Wave Energy Converters and their Impact on Power Systems

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Abstract—The objective of this paper is to give an introduction into ocean wave energy converters and their impact on power systems. The potential of wave energy is very large. There are a lot of different methods and systems for converting this power into electrical power, such as oscillating water columns, hinged contour devices as the Pelamis, overtopping devices as the Wave Dragon and the Archimedes Wave Swing. The main characteristics of these wave energy converters are discussed. A lot of research, development and engineering work is necessary to develop the experimental systems into reliable and cost-effective power stations. The wide variety of systems makes it difficult to say general things about power quality. However, the large variations of output power are a common problem. Whether this can be solved by using wave farms has to be investigated further.

Index Terms—Ocean wave energy, wave energy conversion, renewable energy, oscillating water column, Archimedes Wave Swing, power systems, power quality

I. INTRODUCTION

The objective of this paper is to give an introduction into wave energy converters and their impact on power systems. Ocean wave energy is a renewable energy source with a large potential that may contribute to the worldwide increasing demand for power. High variability rates over both short and long time scales characterise this concentrated form of solar energy. The energy associated with the surface sea waves can be extracted by means of properly designed devices, according to various principles and following different concepts, and thus converted into electricity. Particular attention must be paid to the survivability of the systems during extreme loads in storms. As a consequence, the achievement of a satisfying balance between efficiency and reliability in any cost-effective wave energy tapping scheme leads to tough engineering challenges.

The paper starts with some generalities about wave energy. Next, different types of wave energy conversion systems and examples of systems are discussed. Subsequently, the consequences of wave energy for the power systems will be shortly discussed. Finally, some conclusions will be drawn.

II. WAVE ENERGY

A. History

First patent for wave energy exploitation dates back to 1799 (Girard & Son, France) and the first wave energy activated device, a self-recharging navigation light buoy (Masuda, Japan), was designed and commercialised in the 1960s.

Science and engineering of wave energy conversion, based on appropriate research methods and theory, started mainly after the year 1973, as the oil crises pushed forward the exploitation of all possible alternative forms of energy. Because of the abundance of the resource in the area of North Atlantic, several countries started their own national programs on wave energy. The Shortage of oil, which had negative repercussions on fuels and energy prices, forced thereafter an amplified emphasis on energy saving policies and energy conversion efficiency. Apparently as a sort of immediate side effect, in energetic engineering the attitude established as a general rule, to be applied to whichever energy conversion process. In the field of renewable energy it turned out to be a mistake, at least in part, and possibly hindered developments. Only afterwards it was clearly understood that, if the fuel is for free, the search for high efficiencies may address the first-approach design but the topmost priority has to be the attainment of the lowest cost per kWh generated (environmental impact analysis and related issues stepped in later).

The search for maximum efficiency characterised also the design of most of the first wave energy converters. This often led to the adoption of rather complex, non-conventional mechanisms that hardly matched at once the requirements for reliability and robustness in a cost-effective market perspective. Most converters were simply too expensive and lost their attractiveness when the oil market regained stability.

Other non-technical factors contributed to the weakening of the initial burst of enthusiasm. Wave energy research never came to a standstill, but few of the initial projects survived by the beginning of the 1980s. On a somehow reduced scale, the main research programs went on, especially in some European countries. The progresses succeeded to keep into proper light the large potentials of the resource. Wave energy eventually caught the attention of the European Commission that started...
its own research programs under the 4th Framework Programme in 1994. Some reviews of the R&D work produced so far on the topic are given by [3, 17, 18].

B. Current status

Worldwide demand for energy will increase considerably in the next decades. At the same time, the energy industry has to develop bounded by some new constraints, namely sustainable development and the respect for the environment. Also, world is facing, sooner or later, non-reversible oil shortage.

Renewable energy may play a key role in the attempt of pulling down the emissions of the most common greenhouse agent produced by the energy industry, the carbon dioxide. The market of such technologies is growing fast. Europe is already leading the way in the field of wind energy, with thousands of MW of power installed in the last few years. Offshore wind energy, in particular, is catching the attentions of governments and industry. This quickly expanding field seems to interact positively with some marine renewables and combined offshore power plants for the exploitation of more resources at once have been considered. Featuring one of the most concentrated forms of energy among all renewables, wave energy seems to have good chances of growth in the next years. It seems to represent a good alternative for islands, not only for the production of electricity, but also for water desalination: reverse osmosis requires high pressure that could be provided by pumping systems directly activated by the wave motion. Besides waves, other marine renewable energy resources are those based on the exploitation of tides, tidal streams, oceanic thermal and salinity concentration gradients.

Wave energy technologies, in most cases, still require a considerable amount of R&D work. Perspectives seem to be nowadays brighter than they were the 1970s also because of the development of parallel technologies and the standardisation of power electronics (new converters can be adopted to indicate wave power is the kW/m, kilowatts per meter of crest length. The sea condition is the result of the superposition, at given location and time, of a large number of different waves and is referred to as sea state. The description of the sea state may be given by means of an appropriate wave spectrum, which usually has to take into account both energy and waves direction. For each sea state, characteristic amplitude and characteristic or energy period may be identified. Thus an average power level can be associated with any sea state. Fig. 1 depicts a world map with the wave energy distribution around the world.

Sea characteristic parameters are also used to predict the performances, in terms of power output, of the wave energy converters. Whichever the design, some parameters might be varied to tune the device to the sea conditions. Examples are the speed of the power take-off system or the resistance exercised by the moving parts. In some devices, maximum energy output is yield when the converter works in resonance condition with the sea state. In order to do that, their natural frequency has to be tuned to the sea state’s characteristic period. Local sea conditions tend to vary slowly, so that a sea state may reasonably considered to hold in place, stationary, for several hours. Then, the set of the sea conditions matched during a whole year at given location represents a wave climate. Knowledge of the wave climate is fundamental for the design of well performing converters. The optimum control of a resonant device is obtained by varying its stiffness to match the characteristic period in each sea state of a given climate. If that is not feasible, sub-optimum control methods may be implemented.

Locally, from year to year only limited variations take place and, as a consequence, the yearly average wave power level may be related to a specific geographical site with reasonable approximation. In open seas, variations also small are registered over such distances that a wave climate may extend to characterise areas of hundreds of square kilometres. Related data is taken via oceanographic buoys, left in place for a proper number of consecutive years. Most energetic wave climates are found in the open and deep seas. However, these are also the most difficult to exploit efficiently because of devices maintenance costs and requirements for moorings and long submarine cables used to connect the plant to the grid on the mainland. On the other hand, the less energetic climates near the shore may benefit from wave energy concentration by refraction and diffraction phenomena. A reasonable balance, a nearly optimal location condition that takes into account at once power availability and exploitation feasibility, it’s represented by sites some kilometres away from coast with water depths of about 50-100 meters. Such locations may still feel the shielding effect of the coast, which should reduce the problems related to wave directionality. Along the western coasts of Europe, in the North Atlantic, offshore sites exhibit wave power annual averages that may easily exceed 30-40 kW/m and reach up to 70 kW/m or more on the northern side of the British Isles.

It must be pointed out that there is no direct proportionality between tapped power and device size. Smaller devices may take advantage of the so-called point absorber effect (theory by Budal&Falnes and Evans, in [15]): a small round oscillating body, whose diameter is negligible compared to the wave-length (λ), may absorb the energy contained in a λ/2π
metres wide wave crest. The value represents a theoretical upper limit but the principle holds true and even small converters may produce a significant amount of energy. On one hand, because of limits of the linear theory and the fact that very small devices do not usually have natural frequencies tuned with the useful part of the spectrum, the technique cannot be pushed too far. On the other hand, as the device size is increased, the benefit from the effect is gradually lost.

Wave energy devices rated powers usually vary from few tens of kW up to 1-4 MW. Utilization factors depend mainly on wave climate, may vary in the range 0.15-0.35 and tend to be lower in the larger devices.

A recent study [13] estimated in 290 GW the total amount of available wave power (annual average) along the Atlantic coasts of Western Europe, while the world’s potentially exploitable wave power resource should be of the order of 1 TW (Falnes, in [14]). Besides these orders of magnitude, the perspective of a wave energy-driven world is not realistic for several reasons and the values are presently reported to evidence the potentials of the resource.

III. CLASSIFICATIONS OF WAVE ENERGY CONVERTERS

In contrast with most of the other energy resources, the variety of concepts for wave energy devices is rather large and a univocal classification results inappropriate. Converters are usually classified according to their positioning with respect to shore or to the energy conversion principle adopted.

A. Classification according to positioning

Shoreline devices: devices can be placed on sea bottom in shallow water, integrated in breakwater-like structures or fixed to a rocky cliff. The choice for the location of devices performing wave energy conversion in shallow waters represents a major issue. The wave climate is very sensitive to local bathymetry and coastal geometry. In some areas (the “hot spots”), proper combinations of shallow waters and sea-bottom conformation may cause remarkable energy focusing (by refraction, diffraction, reflection), thus compensating an otherwise weak environment. In other coastal sites, on the other hand, dissipative phenomena may take place. Further, in shallow water the larger waves may break and loose energy before reaching the device. In such conditions, the predictions given by numerical modelling, even if powered by the availability of data acquired before the deployment of the device, may still exhibit some non-negligible uncertainty. Major advantages of shoreline converters lie in easier device installation, reduced maintenance costs, safer environment and requirements for short electrical cables. Shoreline wave energy devices are usually classified as first-generation devices [9]. Though being good as experimental facilities, the development of this class of devices may be hindered by the lack of suitable sites and the impact on coastal landscapes and environments.

Near to shore devices: these devices are thought for the deployment in approximately 10-20 metres of water depth, hundreds of metres or up to some kilometres away from shore. Moderate wave depths are suitable for large, bottom-standing devices. The choice for near-shore is made in first instance to overcome the described problems of the shoreline devices and to avoid moorings. Converters with a sea bottom-fixed structure may exploit wave motion in full, a capability that is lost to floating devices. Near-shore devices represent an interesting compromise. The main problems consist in the extreme wave loads a large fixed structure must resist and the cost of a single unit.

Offshore devices: floating or submerged devices in deep waters, moored to the sea floor, represent the most promising class of wave energy converters. These devices may exploit the huge wave potential of the open seas (see Figure 1). In the past, their development has been delayed or stopped because involved technologies were unreliable or too expensive. High reliability is required to avoid excessive maintenance-related costs. The wave power of the most powerful sea storms in open sea may be up to 1MW/m (but devices are deactivated). Due to the extreme harshness of the sea environment, survivability represents a major issue for these devices, especially for those floating on the sea surface. Mooring systems should be designed carefully since they do not just keep the device in place and/or avoid overturning but usually interact with wave energy absorption. Some offshore devices are composed by two or more parts in relative motion with respect to each other. To generate power, the converter has just to react upon itself and an improper mooring system may change the frequency response of the device. The long electrical submarine (possibly DC) cables required to delivery produced power to the grid on land are sources of relevant losses. It’s unlikely that a small offshore power plant of few units would be justified. Offshore exploitation of wave energy may be profitable with power stations rated tens of MW and counting several units, deployed in array. In the open sea, these large multi-device wave power plants, the so-called wave farms, may seriously interfere with navigation.

B. Classification according principle

Another classification of wave energy devices, according to power conversion principles, was provided by [2, 3].

Oscillating water columns (OWC) are chambers where the water level rises and falls with the waves. The air coming into
and going out of this chamber drives an air turbine.

Hinged contour devices consist of floaters that move with respect to each other when waves pass. The device structure reacts upon itself. From the motion, energy is extracted.

Buoyant moored devices have a floater that is moved by the waves. Energy is extracted from this motion. The motion may be up and down or around an axis.

Overtopping devices are water reservoirs which are filled by waves via some kind of wave concentrator which increases the wave height. The water leaves the reservoir via a water turbine driving a generator.

C. Power take-off systems (PTO)

Besides previous classifications, in the wave to wire energy conversion process also the power take-off system allows some sub-classification of the devices. Usually the power of the waves is transferred to an auxiliary fluid (air, oil or water) in which is induced a pressure difference. This fluid is an energy vector that activates a mechanical PTO system, which drives a variable speed power electronic generator. The resulting wave to wire chain is represented by the scheme:

waves → auxiliary fluid → PTO system → electricity.

There are alternatives to the scheme. Turbines directly activated by waves are being investigated (Wave Rotor, by EcoFys). Mechanical PTO can be omitted (AWS).

IV. EXAMPLES OF WAVE ENERGY CONVERTERS

Several combinations of principles and power-take-off systems were investigated out of an almost limitless number. Here, a brief description of some of the most advanced prototypes of wave energy converters currently under development follows. The list does not claim any completeness, for more details see [20].

A. Oscillating Water Column (OWC)

The OWC is by far the most investigated wave energy converter. It’s a half-submerged device whose concept dates back to the 1970s. So far, a number of full-size pilot plants were built in several different countries, either on-shore, near-shore (the Osprey, Scotland) or floating offshore (the so-called Mighty Whale, Japan). The working principle is illustrated in Figure 2. The incident waves act on the water column, contained in the lower part of the capture chamber, through the submerged entrance on the front side of the device. The upper part of the chamber is filled with air. Inside the hollow structure, the oscillatory motion of the water causes a difference in air pressure with respect to the outside atmosphere. In a duct connecting the air chamber with the outside a turbine is located. The axial air-flow direction in the duct reverses over short periods of time, with an average cycle accomplished in an energy period (say, 7-15 seconds), driven by the sign of the pressure difference. A special design is required for the turbine, since it must be kept rotating always in the same direction. This type of turbine is defined self-rectifying, that is a turbomachine with the capability of operating without a system of rectifying valves, accepting instead the air-flow from both sides. Usually OWCs’ air turbines are provided with geometric symmetry of rotor blades and guide vanes (if adopted) with respect to a cross-sectional plane perpendicular to the shaft axis. Most full-size OWCs have been equipped with the Wells turbine [10, 11], of which several versions exist, with a peak power capability ranging from about 500kW up to 1 MW when the respective diameter sizes are of approximately 2 and 3.5 metres. In these turbines a considerable amount of kinetic energy can be stored, the resulting flywheel effect smooths the fluctuations of the power that is released into the grid. This makes the device more acceptable to small grids, rather demanding in terms of power quality, such as those of the small islands.

To overcome some innate problems of the Wells turbine, namely the aerodynamic stalling at high flow-rates, other turbine types were proposed. Most common examples are the Dennis-Auld turbine (Energetech, Australia) and, most commonly, the impulse turbine (proposed by McCormick in 1981). These machines have still to prove their claimed superiority [8, 9]. Another improvement is represented by the variable-pitch Wells turbine [12].

Highest peak pressures in an OWC, depending on chamber size and turbine type, should vary usually in the range 1.1-1.3 bars. A set of relief and/or throttle valves, if provided, may prevent pressure and flow-rate from exceeding critical values, which cause very high losses.

Because of the air chamber, the OWC requires a remarkably large base structure (made of steel or, most commonly, concrete). Most powerful pilot plants have cross-sectional areas at mid-water level in the range 100-400 m² and heights of 10-20 m. As a consequence, the cost of a single device is rather high. However, costs can be reduced by integrating the device structure, for example, in a breakwater.

A unique characteristic of the OWC concept consists in the absence of moving mechanical parts in direct contact with water. The absence of moving parts that must resist fatigue by repeated heavy loads represents clearly an advantage in terms of device reliability. Two large on-shore OWCs are operative in Europe, the Pico power plant (Azores, Portugal, 1999) and the Limpet (Islay, UK, 2000). Others were built in Norway, India, Japan, Australia.

Fig. 2: schematic cross-section of an on-shore OWC (Wavegen, UK).
B. Pelamis

The Pelamis is produced by Ocean Power Delivery Ltd (Scotland, UK), the device (Fig. 3) seems to be in quite an advanced stage of development. The Pelamis is a floating offshore hinged contour device. It features a long articulated structure composed of four cylindrical bodies, in series, linked by hinged joints. The joints move under wave action, as the cylinders pitch and yaw. Resistance to the motion is provided by inner hydraulic rams that pump high-pressure oil to activate hydraulic motors via smoothing accumulators. The motors drive an electrical generator. Joints stiffness can be regulated to tune the device to sea conditions. Device requirements for survivability leaded to the reduced cross-sectional frontal area to limit drag forces. By proper moorings, the longitudinal axis is kept approximately parallel to waves direction.

A full-size prototype was built and deployed in water (Orkney, UK) for testing. Its total length is 150 m and rated power is 750 kW. Three of the four steel cylinders, whose outer diameter is 3.5 m, host inside independent power modules, each one rated 250 kW. The company claims the device has been performing successful tests for several months. In August 2004 the Pelamis was connected to the grid and delivered first electrical power. It represents a typical wave energy converter of the last generation.

The Pelamis concept is not completely new, being somehow derived from some early experiences, such as the Cockerell Raft (designed by Sir Christopher Cockerell, it consisted of some pitching rafts linked in series with PTO at the hinges, in [16]) and the Duck. The famous Edinburgh or Nodding Duck, designed by S. Salter for the first time in 1974 [21], was based on similar PTO concept. The Duck is an offshore floating device composed of several linked modules (with a cam-like shaped cross-section) disposed in series along the same rotational axis approximately perpendicular to wave direction. Salter’s device taps both kinetic and potential energy, hence it’s capable of very high efficiencies. Due to non-conventional technology, the resulting (initially) high costs hindered its development. Instead, for the Pelamis, the manufacturer claims that almost all the technologies involved in the design were already proved and available on the market. A small wave farm of three units (2.25MW) is under development and will be installed in Portugal.

C. Wave Dragon

The Wave Dragon is an example of overtopping device. It is developed by Wave Dragon Aps/Spok Aps (Denmark). It is a floating offshore converter (Fig. 4). The Wave Dragon has no moving parts (but the PTO system). By means of a reflector and a ramp, the waves are channelled into a water reservoir, the device main body, floating above the sea level. Via the reflector, wave energy focusing and conversion to potential energy takes place (but the point absorber effect is completely lost). By storing this potential energy, the reservoir acts as a huge flywheel with remarkable smoothing effect on delivered power. Reflector’s two half-submerged rigid walls, wide open towards the sea and as high as the filling level of the reservoir, form a short narrowing channel along which the height of the approaching waves is increased. These “arms” represent probably the most fragile part of the device (the rest is well known technology). The raising waves overtop the ramp at the end of the channel and fill the reservoir. The PTO system consists of a number of independent low-head water turbines, some of which may be deactivated in the weakest wave climates. The water lets out the reservoir via ducts on the bottom in which the Kaplan turbines are located. Active turbines work tuned to sea conditions in order to discharge the average amount of water filled in by the waves during a lapse of time equal to the energy period.

A prototype in scale 1:4.5 (58×33 m, with a 28 m reflector and reservoir of 55 m³) was deployed in 2003 at Nissum Bredning (Denmark). It was equipped with a set of 7 turbines, each rated 20kW and driving a separate PM generator. The tests were successful. The Wave Dragon was connected to the grid and delivered power (2004). In the beginning of 2005 the device was damaged in a storm (following moorings failure).
device, was built in Norway, Toftestallen, in 1985. The reservoir was made out of a sort of small bay (≈8500 m²) and the collector was carved into a rocky cliff. After a successful start, coastal site requirements severely limited further developments and the program eventually stopped.

It can be said that the Wave Dragon is an artificial Tapchan. The first full-size prototype will be rated 4MW (260×150 m and 16 turbines rated 250 kW).

**D. Archimedes Wave Swing (AWS)**

The Archimedes Wave Swing is developed by Teamwork Technology (The Netherlands), it is a submerged offshore device activated by the fluctuations of static pressure caused by the surface waves (see Fig. 5), thus exploiting only their potential energy. Basically, the AWS is an air-filled cylindrical steel chamber whose lid, called the floater, is a heaving body while the bottom part is fixed. The active force that moves the floater is given by the pressure difference acting on its top. When the wave crest is above the AWS, the chamber volume is reduced by the high water pressure. When the trough is above, the floater heaves under the action of the chamber pressure. The air within the chamber behaves like a spring whose stiffness can be adjusted by pumping water in or out the chamber (chamber volume changes). In the AWS, direct-drive energy conversion takes place via a Permanent Magnet (PM) Linear Synchronous generator [6]. This type of energy conversion doesn’t allow energy storage. As a consequence the output power exhibits poor quality.

The permanent magnets are located on a translator, fixed to the floater, and the coils are on the stator part. PM machines are capable of rather high force densities. However, it is nearly impossible to make the generator large enough to take all possible forces generated by the waves. Therefore the AWS is provided with strong water dampers that could be activated in case of very powerful sea conditions.

Submerged devices in general are less vulnerable in storms and do not pollute landscapes but, laying just few meters below the surface, still interfere with navigation.

A full-size AWS was built and deployed (May 2004) off the Portuguese coast (nearby Porto) in approximately 40 m water depth. The cylinder was 9 m wide, 38 m high (max) with a stroke of 7 m, maximum floater speed was 2.2 m/s. The maximum peak force the generator could make was 1 MN and rated power was 2 MW. The device was tested and it was connected to the grid, delivering first power in October 2004. In this first version (Fig. 6), the cylinder was placed within a steel cage fixed on a steel pontoon with four ballasts to be filled with water. The resulting support structure was very large, expensive and uneasy to handle. It was built to keep the first prototype safe in place allowing just the floater to heave, but it’s no fundamental requisite to the AWS principle. Future prototypes will be buoyant moored to the sea floor or have smaller concrete gravity foundations. Other current research aims at improvements of the generator design and towards modular architecture in order to reduce maintenance costs.

![Fig. 5: Working principle of the Archimedes Wave Swing.](image1)

**E. Other devices**

**Aqua BuOY:** under development by Aqua Energy Group Ltd (USA), it’s an example of buoyant moored device that make specific use of the point absorber effect. Units will be of limited size (say, 4-5 metres in diameter), hence more reliable and cheap. The device is a heaving floating body that converts kinetic energy of vertical water motion into electricity via a hose pump system. First experiences with power generating buoys, dating back to the 1970s, were carried on by Budal and Falnes [16].

In some cases, the exploitation of the point absorber effect allowed improvements of older concepts. The **Bristol Cylinders** (D. Evans, in [16]) was an early submerged device featuring long cylindrical bodies hinged to hydraulic pumps which, in turn, were hinged to fixed points on sea bottom. The cylinder axis was horizontal and the system of pumps was positioned in such a way that the resulting motion of the axis was constrained to a circular orbit. A Pelton turbine was activated via the pumped water. The design of the Bristol Cylinders was modified by replacing the cylinders with a set of smaller spheres (point absorbers) to save on materials (Tecnomare, Italy, 1981) [19].
V. IMPACT ON POWER SYSTEMS

A. Power quality

The electrical power system has to distribute electrical power with a high power quality: the power must be delivered with a fixed frequency and at a fixed voltage level and in a reliable way. With a limited number of large (thermal) power stations and a transmission and distribution system, this can be achieved rather well. These large power stations have well-proven voltage control using reactive power variation and frequency control using active power variation. The power is then transmitted via high voltage transmission lines and distributed via medium and low voltage distribution systems with good protection systems. The activation of these protection systems is based on a power flow from the power stations via the transmission lines to the distribution system.

With the increasing contribution of distributed generation (among which form renewable sources), this becomes more difficult because these systems:
- mostly do not vary reactive power and therefore do not contribute to voltage control;
- mostly deliver varying active power instead of controllable active power and therefore disturb the frequency control and cause voltage variations;
- may disconnect in case of grid faults, which may lead to important loss of generation and disturb the power balance;
- may change the power flow direction in the distribution system if connected to the distribution system, and therefore disturb the protection system.

For wind energy, these things are being investigated, and several problems have been solved. Because of the similarities between wind and wave energy, wave energy can profit from this knowledge. Below, power quality related problems due to wave energy are listed. Before commenting on power quality, some generator systems are discussed, because of the impact of these generator systems. Next, the problems for a single wave energy conversion system are discussed. Then the problems for large numbers of devices will be discussed.

B. Generator systems

Because of the wide variety of wave energy converters and their grid connections, there are important differences between different systems. Furthermore, because the systems are in an early stage of development, it is too early for very detailed studies. However, some trends can be identified.

In many devices, there are energy buffers in the devices that smoothen the electrical output power compared to the mechanical input power. In oscillating water columns, the variable speed turbines are connected to rotating generators, mostly via a gearbox. The relatively large inertia of the turbine and the generator system makes the output power smooth compared to the input power from the waves. It acts as a low pass filter for the power with a time constant of typically a few seconds. In a hinged contour device as the Pelamis, the hydraulic system contains an energy buffer that smoothes the output power. In overtopping devices like the Wave Dragon, the water reservoir has a strong smoothening effect.

However, in a system like the Archimedes Wave Swing, the mechanical energy that the waves give to the floater is directly converted into electrical output power without energy buffering in the device. Therefore, this device might be expected to have the largest power quality problems. Some typical waveforms are depicted in Fig. 7. Because the measurements were done during the first tests, the tests were done in a careful and safe way, with all the safety brakes on. Therefore, the tests reported here are with limited power, limited stroke and limited speed.

![Fig. 7: Measured position, phase current and output power during the first tests of the Archimedes Wave Swing.](image)

C. Single wave energy converters

A single wave energy converter will probably be connected to the distribution system close to shore. Such a single wave energy converter is not large enough to influence the voltage and frequency control of a large strong grid. However, there may be some local effects in the distribution system where the wave energy converter is connected, such as:
- harmonics;
- flicker;
- performance during grid faults.

If a power electronic converter is used for the grid connection, it probably produces harmonics. Mostly, there are grid requirements specifying that harmonics are below a certain value. Some filtering may be necessary. However, this is not a major issue, because filtering is a well-known technology.

If there is no energy buffer in the device, the power delivered to the grid will vary with a frequency of around 0.2
Hz, twice the wave frequency (see Fig. 7 and Fig. 8). This will cause a variation of the voltage in the point of connection to the grid. The magnitude of this variation depends on the strength of the grid; the weaker the grid, the larger the variations. These variations, called ‘flicker’ are very disturbing for the other customers connected to this connection point. This problem could be solved in different ways:
- use a connection point with a strong grid (which may not be available),
- use an energy buffer in the device (which is rather expensive).

If there is a short-circuit in the grid, the large short-circuit currents will activate the protection system and the short-circuit will be disconnected. In the rest of the grid, this will been seen as a voltage dip. Wave energy converters with power electronics mostly can not significantly contribute to the fault currents to activate protection systems: they can not deliver more than the rated current. Wind turbines connected to the distribution system used to be disconnected from the grid in case of grid faults as voltage dips or short-circuits. However, with the increasing amount of wind power, disconnecting all wind turbines led to a considerable loss of production. Therefore, new grid regulations nowadays require that wind turbines stay connected to the grid during grid faults: wind turbines now need grid-fault-ride-through capabilities. The same may be expected for wave power. For variable speed systems with a full converter between the generator and the grid, it is not a problem to stay connected. For variable seed systems with a doubly fed induction generator, special measures might be necessary, comparable to the measures developed for wind turbines.

D. Large numbers of wave energy converters in farms

Large numbers of wave energy converters in wave farms have to be connected to the grid via an offshore electrical infrastructure and a suitable connection point to the on shore grid. Like wind farms, wave farms will not be connected to the distribution systems, but to the high voltage transmission system. In that case, the existing protection system is again suitable. Like wind farms, wave farms will have to be operated as power plants. This means that they have to contribute to voltage control by controlling reactive power generation and to frequency control by controlling active power generation.

Most wave energy converters have variable speed generator systems, connected to the grid via power electronic converters. Some converters can control the reactive power flow, such as voltage source inverters. Other converters can not control the reactive power control or even deliver a varying reactive power, such as current source inverters. If converters are chosen that can control the reactive power, these converters can contribute to voltage control in the grid as long as the rating of these converters is large enough.

For frequency control, it is necessary that the active power can be controlled. Especially in systems without energy buffer, this is difficult, because they depend on the incoming power from the waves. In a wave farm, it could be decided that the wave energy converters do not produce the maximum power they can so that the output power can be increased when the control requires that. However, as appears from Fig. 9, even for a large wave farm, the power variation may be so large that it is difficult to realize this without losing a lot of energy.

To be able to control the frequency of the grid even when there are important uncontrolled variations of the power delivered by a wave farm, it may be necessary to have a considerable amount of thermal power as back-up. This back-up is also necessary during heavy storms, when the systems are shut down to minimize the risk of damage.

VI. CONCLUSIONS

The potential of wave energy is very large. There are a lot of different methods and systems for converting this power into electrical power. A lot of research, development and engineering work is necessary to develop the experimental systems into reliable and cost-effective power stations. The wide variety of systems makes it difficult to say general things about power quality. However, the large variations of output power are a common problem of the wave energy converters. Whether this can be solved by using wave farms has to be investigated further.

VII. REFERENCES


