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The Benefits of Device Level Short Term Energy Storage in Ocean Wave Energy Converters

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1. Introduction

This chapter presents an outline of the requirements for, and the benefits of, short term energy storage at the level of individual wave energy devices, in the field of ocean wave energy conversion. A general background introduction to ocean renewable energy from the perspective of industry growth and incentives, as well as an overview of the different technology types is provided. The unique and challenging features of the short term variability of wave energy is presented and its implications for equipment and grid connectivity are outlined. Short term energy storage is considered as a possible element in the amelioration of this fluctuating output. A case study of a supercapacitor based storage system is presented for an oscillating water column type wave energy device. The issue of supercapacitor lifetime is then addressed in a comprehensive manner in conjunction with results from a lifetime testing rig. Finally, some of the ancillary benefits associated with such a short term energy storage system are briefly described.

2. Ocean renewable energy

Renewable energy technology is steadily gaining importance in the world energy market, due to the limited nature and unstable costs of fossil fuel supplies, national requirements for security of supply, as well as political pressure towards the reduction of carbon emissions. In the European context, wind energy is leading the way in terms of installed capacity, with over 84 GW of cumulative installed capacity in the EU by the end of 2010, representing almost 10% of total installed power capacity (European Wind Energy Association, 2011). The vast majority of this installed capacity is located onshore with a mere 2.9 GW located in the near or off-shore environment. However, offshore installations had a record-breaking year in 2010 with 883 MW of new installed capacity, reflecting an underlying trend of a gradual movement towards the offshore environment. Interestingly solar PV installations in the EU represented the largest single block of renewable energy sources installed capacity in 2010 with 12 GW installed, although the total installed capacity in solar PV still lags behind that of wind with 25 GW of total installed capacity within the EU (European Wind Energy Association, 2011).

The next wave of renewable energy development is anticipated to be offshore renewable energy, which mainly comprises offshore wind, ocean wave and ocean tidal flow technologies. As an industry, ocean energy is still in its relative infancy, although there has been a rapid acceleration in recent years in research and development funding, infrastructure creation, foreshore license policy streamlining, and policy development.

2.1 Roadmaps and targets

The European Union Ocean Energy Association (EU-OEA) has created a 2010-2050 roadmap for the development of the ocean energy industry in Europe, which aims to enable the industry to reach 3.6 GW of installed capacity by 2020 and close to 188 GW by 2050. This roadmap trend is plotted in conjunction with current and projected trends in onshore and offshore wind energy development in fig. 1.

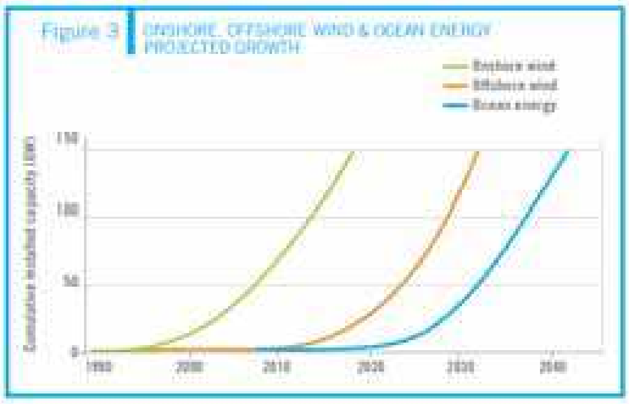


Fig. 1. Ocean Energy Roadmap and Trends in Wind Energy

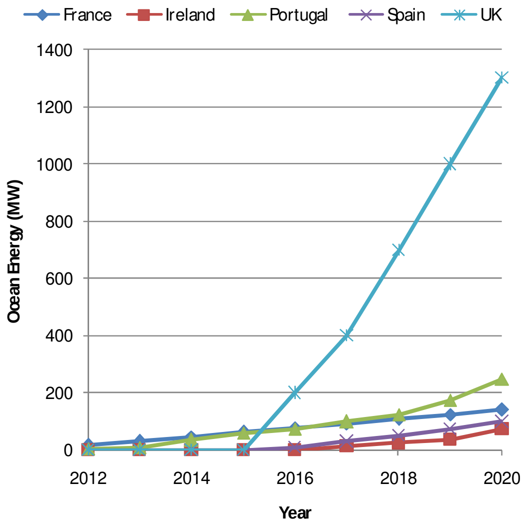


Fig. 2. Ocean Energy Deployment Scenarios by Country

A further incentive to the ocean energy industry and to national and regional funding bodies has been the targets or scenarios for the deployment of ocean energy technology produced by the EU, national governments, as well as industry associations such as the EU-OEA. These range from aspirational roadmaps such as that represented in fig. 1, to legally binding targets such as EU Directive 2009/ 28/ EC. This directive mandates a percentage target for share of energy from renewable sources for each EU member state country in gross final consumption of energy by 2020. These targets are legally binding and can be met by the individual member state across electricity, heat and transport sectors in whatever proportion they see fit, once the overall target is complied with. Each member state is also required to produce a National Renewable Energy Action Plan (NREAP) detailing how they intend to meet their targets. The NREAP generally results in a set of scenarios for different levels of deployment of various renewable energy technologies, consistent with the natural resources of the specific member state. In particular, some member states have specifically identified the deployment of various levels of ocean energy as part of their renewable electricity contribution. Unlike the overall renewable targets outlined in the Directive, the specific mix of contributions contained in the NREAPs is not legally binding. It will nonetheless act as a driver of policy, technology development and investment. A summary of some of the more important ocean energy deployment scenarios as outlined in the individual member state NREAPs (e.g. (Department of Communications, Energy and Natural Resources, Irish Government, 2010)) is portrayed in fig. 2. These scenarios include ocean wave and tidal current plant (Beurskens & Hekkenberg, 2011).

2.2 Electricity grid developments

In parallel with the policy developments and incentives outlined in the previous section, electricity network operators have been active in working to facilitate the large scale integration of renewable energies into transmission and distribution networks. This has been focussed primarily on the wind sector, however, the reinforcements and upgrades to the network to facilitate wind energy will in many cases indirectly facilitate the development of ocean energy farms also. For instance, in Ireland the greatest wind resource is located along the western seaboard. This is also the location of the majority of the ocean energy resource in the form of wave energy. The anticipated creation of a North Sea offshore grid, as well as feasibility studies such as the ISLES project (Scottish Govt., Northern Ireland Executive & Govt. of Ireland, 2011) will further prepare the ground for large scale interconnection of offshore wind, wave and tidal resources. A possible projection of the 2050 electricity grid in Europe (European Climate Foundation, 2010) in the scenario of 80% renewables penetration is illustrated in fig. 3.

Fig. 3. Projected European Electricity Grid

2.3 Job creation

As well as being a vehicle for satisfying renewable energy targets, the development of the marine renewable sector is seen as a potential catalyst for economic growth and job creation.

Ocean energy is well positioned to contribute to regional development in Europe, especially in remote and coastal areas. This is of particular value in locations where the redeployment of resources and infrastructure previously associated with more traditional marine sectors such as fisheries can revitalise economically depressed communities. The manufacturing, transportation, installation, operation and maintenance of ocean energy facilities will generate revenue and employment. Studies suggest that ocean energy has a significant potential for positive economic impact and job creation(Department of Communications, Energy and Natural Resources, Irish Government, 2010). Parallels can also be drawn with the growth of the wind industry. Export of clean technology now accounts for €7.1 billion annually in Denmark, while in Germany export of wind technology alone is worth over €5.1 billion. Based on the projections for installed capacity in the EU-OEA report, it is anticipated that by 2020 the ocean energy sector will generate over 26,000 direct and 13,000 indirect jobs, increasing to over 300,000 direct and over 150,000 indirect jobs by 2050 assuming the targeted 188 GW is installed (Department of Communications, Energy and Natural Resources, Irish Government, 2010).

2.4 Ocean energy technology

The term ocean energy can encompass a wide range of technologies including ocean wave, tidal current, ocean thermal energy conversion, and ocean salinity gradient. Practically speaking, only tidal current and ocean wave energy are currently anywhere close to commercial operation.

There are many different methods for wave and tidal current energy conversion. The majority of devices, however, follow an approximately similar general outline in terms of energy conversion and capture. This section looks at the various stages in the energy conversion process and discusses the different methodologies used within the main converter technologies.

The energy conversion process can be broken down as follows:-

Primary Energy Capture: This is the means through which the device interacts with the energy source, transferring energy from the waves or tidal currents to a medium which can be captured by a ‘prime mover’.

Prime Mover: This is a component which can convert the energy captured at the primary energy capture stage to a more useful form of energy, usually mechanical energy, which can be connected to a generator. In some devices, such as tidal turbines, the primary energy capture and prime mover functions are embodied in the same component. In such a case, this component will be referred to as the primary energy capture component as this more completely describes its functionality.

Generator: The generator converts the mechanical energy of the prime mover into electrical energy and can also act as one of the main control elements in the system.

Storage: Energy storage is used to smooth the time variation of the output electrical power, thus enhancing the power quality of the device.

Control: Control systems are required to optimise, coordinate and control the operating points of some, or all, of the power take-off components and also to protect the device in undesirable operating conditions.

In an attempt to group and classify ocean energy devices, the primary energy capture technique is typically used as a demarcation between device classes. Often, the same or similar prime movers and generators are employed in very different devices, and so it is reasonable to classify devices according to the dynamics of the primary energy capture method as mentioned previously, in some tidal current devices the primary energy capture component can also be considered as a prime mover. The following device classifications are representative of the majority of ocean energy devices (O' Sullivan et al., 2010).

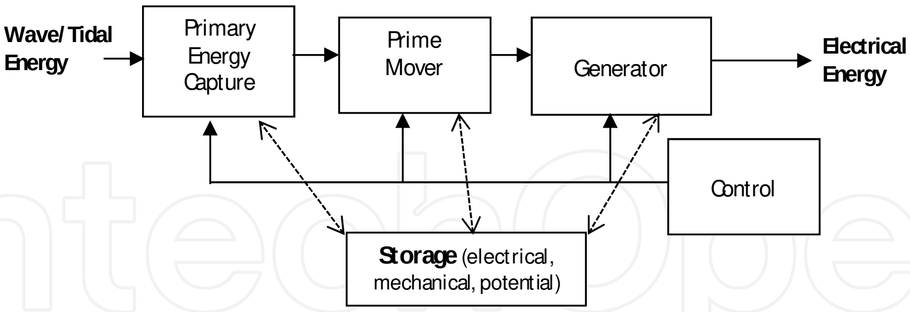


Fig. 4. Typical Ocean Energy Conversion Process

Wave Energy	Tidal Current Energy
Oscillating Water Column (OWC)	Tidal Turbine
Attenuator	Oscillating Hydrofoil
Point Absorber	Tidal Sail Device
Submerged Pressure Differential	Venturi Effect Device
Oscillating Wave Surge Converter	
Overtopping Device	

Table 1. Major Device Classifications

The focus in this article is on ocean wave energy so a brief description of each of the primary power capture processes is provided for the wave energy technologies. Most of these technologies are described in more detail in other technology overview publications (2008, Khan & Bhuyan, 2009).

2.4.1 Oscillating water column

The Oscillating Water Column (OWC) device (Evans, 1978, Falcão, 2002) converts wave motion into pneumatic energy within an enclosed air chamber through the action of external wave pressure fluctuations on a column of water tuned to resonate with the dominant wave frequency. The air is then passed through a turbine which is connected to a generator. The air turbine is typically a Wells turbine (Raghunathan, 1995) or impulse turbine (Setoguchi & Takao, 2006) both of which have the ability to convert bidirectional airflow into a unidirectional torque. An illustration of a typical system is shown in fig. 5:

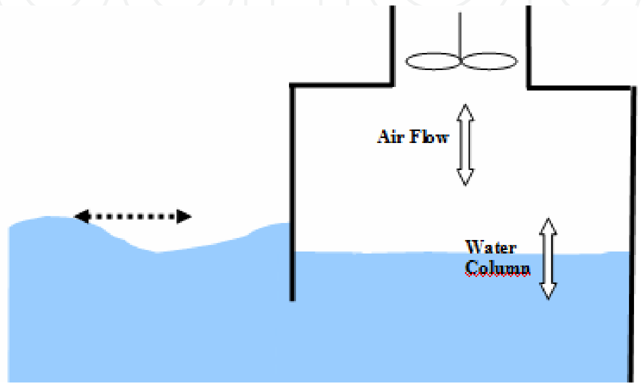


Fig. 5. OWC Illustration

An example of an OWC device is the Ocean Energy Buoy (O'Sullivan et al. 2011).

2.4.2 Attenuator

Attenuators (Henderson, 2006) are floating devices aligned to the incident wave direction. Passing waves cause movements along the length of the device. Energy is extracted from this motion.

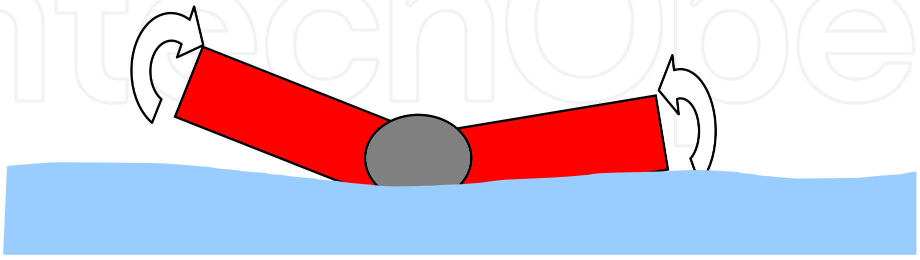


Fig. 6. Attenuator Illustration

These types of devices are typically long multi-segment structures. The device motion follows the motion of the waves. Each segment, or pontoon, follows oncoming waves from crest to trough. The floating pontoons are usually located either side of some form of power converting module. Passing waves create a relative motion between each pontoon. This relative motion can then be converted to mechanical power in the power module, through either a hydraulic circuit (most common) or some form of mechanical gear train. An example of an attenuator is the Pelamis device (Henderson, 2006).

2.4.3 Point absorber

Point absorber devices (Ricci et al., 2009) are generally axi-symmetric about a vertical axis. They are small in comparison to the incident wave length. Point absorber devices usually consist of two main components – a displacer which is a buoyant body which moves with wave motion, and a stationary or slow moving reactor. Energy can be extracted through the relative motion between the displacer and the reactor. This can be accomplished using electromechanical or hydraulic energy converters. The hydraulic converters usually involve hydraulic rams, rectifying valves, gas accumulators and hydraulic motors. An illustration of a typical point absorber is given in fig. 7.

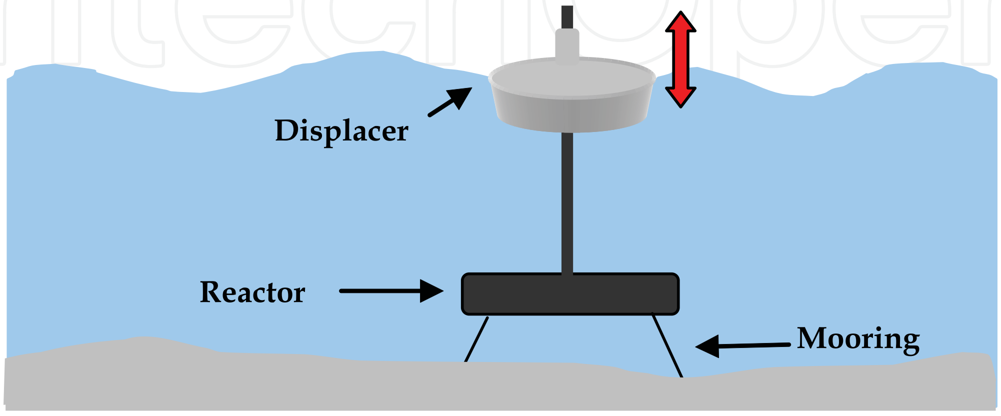


Fig. 7. Point Absorber Illustration

2.4.4 Submerged pressure differential

This type of device can be considered to be a fully submerged point absorber (Polinder et al., 2004). The PTO for the device consists of two main components, a reactor and a displacer. Passing waves cause the sea surface elevation above the device to rise and fall. A pressure differential is created above the device as waves pass. This causes an air chamber within the displacer to decompress and compress, thus causing the displacer to rise and fall. The reactor is typically secured to the sea bed. Power can be extracted from the relative motion between the displacer and reactor, by using a hydraulic or electromechanical system connected between the displacer and reactor.

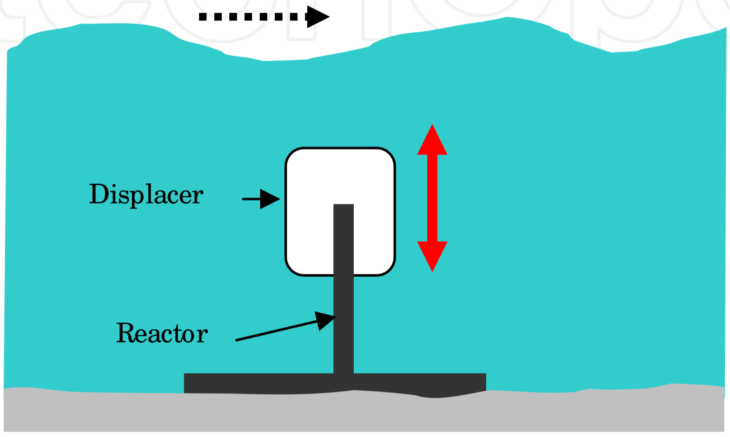


Fig. 8. Submerged Pressure Differential Device Principle

2.4.5 Oscillating Wave Surge Converter

The Oscillating Wave Surge Converter (OWSC) (Chaplin et al., 2009) extracts the energy caused by wave surges and the movement of water particles with them. At the sea bed, on or near the shore, the water particle motion becomes a back and forth motion. It is from this oscillating surge motion that the OWSC extracts energy. The devices can be secured to the sea bed, on or near the shore. They consist of a surge displacer which can be hinged at the top or bottom. Energy is typically extracted using hydraulic converters secured to a reactor.

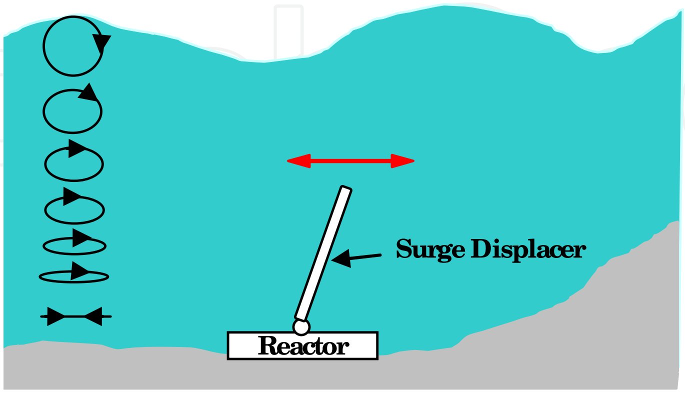


Fig. 9. OWSC Schematic

It is also common to place the device on the shoreline and hinge the displacer above the water. Incoming waves first impact on the displacer and are then captured within the device to form a water column. This water column then empties, moving the displacer in the opposite direction, and the water is returned to the sea. It is also possible to use the surge action of the waves to trap and compress air within a pneumatic chamber (Kemp, 2011). In this case, the OWSC is usually semi-submerged, to allow for the trapping of air at the surface of the wave troughs.

2.4.6 Overtopping devices

Overtopping devices (Jasinski et al., 2007) extract energy from the sea by allowing waves to impinge on a structure such that they force water up over that structure thus raising its potential energy. The water can then be stored in some form of a reservoir. The potential energy of the water is converted to kinetic energy using a conventional hydro turbine. After exiting the turbine, the water is then returned to the sea.

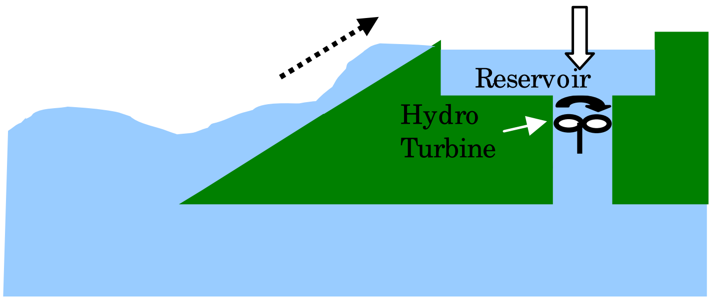


Fig. 10. Overtopping Device Illustration

These devices are fundamentally low-head hydro power plants, except the source of water is from the sea rather than rivers or lakes. They tend to be typically much larger than other devices as significant volumes of water capture are necessary. These devices have one clear advantage over other wave energy devices - the inclusion of a reservoir allows for inherent energy storage. This can be used to produce a more consistent level of power supplied to an electrical grid.

2.5 Wave energy variability

Time variability in wave energy occurs over both long and short time horizons. Long term variability follows somewhat similar patterns to those seen in wind energy in that wave action is generally much lower in summer than in winter, as illustrated in fig. 11 for the Irish wave atlas (Marine Institute/ Sustainable Energy Ireland, 2005). This is due to the fact that wave energy largely depends on wind: wind speed, duration of wind blow, and fetch area typically define the amount of energy transferred.

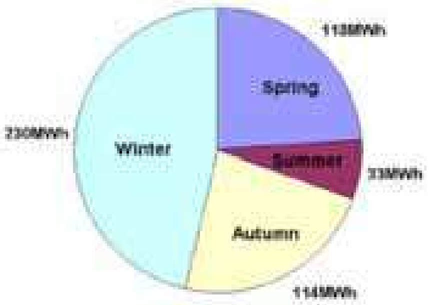


Fig. 11. Seasonality of Technical Wave Energy Resource off Ireland in MWh/ m width of wave front (2005)

Despite this wind dependency, the fluctuations seen in wave energy are quite different. The waves in effect ‘integrate’ the wind energy, smoothing out some of the more rapid fluctuations seen in the wind. Wave energy thus builds up more slowly over large areas of water, and in deep water tends to lose energy only very slowly. Thus over time periods of days, wave energy is more predictable and more persistent than wind energy. This represents a considerable advantage in the integration of wave energy into the electricity grid, as despatch planning becomes significantly easier.

It is at time periods of seconds that significant divergence takes place between wind and wave energy in power time variability or fluctuation. Wind speed, and hence power, fluctuations occur as divergence around a mean value, however, wave power, which is a function of wave elevation returns to zero twice in every wave period. This is illustrated in fig. 12 over a 40 s time window for normalised traces of wind speed and wave elevation.

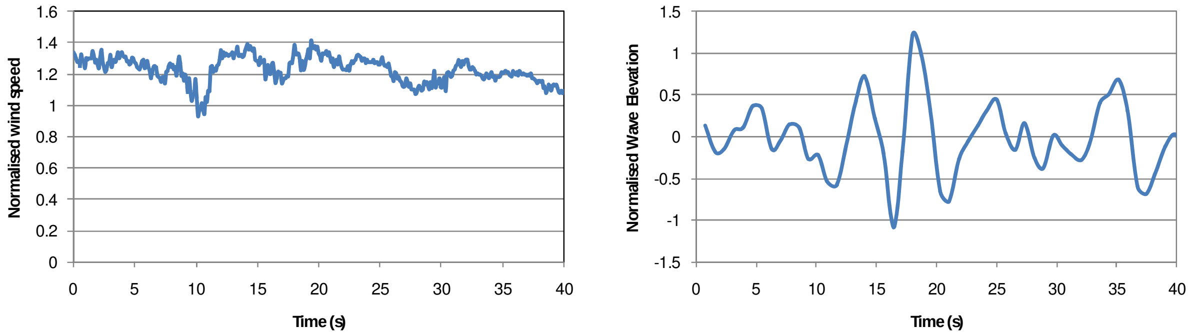


Fig. 12. Comparison of wind speed and wave elevation short term variability

It should be clear from the previous sections that the widely divergent operation modes of the different wave energy converters will result in differing output power responses to the same wave input. Evidence of this is illustrated in fig. 13, where the generated electrical output power from an attenuator wave energy converter with significant hydraulic accumulator storage (Henderson, 2006) is contrasted with the electrical power output from a floating OWC device (O'Sullivan et al., 2011) with an impulse turbine and limited inertial energy storage. Both devices have a mean power output close to 200 kW. However, the peak power output of the OWC is close to 2 MW whereas the peak power output of the hydraulic attenuator device is around 300 kW.

In the case of the attenuator device, the inherent operation of the converter and its own internal energy storage in the hydraulic accumulators act to significantly filter the fluctuations in the wave power incident on the device. In the case of the OWC device, the only inherent energy storage within the conversion chain is some inertial storage in the rotating mass of the turbine and generator. Variable speed control of the turbine allows for this rotating mass to be used to absorb some of the power fluctuations (Justino & Falcao, 1999). It is clear however, from fig. 13 that its impact is not as significant as that of the hydraulic accumulators in the attenuator device.

Apart from the inherent operation of the converters themselves, the control of wave energy converters can also influence the extent of the power fluctuations seen in the output power. Clearly control action in conjunction with energy storage will have an impact on power fluctuation, however some control schemes whose objective is to enhance power output can inadvertently result in significantly larger power fluctuation. The control scheme known as latching, for instance, forces a reduction in the duty cycle of the power take-off period in order to maximise the output power. This has the effect of producing shorter, higher amplitude pulses of output power, in effect increasing the power fluctuations.

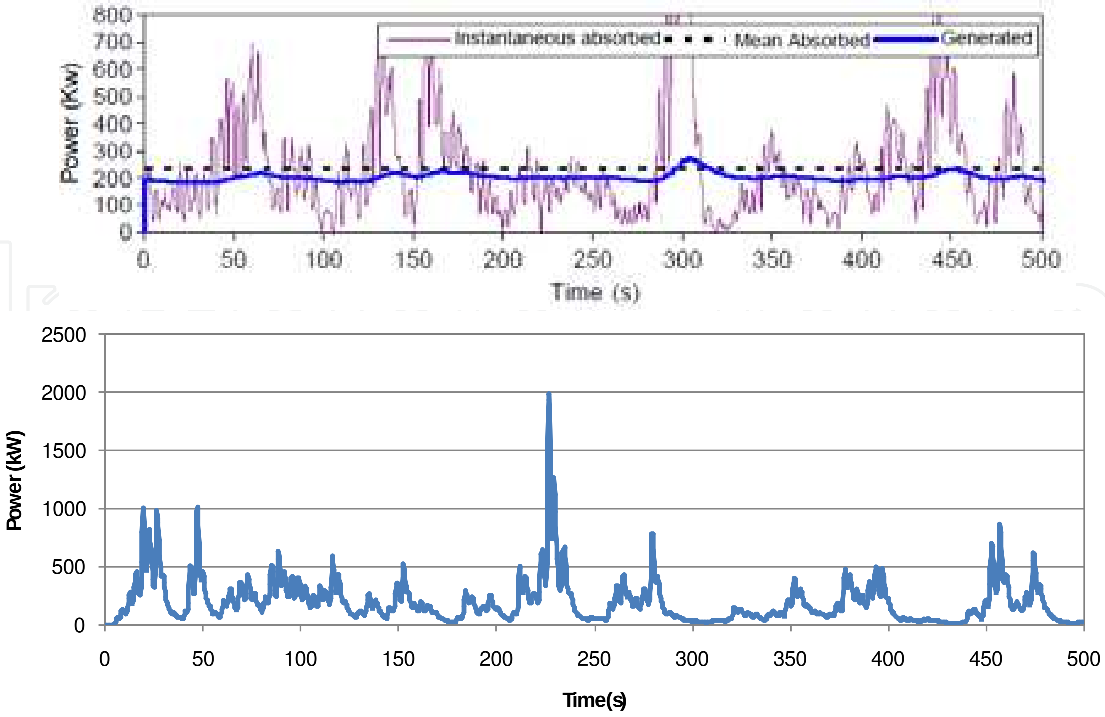


Fig. 13. Output electrical power time series from (top) attenuator device with significant hydraulic accumulator storage (bottom) OWC device with impulse turbine.

2.6 Impact of power fluctuations

The impact of large power fluctuations in a grid connected wave energy converter device or array is generally detrimental. Four main areas of concern can be readily identified:

- Equipment rating
- Equipment lifetime
- System losses
- Power quality

2.6.1 Equipment rating

The issue of equipment rating is related to the peak-to-average ratio of nominal power output (i.e. apart from fault conditions or transient overloads). A 1:1 ratio is optimal, as the usage of the equipment is optimised. This results in enhanced performance since the equipment is being operated at its design point and best cost since needless over-rating is not being purchased. It is evident that the peak to average power output ratio of some wave energy converters is significantly higher than 1:1 as already illustrated in fig. 13. This is a particular issue for devices that utilise power electronics converters as part of the generator and grid power control. In reality, the vast majority of renewable power generation equipment requires the use of power electronic converters in order to optimise the power control. Power electronics converters do not have a long thermal time constant. It is typically of the order of hundreds of milliseconds, so in effect, for wave energy devices, the power converters must be rated for the peak power output. There is some flexibility in the rating of other equipment such as machines, cables and transformers. These will typically have thermal time constants of the order of minutes, and so can be operated transiently at higher peak powers than their mean rating. However, without some means of mitigation such as inherent or added short term energy storage, or deliberate power release, rating of all of the electrical equipment can be several times higher than the mean power output of the device.

2.6.2 Equipment lifetime

One of the main factors in shortening the lifetime of electrical equipment is the extent and frequency of the thermal cycling that takes place within the equipment. This has a particular impact on the power electronic converters. The transistor modules in these converters are inter-connected through wire bond technology. Differing thermal coefficients stresses the interface between the wire bond and the silicon, and this eventually leads to transistor failure. Hence, component lifetime is directly related to the number and depth of the thermal cycles endured by the equipment. Clearly, fluctuating power in the system results in a fluctuating thermal profile which in turn leads to degradation of system lifetime and reliability. Once again, the power electronic components are the most susceptible due to their very low thermal time constant.

2.6.3 System losses

Large power fluctuations result in increased power losses in system equipment when compared to a system with the same mean power output and the same equipment, but with no power fluctuations. This is mainly due to the fact that resistive power losses are proportional to the square of the current. Hence, a system with fluctuating power has an additional conductive power loss component ΔP_{loss} where

$$\Delta P_{loss} = R_{sys}\left[\frac{1}{T}\int_0^T {I_{rms}}^2(t)\,dt - I^2{}_{av}\right] \tag{1}$$

R_{sys} represents the total equivalent resistance in the system incorporating all loss mechanisms, T is the time window in consideration, I_{av} is the mean rms current over the time T and $I_{rms}(t)$ is the quasi-static approximation of the time varying rms current in the system.

2.6.4 Power quality

Power quality issues arise due to the interaction of fluctuating current with the impedance of the electrical network. This results in voltage fluctuations in the network that are proportional to the current fluctuation levels and also to the short circuit impedance of the network. Weaker networks have higher impedance, and thus the voltage fluctuations will be more evident.

In a case study assessing the impact of the integration of a small wave farm at the national wave energy test site in Belmullet, off the north west coast of Ireland, the impact on the local network voltage of varying levels of power fluctuation was examined (Santos et al., 2011). A 3% limit is applied to the voltage change magnitude, and the maximum allowed power fluctuation amplitude is plotted. The power output is assumed to consist of a mean power level added to the sum of three sinusoidal terms representing the dominant wave periods within the wave spectrum. The resultant fluctuation amplitude is defined as the ratio of the peak power to the mean power, i.e. 100% fluctuation implies that the output power increases to twice the mean power and drops to zero over the course of several wave periods.

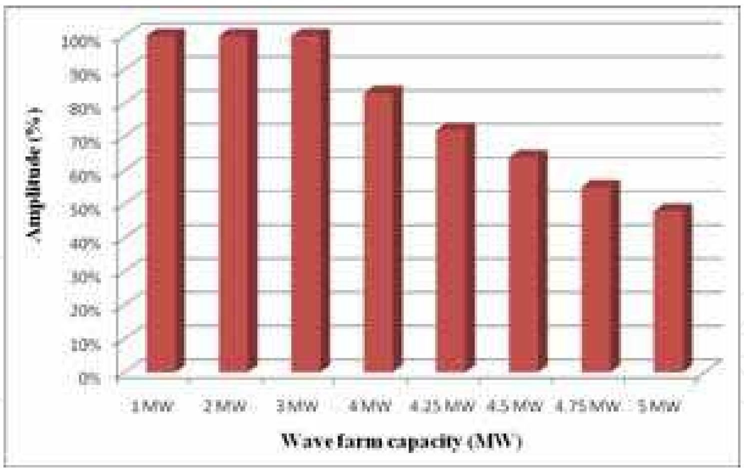


Fig. 14. Maximum allowed power fluctuation amplitude

The results are graphed in fig. 14. It is evident that above a certain power level, the power fluctuation amplitude must be reduced in order to avoid breaching the 3% voltage fluctuation limit.

3. Short term energy storage options

Energy storage can be a very useful feature in ocean energy applications. Due to the highly varying nature of the resource, particularly the wave resource, designing a device that can deliver a relatively constant electrical power output at an optimum efficiency is an onerous task. Large scale electrical storage would be an ideal scenario as devices could store the varying power produced, and supply it to the electricity grid at a constant rate when required. This would not only improve the efficiency of the device but it would also enable grid code requirements to be met with greater ease. The injection of a rapidly varying power output into a weak electricity network can result in significant voltage deviation that may be in danger of breaching grid code requirements, as discussed in the previous section.

However, although the technology for large scale electrical storage currently exists it is extremely expensive and its use would render most ocean energy projects uneconomical. Despite this, developers continue to investigate other methods for some form of energy storage for their devices.

There are a number of wave energy devices that *inherently* contain energy storage methods i.e. energy storage forms part of their fundamental operation mode, as opposed to being explicitly added to the device. The most obvious is the overtopping device – this contains a reservoir which is essentially a large storage tank for potential energy. The reservoir is often an integral part of these devices, so it does not cost an energy loss to include this storage method. Also, devices containing a gas accumulator within a hydraulic circuit are inherently capable of storing energy, although, generally only relatively small amounts of energy can be stored within accumulators. Furthermore, energy is released over a relatively short periods of time. This factor means that accumulators are not good for long term energy storage, but can be used over the short term to reduce power fluctuations in the hydraulic circuit.

It is also worth noting that rotating turbines in both tidal and wave devices can contain significant mechanical inertia which is effectively a form of energy storage. The energy of a rotating turbine with inertia Jbetween two speed limits, ω_1 and ω_2 is:

$$W_{turbine} = \frac{1}{2}J\left(\omega_1^2 - \omega_2^2\right) \tag{2}$$

To utilise this inherent energy storage device, a variable speed control scheme is needed which accounts for the power flow and speed variation of the turbine. The basic governing equation is:

$$P_{mech} = T_{mech}\omega = P_{gen} + P_{loss} + \frac{d}{dt}\left(\frac{1}{2}J\omega^2\right) \tag{3}$$

where P_{mech} is the mechanical power applied by the turbine, T_{mech} and ω are the corresponding mechanical torque and speed, P_{gen} is the electrical power output through the generator, P_{loss} represents the power losses in the rotating system, and J is its combined inertia. Depending on the level of inertia available, the electrical power output can be maintained relatively constant or at least with reduced power fluctuation through control of the system speed.

With so many WECs in development, it is recognised that any implemented variable speed strategy is unique to each device and its location. Factors to be considered when devising a control strategy are discussed in (Justino & Falcao, 1999) and consist of

i. remaining within speed limits
ii. efficient performance
iii. power quality to the grid
iv. a realistic control procedure where measurable quantities are used such as pressure and speed

Utilising the turbine as an effective flywheel, or utilising a separate flywheel where the speed variation will not directly affect the power take-off, is a proven, robust method of energy storage.

Devices without inherent energy storage are reliant on conventional added energy storage techniques. These include compressed air storage, hydrogen storage, supercapacitors, batteries (including flow batteries and fuel cells) and flywheels. These options all have their own advantages and limitations (Santos et al., 2011).

3.1 Lifetime requirements

Maintenance intervals in offshore wave energy devices should be long and not limited by a prototype energy storage system. The difficulty in carrying out on-board maintenance on an offshore WEC is highlighted in (O'Sullivan & Lewis, 2008), where docking issues and working in an unstable environment are key concerns and results in severe costs. A typical desired interval for non-routine, disruptive maintenance in an offshore plant is five years, giving the minimum desired lifetime of any employed energy storage element.

An average wave period of 10 s is typical for most full scale WECs. Due to the unidirectional turbine torque from the bidirectional airflow in OWCs, the average input pneumatic power period is half this value. This calculates the total number of wave power cycles on an offshore wave energy converter over a five year maintenance period, taking account of the expected operational time and availability, to be around 21 million. This poses serious lifetime issues for any energy storage equipment that is likely to be cycled at every wave cycle.

3.2 Electrical storage

Electrical storage technologies include batteries, supercapacitors and Superconducting Magnetic Energy Storage (SMES).

3.2.1 SMES

SMES is currently costly and consists of many essential parts, including a cryogenically cooled refrigerator, that increase breakdown vulnerability in the harsh offshore wave climate, as well as increasing the necessary available space and mechanical support. For these reasons SMES has not yet been considered for offshore ocean energy applications.

3.2.2 Batteries

Batteries are high energy density electrical storage devices that have undergone significant development in recent times. With the increased research into electric vehicles, suitable rechargeable batteries are being developed. Currently lithium ion batteries are the chosen technology installed in new electric vehicles as their improved performance over NiMH batteries are now being realised as production costs decrease. Some lithium ion batteries for electric and hybrid electric vehicles have energy densities as high as 140 Wh/ kg and power densities of up to 745 W/ kg (Amjad et al., 2009). Their cycle durability at present is in the range of several thousand. These small power densities and cycle lifetimes prevent lithium ion batteries from making contributions of power smoothing over time periods near those of the ocean waves.

3.2.3 Supercapacitors

Supercapacitors (SCs) are also known variously as electric double layer capacitors, Ultracapacitors, and electrochemical double layer capacitors (EDLC). They utilise high surface area porous carbon based electrodes, and have capacitances ranging from a few farads up to 5,000 farads. Due to the very small charge separation distance in the 'double layer', voltage ratings are low; close to 2.7 V. To achieve higher voltages, strings of series-connected supercapacitors are created. Usually voltage balancing circuits are added, as due to the manufacturing process relatively large tolerance values of capacitance exist between individual SCs.

SCs are governed by the same equations as conventional capacitors. While SCs cannot compete with batteries in terms of energy density, their much longer cycle life, power density, operational temperature range, and ability to fully discharge make them an energy storage option that must be considered in many applications. A typical supercapacitor has an energy density of over 5 Wh/ kg, a power density of over 6,000 W/ kg, and a rated lifetime of 1 million cycles. Coupled with this, SCs have charge/ discharge efficiencies ranging from 0.85 to 0.98 (Douglas & Pillay, 2005).

SCs have a demonstrated robustness. Applications with photovoltaics were shown in (Glavin et al., 2008), (Weeren et al., 2006) where the supercapacitors complemented battery storage and improved system performance and battery lifetime. The ability of SCs to operate at sea for long periods of time was shown in (Weeren et al., 2006). SCs have also been used in wind turbine pitch systems, hybrid vehicles, trains, buses, and lift trucks. The time constant of SCs is typically around one second, and their small energy density but large power density suggest they are ideal short term energy storage options, especially for ocean energy applications if their lifetimes can be shown to be compatible with the required service life of such equipment in an offshore wave energy converter.

4. Case study

Power smoothing in a full-scale offshore Oscillating Water Column (OWC) Wave Energy Converter (WEC) was investigated by integrating supercapacitors (SCs) with the inertia of a Wells turbine controlled at variable speed. In effect, this case study examines an integrated approach for short term energy storage combining inertial and electrical methods.

An experimentally derived Simulink model represents the full-scale 500 kW WEC system, and available sea-state data is utilised to obtain the full-scale power flows and system speed response. From this, a SC system is sized and integrated into the Simulink model.

In an effort to help validate SC cycle life and robustness, lifetime testing was also carried out. Test setups were built to establish the SC lifetimes under standard and application test conditions as at the time of writing results of documented SC cycle lifetime testing did not approach the 1 million cycle lifetime figure often quoted in datasheets.

4.1 Case study description

4.1.1 The system model and speed control

The Oscillating Water Column (OWC) WEC considered employs a Wells turbine without actuating valves. To predict realistic power take-off (PTO) data from the device at variable speed, the Simulink model created in (Cashman et al., 2009) is used. This was based on experimental data from a quarter-scale prototype operated offshore in an Atlantic test site. The inputs to the model are pneumatic power and turbine speed, and the output is turbine torque and takes account of the effect variable speed has on the pneumatic power production. The model uses non-dimensional quantities to allow scaling to full size.

Variable speed strategies developed in (Duquette et al., 2009, Falcão, 2002, Justino & Falcao, 1999) were examined and compared using the turbine model described above with sea state data. The strategy that produced optimum performance was developed in (Falcão, 2002) where generator torque is evaluated from a measure of turbine speed.

This control scheme consisted of two parts. The first part was developed by measuring the average mechanical power produced at a fixed machine speed. The fixed machine speed maximising the average power for each of the 13 sea states was found and these speeds and powers were plotted. Results from two mid-power examined sea states are shown in fig. 15.

Using the curve fitting tool in Matlab with these maximum average powers and corresponding fixed speeds for each sea state, the power coefficients in (4) were derived (producing an R-square value of 0.9996). This curve is also shown in fig. 15.

$$P_{gen} = 0.0005307\omega^{3.797} \tag{4}$$

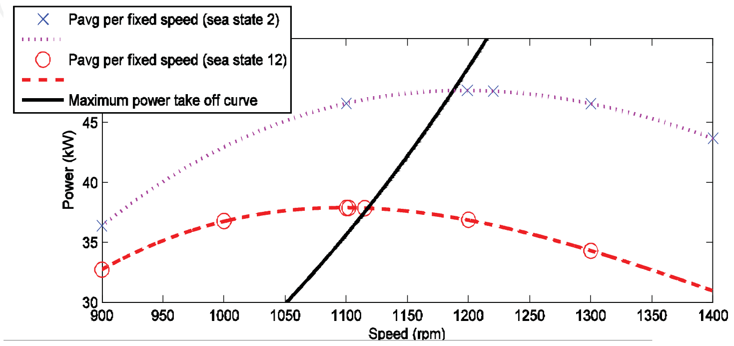


Fig. 15. Average mechanical power versus fixed speed for two of the thirteen case study sea states and maximum power curve

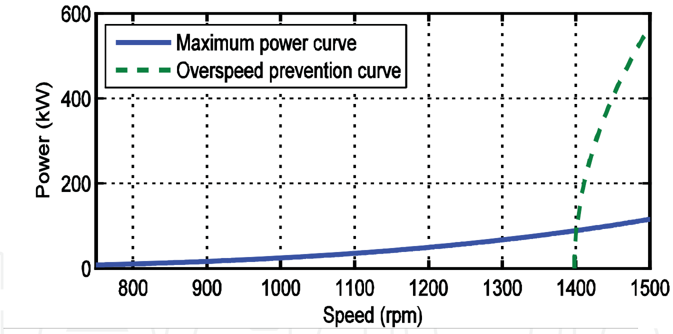


Fig. 16. Speed control power curve of generator power drawn versus speed

The second part of the developed control scheme limits the generator power as shown in (5) and ensures that the turbine does not over-speed to avoid mechanical stress and possible failure.

$$P_{gen} = \left[P_{\max}^2 - J\left|\frac{dP_{gen}}{dt}\right|\left(\omega_{\max}^2 - \omega^2\right)\right]^{\frac{1}{2}} \qquad (5)$$

where $J|\,dP_{gen}/dt\,| = 100$ MW s^{-2} kg m^2 as in (Falcão, 2002), and turbine inertia was set at 595 kg m^2 (in line with other full scale OWC Wells turbines (Falcão, 2002)).
The control algorithm sets the generator power to the maximum value evaluated from (4) and (5) according to the turbine speed as shown in fig. 16. Simulated plots of input pneumatic power, electrical power and speed are shown in fig. 17 (a), (b) and (c). Chattering of the generator power occurs around the speed where (5) comes into effect. To prevent this chattering, a switched controller is used where the local maximum generator torque achieved is maintained until the speed drops by a predetermined level (this hysteresis value was set at 80 rpm). The resulting power profile and turbine speed are shown in fig. 17 (d) and (e).

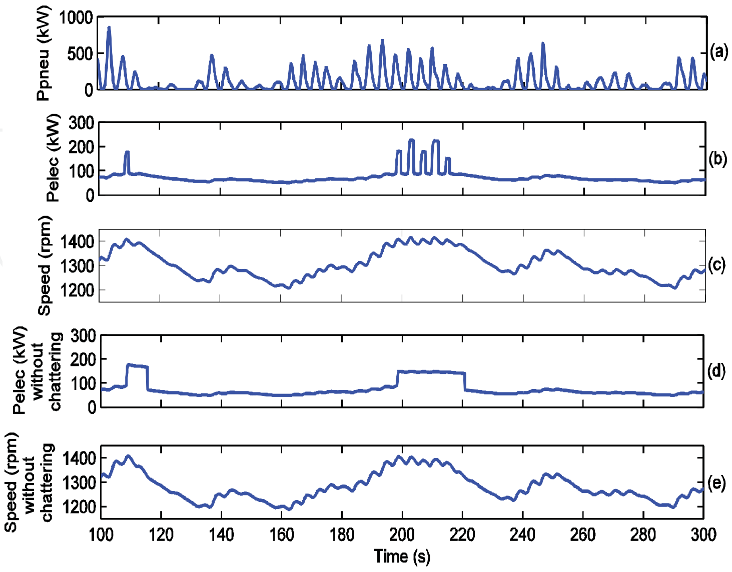


Fig. 17. Generator power and speed with and without the switched controller to prevent chattering for a given input pneumatic power.

4.1.2 Power smoothing with supercapacitors

As shown in fig. 17, the generator electrical power contains large peaks that occur only occasionally. It is proposed to further smooth this power with SCs connected to the dc-bus of the back-to-back power electronics frequency converter which couples the generator to the grid.

The number of generator power peaks for each sea state were measured, and multiplied out by occurrence data values to evaluate the total number of peaks over the five-year WEC maintenance interval. It was assumed that the WEC would not be operational in very low or high energy sea states. Therefore, the device would be operational over 70% of the time with approximately 990,000 peaks of electrical power to be smoothed. This number of peaks is within the specified lifetime of many SC modules.

The discharge strategy attempts to maintain the SCs at their lowest operational voltage (half rated voltage) to make the SC energy capacity available for absorbing power peaks. Once the generator power exceeds a predetermined value (dependent on the sea state), the SCs prevent any excess power flowing to the grid and absorb the difference. Once the input power drops below this value, the SCs maintain this power to the grid until their minimum voltage is achieved. A voltage hysteresis band prevents discharge of the SCs until the band is exceeded toto prevent rapid charge and discharge cycles occurring.

The SCs are sized for the maximum energy sea state of the WEC which produces 152 kW on average. Sizing was based on multiples of the BMOD0063 P125 63 F 125 V module from Maxwell Technologies (utilising SCs of the same technology as the SCs under test). Five parallel strings of two modules in series satisfied all ratings and limited the grid power to 185 kW.

4.1.3 Supercapacitor lifetime testing

While SC lifetime has been tested before, it has typically been accelerated testing, where elevated voltages and temperatures were used. Based on changes in lifetime at small deviations of voltage and temperature at elevated values, typical lifetimes at normal conditions were determined from extrapolations (El Brouji et al., 2008, Lajnef et al., 2007, Paul et al., 2009). Maxwell Technologies provide some results from their lifetime testing but only up to 150,000 cycles and then extrapolate to one million (Maxwell, 2011). Also, this testing procedure provided 15 seconds of rest between every cycle.

Two different types of lifetime testing are carried out – the first is standard lifetime testing at rated current levels, and the second is application testing with the type of power profile expected in a wave energy converter device.

Thirty BCAP0005 P270 cells have been characterised. Each SC is charged at the rated current of 1.6 A to the rated voltage of 2.7 V, undergoes a five second rest period (approximately five time constants) and the voltage and time are measured. The SC is discharged at rated current to half rated voltage (1.35 V), and another five second rest period takes place before measuring the final voltage. Plots of this characterisation profile are shown in fig. 18. From this the capacitance, C and the equivalent series resistance (ESR), R are evaluated according to (6) and (7).

$$C = \frac{I_{rated} t_d}{V_{start} - V_{finish}} \tag{6}$$

$$R = \frac{V_{finish} - V_{rated}/2}{I_{rated}} \tag{7}$$

A SC with close to average specifications was chosen for testing. The test setup, shown in fig. 19, consists of a power supply to charge the SC, an electronic load, a high precision voltmeter, and a thermocouple monitor taking temperature readings of the top, body and leg of the SC, as well as the ambient temperature. These devices are operated using GPIB hardware under the control of a Matlab file. The testing is carried out at ambient temperature with continuous rated current.

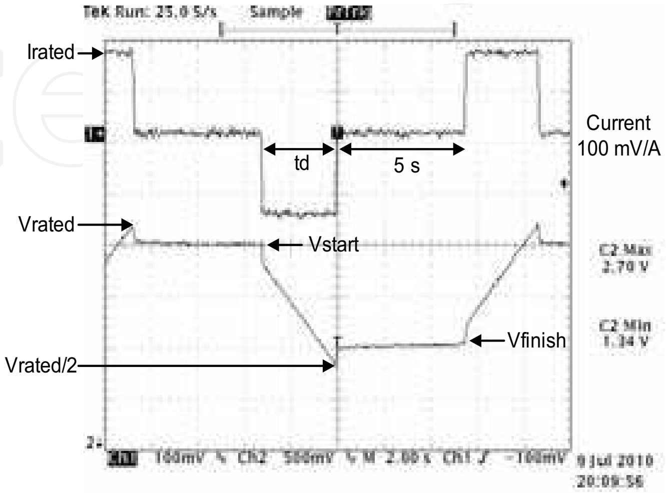


Fig. 18. SC current and voltage during characterisation

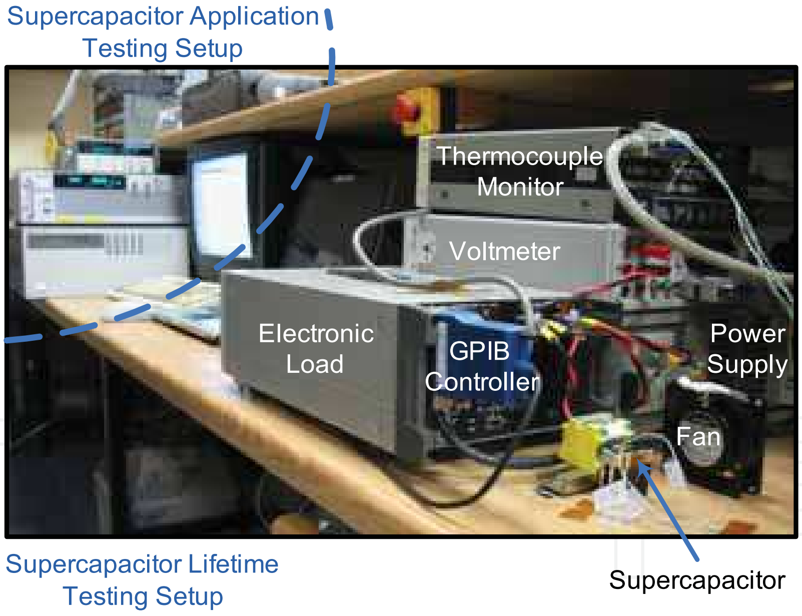


Fig. 19. SC lifecycle test setup

Constant current cycling between rated and half rated voltage is carried out continuously during the day and the apparatus is shut down at night. There is no rest time between charge and discharge cycles except for during characterisation. Characterisation tests occur every 100 cycles and are performed over five consecutive cycles, from which average values are obtained giving more accurate readings. The BCAP0005 P270 SC has a specified lifetime of 500,000, where end of life is specified as a 30% reduction in capacitance, or a 100% increase in ESR. The degradation is shown in the results section.

From the modelling work, the full scale SC power profile is obtained. Using Froude scaling (Wavenet, 2003), these powers are scaled down to values relevant to the BCAP0005 P270 SC under test. A scale factor of 21.135 was chosen and the resultant scaled values compared to the tested SC ratings are shown in table 2. As the resultant usable energy of the SC is lower than the scaled value, the maximum voltage limit is expected to be reached during the application testing.

The model SC power profile is developed from the most occurring sea state before voltage limits are encountered, with the grid power limited to 150 kW. This sea state contains over 30 minutes of data and produces 10 power peaks; close to the average power peak rate over yearly operation. The application SC test utilises similar equipment as outlined in the lifecycle testing. Due to Froude scaling the applied power profile lasts 395 seconds. This is looped three times before characterisation tests are carried out. Again, the process is continued for the day and the apparatus is switched off at night.

	SC modules scaled	Tested SC
Continuous power (W)	4.32	4.32
1 sec power (W)	10.17	9.18
Usable energy (J)	18.5	13.7

Table 2. SC modules scaled to values relevant to tested SC.

4.2 Case study results

The modelling work produced the following results for the most common sea-state: a peak-to-average mechanical power on the turbine of 6.8, a peak-to-average generator power of 4.6, and a peak-to-average grid power of 2.3. A further level of power smoothing was indicated by measuring the standard deviations of the different powers in the system. These results were: 1 pu for mechanical power, 0.43 pu for electrical power, and 0.33 pu for grid power.

Over 750,000 cycles have been tested on the SC under standard test at constant room temperature. The degradation of capacitance and ESR are seen in fig. 20 and fig. 21 respectively. The SC itself is rated for 500,000 cycles, and to date the authors have not found this validated in another source. Also, all initial values are within manufacturer's specifications. Fig. 20 and fig. 21 validate SC performance discussed in where there is an exponential decrease of capacitance initially before capacitance degradation becomes more linear. It is expected that near end of life an exponential fall off of capacitance will occur.

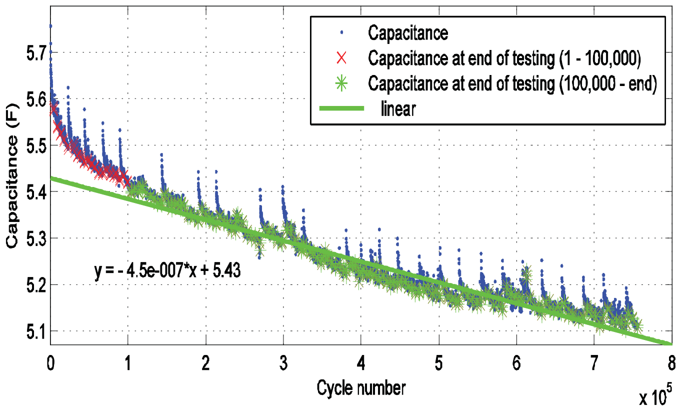


Fig. 20. Capacitance versus cycle number during cycle lifetime testing

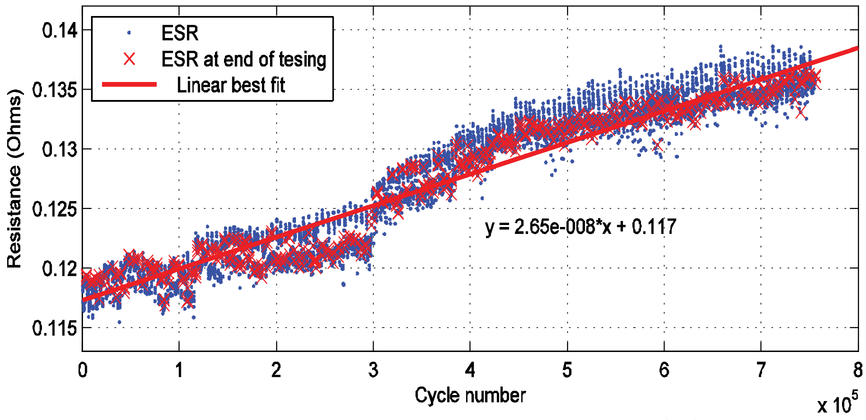


Fig. 21. ESR versus cycle number during cycle lifetime testing

Application lifetime testing has achieved over 85,000 cycles to date. This corresponds to almost six months operation at full scale. The degradation of capacitance and ESR are seen in fig. 22 and fig. 23 respectively. If these trends continue, capacitance will reach end of life first after just over one million cycles, corresponding to over five years operation.

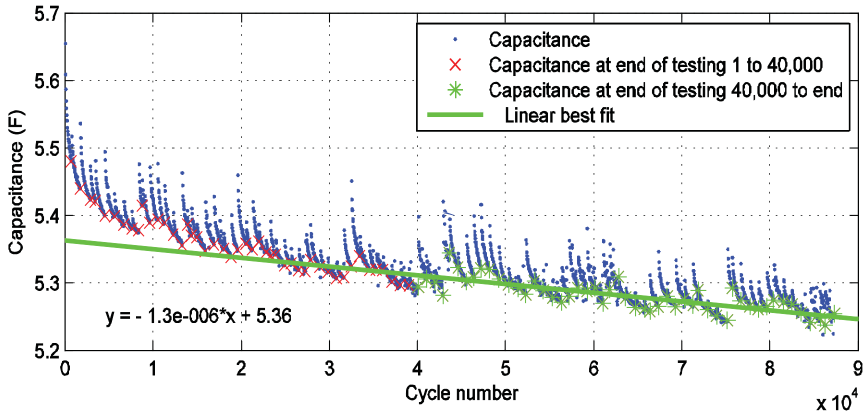


Fig. 22. Capacitance versus cycle number during application testing

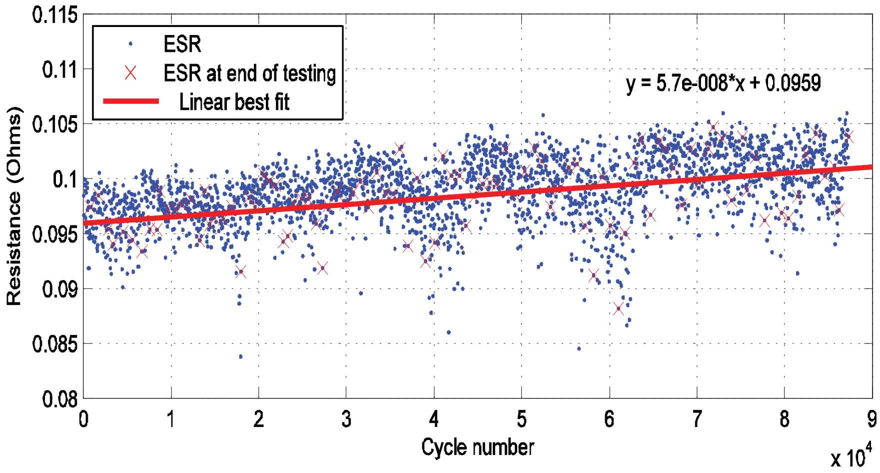


Fig. 23. ESR versus cycle number during application testing

4.3 Ancillary benefits

In a separate study (Murray et al., 2009) other ancillary uses of SCs were investigated. A similar Matlab model was created representing an OWC utilising a Wells turbine. The Wells turbine is a non self-starting device. It was found that supercapacitors had suitable energy and power capabilities to quickly speed up the turbine from rest. The study employed two Maxwell modules to speed up the 135 kg m^2 turbine to 1,000 rpm in 10 to 17 seconds. This feature can be of value where significant import power is required for start-up of offshore equipment, as import power rating can be quite costly.

Low voltage ride through is a problem when a nearby grid fault causes a reduction in the grid voltage at the generator grid connection. This limits the power that can be extracted from the device. If there is large input power, and the powers are not controlled, the power imbalance leads to an unregulated increase in the turbine speed, or dc bus voltage of the back-to-back converter. The study demonstrated that the SC bank could prevent turbine over-speed, maintain dc-bus voltage ratings, and satisfy the grid requirements.

5. Conclusion

This chapter has considered the use and value of short term energy storage in the field of ocean wave energy converters. A background to the area of ocean renewable energy has been outlined, emphasising the development of the industry, its potential benefits to society, and an overview of the different device technologies. Some detail has been given on the main device categories relevant to ocean wave energy. The particular challenges of short term power variability in ocean wave energy technology have been illustrated, and the disadvantageous effect this can have on power quality, power performance, and equipment rating demonstrated. Options for amelioration through short term energy storage have been explored, and a judicious combination of mechanical and electrical energy storage in an OWC device has been selected as an appropriate case study. The lifetime issues, particularly associated with supercapacitors have been examined, and tested as an integral part of the case study. Standard life cycle testing has been performed along with application testing under the charge-discharge profiles likely to be seen in the study device. The findings of this study indicate the following:

- A combination of mechanical and electrical energy storage can reduce power fluctuations to the grid from a single OWC, reducing peak-to-average ratios almost threefold.
- Combining mechanical and electrical storage in an intelligent algorithm enables the supercapacitor usage to be extended to a sensible service life of 5 years.
- Application based life cycle testing indicates that the supercapacitors will have a cycle lifetime of one million cycles, enabling the 5 year target to be met.

Finally, some ancillary benefits of the presence of short term energy storage in the OWC system have been described.

6. References

Amjad, S., Neelakrishnan, S. & Rudramoorthy, R. (2009). Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews*, *14* (3). 1104-1110.

Energy Research Centre of the Netherlands. (2011). In:*Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States*, Available from: <http://www.ecn.nl/docs/library/report/2010/e10069.pdf>

Cashman, D.P., O'Sullivan, D.L., Egan, M.G. & Hayes, J.G. (2009). Modelling and analysis of an offshore oscillating water column wave energy converter. *Proceedings of 8th European Wave and Tidal Energy Conference*, (Uppsala, Sweden, 2009), pp. 924-933.

Chaplin, R.V., Rahmati, M.T., Gunura, K., Ma, X. & Aggidis, G.A. (2009). Control systems for Wraspa. *Proceedings of International Conference on Clean Electrical Power,* (2009), 93-97.

Department of Communications, Energy and Natural Resources, Irish Government. (2010). In:*DRAFT National Renewable Energy Action Plan (NREAP)*, Available from: <http://www.dcenr.gov.ie/NR/rdonlyres/0E9749D9-BB72-49D6-B5BC-DC4EE41A6302/0/DraftNREAPv17June2010forwebsite.pdf>

Douglas, H. & Pillay, P. (2005). Sizing ultracapacitors for hybrid electric vehicles. *Proceedings of 31st Annual Conference of IEEE Industrial Electronics Society, 2005.*

Douglas Westwood Ltd. (2008). In:*The World Wave & Tidal Market Report 2009-2013*.

Duquette, J, O'Sullivan, D., Ceballos, S. & Alcorn, R. (2009). Design and Construction of an Experimental Wave Energy Device Emulator Test Rig. *Proceedings of European Wave and Tidal Energy Conference*, (Uppsala, Sweden, 2009).

El Brouji, H., Briat, O., Vinassa, J.M., Bertrand, N. & Woirgard, E. (2008). Comparison between changes of ultracapacitors model parameters during calendar life and power cycling ageing tests. *Microelectronics Reliability*, *48* (8-9). 1473-1478.

European Climate Foundation. (2010). In:*Roadmap 2050: A Practical Guide to a Prosperous, Low-Carbon Europe*, Available from: <http://www.roadmap2050.eu/attachments/files/Volume3_FullBook.pdf>

European Ocean Energy Association. (2010). In:*Oceans of Energy: European Ocean Energy Roadmap 2010-2050*, Available from: < http://www.eu-oea.com/euoea/files/ccLibraryFiles/Filename/000000000827/ocean%20vectorise%2010%20mai%202010.pdf>

European Wind Energy Association. (2011). In:*Wind in Power: 2010 European Statistics*, Available from: <http://www.ewea.org/fileadmin/ewea_documents/documents/statistics/EWEA_Annual_Statistics_2010.pdf>

Evans, D.V. (1978). The Oscillating Water Column Wave-energy Device. *IMA JAppl Math*, *22* (4). 423-433.

Falcão, A.F.d.O. (2002). Control of an oscillating-water-column wave power plant for maximum energy production. *Applied Ocean Research*, *24* (2). 73-82.

Glavin, M.E., Chan, P.K.W., Armstrong, S. & Hurley, W.G. (2008). A stand-alone photovoltaic supercapacitor battery hybrid energy storage system. *Proceedings of Power Electronics and Motion Control Conference,* (2008), 1688-1695.

Henderson, R. (2006). Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter. *Renewable Energy*, *31* (2). 271-283.

Jasinski, M., Knapp, W., Faust, M. & Fris-Madsen, E. (2007). The Power Takeoff System of the Multi-MW Wave Dragon Wave Energy Converter. *Proceedings of European Wave and Tidal Energy Conference*, (2007).

Justino, P.A.P. & Falcao, A.F.d.O. (1999). Rotational Speed Control of an OWC Wave Power Plant. *Journal of Offshore Mechanics and Arctic Engineering*, *121* (2). 65-70.

Kemp, J. (2011). In: *The Owel Wave Energy Converter*, Mar 2011, Available from: <http://www.owel.co.uk/owel.htm, (Link to News and Press Releases)>

Khan, J. & Bhuyan, G. (2009). In: *Ocean Energy: Global Technology Development Status*, Mar 2011, Available from:
< www.iea-oceans.org>

Lajnef, W., Vinassa, J.M., Briat, O., El Brouji, H. & Woirgard, E. (2007). Monitoring fading rate of ultracapacitors using online characterization during power cycling. *Microelectronics Reliability*, *47* (9-11). 1751-1755.

Marine Institute/ Sustainable Energy Ireland. (2005). In:*Accessible Wave Energy Resource Atlas : Ireland : 2005*, Available from:
<http://www.seai.ie/Renewables/Ocean_Energy/Ireland%E2%80%99s_Wave_Energy_Resource/Wave_Energy_Resource_Atlas_Ireland_2005.pdf>

Maxwell. (2011). In: *Maxwell Technologies*, Mar 2011, Available from:
www.maxwell.com

Murray, D. B., Egan, M. G., Hayes, J. G., O'Sullivan, D. L. (2009). Applications of supercapacitor energy storage for a wave energy converter system, Proceedings of 8th European Wave and Tidal Energy Conference (2009), pp. 786-795

O'Sullivan, D., Griffiths, J, Egan, M.G. & Lewis, A.W. (2011). Development of an electrical power take off system for a sea-test scaled offshore wave energy device. *Renewable Energy*, *36* (4). 1236-1244.

O'Sullivan, D. & Lewis, A.W. (2008). Generator Selection for Offshore Oscillating Water Column Wave Energy Converters. *Proceedings of European Power Electronics and Motion Control (EPE-PEMC) Conference*, (2008).

O' Sullivan, D., Mollaghan, D., Blavette, A. & Alcorn, R. (2010). In: *Dynamic characteristics of wave and tidal energy converters & a recommended structure for development of a generic model for grid connection*, Mar 2011, Available from: <www.iea-oceans.org.>

Paul, K., Christian, M., Pascal, V., Guy, C., Gerard, R. & Younes, Z. (2009). Constant power cycling for accelerated ageing of supercapacitors. *Proceedings of 13th European Conference on Power Electronics and Applications* (2009), 1-10.

Polinder, H., Damen, M.E.C. & Gardner, F. (2004). Linear PM Generator system for wave energy conversion in the AWS. *Energy Conversion, IEEE Transactions on*, *19* (3). 583-589.

Raghunathan, S. (1995). The Wells air turbine for wave energy conversion. *Progress in Aerospace Sciences*, *31* (4). 335-386.

Ricci, P., Lopez, J, Santos, M., Villate, J.L., Ruiz-Minguela, P., Salcedo, F. & O.Falcão, A.F.d. (2009). Control Strategies for a simple Point-Absorber Connected to a Hydraulic Power Take-off. *Proceedings of European Wave and Tidal Energy Conference*, (2009).

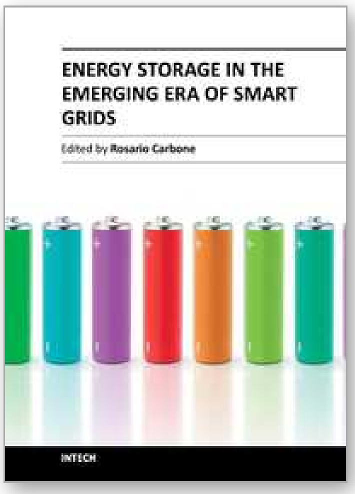
Santos, M., Salcedo, F., Haim, D.B., Mendia, J.L., Ricci, P., Villate, J.L., Khan, J, Leon, D., Arabi, S., Moshref, A., Bhuyan, G., Blavette, A., O' Sullivan, D. & Alcorn, R. (2011). In: *Integrating Wave and Tidal Current Power: Case Studies through Modelling and Simulation*, Mar 2011, Available from: www.iea-oceans.org

Scottish Govt., Northern Ireland Executive & Govt. of Ireland. (2011). In:*Irish-Scottish Links on Energy Study (ISLES)*, Available from: <http://www.islesproject.eu/>

Setoguchi, T. & Takao, M. (2006). Current status of self rectifying air turbines for wave energy conversion. *Energy Conversion and Management*, *47* (15-16). 2382-2396.

Wavenet. (2003). In:*Results from the work of the European thematic network on wave energy*, Available from: <http://www.wave-energy.net/Library/WaveNet%20Full%20Report%2811.1%29.pdf>

Weeren, D.V., Joosten, H., Scrivens, R. & Schnewly, A. (2006). In: *Ultracapacitors double operational life of wave measurement buoys*, Mar 2011, Available from: <www.maxwell.com>



Energy Storage in the Emerging Era of Smart Grids
Edited by Prof. Rosario Carbone

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Reliable, high-efficient and cost-effective energy storage systems can undoubtedly play a crucial role for a large-scale integration on power systems of the emerging â€œdistributed generationâ€ (DG) and for enabling the starting and the consolidation of the new era of so called smart-grids. A non exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. The main goal of the book is to give a date overview on: (I) basic and well proven energy storage systems, (II) recent advances on technologies for improving the effectiveness of energy storage devices, (III) practical applications of energy storage, in the emerging era of smart grids.

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