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Frequency support by wave farms in low inertia power systems

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Abstract

New ancillary services and additional requirements for the grid integration of variable renewable energy (VRE) are being defined worldwide, in response to the technical challenges caused by increasing levels of VRE utilization in electric power grids. Currently, the use of wave energy is still limited to a few applications or demonstrations, where the level of penetration of wave power into the grid is not significant. To anticipate the future requirements for wave power integration, and the possibilities for provision of services, this paper considers the lessons being learned through the challenges caused by high penetration levels of other VRE sources into the grid, particularly wind power. On this basis, this paper presents an overview of grid support services that wave power plants can be expected to provide in power systems dominated by converter-interfaced generation, i.e. low inertia systems. Specifically, the focus is on services that support the active power balance in the power system. Then, the current capabilities and future perspectives for the provision of frequency support by wave farms are discussed.

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Keywords: Wave energy; Grid integration; Frequency support; Variable renewable energy

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1. Introduction

Currently, wave energy conversion systems are still at an earlier stage of development than wind farms and solar power plants, and only a few wave energy converters (WECs) have exported power to electricity grids. These WECs represent mainly oscillating water column (OWC) plants, such as the Pico Power Plant in Portugal, the LIMPET on the Scottish island of Islay, the Oceanlinx demonstration tests in Australia, and the Mutriki Wave Energy Plant in the Basque Country [1]. Other examples of WECs that exported power to local grids during prototype tests include the Wave Dragon in Denmark [2], WECs tested at the Lysekil research site in Sweden [3], and WECs deployed at the EMEC wave test facility in Orkney, Scotland [4].

As the level of penetration of wave power into grids is not significant yet, the actual impact of integration is still uncertain. However, similar technical challenges from the grid integration of other variable renewable energy (VRE)

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systems, such as wind and solar power plants, can be expected. The use of wind and solar power generation has increased significantly in the last decades due to reduction of costs and requirements for cleaner energy solutions. At the same time, the large-scale deployment has posed many challenges in the operation of ac power systems, as a result of the output power variability, uncertainty, and the reduction of rotational inertia in the system [5,6]. This has led grid operators to develop more stringent requirements for the integration of VRE in power grids. For instance, recent regulations have been defined for wind power plants in islanded networks, such as Ireland and United Kingdom, but it is expected that stricter requirements will also follow in interconnected continental grids [7].

At early stages of development, wind power plants have traditionally maximized their power output and exported to grids whenever the power was available. Nowadays, however, wind power plants should also provide support to the grid to ensure the security of supply, e.g., through frequency control and reactive power provision, depending on their rated power [8]. In the past, grid support services were mainly provided by conventional synchronous generation. Conventional generation can easily change the power output to meet changes in electrical load, and provide rotational inertia and synchronous torque that contribute to mitigate large active and reactive power imbalances [6].

In the wave energy literature, different aspects related to wave power integration have been studied. For instance, aspects related to energy storage systems for power smoothing, power quality assessment, as well as control of power electronics for voltage regulation and maximum power tracking [9–13]. This paper addresses grid support services that wave power plants should be expected to provide in low inertia power systems, and the inherent technical challenges. To this end, the lessons being learned through other VRE systems are utilized, particularly from wind power integration. The focus is on services targeting the provision of active power, as reactive power can be provided by any converter-interfaced generation. An overview of the main challenges with high levels of VRE integration on ac power systems is also presented to introduce the problem.

2. Challenges with large-scale integration of variable renewable energy

To ensure stable and reliable operation, the electrical voltage and frequency of ac power systems must be kept within nominal values. Allowed deviations during normal operation and large faults (or contingencies) are specified according to the local *grid code*.[1] In power systems with high levels of VRE, the main technical challenges for a safe and reliable operation originate from the need to keep the balance between generation and electrical load demand at all timescales [5]. The challenges are associated with the reduced rotational inertia in the system, in the short timescale, as well as the variability and uncertainty of the output power, in the long timescale.

To illustrate the timescales for active power balance in power systems, Fig. 1 shows a generic daily load curve as depicted in [5,14]: (1) from seconds to minutes, regulation of active power reserves is performed automatically through frequency control, and manually by grid operators, to maintain the grid frequency within the operational range in case of disturbances; (2) from tens of minutes to hours, the generation must be slowly adjusted (increased/decreased or turned on/off) to follow the load pattern; (3) on a daily basis, scheduling is performed to match the energy and peak power of the day, which requires forecasts of load, generation output and availability.

2.1. Rotational inertia

In what relates to the fastest timescales in regulation (Fig. 1), the rotating components of synchronous generation play an important role in the frequency dynamics and stability of traditional power grids. Such rotating components store kinetic energy and add mechanical inertia to the system. During power disturbances, energy is either extracted or absorbed from the rotating masses, contributing to lower frequency deviations naturally. This increases the available response time before the system must react to maintain the frequency within acceptable limits of operation [6]. In modern VRE generation, the grid interconnection is based on power electronic interfaces, which decouple the frequency of the generator from the voltage and frequency of the power grid [5–7]. This allows wind turbines, and WECs, to operate at variable speeds for maximizing the output power in different input conditions. Furthermore, power electronic interfaces convert the dc output of solar photovoltaic (PV) panels into ac output.

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[1] Grid code is a set of national (or regional) technical specifications that define the requirements for interconnection of power plants and other facilities to the grid.

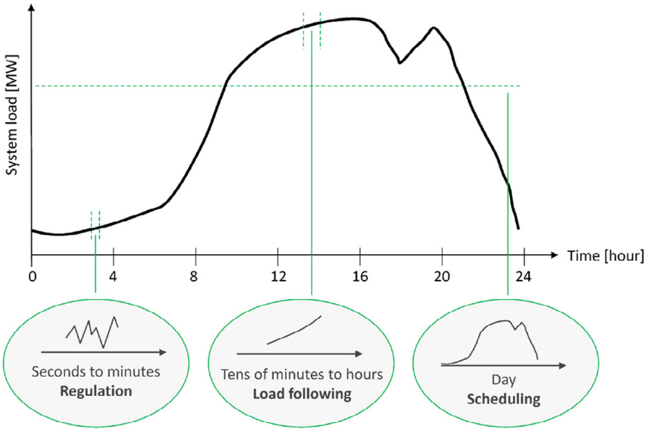

Fig. 1. Generic daily load curve in a power system [14].

In contrast to the rotational inertia response inherently provided by synchronous generators, converter-interfaced generation does not add rotational inertia to the power system. During large power disturbances, systems with high penetration levels of VRE become vulnerable to large frequency deviations. As a result, the transient behavior, commonly characterized by the rate of change of frequency (RoCoF) and frequency nadir, might be significantly affected [6,15,16]. The system undergoes a higher RoCoF and a lower frequency nadir in a shorter time than would have been observed in large ac power systems either based only on synchronous generation or with low levels of VRE, as illustrated in Fig. 2. Large frequency deviations affect the grid stability and might lead to load shedding, excessive torsional stress in machines and blackouts [6].

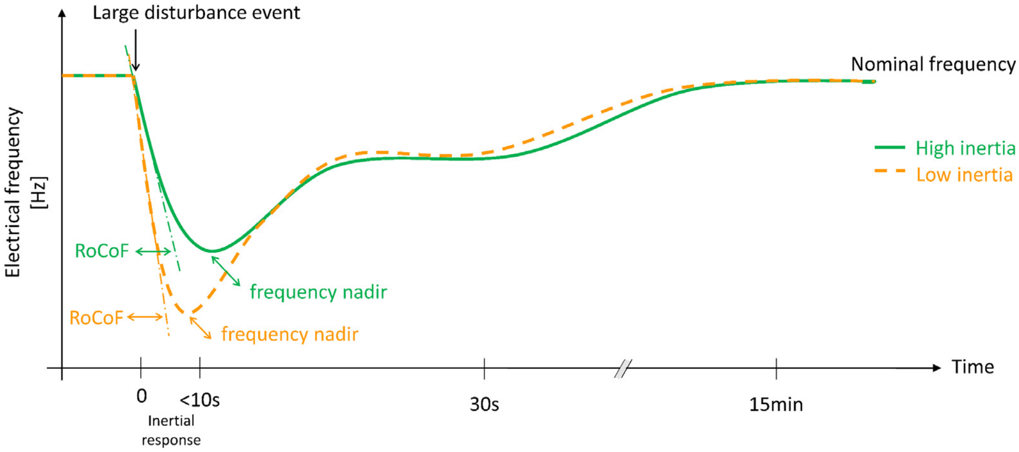

Fig. 2. Typical behavior of the electrical frequency after a large power disturbance event in a power system.

2.2. Variability and uncertainty

While conventional power plants have the capability to store primary energy source on site for quick adjustments at the request of grid operators, VRE generation is not *intrinsically* dispatchable. Downward adjustments are possible by curtailing generation, but upwards adjustments are only possible if the plant is operating below the maximum power point. Thus, a reserve must be available [6].

Since VRE generation is highly dependent on weather conditions and seasonal patterns, the variability of the output power has different timescales. To illustrate the wave power variability, Fig. 3 shows the wave power level available over one day of the year of 2010 off the west coast of Ireland. In this figure, the wave power level

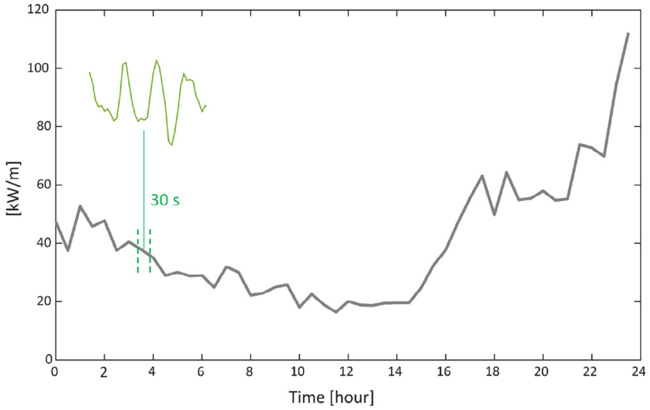

Fig. 3. Wave power level off the west coast of Ireland in 07/11/2010.

(in kW/m) is calculated for every 30 min using the statistical parameters of significant wave height (in meters) and energy period (in seconds) obtained from the wave spectra. More details about the wave data used can be found in [17]. The output power variability (in kW or MW) depends on the WEC technology type, the number of WECs in an array, in case the system is deployed as a wave farm, as well as the power take-off (PTO) system and its smoothing characteristics. Many WECs have short-term energy storage components in their PTO systems, e.g., hydraulic accumulators in oscillating bodies [9,18] and flywheels in air turbines of OWC systems [19].

The output uncertainty of VRE is another challenge for grid integration, especially in scheduling and dispatch procedures in power systems with high penetration levels of VRE. In this respect, accurate VRE forecasting techniques are fundamental for a cost-effective integration [20].

3. Participation of wave power plants in active power balance

It should be expected that the requirements for grid connection of wave power plants will follow the developments from the large-scale utilization of VRE, particularly, wind power. In the early stages of development, wind power plants were generally excluded from providing grid support services mandatory for conventional power plants. Then, most developments considered grid codes as constraints and focused on maximizing the produced power (and consequently, the profits) [8].

As a consequence of the challenges of high penetration levels of VRE in power systems, many grid operators are adapting the local grid codes to the evolving conditions. In addition to more stringent requirements for grid interconnection of VRE generation, new services for grid support are also being developed. In particular, wind power plants are now required to provide frequency control support, e.g., in Ireland and UK power systems [7], depending on their rated power. Furthermore, new services related to low inertia systems have been developed, e.g., in the Nordic synchronous area and in Ireland [21,22].

3.1. Frequency support services in power systems

After disturbances or major power imbalances between generation and load demand, active power reserves are activated automatically through the frequency control loop of synchronous generators, and manually by grid operators, to restore the electrical grid frequency. The frequency control in a power system maintains the frequency within the allowed operational range. Following the nomenclature of the *European Network of Transmission System Operators for Electricity* (ENTSO-E) [23], active power reserves are categorized into frequency containment reserves (FCRs), frequency restoration reserves (FRRs), and replacement reserves (RRs). The reserves are activated subsequently within seconds or minutes after disturbances: FCRs stabilize the frequency at acceptable values, FRRs restore the rated frequency and release the FCRs, and RRs either restore the rated frequency in case restoration reserves were not enough or anticipate an action to expected imbalances [23]. A short description of the reserves including their timescales is presented in Table 1.

Table 1. Frequency support services in a power system.

Service name	Acronym	Short description
Frequency containment reserve	FCR	MW delivered through automatic control loop a few seconds after power imbalance events
Frequency restoration reserve	FRR	MW delivered through automatic control loop (or manual activation) within 30 s to 15 min after power imbalance events
Replacement reserve	RR	MW delivered through manual activation within 15 min up to hours after power imbalance events or to anticipate an action to expected imbalances
Synthetic inertia	–	MW delivered within milliseconds after power imbalance events to support low inertia systems
Fast frequency reserve	FFR	MW delivered faster than FCRs to support low inertia systems

Traditionally, conventional power plants have been the main providers of FCR, FRR and RR. However, wind power plants have been required to participate in the provision of frequency containment reserves, e.g., in Ireland and UK, if their rated power is greater than 2 MW and 50 MW, respectively. Then, the wind turbines do not extract maximum power from wind but operate in derated mode for ramping up and down the output power during specific frequency deviations [7].

Furthermore, new services such as the fast frequency reserve (FFR) from the Nordic power system [21] have been developed. Fast acting reserves act as mitigation measures to address the challenges of low inertia systems. In this context, converter control schemes that provide virtual (or synthetic) inertia have been proposed in the scientific literature [24]. However, synthetic inertia conceptually differs from FFR; while the former mimics the inertial response of synchronous generators typically including droop control characteristics, FFR provides mainly a constant power response a few seconds after a major imbalance [25].

3.2. Current capabilities and future perspectives of wave farms

Following the qualification process from the Irish grid operators [26], wave energy conversion systems have not yet demonstrated capabilities to provide frequency support to power systems. In contrast, wind power plants have proven capabilities for contributing to frequency support services on time scales from 2 s to 5 min [26]. As discussed in the introduction, wave energy technology is at an earlier stage of development than wind energy, and only a few WECs have exported power to grids. To be able to provide frequency support, a number of factors should be taken into account including, mainly, the availability of power reserves and a proper control system in place to modify the operating conditions of the WEC. Furthermore, many WECs have short-term energy storage components built into their PTO systems, which can be particularly useful in the provision of fast frequency support.

Fig. 4 outlines typical timescales of active power provision in power systems together with a few aspects of wave energy conversion systems, namely, the timescales of wave power and PTO energy maximizing control, as well as discharging times (at rated power) of energy storage components commonly used in the PTO. Noticeably, there are many overlaps in the displayed time range of Fig. 4. In the range of seconds, oscillating body WECs with hydraulic accumulators, or OWC systems with flywheels, could increase the export of active power within timescales of FFR or FCR support, provided that the control system, which includes the actuators in the PTO, responds fast enough to the required commands. For instance, the energy stored in the form of pressurized air (or water), for WECs with accumulators can be used during fast provision of active power.

Alternatively, and similar to wind turbines, the WEC can also operate below the available maximum power to have a margin for ramping up and down the output power. It is worth mentioning that in the wave energy literature, the PTO control is commonly designed to maximize the power captured from waves, either in a wave-by-wave basis or according to sea state variations, which can last from about 20 min to hours. The provision of active power for frequency support adds another layer to the PTO control, which will require proper integration and coordination with existing controllers by developing a hierarchical control structure at a farm level.

In addition, wave farms should also be capable of providing active power support in the timescales of scheduling, for replacement reserves or balancing purposes. However, the main challenge is the need for accurate resource forecasts to ensure the availability of output power at the required time. The coordination with batteries built into the PTO system can be particularly beneficial in this case, especially for the time range from tens of minutes to an hour.

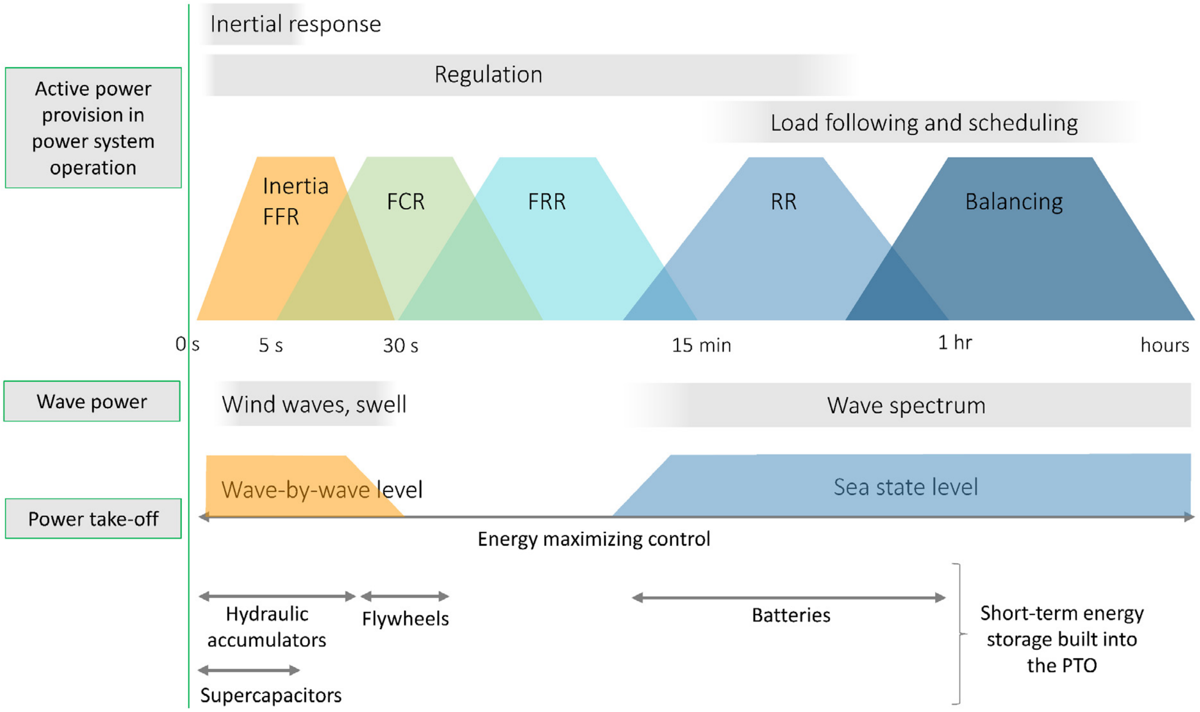

Fig. 4. Timescales of active power provision services in power system operation, timescales of wave power and PTO control, and discharging times of energy storage systems commonly used in PTO systems.

4. Conclusion

In view of the technical challenges from high penetration levels of variable renewable energy in ac power systems, new services for grid support and more stringent requirements for converter-interfaced generation have been defined. By focusing on frequency support functionality, this paper provides an initial discussion about the current capabilities and future perspectives for wave power integration.

Wave power plants with frequency support capabilities have not yet been demonstrated. However, the overlap in timescales between the power system operation and wave energy conversion systems indicates that there is significant potential for wave farms to support the stable and reliable operation of the grid. The ability for providing frequency support functionalities relies on the capabilities of the power take-off system, the corresponding controller design, and the availability of power reserves.

Wave energy converters can operate below the available maximum power to have a margin for either ramping up or ramping down the output power, in a similar way as demonstrated for wind farms. WECs can also rely on short-term energy storage components built into their PTO systems for providing fast and short frequency support. In addition, the coordination with batteries built into the PTO can be beneficial in long timescales. Accurate wave power forecasting will be essential to minimize the uncertainty related to reserves.

The provision of active power for frequency support, or balancing, adds another layer to the PTO control system, which has commonly targeted maximization of the power extracted from waves. This will require the development of a hierarchical control structure at a farm level, a topic not widely discussed in the wave energy literature yet.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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