Grid connection and system services of a wave power plant - a case study

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Abstract—**Grid integration aspects and system service provision possibilities are studied for a hypothetical wave power plant at a location off the west coast of Ireland. This wave power plant, consisting of eight wave energy converters, is based on the MegaRoller technology, an oscillating wave surge converter, which is developed by AW-Energy in Finland. Different cable topologies for the collection grid have been studied and compared with RMS simulations conducted in DIgSILENT PowerFactory. Power-variation-induced voltage variations have been studied for a range of short circuit ratio levels. The possibilities to provide fast frequency response services has been elaborated, where the hydraulic-accumulator-based energy storage of the MegaRoller provides a good basis for short-term power output boosts. Achievable payments for system service provision, according to the Irish payment scheme, have been calculated. This study is part of the MegaRoller EU Horizon 2020 project.**

Index Terms—**Grid connection, system services, wave power.**

I. INTRODUCTION

WITH growing concern about global energy supplies, political and economic drivers are creating pressure to develop and implement new renewable energy sources. Through international accords, countries have agreed to a transition away from fossil fuels to reduce CO_2 emissions and avoid catastrophic climate change.

In the present day, wind turbines and solar photovoltaics are the dominant sources of renewable energy, along with hydropower. The total installed capacity of wind and solar power at the end of 2020 was 733 GW and 714 GW respectively [1], together accounting for approximately 10 % of global electricity generation [2].

However, when relying on weather-driven electricity sources, it is beneficial to miminise production correlation between the different sources, to have a more steady supply of electricity. This can partly be achieved by geographical distribution of power plants (the wind will always blow somewhere), but within a given region, the best way is to increase the variety of sources. When aiming at 100 % sustainable energy, correlation of production becomes increasingly important. Therefore, additional renewable energy source alternatives are beneficial to complete the *Energiewende*. The effects of production correlation between wave power and wind & solar on electricity market value have been investigated [3].

The potential for wave power is large, making it a suitable candidate to form part of the world's energy supply in a sustainable future. It is the largest untapped form of renewable energy in the world, with an estimated global potential of 30 PWh/a [4].

Yet, the potential of this significant renewable energy source remains to be unlocked as Wave Energy Converter (WEC) technology is still at an early stage of development and real-world implementation. There are various WEC technologies under development, but few have reached a (MW-scale) demonstration phase. None have been deployed at scale or have achieved a sufficiently high operational efficiency to make them a viable option for commercial take-up.

This study is part of the MegaRoller EU Horizon 2020 project, which was initiated in 2018 to upscale the WaveRoller WEC from a 350 kW device to the 1 MW MegaRoller implementation, and to enhance its energy conversion efficiency and reliability. The WEC technology and the studied hypothetical power plant are described in Section II. Electrical grid connection has been studied in Section III and provision of system services in Section IV. The findings are discussed in Section V and the article is concluded in Section VI.

II. MEGAROLLER WAVE POWER PLANT

The grid integration and system service provision of a hypothetical wave power plant is considered for a location off the west coast of Ireland.

A. MegaRoller wave energy converter

The MegaRoller WEC developed by AW-Energy (Figure 1) is a bottom-mounted flap device, specifically an Oscillating Wave Surge Converter (OWSC).

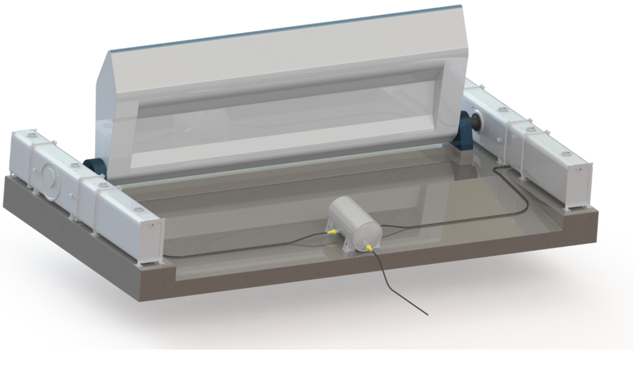

Fig. 1. MegaRoller wave energy converter

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Wave power extraction using OWSCs presents a number of advantages over other WECs:

- OWSCs work well for a wide range of wave frequencies
- OWSCs are installed in nearshore locations, where survivability requirements and grid connection costs are lower

The MegaRoller is based on the smaller WaveRoller design, which has a single Power-Take-Off (PTO) unit and a power capacity of 350 kW. A full-scale WaveRoller was deployed in Portugal in 2019. The MegaRoller can be seen as an upscaled version of the WaveRoller concept to reach MW level, whereby two 500 kW PTO-units are placed on either side of the prime mover.

The MegaRoller unit consists of a large moving 25-30 m wide panel, hinged on a seabed-mounted foundation, oscillating in pitch following the surge movement of the water molecules in the nearshore zone (10-25 m water depth), and being designed to absorb wave energy through horizontal motion of the panel. The PTOs on either side of the panel convert the back-and-forth (linear) motion of the panel into electrical energy.

In the PTO, the energy captured by the panel is transferred to hydraulic circuitry utilising hydraulic cylinder groups. The peaky energy of the waves is smoothed using hydraulic accumulators, and converted to electricity using hydraulic motors running induction generators followed by frequency converters and step-up transformers. The energy conversion process for the MegaRoller is shown in Figure 2.

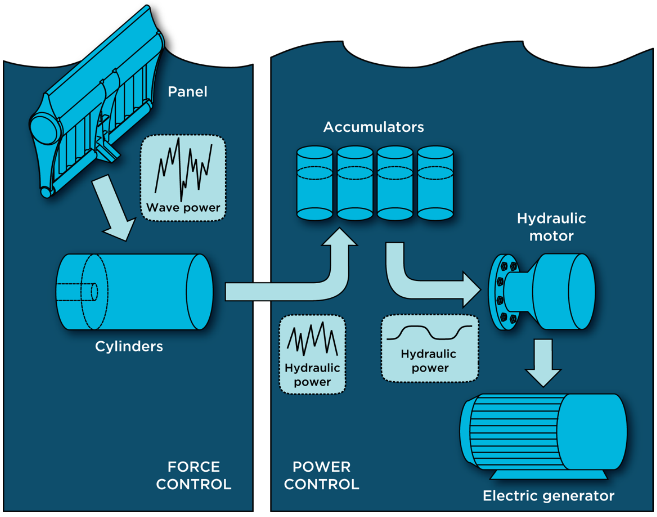

Fig. 2. Energy conversion process inside the PTO

In addtion to smoothing the energy peaks and valleys, the energy storage of the accumulators enables steady energy production over short calm periods ($\approx$ 30 s) between the incoming waves. The same energy storage also makes it possible to (briefly) boost the output power, as further elaborated in Section IV.

B. *MegaRoller eight-WEC Array*

An array of eight MegaRoller WECs is considered in this study, as shown in Figure 3.

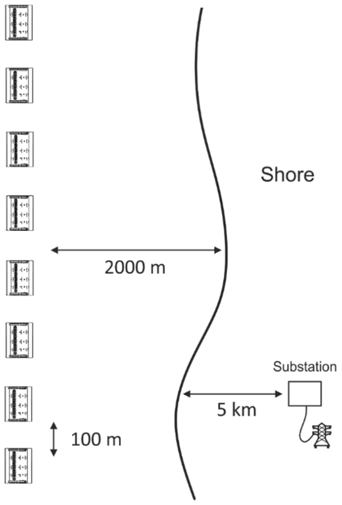

Fig. 3. The MegaRoller 8-WEC Array

The distances given in the picture are at the long end of the range, and the straight line of WECs is a simplified visualisation. For many cases, depending on the bathymetry of the site, distances can be shorter and placement of the WECs will be more sophisticated (e.g. two interlocked rows).

III. GRID CONNECTION

Any offshore energy source needs to be connected to an onshore substation via power cables. Four different topologies have been investigated here, although, as the onshore subterranean cable is identical in all four topologies, the focus is placed on the subsea cable network.

The conducted systematic approach is generally applicable and could also be applied for other wave power plants (based on different technological concepts) at locations further away from shore. In such cases, cables will be significantly longer causing more challenges, and the benefits of the approach will be more visible and valuable.

A. *Cable Network*

Four different topologies have been studied for connecting the WEC array which are briefly listed here before examining them in more detail later: an individual connection, a hub-based connection, an integrated connection and a grouped connection. The direct (or radial) individual connection to shore (Topology A) is shown in Figure 4.

Topology B, which incorporates a subsea hub, collects power offshore from all WECs, as shown in Figure 5.

An integrated topology where one WEC collects all the power from the other seven, and sends it to shore (Topology C) is shown in Figure 6.

Finally, topology D represents an option whereby two sub-groups of four WECs are formed, as shown in Figure 7.

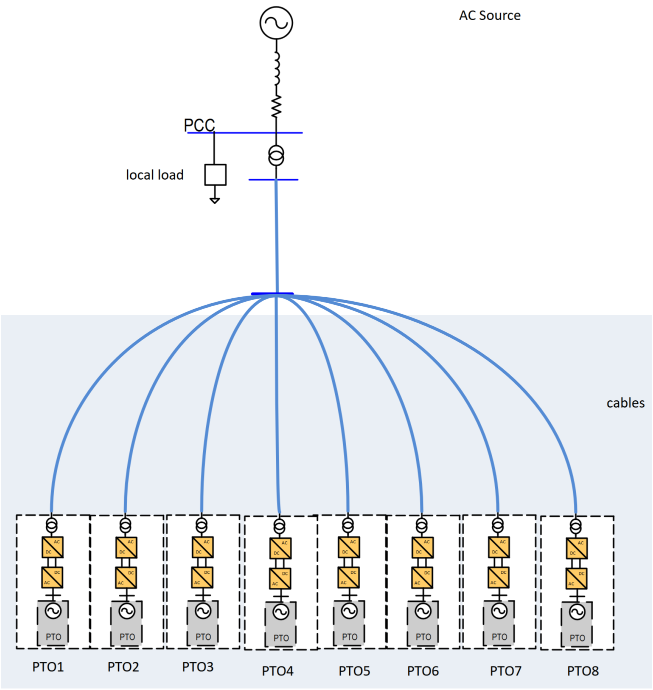

Fig. 4. Topology A: individual cable connection

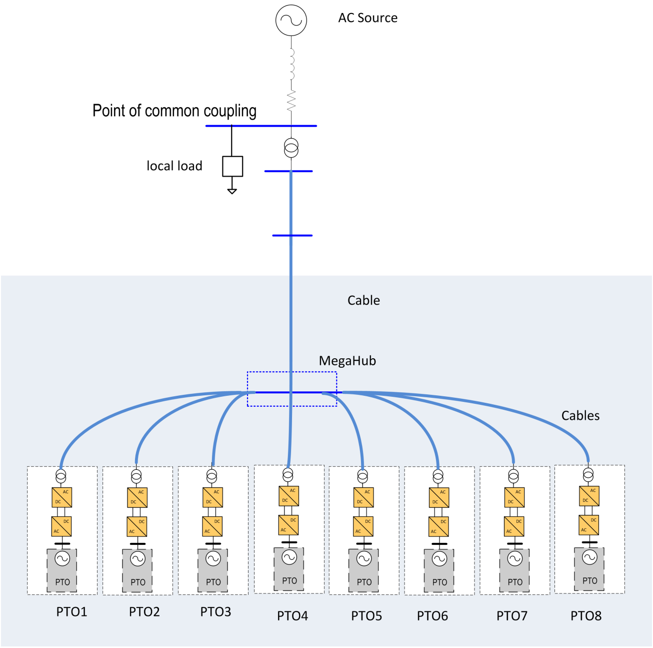

Fig. 5. Topology B: hub-based cable connection

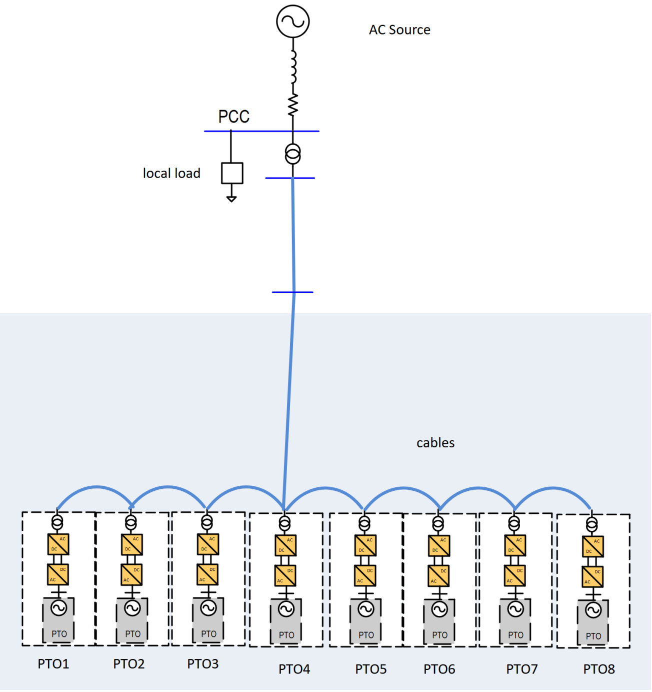

Fig. 6. Topology C: integrated cable connection

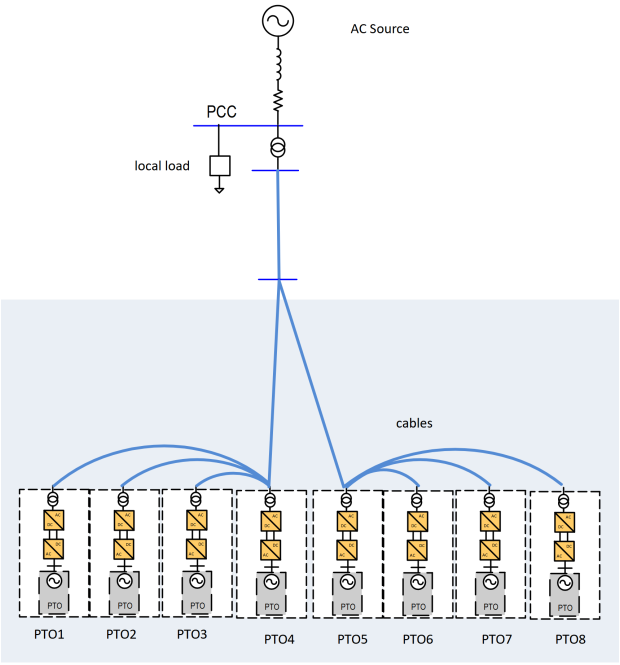

Fig. 7. Topology D: grouped cable connection

B. Simulation model

An electrical network model has been created using DIgSILENT PowerFactory, with the possibility to switch between the four topology options. This model was realised in both RMS and EMT domain. The phenomena studied here were adressed with the RMS model, and all results shown in this article were created with the RMS model, mainly due to the slow time resolution of the used input data. The EMT model (and EMT phenomena) will be adressed in a future publication. A single line diagram of the network model, with the four topologies connected in parallel through configuration switches, is shown in Figure 8.

The grid connection was modelled using a Thévenin equivalent, i.e. an AC voltage source behind a series reactor, which is calculated as follows:

$$X_{\mathrm{SC}} = \frac{V^2}{\mathrm{SCR} * S_{\mathrm{WPP}}} \tag{1}$$

SCR is the short-circuit ratio, X_{SC} is the Thévenin reactance, S_{WPP} is the rated power of the wave power plant, and V is the rated voltage at the point of commnon coupling (PCC) with the external grid. The calculations have been executed with SCR = 3, which resembles a very weak grid (worst case scenario).

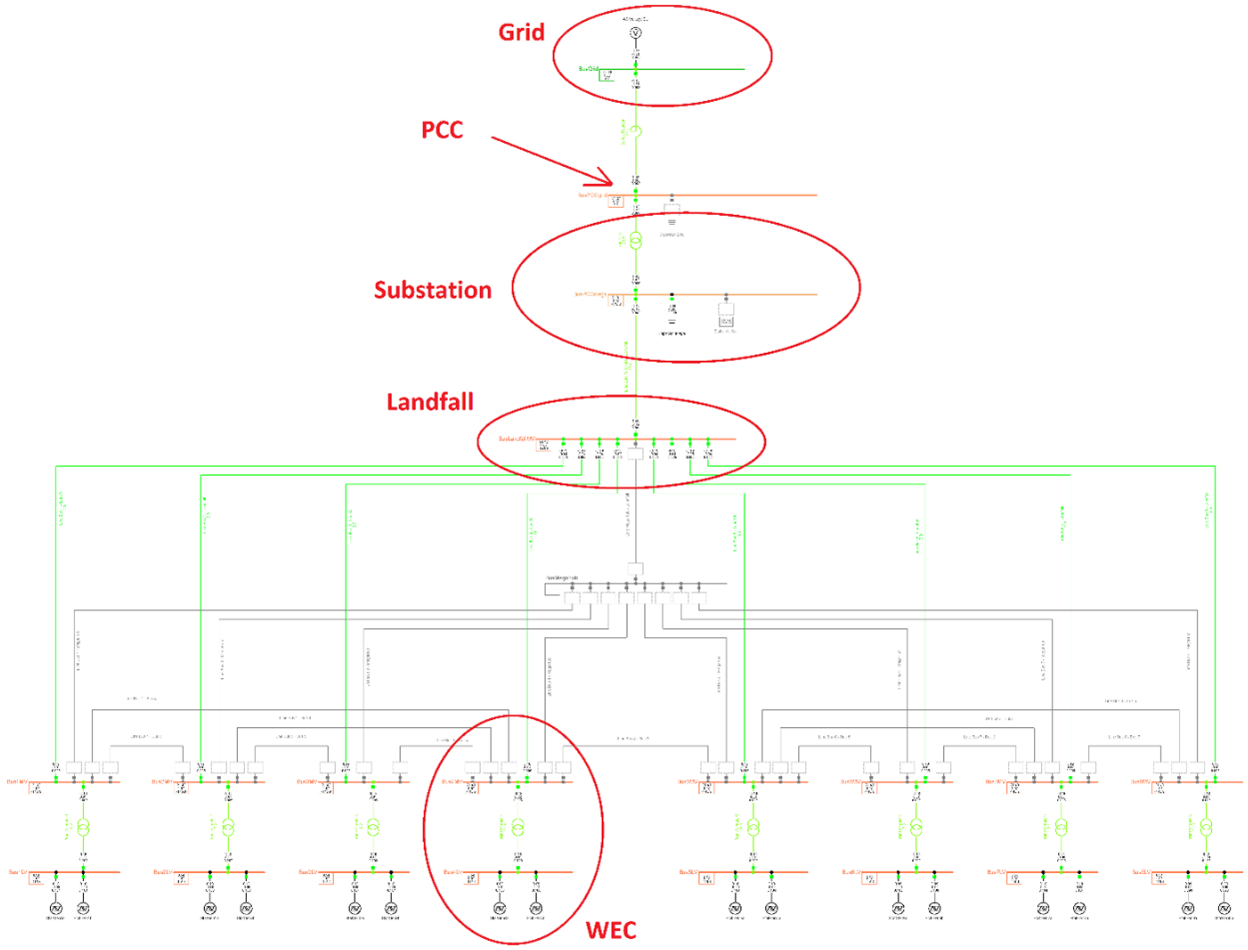

Fig. 8. PowerFactory Model comprising topologies A-D

The cables are assumed to be three-core 20 kV copper cables with a cross-sectional area of $35\,\mathrm{mm}^2$ or $70\,\mathrm{mm}^2$. The larger cable type is applied in all cases where a single cable transmits the power of all eight WECs, while the smaller cable type is applied elsewhere (one to four WECs) [5]. The cable data relates to a particular subsea cable product design, but for simplicity, the same option has also been applied for the onshore cable section. This simplification is considered valid, as the differences (e.g. inductance) between a submarine and a subterranean cable are not significant for the phenomena studied here.

The WECs are modelled using two static generators connected to a step-up transformer, based on the "static generator" model within the PowerFactory library. The model is equivalent to a active grid connected power converter in current-control mode. In the simulation, the two PTO units have one machine rated 500 kVA, while in the real design, each of the two PTOs has two parallel 250 kVA machines, to improve redundancy and partial load efficiency. Considering the slow variability of the input data (power output time series with 250 ms sampling rate, see next subsection) the static converter behaves like an ideal active power source, as it can "almost perfectly" follow the slowly changing active power reference.

A two-winding three-phase transformer connects every WEC with the corresponding medium voltage bus, which, in turn, connects to the cable(s). A 0.5 – 20 kV, 1 MVA, $\Delta-Y$ step-up transformer is employed, with a short circuit voltage of 6 % and 1 % losses. The control framework for each generator ensures that the respective power output is based upon feeding the input power time series to the static generator's internal current controller. A LP-filter is used to smoothly increase the sampling rate from the 250 ms steps of the input data file to the 10 ms time-step resolution of the simulation. Voltage control has been implemented to exploit the possibilities to improve the PCC voltage using the wave power plant, but it has not been switched on for the main simulations. The reactive power output of all WECs is $Q = 0$. Again, this can be seen as a worst case scenario.

C. Input data

A power output time series of a single WEC, showing a five minute period with heavy power fluctuations, was used as input. This series shows a moment with fast and large changes of the wave levels, and implements a WEC control to extract as much energy as possible (at the cost of power output smoothness). The selected series does not show regular operation under normal conditions, but represents rather a worst case.

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Individual waves are not visible in this time series, as it resembles the electrical power output behind the hydraulic accumulator, which closes the "gaps" between individual waves. The underlaying wave data (taken from a single measurement point) and what is happening inside the WEC are not published here.

Based on this single input time series, a composite power time series with eight individual time series for each WEC was created by introducing a time-offset (3 s) between neighbouring devices. This time shift creates power output differences between the different WECs, while maintaining similar (identical besides time delay) power profiles for all WECs. These power output differences cause the appearence of voltage variations within the power plant, which are also expected to show in reality.

This composite time series was applied as an input to the simulation model, and it is shown in Figure 9.

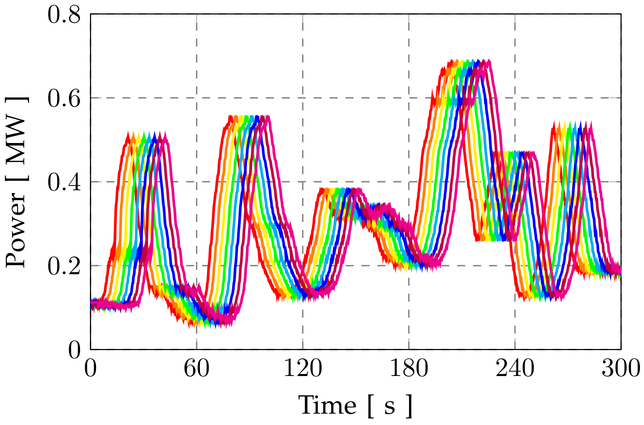

Fig. 9. Electrical power output of the eight WECs

It should be noted that the provided curves resemble single WECs, and that the aggregated output of the power plant (not shown) is smoother than of the individual WECs. This is because the time shift avoids that all eight WECs "hit the peaks" at the same time.

A side effect of the time-shift approach is the introduction of oscillations with a period of the 3 s time shift. These oscillations can be observed in Figure 10, Figure 11 and Figure 12, but they can be ignored as they are simply an artifact of the input data processing.

The shortcomings of the presented approach are noted, and as part of future work it is intended to:

- implement a full wave-to-electricity model of the individual WECs
- utilise a 2D wave field model, showing how the different WECs are impacted differently by the individual waves, and with time delays

D. Voltage variations at PCC

One major requiment for the grids integration of renewable sources is to ensure that the voltage variation at the connection point is kept within permissible levels. Different requirements for low voltage and medium voltage grid of a few European power systems, in terms of maximum and minimum voltage, are shown in Table I.

TABLE I
DIFFERENT REQUIREMENTS IN TERMS OF VOLTAGE LIMITS [6]

Code/Standard	Region/Country	Min (pu)	Max (pu)
EN 50160	Ireland/Europe	-0.1	+0.1
Grid Code	UK	-0.06	+0.06
ENTSO-e grid code	Nordic/Baltic	-0.1	+0.1

The voltage variations at the PCC that result from the fluctuating power production (Figure 9) are shown in Figure 10.

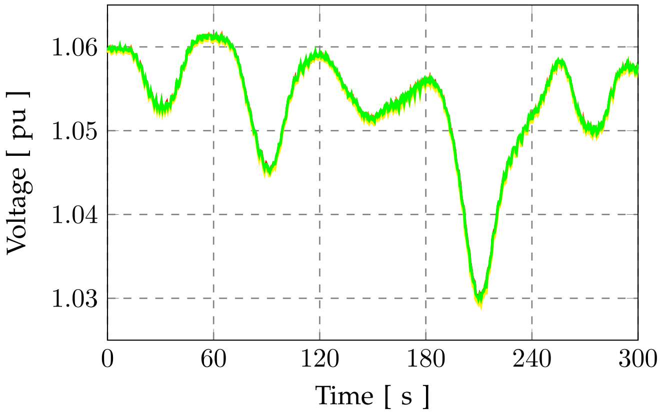

Fig. 10. Voltage variations at the PCC for different cable topologies

All four topologies are plotted within Figure 10. It can clearly be seen that the cable topology does not noticeably influence the results, with all four curves looking very similar. The voltage variations are maintained within the limits in the most common standards, as shown in Table I.

In case of more stringent requirements, the voltage fluctuations can be significantly reduced by reactive power control of the WECs, as shown in Figure 11.

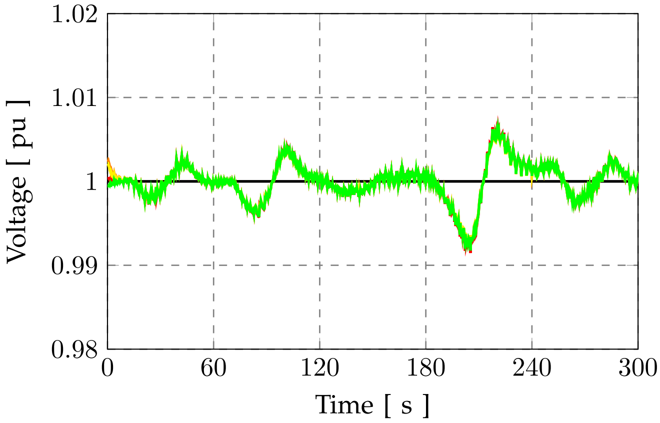

Fig. 11. Voltage variations at the PCC with activated voltage control

This countermeasure comes at low cost, since no additional equipment is required. The simulations indicated that this countermeasure achieves good results. The implemented voltage control has no relation to the control design of the MegaRoller WEC, and it was only implemented in a simple way in PowerFactory to visualise the impact of such a voltage controller.

E. Voltage variations within the power plant

Following on from the above, voltage variations within the power plant were also investigated, arising from the time delay of the power production variations between the individual WECs. These fluctuations are shown in Figure 12 for Topology A, which results in the largest differences between the individual WECs (longest cables route between individual WECs).

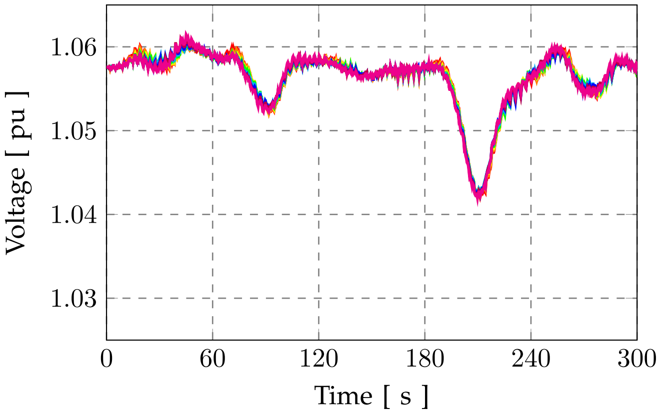

Fig. 12. Voltage at the WECs

Small, but negligible, differences can be observed between the WECs. It follows that the cable topology does not significantly influence the results, with the voltage variations being very similar in all cases.

F. Influence of the short circuit ratio

The previous figures show dynamic RMS simulations with a short circuit ratio of SCR = 3, as explained in Subsection III-B. In order to visualise the influence of the SCR on the voltage fluctuations, steady-state power flow calculations have been performed for a range of different SCR values (2-10). The following metrics have been identified:

- lowest voltage (in per-unit) of all busses in the system during zero power output at all WECs
- highest voltage (in per-unit) of all busses in the system during rated power output at all WECs

These metrics give an indication of the maximum voltage fluctuation range at each given SCR value. The results are plotted in Figure 13.

The voltage range shown in Figure 13 can give an indication regarding the dimensioning of countermeasures (votlage control, tap changers) to limit the voltage variation at low SCR.

G. Preferred cable topology

As the simulations have shown, the choice of cable topology is not significant from an electrical perspective, assuming, of course, that the cable ratings are respected. The main impedance source in the electrical system are the transformers, while the cables only play a minor role. When comparing against offshore wind power, the challenges are generally smaller here:

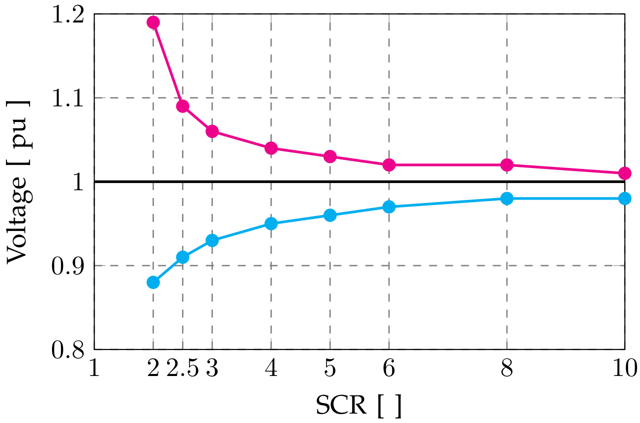

Fig. 13. Influence of short circuit ratio on voltage variations

- The power rating per WEC (1 MW) is much smaller than what is seen for offshore wind turbines
- The distance between WECs (100 m) is much shorter than that seen for offshore wind turbine spacing
- As a nearshore device, the distance to the PCC (7 km) is also much shorter

Consequently, other aspects of the design process ultimately determine the preferred topology choice, i.e. capital cost, installability, reliability, availability and maintainability of the setup. Topology C (Figure 6) has some advantages over the other solutions which will now be described and discussed.

Having more than one cable to shore is advantageous from a reliability point of view. However, the shore crossing area is regulated by local authorities. Generally, the right-of-way channel for the cables and the contruction works at the shoreline should be minimised. Access cost is also an issue - if bed rocks prevent trenching, directional drilling or rock cutting/excavation will be used to create the route for cable crossing. In the majority of cases, the limitations set by the cable shore crossing rule out Topology A (Figure 4). Also, Topology D (Figure 7) has a similar disadvantage in that two parallel cables to shore are required instead of one.

It is advantageus to be able to disconnect any single WEC from the eight-WEC setup for servicing without having to disconnect or impact the other WECs. A subsea hub, as considered in Topology B (Figure 5), where only one cable is connected to each WEC, enables for such easy disconnection. However, such a solution tends to be costly and introduces a critical reliability concern for the whole setup. The above disadvantages tend to outweigh the relative advantages.

Overall, the electrical transfer system comprises a multitude of system parts: the subsea cable itself, dry/wet-mate connectors, necessary protection measures, e.g. bend restrictors, corrosion protection and stabilizing concrete mattresses. The overall lifetime cost of the entire system with required service actions defines the topology details, but such aspects have not been considered here.

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IV. SYSTEM SERVICES

A wave power plant, like any other power plant, can access different income streams in parallel. While producing and selling electricity is the main activity, the provision of system services is gaining relevance. Some systems also provide capacity (adequacy) payments. However, the focus here is on fast frequency response services, due, in paticular, to the presence of an accumulator within the WEC to provide short-term storage capability.

It should be recalled that the operation shown in Section III resembles a worst case scenario:

- heavy wave level fluctuations
- maximum power extraction control (at the cost of smoothing effect)
- SCR of only 3
- voltage control switched off

Real operation looks much smoother, serving as a suitable basis for service provision. This is to be covered in a future publication, including the implementation of the fast frequency response in the electrical model.

A. Service payments in Ireland

The transmission system operator for Ireland has already implemented a payment scheme for a range of system services [7]. The most suitable sytem service for a wave power plant to provide seems to be Fast Frequency Response (FFR), due to the short-term nature of the response involved. Following a generator trip, or other major generation-demand imbalance, a sustained increase in power output is required in the time period of 2 s to 10 s after the original disturbance. The quality of service provided is measured against the minimum sustained increase in power output, and is not related to the magnitude of the frequency dip. Limits are imposed on the magnitude and duration of the subsequent energy recovery phase of the response provider. It should also be noted that the FFR service only applies to frequency dips, implying an increase in service provider output, and not to a frequency rise.

The system service can potenitally be provided by any fast-responding generation, including thermal power plant, battery energy storage systems and wind power plants. The inclusion of the latter possibility suggests that a wave power could potentially also take advantage of the same additional remuneration option.

The base payment rate for the fast frequency response is set at 2.16 €/ MW*h [8]. There is a unit-less *Product Scalar* which is multiplied with this base payment rate, to calculate the actual payment rate. This product scalar ranges between one and three, depending on response speed, and it was included to encourage responses faster than the maximum delay of 2 s. The maximum product scalar weighting of three is achieved if the response can be provided within 150 ms [9] [10], as shown in Figure 14. The red dots show different response times of the MegaRoller WEC and the relating product scalars, as explained below.

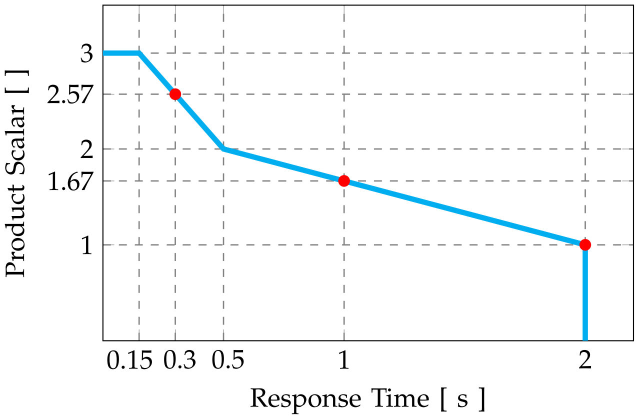

Fig. 14. FFR faster reponse activation product scalar [9]

B. Response of a MegaRoller WEC

The MegaRoller WEC is well suited for providing FFR service, as the hydraulic accumulator can provide (short-term) energy storage capability. The size of the hydraulic accumulator is sufficient to provide the demanded response at any time, not depending on the waves at that moment.

The MegaRoller WEC consists of four parallel 250 kW units. Two of the units operate if the wave power output is below 30 %, while all the units are operational when the power output is above 30 %. Given the preliminary control design as it is today, which is not optimised for fast response, an operational unit can increase its power to rated value within 1 s, while a non-operational unit will require upto 2 s to reach full power. However, the technical capabilities should allow for a response within 300 ms for operational units if the control is adapted accordingly. This is however not investigated in detail, and the final operation scheme and response times are not fully decided yet.

C. Achievable payments

The achievable payments depend on the upward power regulation capability, which depends on the power output. The power output probabilty distribution for the given location at the Irish west coast is shown in Figure 15, based on unpublished wave data provided by the Electricity Supply Board in Ireland. Blue indicates when two units are running and red indicates when all four units are running.

A response time of 2 s for non-running units (product scalar = 1) results in the payment of 2.16 €/ MW*h. The response time of 1 s for running units (product scalar $= 1\ {}^2\!/_3 \approx 1.67$) results in that the FFR payment level would be set at 3.60 €/MWh. Considering that response speed can probably be increased to 300 ms gives product scalar $= 2\ {}^4\!/_7 \approx 2.57$, leading to the payment of 5.55 €/ MW*h.

It is assumed here that the full capability of the technology can be used for service provision. However, the provision of two different services with different response times in parallel might be problematic with regard to the market rules. Also other factors like

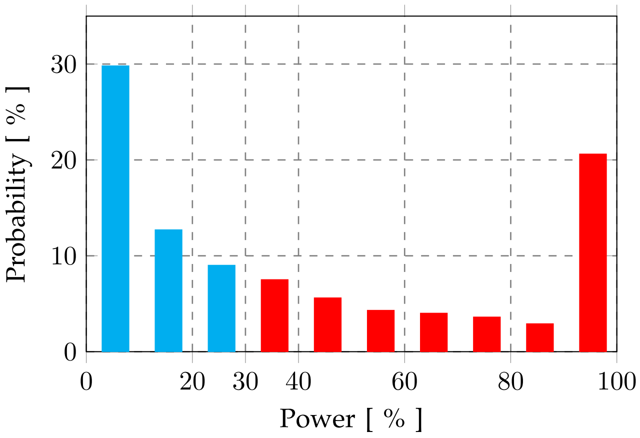

Fig. 15. WEC power output probabilty distribution

forecast uncertainty or time resolution of service procurement can have an influence. The details of the market rules are not further elaborated here.

Given the response speed of the controller in its current state, the calculated payment levels and the power output probability distribution:

1) 51.5 % of the time, power is below 30 % and two machines in each WEC will operate, at an average power of 110 kW. In this situation, the WEC can provide on average 390 kW at 1 s response speed, and another 500 kW at 2 s response speed. This qualifies for a payment of 1.40 €/h + 1.08 €/h = 2.48 €/h.
2) 48.5 % of the time, power is above 30 % and all four units will operate, at an average power of 716 kW. The WEC can provide on average 284 kW at 1 s response speed. This qualifies for a payment of 1.02 €/h.

This results in an average payment of 1.78 €/h per WEC, giving 14.20 €/h for the eight-WEC power plant. Considering the number of hours in a year (8766 h/a), the extra income for providing FFR can be calculated to 124 k€/a (assuming full availability). Considering the faster response speed of 300 ms, income increases to 2.44 €/h per WEC or 171 k€/a.

The service provision income could be increased even further if all four generators would run even at lower power levels (lower than 30 %), however at the cost of increased energy losses. Always running all four generators would also avoid eventual problems with the market rules, as only one response speed would apply in that case. In the end, this comes down to an economic optimisation to determine how many generators to run, depending on increased income through service provision vs. reduced income through energy production (more losses). Eventual influences of start-stop operations on fatigue should also be considered in this context.

The service income could today account for approximately 5-10 % of the total income, depending on wave power support schemes. This share will increase over time as the importance of system services grows as a result of the ”Energiewende”.

V. DISCUSSION AND OUTLOOK

As elaborated in this article, a MegaRoller wave power plant can contribute to grid stability by supporting the grid frequency. For this task, it has some significant advantages compared to (variable-speed) wind turbines:

- The FFR short-term upward regulation service can be provided from the energy stored in the hydraulic accumulator, and a curtailment-based upward margin is not needed.
- Tapping the energy stored in the hydraulic accumulator is less operation-disturbing than slowing down the wind turbine rotor (with knock-on implications for the tip-speed ratio and energy capture efficiency)
- The recovery period of a WEC is less critical, as ”refilling” the hydraulic storage is not as urgent as returning the wind turbine rotor back to the desired rotational speed
- Wave conditions are highly predictable and can be forecast several days ahead with high accuracy, providing good planning possibilities for grid operators
- Harvested wave power very seldom drops to zero, even in calm conditions, keeping the unit runing most of the time, improving the possibility to provide system services

Wave power plant control (additionally to the control of the individual WECs) will give options for further developing and optimising the grid support functionalities. The energy storage of the individual devices could be co-ordinated as one larger energy storage and, for example, optimise the hydraulic accumulator loading-unloading algorithms and maximise the power and time the grid frequency can be supported.

As important as it might be to maximise the energy conversion efficiency and the system service provision capabilities of a single WEC, it is also critical to get the first wave power plants deployed and in operation. In order to become a competitive renewable energy option and realise the market potential of delivering gigawatts of wave energy, design and commercialisation efforts need to address large wave power plants. The WaveRoller technology is currently in an early stage of commercialisation, and it has not yet been able to reap the extensive benefits of economies of scale, technology improvements and learning curve effects which have lowered the costs of wind & solar. However, as it is based on standardised components and commonly available steel and concrete manufacturing, the potential for cost reduction is high and readily achievable. As the technology shares some common features with offshore wind, it is likely to follow a similar cost reduction path.

In some locations, like California, wave resource is negatively correlated to wind & solar resource on a seasonal scale. This means wave energy could compensate the seasonal variation of the electricity production of wind and solar. In winter time, when wind and solar energy production is rather low, wave energy production is relatively high and can fill the gap. Thus, in combination with wind & solar, wave power plants can lead to a more steady electricity supply, making renewable energy great again and reducing the use of fossil fuel generators to cope with seasonal variations.

This study is based on a framework of existing rules and regulations, grid codes and system services. It should be acknowledged, however, that since WECs are nowadays not deployed in relevant scales, the above framework has not been designed with the characteristics of wave power in mind. It follows that at a later point in time, when wave power has gained a relevant market share, the framework could be updated and revised, to better account for contributions of wave power.

VI. CONCLUSIONS

Several aspects of grid connection and integration have been studied for a theoretical 8 MW wave power plant off the Irish west coast. Grid connection and cabling appears not to be problematic as the power per device and the distance between devices is significantly smaller than that for (offshore) wind power.

The suitability of wave power for anciallary service provision depends very much on the WEC technology applied.

Unlike for wind power, with its standard three-bladed horizontal axis upwind turbines, no technology concept has gained a dominant position within wave power developments.

The Megaroller with its hydraulic accumulator based short-term energy storage seems well suited for provision of short-term active power responses, which fits will with the fast frequency reserve service in Ireland, and might also enable for eventual future virtual inertia services.

The service, when successully implemented and applied, will support the grid stability and foster further deployment of renewable energy sources. Also, it will provide a welcome income contibution when calculating the paypack time for a wave power plant.

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