

### 3.1 Power Fluctuation

The active power outputs as measured at the PCC for the farms at BIMEP and AMETS are illustrated in Figure 5 and Figure 6 without energy storage.



**Figure 5:** Farm active power at PCC for BIMEP



**Figure 6:** Farm active power at PCC for AMETS

In order to assess the impact of differing levels of energy storage on each farm output, the active power at the BIMEP PCC in the high energy sea state is depicted in Figure 7 and at the AMETS PCC in the medium energy sea state in Figure 8.

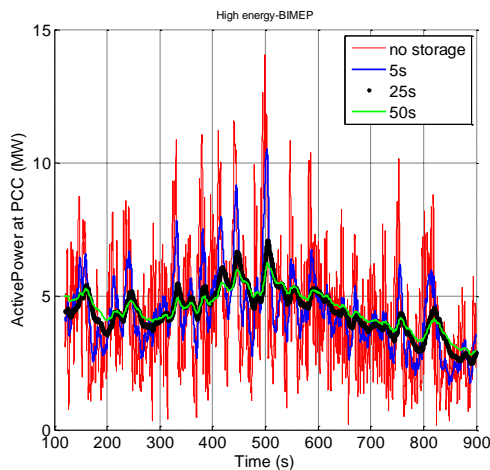


Figure 7: Active power at BIMEP PCC; high energy

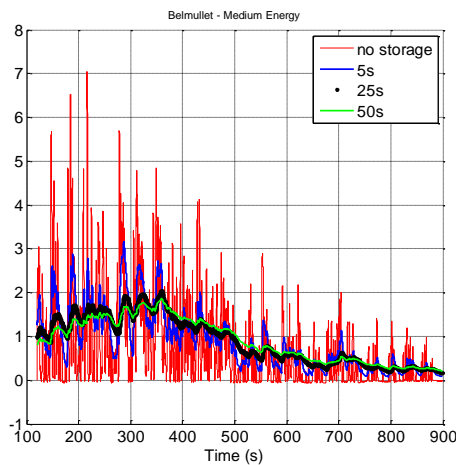


Figure 8: Active power at AMETS PCC; medium energy

The dramatic effect on the power profile is evident in both Figure 7 and Figure 8. There does not however appear to be a significant change from 25s to 50s storage time constants in both cases.

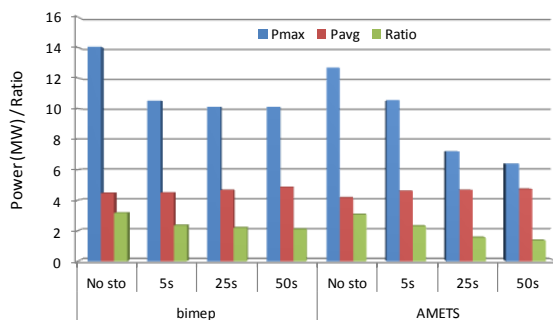


Figure 9: Peak to average power ratios for BIMEP and AMETS; high energy

Despite the significant smoothing of the power time series perceived visually in Figure 7 and Figure 8, with many individual power peaks dropping by 50% or more depending on storage time constant, the actual ratio of peak power to average power does not drop as much as might be expected, as illustrated in Figure 9 for the

high energy sea state. For instance, at 5s storage time constant, the peak to average ratio drops to 2.3 from a level of 3.1 with no storage. At a 50s time constant, this ratio has dropped to 1.35, which is a more acceptable level. This is important for rating considerations, particularly of the power converters where the maximum VA rating level of the converters usually corresponds to the maximum peak power. This underlines the additional importance of implementing some form of power peak limiting [9], as well as energy storage capability.

### 3.2 Voltage Variation

The voltage variations seen at the PCC in both AMETS and BIMEP are illustrated in Figure 10 and Figure 11 for the high energy sea state and for the different levels of storage. Due to the weaker grid strength at AMETS, the storage has a dramatic effect, even at its lowest level of 5s, raising the voltage nadir from 0.92 pu to around 0.965 pu.

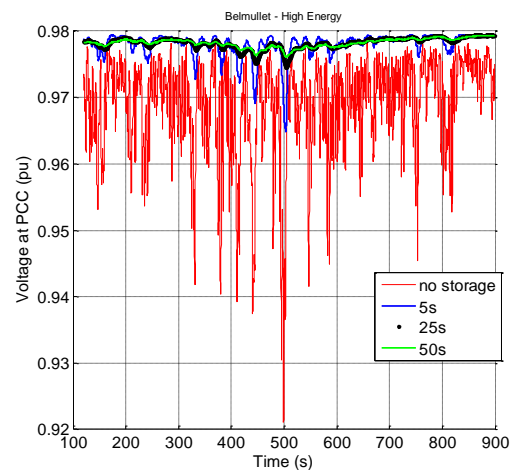


Figure 10: PCC voltage AMETS; high energy

The impact at BIMEP is measurable but less significant as a result of the stronger network at that location even though the power fluctuations are almost exactly the same.

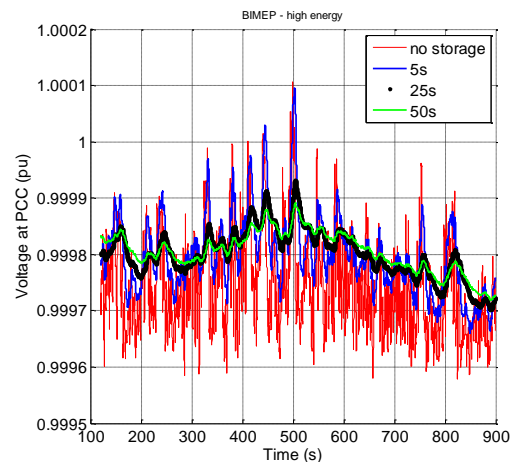


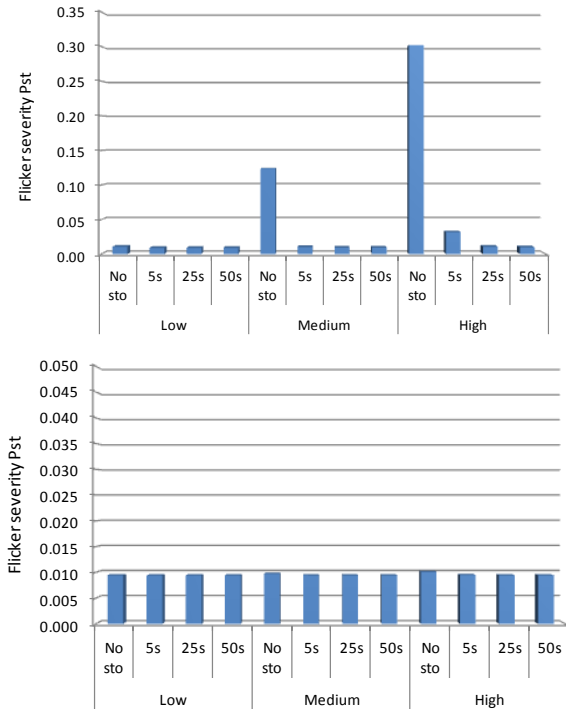
Figure 11: PCC voltage BIMEP; high energy



### 3.3 Flicker

Short term flicker coefficient,  $P_{st}$  is an important measure of power quality [7, 10, 11] and provides an indication of the level of visual disturbance that can be induced in lighting loads by the voltage fluctuations in the distribution network.

The flicker severity level for both sites under the different seaway conditions are plotted in Figure 12.

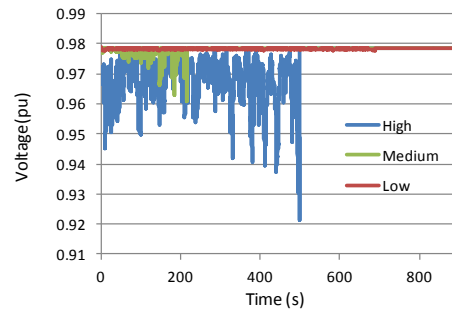


**Figure 12:** Short term flicker severity level at (top) AMETS (bottom) BIMEP (different y-axis scales)

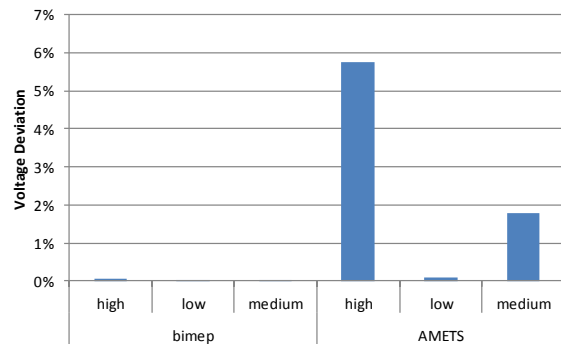
As expected for BIMEP, the flicker level is extremely low due to the strength of the electrical network, and in this regard the effect of the energy storage on the performance is almost indistinguishable. For AMETS however, the reduction in flicker coefficient is dramatic, even with only 5s of energy storage time constant. It should be noted that the flicker limit for the Irish DSO is 0.35, and that the AMETS study comes close to this level with no storage.

### 3.4 Farm Disconnection

The transient step in the PCC voltage on connection or disconnection of a farm is an important power quality consideration [1]. Sudden disconnection is a more likely scenario, since this can happen under fault or protection conditions, whereas farm connection is usually a scheduled event with a ramped approach that gradually increases the farm power output. This phenomenon is illustrated in Figure 13 for AMETS for the high, medium, and low energy sea states. Disconnection is performed at maximum power, so that these graphs represent the worst case scenario.

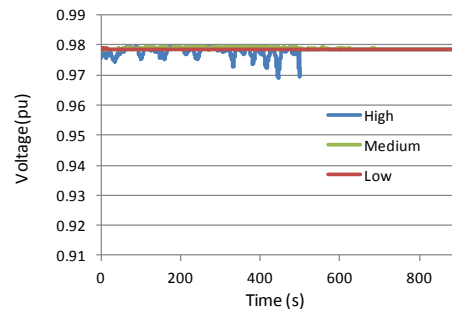


**Figure 13:** PCC Voltage on disconnection of farm (AMETS)



**Figure 14:** PCC Voltage on disconnection of farm for different sea-state energy levels (AMETS)

The variation in voltage deviation with the sea state and for the two sites is illustrated in Figure 14. Again, AMETS shows the most significant deviations due to the weaker grid. The addition of a small amount of energy storage makes a significant difference to this voltage disturbance as evidenced in Figure 15 for AMETS with a 5s energy storage addition.



**Figure 15:** PCC Voltage on disconnection of farm (AMETS) with 5s energy storage

## 4. Conclusions and Summary

This paper has illustrated the potential value of energy storage in the grid integration of wave energy converters with high fluctuation power outputs, such as OWCs. It has been demonstrated that even relatively small values of energy storage time constant - which roughly corresponds to inertia constant - can have a significant impact on the power and voltage fluctuations measured at the grid PCC. Flicker and

voltage deviation during switching events are also reduced significantly. This is more striking and effective in a weaker grid, as illustrated by the AMETS results, in which energy storage can be the difference between grid compliance and non-grid compliance. The effect is less evident in a stronger grid such as BIMEP, where the disturbance on the grid from the wave farm is not as significant in the first place.

Peak-to-average power ratio is not however, reduced as much as would be expected by the presence of energy storage. This implies that rating issues for components such as power electronics converters are still significant and may require other mitigation measures such as peak power limiting.

## Acknowledgements

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