Comparative Analysis of European Grid Codes Relevant to Offshore Renewable Energy Installations

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Abstract

The purpose of this paper is to highlight the most demanding aspects of grid interconnection of marine energy installations while at the same time providing an updated overview and comparative analysis of the connection requirements of eight European Grid Codes. Therefore, the major issues related to marine energy installations will be summarized as well as the requirements of this type of generation. Besides, the extent to which current Grid Codes include marine energy technologies will be analysed jointly with the need of harmonization of different Grid Codes into a generalised European grid code. Apart from this, several future trends of marine energy technology and its interconnection will be provided for the final discussion.

Keywords

Marine energy; Grid Codes; active and reactive power control; voltage; frequency regulation; wave; tidal; offshore wind;

Nomenclature

AAU	Aalborg University.
ATSOI	Association of the Transmission System Operators of Ireland.
Bimep	Biscay Marine Energy Platform.
BALTSO	Baltic Transmission System Operators.
DFIG	Doubly Fed Induction Generator.
DSO	Distribution System operator.
EMEC	European Marine Energy Centre.
EMI	Electromagnetic Interference.
ENTSO-E	European Network for Transmission System Operators for Electricity.
ETSO	European Transmission System Operators.
EWEA	European Wind Energy Association.
EWIS	European Wind Integration Study.
HV	High Voltage.
IEC	International Electrotechnical Commission.
KPI	Key Performance Indicator.
LVRT	Low Voltage Ride Through.
MRED	Marine Renewable Energy Device.
MS	Member States.
NC RfG	Network Code on Requirements for Grid Connection applicable to all Generators.
OPPMs	Offshore Power Park Modules.
OTSDUW	Offshore Transmission System Developer User Works.
OWC	Oscillating Water Column.
PLOCAN	Plataforma Oceánica de Canarias.
PCC	Point of Common Coupling.
PF	Power Factor.

PWTHDi	Partially Weighed Total Harmonic Distortions.
PWM	Pulse-width modulation.
R	Resistance of the electrical transmission network.
REC	Runde Environmental Centre.
RES	Renewable Energy Resources.
RMS	Root Mean Square.
SEAI	Sustainable Energy Authority of Ireland.
THD	Total Harmonic Distortion.
TRL	Technology Readiness Level.
TSO	Transmission System Operator.
TTC	Tidal Testing Centre.
UCTE	Union for the Coordination of the Transmission of Electricity.
UKTSOA	UK Transmission System Operators Associations.
WFPS	Wind Farm Power Station.
WPP	Wind Power Park.
WEC	Wave Energy Converter.
X	Reactance of the electrical transmission network.

1 Introduction

The expected decline in the availability of fossil fuels and the increased environmental awareness have strongly encouraged the research of alternative and sustainable energy resources at global level in the last decades. Although some natural resources exploitation like hydropower, solar and wind energy has been largely investigated and is now consolidated, the ocean still represents a huge source of untapped energy. In this article the main focus is on marine energy, where, in absence of unanimous agreement, but in accordance with several other references, such as [1], [2], the definition "*marine energy*" includes offshore wind and ocean energy. More specifically, ocean energy encompasses all forms of renewable energy that stem from the ocean, such as tides, waves, currents, temperature gradient (subsea geothermal energy and ocean thermal energy) and salinity gradient [3]. The primary goal of their exploitation is the generation of electricity, but they can also be used for other scopes, such as desalination [3,4].

Looking at the potential of marine energy resources, offshore wind energy is a more powerful resource than onshore wind and its commercial exploitation [5] is increasing year after year, taking advantage of the knowledge gained from both onshore wind applications and the oil and gas sector [6]. The capacity of offshore wind turbines installed in European waters in 2017 was 3.1 GW, twice as much as in 2016, and the total installed capacity has exceeded 15 GW by the end of 2017 [7]. Apart from this, investigations on wave energy have also experienced a significant acceleration in the last decades, due to the large estimated potential of such source worldwide [8], and the corresponding technology is now reaching the pre-commercial stage [9–12]. Overall, tidal energy has a lower potential, but it can be a good complement to the energy portfolio at specific locations [13], and the technology is being successfully tested at full scale [14–16]. In summary, in the case of tidal and wave energy converters, unlike offshore wind, just a few technologies have reached a commercial stage, resulting in a corresponding low amount of installed capacity worldwide [17,18]. However, several converters are being successfully deployed at various test-sites.

Even taking into account the most developed ocean energy technologies, i.e. tidal and wave, and the huge potential available along the coasts of certain regions, such as Scotland (where according to [19] half of the power demand could be supplied by tidal energy), the worldwide electricity production of ocean energy installations is still relatively small and has to face significant challenges to reach the maturity of other renewable energy technologies. As ocean energy is still at the beginning of its development, the take-off of the sector can be eased and sustained by means of reachable Key Performance Indicators (KPIs) and support mechanisms relevant to each technology, as seemingly done in the EU. Thus, policy mechanisms in all Member States (MS) are extremely important for the removal especially of non-technical barriers, such as those related to the Administration and Environment. Moreover, the transition to an integrated European Energy System will progressively enhance the necessary grid availability to allow the growth of the sector [20].

Therefore, offshore wind energy, wave energy and tidal energy, will probably reach a consistent share in the energy market in the very next years, especially if they take advantage of their synergies through co-located/combined energy installations [21,22]. On the contrary, gradient salinity and ocean thermal energy are much more immature and they will probably not enter the market in the near future. Despite the differences in the principle of operation of the primary converters and in their consequent designs, the grid interconnection will be the final test-bench to guarantee the commercial development of all these offshore renewable energy sources.

While the grid integration of onshore wind farms has become state of the applied art in many countries, increasing attention is now specifically paid to the grid interconnection of *offshore* wind energy farms [23–27]. Only a limited number of scientific papers or studies so far has focused on the grid connection of wave [28–31] and tidal [32,33] energy systems, due to the lower technological maturity of such conversion systems. One of the lessons learned in ocean energy, especially from the wave energy industry, is the need to adopt a scaled approach to Ocean Energy Converters' development, and to ensure that the different components are thoroughly tested onshore before the installation phase takes place [34,35], as many unsuccessful attempts have been reported in the past decades.

Overall, most of the grid integration analyses targeting ocean energy resources are still focused on energy farms of limited capacity, mostly connected to distribution networks [36]. However, the commercial exploitation of ocean resources will eventually lead to larger deployments, in the range of hundreds of MW of installed power. In this case, they may be connected directly to the transmission system, as in the case of many offshore wind energy farms [24]. It is worth noting that, due to the widespread geographical availability of the marine resources, the requirements for the grid connection are normally influenced by local regulations, which can also partly differ from country to country. One of the major problems regarding grid connection of intermittent renewables in general, is their detrimental impact on the power quality of the local electric network and this demands *ad hoc* regulations by national and international grid-codes.

This paper has a twofold purpose. Firstly, it enables all the readers interested in marine energy and not necessarily experts in electrical engineering to gain a general understanding of the most critical aspects related to the grid interconnection of marine energy farms. This is achieved by reviewing basic concepts and control requirements that represent the cornerstones of the grid integration of marine farms. Moreover, the paper provides an updated overview and systematic comparison of the connection requirements included in Grid Codes by Transmission System Operators (TSOs) of eight European countries and the Network Code on Requirements for Grid Connection applicable to all Generators (NC RfG) developed by the European Network for Transmission System Operators for Electricity (ENTSO-E). Such a review is only partially available through previous literature [34,37–41] but it is here updated and includes more detailed analyses of such Grid Codes. For this purpose the Grid Codes of Denmark [42], Ireland [43], Germany [44,45], UK [46], Finland [47], Italy [48,49], Spain [50–53] and Norway [54] are analysed and compared in a critical way to highlight those aspects that are especially relevant to marine energy integration.

When possible and when the Grid Codes make a clear distinction for it, connection requirements for marine energy sources are specifically recalled, focusing on the case of wind installations, which are addressed by the majority of the Grid Codes in more detail compared to other renewables [55]. In this sense, it is very important to highlight that the technological maturity plays an important role and, based on that, Grid Codes may need to adapt to the evolving reality of tidal and wave energy industries in the next years. This explains why most of the information provided will explicitly refer to wind power parks, although its extension to other marine energies is expected. Requirements for operations both under normal operating conditions and grid disturbances are revised for each Grid Code. Under normal operating conditions, Grid Codes require control of frequency/active power, voltage/reactive power, and power factor. Under disturbances, Low Voltage Ride Through (LVRT) capability, active and reactive power support and power quality, as understood in [56], are expected from the renewable plants. It is worth noting that power quality must be maintained also under normal operation conditions. For the sake of conciseness, the information extracted from each Grid Code will not be entirely reported in this paper, but will be properly summarized and compared.

The structure of this paper is as follows. Grid impact of marine energy systems is introduced in Section 2 whereas Section 3 presents the regulations. Section 4 provides the theoretical background common to all Grid Codes, and the operation conditions from all Grid Codes are analysed and compared in Section 5. The content of the ENTSO-E Grid Code as well as its evolution are reviewed in Section 6. In Section 0, future trends and perspectives of European Grid Codes are discussed. Conclusions are presented in Section 0. Section 9 collects the appendixes used in this article.

2 Grid Impact Issues pertaining to marine energy systems

A peculiarity of marine energy power plants is that they may be deployed off remote areas where network availability is restricted [57,58]. When, depending on the resource availability, marine generation plants are connected to distribution systems or in sites where power generation was not initially planned, several critical power quality problems, capacity limits and special regulatory issues may occur [59]. These problems are due to the fact that distribution systems are usually weaker than transmission systems.

Unlike tidal and wind turbines, wave energy devices operate based on many different principles and can require multiple cascaded conversion stages, as well as hydraulic, pneumatic, or mechanical power take-offs. Moreover, placement parameters (i.e. distance from the coast, water depth and orientation with respect to the dominant wave-front) and other structural characteristics (e.g. directionality, resonance, etc) may change the definition of the operating fundamentals of the devices. The final phases of conversion (i.e., electrical machines and power electronic interfaces) are usually very similar to both wind and ocean energy converters, in spite of having different designs of primary conversion stages.

Ideally, a predictable power flow is needed to ease the grid integration of any generation technology. The predictability of the power generated from wind turbines, and even more from wave and tidal generators, is certainly welcomed by grid-operators. In this spirit, it can be observed that the forecast for wave [60] and tidal [61] energy is more accurate than forecasts for solar and wind energy. Moreover, these farms can use several methods [62,63] to level the variable power output of each individual unit. The reason for implementing these levelling power flow techniques is to decrease the required rating of electrical energy storage regarding power take-off and power electronics rating. The energy storage can be applied in different stages of the power conversion train to compensate the large instantaneous power output at each single WEC. In [62], a simple spatial averaging principle is proposed for smoothing the extracted power extracted from a wave farm, following a specific aggregation of wave energy converters (WEC) and based on a trigonometric principle. The methodology can be used where there is no energy storage locally available in the single WEC. Ref. [63] describes a point absorber in heave in order to evaluate the effect of irregular waves on the power capture when different control strategies are used. The results recommend a trade-off between a high average power extraction and limited power electronics oversizing by implementing power saturation.

Unfortunately, as indicated in Figure 1, a set of possible grid issues can emerge in marine energy farms (especially associated with wave and tidal current turbine farms) which depend on their size and the grid strength at the Point of Common Coupling (PCC). Although many of these factors are interdependent and cannot be completely separated, this approach differentiates between the impact of projects of limited size versus large deployments, currently only realistic for offshore wind [59]. Main issues pertaining to marine energy systems and related to their grid impact can be due to resource intermittency and variability [57,64,65], such as:

a) <u>Limited dispatchability:</u> according to system operators, variable generation sources, such as wind, tidal or wave, can be difficult to adjust with present or forecasted load demand with insufficient prior knowledge (predictions from 1 to 40 hours in advance [65]) on estimated generation and when a certain timeframe of operation cannot be ensured. Resource intermittency and interactions with network control systems may increase the levels of voltage flicker for ocean energy devices [61]. Apart from the direct impact on the power quality of the grid, the limited dispatchability of marine energy systems will also affect the grid on a wider scale. Thus, as presented in Figure 1, it compromises voltage and frequency stability at a system analysis level in medium-high plant capacities and increases the difficulties associated to transmission planning stages and unit-commitment problems, among others at system wide level for high installed capacities.
b) <u>Stress on the electrical grid:</u> many RES (Renewable Energy Resources) have a direct dependence on the alterations of the environmental conditions. Thus, due to "wave grouping" at a given sea state, many devices deployed in an array can be required to limit the short-term variations relative to the average power. When multiple WECs are connected in a wave farm, the large variations of power extracted from the waves can be reduced. However, it may still represent a challenge from the power quality standpoint [64], as presented in Figure 1. The impact of these variations depends on the grid strength at the PCC [61]. Wave energy converters with intermediate energy storage mechanisms are expected to generate a smother power output when compared to processes not embedding storage. As a consequence, flicker levels will decrease. However, energy buffering may represent a serious issue for wave energy converters, as the raw power produced by a single device can cause continuous voltage variations at the connection node [61]. Therefore, severe flicker risk will be present, because such variation occurs at a much lower frequency compared to typical wind ones. Apart from this, operational challenges may be introduced by the effect of harmonics and thermal overload. Regarding harmonic distortion, the use of directly-coupled induction generators in marine energy devices may not contribute to the problem. However, they may consume a large amount of reactive power (35% to 40% in idling condition, 60% at full capacity) and have limited power injection control, which makes their use marginal. Alternatively, Doubly Fed Induction Generators (DFIGs) are being considered for variable speed

operation of wave and tidal devices. Also, another option is the use of permanent magnet generators (linear or rotary) through direct-drive or gear-coupled arrangements. Unfortunately, power electronic systems (full-scale for permanent magnet generators and partial-scale for DFIGs) used in such grid-interfacing schemes can inject harmonics into the grid, but they greatly improve active and reactive control capabilities.
Thus, as appreciated in Figure 1, it can be stated that the stress on the electric grid is due to power quality and system analysis issues at both transmission and distribution networks, but also more related to capacity limits and system-wide issues when considering the connection to transmission networks. As well as the generators and power electronics, the new farm cables on the network exacerbate the problem by changing the network impedance and possibly amplifying any harmonic emission present.

c) High penetration effects: generation time variations are hidden in the total generation mix when there is a minimal level of renewable generation. Nonetheless, as RES integration levels increase, system inertia decreases. Thus, occasional mismatches between generation and demand levels may cause higher instability in the system. As a matter of fact, resource variability and intermittency are considered the main obstacle towards the grid integration of many RES. Marine plants of medium and large capacity connected in distribution grids may cause impacts such faults, transient voltage and frequency stability issues and small signal oscillations. Regarding high capacity marine plants, the most critical aspects observed at both distribution and transmission levels are system wide issues such low voltage ride through capability, transmission planning, market operations, unit commitment and ancillary services. Thus, high penetration effects would be responsible for every impact presented in Figure 1, namely power quality, capacity limits, system analysis and system wide issues. Those effects are amplified for scenarios with higher contribution of renewable generation.

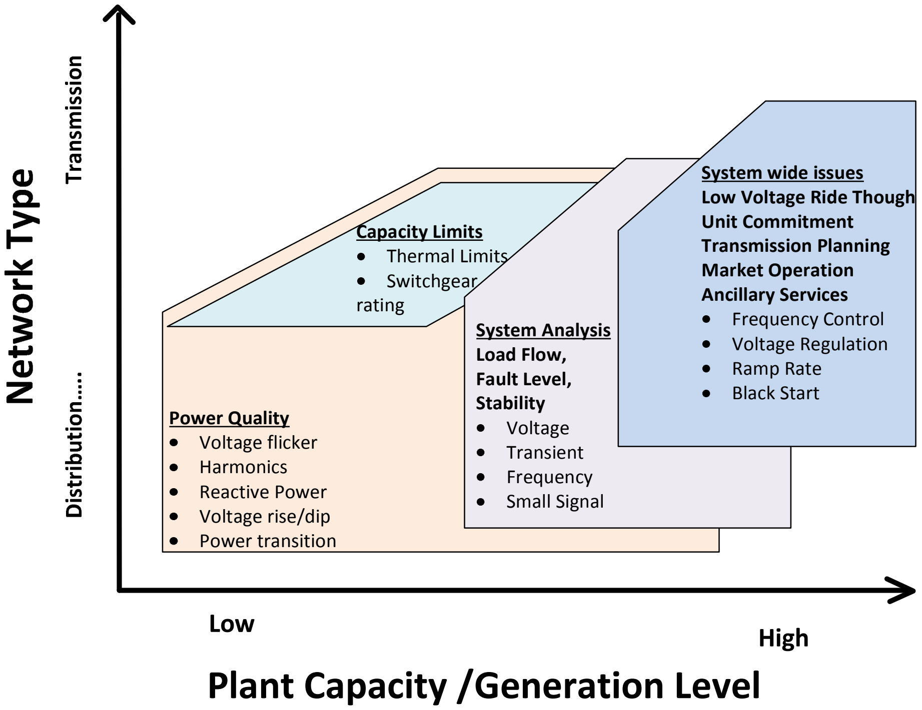

Figure 1: Possible grid impact issues of marine energy systems [59].

3 Regulations for marine energy systems

Initially, no standards existed for the certification or testing of wave and tidal energy converters. So, EQUIMAR protocols [66,67] set out a list of good practices for testing wave and tidal devices in a controlled laboratory environment with the intention of supporting the development processes and securing funding for development or promotion of devices. The methods suggested by those protocols were adapted from several industries including the aerospace and maritime industries. Also, the Structured Development Plan [68] set out the development stages required for a marine renewable energy concept to achieve commercial reality and uses Technology Readiness Levels (TRLs) and other metrics [69].

A general setback in the assessment of power quality and grid impact of any Marine Renewable Energy Device (MRED) is that the main applicable provisions were developed with focus on wind energy. National and international groups are now in the process of adapting these regulations to the marine particular case where special conditions have to be considered. Therefore, there is not a well-established regulation to follow, since the reference documents are still at a draft stage.

In this sense, only two of the Grid Codes under study, i.e. TenneT [44,45] and National Grid[46], have a special focus on offshore wind and in the case of National Grid, the code considers in a general way “offshore power generating units powered by intermittent sources”.

Apart from national Grid Codes, the International Electrotechnical Commission (IEC) technical committee 114 is currently working on power quality requirements for wave, tidal and other water current energy devices [64]. This document is based on [70]. This international standard will have the form of recommendations and will focus on:

- Power quality aspects and parameters (non-device specific and non-prescriptive) for single/three-phase, grid-connected/off-grid (including micro-mini grid) marine tidal, wave and other water current converter-based power systems.
- Establishing the application techniques, measurement methods, and guidelines for result-interpretation.

Therefore, the technical specification only evaluates the power quality of marine installations. It only gives general rules but it does not give indications about the compliance of the installation with quality criteria. For that purpose, the user should refer to the corresponding Grid Codes.

Besides, the IEC technical committee 88 [71] is working on the standardization of the latter. It gives a general basis for design, quality assurance and technical aspects for certification. This guide of recommendations is focused on:

- Dealing with requirements corresponding to specific sites.
- Addressing all subsystems of wind farms, including communication systems and environmental aspects of wind power development.

4 Common background of the selected Grid Codes

The key aspects described in section 2 limit grid connected marine energy systems in terms of frequency and active power control, voltage and reactive power control, LVRT, and power quality issues like flicker and harmonics among others [41]. New Grid Codes adapted for marine energy farm connection will deal with aforementioned and new aspects. Indeed, the present paper studies these specific requirements. Resource predictability is also an important factor in the operation of grid-connected ocean farms, given that their primary power capture stage has limited control. Thus, ocean energy farms are generally non-dispatchable. However, partially dispatchable plants can also be found, such as tidal hydro-turbine with blade pitching capability. Since wind energy technology and control strategies are in a more advanced research state than other marine energy technologies, the following control structures are based on those developed for wind energy technology context and are extended to all marine energy technologies.

4.1 Voltage and reactive power control

The following four factors affect the required amount of reactive power: machine parameters, reference value of the voltage controller, values of resistance (R) and reactance (X) of the grid connection and the amount of active power exchanged at the point of grid connection. Therefore, various methods for voltage control have been used in wind energy technologies and can possibly be extended to the ocean energy case [72,73].

4.2 Frequency and active power control

The control of active power is accounted as an important ancillary service to be provided by generation units, in order to contribute to the power system stability. The frequency regulation ancillary service is composed by three functions, namely [26]: primary, secondary and tertiary control.

The Grid Codes consider that all power plants should be able to operate without interruption within a certain range around the nominal frequency of the grid. They are also requested to operate for different periods of time with lower/higher frequencies down/up to a minimum/maximum limit. Whenever these limits are exceeded, the generating units could suffer damage. Therefore, even very short deviations from the nominal frequency can activate load shedding relays. Thus, a major generation capacity loss can occur, leading to a black-out.

4.3 Low Voltage Ride Through capabilities

The term Low Voltage Ride Through is referred as the capability of a generator to stay operational and not to disconnect from the grid in the event of a voltage dip and by supporting the grid with reactive power [74]. The generator capability to operate during short periods of voltage dips is important so as not to disconnect from the grid. This could lead to control issues regarding active and reactive power [75].

4.4 Power Quality

For the evaluation of the impact of marine installations on power quality, different parameters at PCC (or at the Connection Point in case of Irish Grid Code) can be studied [72]: DC content, asymmetry, rapid voltage changes, flicker, harmonic distortions, inter-harmonic distortions and distortions 2-9 kHz-30 MHz.

4.5 Relevance for marine energy installations

Future implementation of big ocean energy projects will require modifications of national Grid Codes, similarly to what happened lately with increasing levels of wind energy. Besides, in the future, ocean energy farms will need the capability to control the voltage and/or the reactive power at the main point of connection with the grid. Also, some voltage control techniques already used in the wind energy industry should be considered. On the other hand, several codes establish the participation of wind farms in the grid frequency by varying the active power output. Unfortunately, in contrast to the full controllability of the output power generated by conventional power plants, ocean farms are unable to control the resource energy input (i.e. from wave or tidal current) to such an extent [65].

Also, similarly to wind power plants, large ocean energy farms may be required to contribute to voltage control through the reactive power exchange, and to frequency control by regulating the active power generation. In fact, variable speed generator systems are present in most ocean energy devices, connected to grid using power electronic interfaces. Some power electronic converters, such as voltage source inverters, can fully control the reactive power exchange, whereas other devices, such as current source inverters, can not. Devices with reactive power control capability can contribute to voltage control on the network, as long as their MVA rating is sufficient to export the active power plus the reactive power required for voltage control. However, long subsea cables will limit the offshore power station capability to provide these services. Indeed, this is because subsea transmission cables present higher capacitance and lower inductance compared to overhead transmission lines, because the conductors and sheath are closer. Therefore, submarine cables have a lower inductive reactive power than overhead cables. As a consequence, reactive power losses become significant in the case of long submarine cables and marine energy installations. Thus, special provisions may be needed at the PCC [76]. This is also the reason why DC systems must be considered beyond a certain cable length, in order to limit the losses by eliminating the reactive current flow and the corresponding losses. The frequency control is particularly challenging for systems with no energy storage element, due to the MRED dependency on the incoming renewable source. So, ocean energy converters in an ocean farm could be required not to generate the maximum power they can extract, to let a margin for increasing their output power when required by the control system. Also, the frequency control in a grid subject to variations in the power an ocean farm delivers, may require the increase of short-term reserve capabilities. This corresponds to the provision of more flexibility from present conventional power plants, demand side, and balancing bigger areas.

Moreover, the way marine energy converters are affected by a grid fault and their capability to keep connected to the grid depend on what type of electrical generator and power electronics interface (e.g. Permanent Magnet Synchronous Generator with Full-Scale Converter, Doubly Fed Induction Generator, etc.) they use. A detailed survey can be found in [77].

Last, regarding power quality, DC content is a feature of power quality distortion whose production may be increased by HVDC systems, when AC and DC transmission lines are in close proximity and also by Static VAr Compensators, or in general, in cases where anti-parallel power electronic switches are used [81]. Besides, the importance of inter-harmonics is also increasing because of the power electronics introduction, arcing loads, variable-load electric drives, ripple controls and static frequency converters [78]. The new emerging faster power electronic switches are increasing the switching frequency significantly, which results into an improvement in the efficiency of the power conversion and the reduction of harmonic and inter-harmonic current distortion in frequency range up to 2 kHz. However, this provokes the displacement of harmonic and inter-harmonic spectrum towards higher frequencies and involves the extension of typical harmonic analysis up to 9 kHz that is the lowest frequency considered for typical electromagnetic interference (EMI). One of the technologies related to this phenomenon is the recently introduced PWM (Pulse-Width Modulation) boost rectifier [79], whose PWM modulation carrier frequency often belongs to the 2-9 kHz range.

5 Comparative analysis of Grid Code requirements for integration of renewable generation

In this section, Grid Codes from TSOs in eight different countries (Finland, Denmark, Germany, Italy, UK, Ireland, Italy, Norway, Spain and UK) are analysed and compared with each other. As mentioned in section 4, the analysis is focused on the most important grid connection requirements for the steady state conditions and the regulations affecting operation under grid disturbances. With a view to easier reading, only the results of the comparative analysis among Grid Codes will be shown in the next section, providing an analysis of major similarities and differences among them. Further details can be found in [80].

5.1 Overview of the major similarities and differences among Grid Codes

All the reviewed Grid Codes are divided into different sections where important conditions for an efficient and secure performance of the national grids are laid out. The information presented in this paper has been extracted from the "connection conditions" section from each country's Grid Code.

Denmark, Ireland, and Finland have detailed specifications particularly focused on operational performance of wind power parks (WPPs) as separate sections or appendixes in their Grid Codes. The requirements a WPP needs to comply with are clear and well-defined. TenneT has separate regulations for offshore wind farm connections. Furthermore, the National Grid has requirements for offshore power park modules, which refer to offshore power generating units powered by intermittent sources (thus including wind, wave, solar and any other relevant source) with single PCC to the offshore transmission system. This is unique only for these two grid codes and is not present in any other Grid Code. Some connection requirements are defined for particular categories of generators, and the categories are formed based upon generation capacity (as in Denmark, Ireland, and Finland), voltage level at the connection point (as in Italy and Norway) or year of commissioning and control area (as in UK). Table 1 shows the Grid Codes that have particular focus on WPP and offshore WPP.

Frequency and voltage deviations, power quality, voltage control, active and reactive power control, protection, remote control and communication requirements, operation and maintenance, Low Voltage Ride Through requirements, are included in all Grid Codes. Under normal operation conditions, limited frequency and voltage deviations are allowed in all the reviewed Grid Codes. All Grid Codes require the possibility to control active power to a value lower than the maximum available power. Frequency control capability is required in all Grid Codes except the Spanish one, for WPPs greater than certain level of power generation/rating. For example, WPPs in Denmark and Norway and marine power plants in UK with generation capacity greater than 25 MW, 10 MW and 50 MW, respectively, are required to have frequency control capability. However, actual participation in frequency control and/or droop curve (frequency vs. active power) setpoints have to be agreed with the grid operator. The Spanish Grid Code requires only active power curtailment control such as delta control or ramp rate limitation [50], [51]. Reactive power control to keep voltage or power factor to a set-point value is mandatory in all Grid Codes. LVRT capability is also another important requirement that is common in all reviewed Grid Codes, but only the Spanish and Italian Grid Codes have high voltage ride through requirements.

Table 1: Particular focus of specifications in analysed Grid Codes

Country	WPP	Offshore WPP
Denmark	X	
Ireland	X	
Germany		X
UK		X
Finland	X	
Italy		
Spain		
Norway	X	

In addition to the different limit values set for the different requirements, the major differences among the Grid Codes include terminology, levels of detail and jurisdiction. There are differences in the use of terms describing identical/similar elements and phenomena. For example, the term "wind power plant" is used in Denmark, Finland and Norway while "controllable wind farm power station" (controllable WFPS) is used in the Irish Grid Code. In UK, offshore wind power plants are included under OTSDUW (Offshore Transmission System Developer User Works) plant and apparatus, a term used for plants and apparatus under a special agreement. Another example is the use of "interface point" (UK) and "reference point" (Finland) as synonymous of connection point.

5.2 Voltage and Reactive Power Control

The allowed voltage ranges for operation under normal conditions are different depending on the country and the voltage level of the power transmission. Normally, continuous operation needs to be ensured within ±10% of the nominal voltage at the point of connection. Excluding the case of abnormal operations, the voltage at point of connection shall be within the ranges indicated in Table 2 for different grid voltages in the eight considered countries.

Table 2: Ranges of allowed voltage variations under normal operation in different countries

Denmark		Ireland		UK		Germany		Finland		Italy		Spain		Norway	
pu	Nom. voltage	pu	Nom. voltage		Nom. voltage	pu	Nom. voltage	pu	Nom. voltage	pu	Nom. voltage	pu	Nom. voltage	pu	Nom. voltage
0.9 - 1.1	400 kV	0.875 - 1.05	400 kV	0.95 - 1.05	400 kV	0.92 - 1.105	380 kV	0.90 - 1.05	400 kV	0.85 - 1.10	220 and 380 kV	0.90 - 1.115	400 kV	0.93 - 1	420 kV
	150 kV	0.91 - 1.12	220 kV	0.9 - 1.10	275 kV	0.877 - 1.113	220 KV		220 kV		150-132-120 kV		220 kV		300 kV
	132 kV	0.90 - 1.12	110 kV	0.90 - 1.10	132 kV	0.903 - 1.097	155 kV		110 kV		15 and 20 kV		150 kV		
				0.94-1.06	Under 132 kV	0.873 - 1.118	110 kV						132 kV		
													110 kV		

Allowed ranges of voltage variation depend on the frequency at the point of connection and the values shown in Table 2 are for normal frequency conditions. Denmark, Italy, Spain, Finland and Norway have the same operating ranges (in pu) at different rated voltage levels, while UK, Ireland and Germany have different operating ranges at different rated voltage levels (in pu) in the transmission system. Norway has the narrowest, voltage range for continuous operation, i.e. within 0.93 pu and 1 pu. In Germany, the upper values can be overcome for a maximum of 30 minutes.

The requirements for reactive power regulation depend on active power (production level or installed capacity), voltage at the point of connection, or both. These regulations allow voltage, power factor or reactive power control at the point of connection as explained in Section 4.1. Summary of reactive power requirements from the studied Grid Codes is presented in Table 3.

Apart from Denmark, all countries require 0.95 PF (leading and lagging) at the nominal power production from WPPs with important installed capacity (for example, in UK it is considered to be over 100MW [81] in marine power plants) or from WPPs interconnected to High Voltage (HV) grids. In most countries, participation in reactive power regulation is not expected when the plants are producing less than 20% of their nominal power. But according to [82], even if they are not producing active power, big wind energy parks can be required to ensure zero reactive power exchange at the connection point. Requirements from the Grid Codes take necessarily into account the Active and Reactive Power Control capability and the technology of the marine energy converter. Exceptions to the above-mentioned requirements can exist based on local agreements with DSOs (Distribution System Operators) or TSOs.

Table 3: Requirements for reactive power regulation in different countries

Denmark	- 11 kW - 25 kW: 0.95 < Power Factor (PF) < 1 at 20% of the rated power[2] or more - 25 kW - 1.5 MW: Higher than 0.995 (leading and lagging), but depending on active power production, P - >1.5 MW: 0.975 leading and 0.975 lagging for 20 – 100% of the rated power[2]. The range is reduced for lower power production levels
Ireland	- Between 0.95 leading and 0.95 lagging at the rated power[2] - Reactive power is kept constant at 50 - 100% of the rated power - Between 0.84 leading and 0.84 lagging at 0 – 50% of the rated power[2]
UK	- Between 0.95 leading and 0.95 lagging at 50 - 100% of the rated power[2] - Reactive power consumption (leading PF) requirement decreases linearly for power outputs between 20 - 50% of the rated power while the 0.95 lagging limit remains constant

Germany	- Between 0.95 leading and 0.925 lagging at the rated power[2] - Constant reactive power at 20 – 100% of the rated power[2] - Between 0.55 leading and 0.45 lagging at 0 – 20% of the rated power[2]
Finland	- 0.5 - 10 MVA: Between 0.995 leading and 0.995 lagging at active power above Pmin[1], - >10 MVA: between 0.95 leading and 0.95 lagging at active power levels above Pmin[1]
Italy	- Between 0.95 leading and 0.95 lagging from 50% - 100% of the rated power[2] - Constant power factor from 20 – 50% of the rated power[2] - Reactive power regulation as a function of voltage is required outside of voltage control dead-band
Spain	- Minimum of 0.99 leading and lagging for all active power productions and nominal voltages For connections to 220 kV and 400 kV networks: Minimum of 0.95 leading and lagging at maximum power production
Norway	- Between 0.95 leading and 0.95 lagging at the rated power[2]

In the case of Spain, the voltage ranges presented in Table 2 and reactive power regulation requirements included in Table 3, correspond to mainland system, whereas slightly different voltage ranges and reactive power requirements can be found in non-mainland systems, as stated in [83].

5.3 Frequency and Active Power Control

The nominal frequency is 50Hz in all the Grid Codes under analysis. All countries generally demand continuous operation, above or below this value, within determined ranges. Moreover, operation beyond the continuous operation range is required for a limited time duration. When the frequency falls outside the time-limited operation range or in the case it does not return to the continuous operation range after a pre-defined time duration, disconnection is permitted.

From Figure 2 it can be noted that Germany allows the largest operation range for frequency (i.e. between 46.5 – and 53.5 Hz) and then Finland (between 47.5 and 53.0 Hz). Nevertheless, in Germany, offshore wind power plants are allowed to operate within the ranges 51.5 – 53.5 Hz and 46.5 – 47.5 Hz only for a maximum duration of 10 seconds. Italy and Spain have, overall, the narrowest frequency operation range (i.e. between 47.5 and 51.5 Hz) and operation within 47.5 – 48 Hz is allowed in Spain only up to 3 seconds. In case of voltage levels higher than 35 kV and lower than 150 kV, the widest range of continuous operation (47.5 – 51.5 Hz) is then allowed by the Italian Grid Code, and then the Spanish grid code (48 – 51.5 Hz). The Danish Grid Code allows the narrowest frequency range under continuous operation (49.5 – 50.2 Hz). However, for frequencies in the range 49 - 49.5 Hz, Denmark has a minimum connection requirement of five hours. Ref. [55] includes a similar study for different Grid Codes covering only wind energy.

Frequency control under normal conditions is obtained by varying the output (active) power based on the system frequency (primary control). UK Grid Code demands the power output to be kept constant at frequencies below the nominal in order to support the system frequency. Italian and Irish Grid Codes prevent from injecting more power when frequency is higher. With the exception of the Spanish one, all the considered Grid Codes, expect selected WPP (and in the case of UK, selected marine power plant) to embed frequency control functions with droop control and dead-band ranges. Generation capacity and/or specific agreements with the TSOs are the basis for the selection. The power-frequency curves can be defined in the Grid Codes or provided directly by TSOs.

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[1] P_{min} is the minimum output power at which the power generating facility is not required to generate reactive power.

[2] Rated Power, in the case of wave energy farms it corresponds to the maximum output power (rating of the power electronic interface in the case of a full-scale back-to-back converter) or the rating of the Power Take-Off (which can be exceeded for short time intervals)

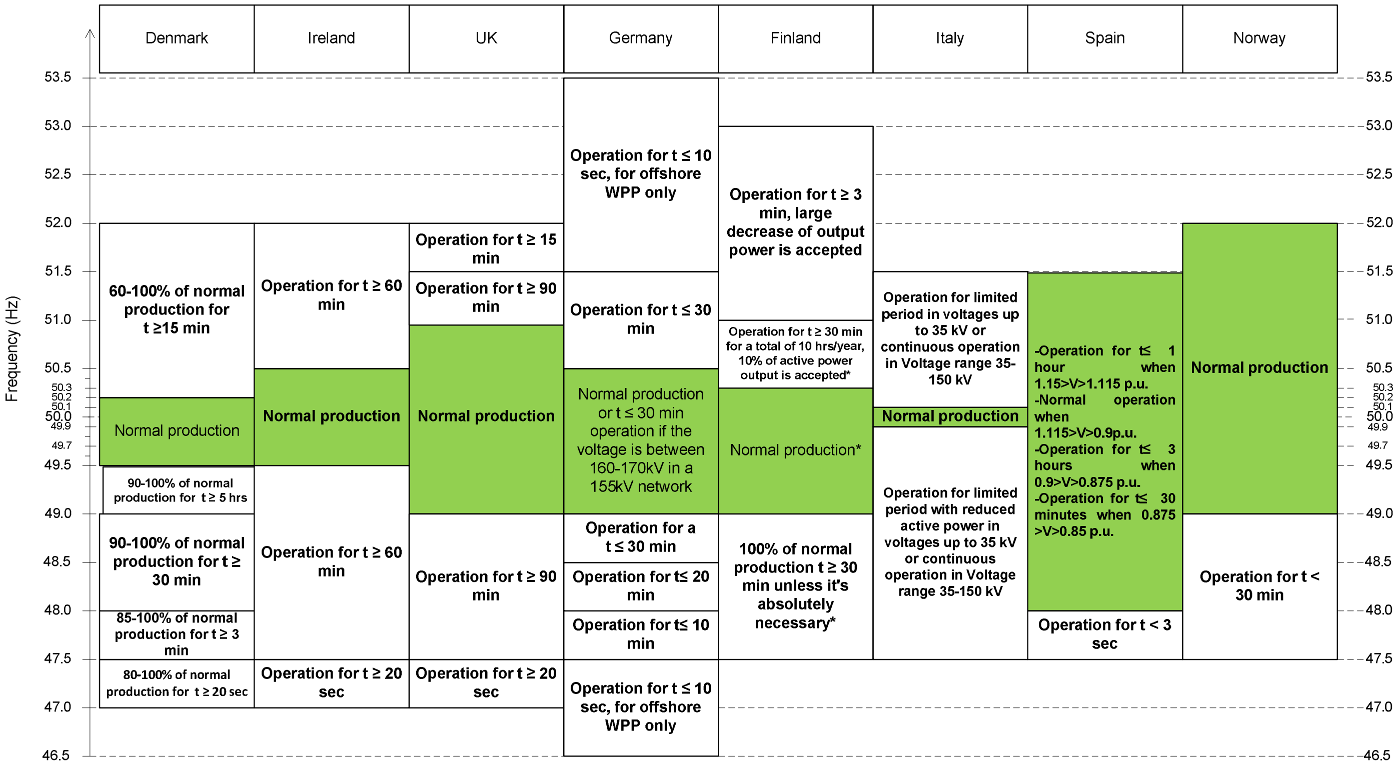

Figure 2. Frequency ranges of operation in the different countries.

WPPs in Ireland, Denmark, Finland, Germany, Norway and Spain are also required to contribute to secondary control through constraint functions like operating at a lower production level than possible, limiting rate of increase/decrease in production, etc. In the case of Spain, it is worth noting that the ranges included in Figure 3 correspond to mainland system, whereas another distribution of ranges can be found for non-mainland systems, as stated in [83].

5.4 Low Voltage Ride Through capabilities

LVRT requirements differ depending on generation capacity, voltage at the point of connection or duration of the voltage dip. Denmark enforces LVRT requirements only for WPPs bigger than 1.5 MW. Finland has two different LVRT curves; the first refers to WPP of installed capacity in the range 0.5 – 10 MVA and the other is for WPPs greater than 10 MVA. LVRT curves in Norway and Italy are different depending on the voltage levels at the connection point. LVRT curves in UK for marine power plants depend on the voltage dip duration.

The strictest requirements in terms of LVRT for all the considered countries are shown in the same graph for comparison purposes (Figure 3). The corresponding maximum residual voltage and durations are presented in table format (Table 4) for completeness. It can be noted that Finland, Germany, Italy and Norway require riding through complete short circuits at the point of connection. Finland requires the longest duration for zero voltage ride through (250 ms). Ireland, Spain and UK require a 15% voltage ride through capability, while Ireland has the longest duration (625 ms). Grid Codes in Germany and Spain require WPPs to provide voltage support by reactive current injection during voltage dips.

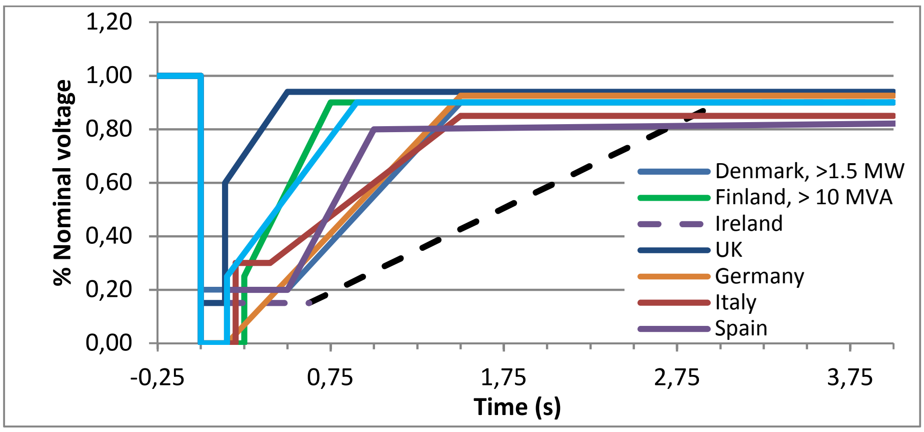

Figure 3. Low Voltage Ride Through curves for different countries.

In the case of Spain, the Low Voltage Ride Through curve presented in Figure 3 corresponds to the mainland system, whereas a different profile is required in case of non-mainland territories, as stated in [83].

Table 4: Maximum residual voltage and duration values of the LVRT curves

Country	**Residual voltage (%)**	**Duration (ms)**
Denmark	20	500
Ireland	15	625
Germany	0	150
UK	15	140
Finland	0	250
Italy	0	200
Spain	0	150
Norway	0	150

5.5 Power Quality

A comparison of the regulations regarding power quality in the considered countries is presented in Table 5. The power quality aspects included are those presented in section 4.4, namely: DC content, Asymmetry, Rapid Voltage Changes, Flicker, Harmonic Distortions, Inter-harmonic Distortions and Distortions 2-9 kHz.

Table 5. Power quality aspects covered by different European Grid Codes

Country	**Denmark**	**Ireland**	**Germany**	**UK**	**Finland**	**Italy**	**Spain**	**Norway**
DC content	X	*	*			*		
Asymmetry	X			X	X		X	X
Rapid Voltage Changes	X			X	X			X
Flicker	X			X	X		X	X
Harmonic Distortions	X			X	X		X	X
Inter-harmonic Distortions	X							**
Distortions 2-9kHz	X							

*According to IEC Standards

** Optional according to Norwegian Water Resources and Energy Directorate [84].

As Table 5 shows, the Danish Grid Code is the most complete in terms of power quality. In the rest of the Grid Codes, power quality requirements that are special for WPPs are not defined and have, therefore, similar requirements to those imposed on the conventional power plants connected to the main grid. The Spanish and Norwegian Grid Codes mention the possibility of short term reactive power supply during grid disturbances. Grid Codes corresponding to Ireland, Germany and Italy entrust their power quality section to IEC Standards. Grid Codes belonging to UK, Spain and Finland fulfil almost the same requirements, but do not treat DC content, distortions 2-9 kHz and inter-harmonic distortions and the Spanish regulation does not include rapid voltage changes.

5.6 Harmonization of national Grid Codes and development of a European Grid Code

Several joint activities and recommendations aimed at harmonizing Grid Codes have been launched in recent years. The activities have been carried out by TSO associations, both regional [85] and EU-wide, the European Wind Energy Association (EWEA) [86], as well as EU funded projects such as EWIS (European Wind Integration Study) [87] and Offshore Grid [88].

The EWEA published a generic Grid Code format for WPPs [86] in 2009. The objective of the generic Grid Code was to introduce structural harmonization where designations, structure, figures, definitions, method of specification, and units in a Grid Code are fixed and agreed upon. The numerical requirements will be decided by the TSOs according to local system needs. Grid Codes indicate requirements for the grid interconnection and operation of both consumers and generating plants, in order to guarantee a secure and safe performance of the network. Renewable energy-based generation plants have an intermittent power generation due to the intrinsic characteristics of the natural resources. Hence, their large-scale integration represents a challenge to the proper operation of the local power system. To ensure that power systems operate smoothly, Grid Codes address issues related to the connection of generation plants, under normal and grid disturbance operations. They may also include power quality specifications.

To analyse the power quality of the grid interconnection, a wide range of aspects are included (section 4). Those phenomena are proposed following one of the most complete technical guides to assess power quality, the Danish technical regulations [72]. Nevertheless, there are test sites like the European Marine Energy Centre (EMEC), that have their own guides for connecting installations to grid, “Guidelines for Grid Connection of Marine Energy Conversion Systems : EMEC: European Marine Energy Centre” [89].

Next table indicates several grid-connected European test sites, with the indication of the regulation applied.

Table 6: Applied regulations at grid connected European test sites

Test site	**Location**	**Responsible**	**Max. capacity**	**Applied regulations**
Amets-Belmullet [103]	Ireland	SEAI	10 MW	Not yet connected
Nissun Bredning	Denmark	AUU	66-84 MW	Technical Regulation 3.2.1 for electricity generation facilities with a rated current of 16 A per phase or lower [104]
Pico	Portugal	WavEC Offshore Renewables	700 kW	Portaria nº 596/2010 (Appendix II - Regulamento da Rede de Distribuição (MAT>110kV) [105] and Regulamento nº 455/2013 and Regulamento da Qualidade de Serviço do Sector Eléctrico [106]
Portuguese Pilot Zone	Portugal	WavEC Offshore Renewables	18-80-250 MW	Portaria nº 596/2010 (Appendix II - Regulamento da Rede de Distribuição (MAT>110kV) [105] and Regulamento nº 455/2013 Regulamento da Qualidade de Serviço do Sector Eléctrico [106]
Wave Hub [107]	UK	Wave Hub Limited	30 to 48 MW	
EMEC Wave Test Site [108]	North Scotland	EMEC	7 kW	UK Distribution Code (Small Power Station <10MW) [109]
EMEC Tidal Test Site [110]	North Scotland	EMEC	5 MW	UK Distribution Code (Small Power Station <10MW) [109]
Bimep [111]	Spain	Bimep	20 MW	Not grid connected yet
Mutriku	Spain	Bimep	296 kW	Grid connected
SEM-REV	France	ECN	8 MW	Grid connected
Tidal Testing Centre(TTC)	The Netherlands	Tidal Testing	160 kVA	Netcode Elektriciteit
Runde Environmental Center (REC)	Norway	REC	½ MW	REN Rasjonell Elektrisk Nettvirksomhet, ”Tilknytnings- og nettleieavtale for Innmatingskunder i distribusjonsnettet”. Vedlegg 3 – Tekniske funksjonskrav [112]
Marine Test Site for Ocean Energy Converters	Spain	PLOCAN	15 MW	REE. Resolution O.P.: 12.1 [113], 12.2 [114] and 12.3 [50]

The TradeWind project [90,91] which addressed reliable and maximal integration in the Trans-European power markets, gave recommendations for market rules, interconnector allocation methods and policy development in order to support wind energy integration.

TSOs have been working together for a long time through regional associations like Union for the Coordination of the Transmission of Electricity (UCTE) [92], European Transmission System Operators (ETSO) [93], Nordel [94], Baltic Transmission System Operators (BALTSO) [95], Association of the Transmission System Operators of Ireland (ATSOI) [96] and UK Transmission System Operators Associations (UKTSOA) [97] to ensure reliable operation and interconnection of the regional transmission grid and electricity market [98]. The regional TSO associations created a harmonized Grid Code for their respective regions that was used as a basis for each member TSO's Grid Code and set minimum requirements to be met. In July 2009, the operational tasks of these associations were transferred to ENTSO-E. ENTSO-E is an association of all TSOs in European Union (and some others interconnected to their networks), and represents all their market and technical issues. Following Regulation (EC) 714/2009 [99] which determines that network codes should be created for market integration and cross-border network issues, ENTSO-E, as detailed in Section 6, has started a Grid Code for grid interconnection requirements for all generators [100]. The document has been discussed and commented on by various user groups, stakeholders and technical experts, and now awaits adaptation by the European Commission. This document is expected to complement national Grid Codes by different TSOs in order to tackle cross-border issues in a systematic manner.

Technology maturity plays a very important role regarding the capability to accomplish the requirements stated by the Grid Codes. Hence, in most cases isolated devices or testing sites for new pre-commercial devices are installed and grid connected. In these cases, the applied Grid Codes are not unified, as

shows.

Detailed description of these and other test-sites around the world can be found in [101].

Galway Bay located in Ireland, or Smart Bay, is a ¼ scale Test Site which is not conceived for grid connection purposes but for validating ocean energy converters [102] and because of this, the test site was not included in Table 6.

6 ENTSO-E: Network Code on Requirements for Grid Connection applicable to all Generators (NC RfG)

Network Code on Requirements for Generators (NC RfG) is developed by ENTSO-E to increase cooperation and coordination among member TSOs [100]. The network (grid) code aims at establishing objective and clear requirements for the connection of power generation units to grid. In addition, it aims to provide transparent access to the transmission networks across borders, and to guarantee coordinated and prospective planning. The NC RfG sets a shared basis for the requirements of power generating facilities connected to grid; such as synchronous generating facilities, generating facilities connected to the network non-synchronously or through power electronics interface (power park modules), and offshore generating facilities. Some of the requirements have to be defined by the relevant TSOs/DSOs.

The requirements apply to new generating units and to the already existing ones to the extent of applicability determined by the national regulatory authority or TSO. Thus, the Grid Code is prepared in such a way that depending on the requirement it leaves room for conditions and particularities for connection and access to networks to be established by the relevant TSOs with principles of transparency, proportionality and non-discrimination.

The NC RfG was finalized in March 2013 and in June 2015 it was adopted by MS in Comitology. RfG is now under scrutiny from the European Parliament and Council [115]. It became a binding regulation in Europe in April 2016 [116], that will result in supranational and binding legislative deeds that will prevail over the national ones.

The basic content of the ENTSO-E network code is summarized in this section. It is treated separately from the previously presented national Grid Codes because the ENTSO-E Grid Code defines limit values in ranges and not with a specific value, and leaves several conditions to be set by the correspondent TSOs/DSOs. In addition, the requirements are for four types of generation units/plants in five synchronous areas. All this makes it impossible to make a one-to-one comparison of the ENTSO-E Grid Code with the other considered Grid Codes developed for a specific country.

As per the ENTSO-E Grid Code, generating units are classified into four types, i.e. Type A, Type B, Type C and Type D, based upon connection point voltage and generation capacity. Types A, B and C have connection point below 110 kV, while Type D has connection point voltage above 110 kV. Generation capacity based classification is shown in Table 7.

Offshore power park modules are not governed by generation and connection point voltage criteria and shall be considered type D units. Moreover, those offshore generating plants connected to onshore connection points are considered same as onshore generation plants.

Table 7: Thresholds for different types of power plants

Synchronous area	Capacity limits from which on a power generating module is of Type: A, B, C or D			
	A	**B**	**C**	**D**
Continental Europe	0.8 kW	1 MW	50 MW	75 MW
Nordic	0.8 kW	1.5 MW	10 MW	30 MW
Great Britain	0.8 kW	1 MW	10 MW	30 MW
Ireland	0.8 kW	0.1 MW	5 MW	10 MW
Baltic	0.8 kW	0.5 MW	10 MW	15 MW

6.1 NC RfG Main Requirements classification

The NC RfG catalogues and differentiates in a very detailed manner the variety of possibilities among the generators or group of generators that may be grid connected. According to NC RfG, each installation will have to meet different requirements and they are presented incrementally in such a way that an installation must fulfil all the previous requirements (exceptions may be applicable) in addition to specific new ones (see Table 8).

Table 8: Overview of the incrementally demanding requirements for grid connection of installations in the NC RfG of ENTSO-E [116].

	Installation type	Article in NC RfG	Comprises articles	Adds requirements referring to:
General requirements (GR)	Type A power generating modules	8	-	Frequency stability
	Type B power generating modules	9	8	Frequency stability Robustness-LVRT System restoration System management
	Type C power generating modules	10	8, 9	Voltage stability Robustness Frequency stability System management System restoration
	Type D power generating modules	11	8, 9, 10	Voltage stability Robustness-LVRT System management
GR for Synchronous PGM	Type B Synchronous power generating modules	12	8, 9	Voltage stability Robustness-LVRT
	Type C Synchronous power generating modules	13	8, 9, 10, 12	Voltage stability
	Type D Synchronous power generating modules	14	8, 9, 10, 11, 12, 13	Voltage stability Robustness
GR for Power Park Modules	Type B Power Park Modules	15	8, 9	Voltage stability Robustness-LVRT
	Type C Power Park Modules	16	8, 9, 10, 15	Frequency stability Voltage stability
	Type D Power Park Modules	17	8, 9, 10, 11, 15, 16	-

For example, Type D power generating modules must satisfy all the conditions demanded to Types A, B and C plus some others specific to them.
The requirements covered under the NC RfG are divided in five categories: voltage stability, frequency stability, general system management, robustness of generating units and system restoration. In addition to this classification, the NC

RfG has a separated section to include the requirements for Offshore Power Park Modules (OPPMs). They are organized considering two separate Offshore Grid Connection System configurations: AC connection to a single onshore point and meshed AC connection. In the case of OPPMs, the NC RfG does not make distinction between Types A, B, C and D and it makes reference to previous articles (8-17) and thus, to previous requirements for each kind of requirement category.

Again, offshore wind, wave and tidal power plants have to meet the same requirements and they do not depend on the maximum capacity or connection voltage of the power plant.

7 Future trends and perspectives in the grid integration of marine energies

Projects related to offshore renewable energy mostly take place in remote areas where grid connection is not easily accessible. For this reason, the connection of those installations to the grid often requires network expansion through new electrical lines. However, this grid issue is not that critical in countries such as Spain, France, The Netherlands and Portugal where ocean energy resources off their coasts are well connected to the grid [117], and this facilitates these countries the development of offshore energy projects. Most wave energy converters are intended for installation offshore, even with the fact that 23 km from shore is the further installation of WECs from the coast [107].

Operation of these technologies depends on the availability of natural resources and this marks a high difference on how the Grid Codes have being built, since they are currently based on the installation availability and usage. Therefore, ocean and offshore wind energy sectors can share efforts in order to develop Grid Codes that include the effect of dependency on wind and marine energy.

7.1 Current research on the impact of marine farms on the grid

There is an increasing need to perform detailed grid impact studies of ocean energy farms. On the one hand, this represents required knowledge-building that is necessary to the overall progress of the wave energy sector. On the other hand, test-site owners/operators need to provide the local DSO/TSO with the detailed power system models of their wave farm and/or detailed analyses quantifying the corresponding grid impact to be interconnected to the local electricity network. Current research studies the impact of marine farms on the grid through numerical power system simulators. The aspects that are normally covered in such studies are those related to system stability under normal operating conditions as well as under fault scenarios: in particular, monitoring of voltage levels, evaluation of flicker risks and other power quality phenomena are generally assessed.

Some works evaluate the grid impact of medium-sized wave farms when interconnected to specific test sites. In particular, the impact of a wave farm of 20 MW composed of OWC (Oscillating Water Column) devices on the local power system of the AMETS test site in Ireland [103] and on the Bimep test site in Spain [111] have been analysed in [118] and a companion study focused on point absorbers has been presented in [119]. Their main focus is on how variable the power injection at the PCC is and how this impacts the local voltage profile, including flicker risk assessment. Moreover, both studies include an assessment of the advantages introduced by short-term energy storage. Similar types of devices (e.g. OWC and point absorbers) are considered in [30] to analyse the impact of an array of 20 WECs when connected to Pacific Marine Energy Center Wave Farm in Oregon [120]. Such study also includes analysis related to the harmonic pollution at the PCC.

In some cases, similar investigations analyse also the impact of the same wave farm when different grid strengths are considered [28,29]. The study in [29] compared the short-circuit ratio limit over which power quality impact can be neglected in wind and wave power parks. It turned out to be that it is smaller for wave farms than for wind farms since wave farms present lower frequency range of the voltage fluctuations.

Although some electrical studies have been specifically focused on the proper sizing of electrical components and energy storage systems for wave energy applications [31,121], few papers evaluated how the application of different wave-side control strategies [28,122] and grid-side control strategy (potentially coordinated at farm level) can affect the grid impact of a group of wave energy converters [123]. One of the main conclusions in the former article is that by means of the reactive power exchange the impact on the grid can be controlled without worsening the farms efficiency, whenever a centralized control scheme is followed.

Other recent wave-to-wire analyses [124] aim at representing with full detail and flexibility the grid impact of array of WECs including with full details also the hydrodynamic interactions of the different WECs. A recent review of wave-to-wire approaches can be found in [125].

7.2 Grid Code evolution in Europe

Integration of renewable energy has experimented a strong increase in Europe in the last two decades. This trend will continue at an even larger scale in the future in order to meet the ambitious objectives fixed by the European Commission which establish 20% share of RES in gross consumption of energy by the year 2020 [126] and a greenhouse gas emission reduction to 80-90 % below the levels of 1990 by 2050 [127]. In countries such Germany, recent Network Codes which align to ENTSO-E guidelines have been published [128] and in principle they do not contradict guidelines established by Tennet [44,45].

A report from the European Wind Energy Association [129] gathers the main topics regarding grid connection of large wind farms and similar considerations have been more recently developed for other marine energy technologies [130].

WPPs are now expected to behave almost like conventional power plants and the same requirements are expected to be extended to other marine energy farms in the near future. Although the experience with the offshore wind energy farms can serve as example for other marine energy sectors, the operation of electrical networks still poses challenges since they include more subsea components [131]. Therefore, the extension of high restrictive cases of conventional generation to all marine energy farms may lead to consequences in their operation of interconnection grids.

WPP are now required to have both local and remote *control of active power vari*ations except for power variations caused by sudden decrease in wind speed. In one of the demonstration under Twenties EU project [132], controlled shutdown of wind farms during storm passages was tested, which delays the shutdown of wind farms and therefore leaves enough time for the activation of secondary controllers. If this technology is developed further and applied to offshore wind farms, then, controlled shutdown of WPPs beyond cut-out wind speeds might be addressed in future Grid Codes. WPPs currently participate in steady state frequency control by slowly varying their active power output, but it seems that in the near future, they will also be demanded to participate in dynamic frequency control (inertia emulation, [133,134]). As per today, this requirement is included as a recommendation in the Spanish and Norwegian Grid Codes and can be extended to other marine energy installations.

Similar participation to steady state and dynamic frequency control may be required to wave and tidal energy farms of significant size. Their capability to comply will depend on the specific device design (i.e. presence of rotating masses and/or storage systems) and properly controlled power electronics interfaces.

Grid Codes now require wind farms and will require marine energies to not disconnect, and possibly support the grid voltage, during faults. *Low Voltage Ride Through* curves have evolved over the years to larger depth and longer fault duration. A number of Grid Codes currently require complete short circuit ride through at connection point. In addition, active power production and voltage support during disturbance conditions are also prescribed by Grid Codes. This will also ultimately be extended to other marine energy farms.

Marine energy farms will have large capacity in the near future. According to [135], by mid- 2020´s the most promising consolidated concepts in wave energy farms will slightly exceed 100MW, while tidal stream farms will strive for reaching from 20 MW to 30 MW. As soon as power plants become larger they will eventually be expected to actively participate in voltage and frequency control both in normal operation and in the event of faults, in order to support and not compromise grid stability [136].

8 Conclusions

The purpose of this article was to perform a comparative analysis of Grid Codes in order to highlight their relevancy to marine energy installations.

Firstly, the main conclusions related to the major issues affecting marine energy installations are drawn. Unlike offshore wind turbines, ocean energy converters are still mainly deployed at test-sites. Thus, enough time at the test stage can be ensured to verify properly that requirements are fulfilled before the offshore commissioning. Another key issue for ocean energy technologies is their dependence on suitable policy mechanisms to remove administrative and technical barriers representing an obstacle to their expansion. A potential issue with marine energy plants is their possibility to be installed offshore distant coastal sites having the network access limited. When interconnected to sites where the power generation was not initially planned, critical power quality issues and several capacity limits can be reached. A significant advantage of wave and tidal energy resources for the integration into the grid is their higher predictability than offshore wind. However, the impact of marine and especially ocean energy technologies on power quality is a concern to be analysed carefully.

Apart from the lack of specificity related to Ocean Energy Converters in Grid Codes, only few research studies have dealt with grid connection of ocean power plants. Marine energy plants may cause different grid impacts, that can be divided into three principal categories, namely: limited dispatchability, high penetration effects and electrical grid stress. These effects gain importance depending on the size of the deployment, although large projects are currently only realistic for offshore wind plants. An important effect of offshore marine energy installations is related to the influence of reactive power exchange due to the limitation of the capability of offshore power stations to provide precise voltage or reactive power control in case of long submarine cables. This often calls for special compensation measures at the PCC. Another concern related to frequency control under uncontrolled variations of power delivered by marine farms is the increase in the power system of the short-term reserve capabilities to provide more flexibility from existing conventional power plants. Nevertheless, these integration studies for ocean energy technologies are mainly focused on the grid connection of relatively small ocean power plants to distribution networks.

As a second contribution, the most important requirements of marine energy generation plants are hereafter summarized. The requisites for the grid connection of marine energy installations are normally affected by local regulations that are often established at national or regional level, due to the widespread geographical availability of marine energy resources. Therefore, aspects such as power quality are requiring *ad hoc* regulation by national and international bodies. Moreover, the 114 Technical Committee (TC 114) from IEC also works for developing a technical specification for electrical power quality requirements of marine energy installations. IEC is also preparing a document for the standardization of wind energy generation systems. Furthermore, in the ocean energy sector, there are test sites, such as the EMEC, that have their own guidelines for grid connection of marine energy converters. As soon as ocean energy farms, become as large as existing wind farms, they will have to actively contribute to voltage support and frequency control under normal operation and fault conditions by controlling reactive and active power generation, respectively. Besides, WPP currently participate in steady-state frequency control, but in the near future they will contribute to dynamic frequency control and this requirement could be extended to marine energy technologies. They also should have LVRT capabilities as an extension of the requirements of wind energy systems, where the evolution of LVRT curves is towards encompassing larger depth and longer fault duration. Several Grid Codes also require complete short circuit ride-through at PCC. Furthermore, power quality issues are one of the listed phenomena of special importance in marine energy field. To compensate the large instantaneous power output of each independent WEC, energy storage solutions at different stages of the conversion mechanism or a power smoothing technique for wave farms may need to be implemented.

Several findings can be extracted from the previous analysis about the extent to which the analysed Grid Codes include marine energy technologies. Grid Codes from Italy, Norway, Denmark, Germany, Ireland, UK, Spain and Finland, have been systematically compared. In previous sections, common aspects and main differences have been described in comparative tables. Only two of the analysed Grid Codes (TenneT and National Grid) have already specific requirements for offshore generation units. TenneT refers only to offshore wind farm connections while National Grid Code considers “offshore power generating units powered by intermittent sources”, which includes wind, wave, solar and any other relevant source with single PCC to the offshore transmission system. Apart from this, ENTSO-E presents a specific section in its NC RfG network code, which is focused on requirements for OPPMs. Grid codes have traditionally been built based on operation and installation availability of conventional plants, but being the operation of marine energy technologies dependent on intermittent resources, ocean and offshore energy sectors can share efforts to take into account this dependency on the marine resources in Grid Codes. Offshore wind energy technologies are more mature than ocean energy technologies and this explains why requirements are primarily specified for offshore wind and possibly extended to other marine technologies. However, Grid Codes need to evolve to include the emerging reality of ocean energy industries. National and international groups are currently working on the adaptation of Grid Codes to marine energies where special conditions are under study. Different recommendations have also been introduced to support the harmonisation of national Grid Codes into one European Grid Code. One of the benefits of having one harmonised Grid Code is a better approach to tackle cross-border issues in a systematic manner. Another benefit of a harmonised grid code is the inclusion of specific requirements to deal with issues in marine energy although the extension of high restrictive cases of conventional generation to all marine energy farms may affect the operation of interconnection grids, since they have more subsea components.

The last contribution of this article is to describe the future trends and perspectives on the grid integration of marine energies. We highlighted the presence of barriers such as the scarce grid availability in proximity of proposed ocean energy projects and the maintenance need of offshore devices that complicates the implementation and increases the cost of marine projects. We also underlined the available policy mechanisms to fulfil the demanding requirements established by the European Commission. This will promote the increase of marine projects sustained by reachable KPIs. To include marine energies in Grid Codes it is still necessary to properly model their impact on the local electric grid. For this purpose, ocean test-site operators are required to provide local TSOs/DSOs with detailed power system models so that the system operator can perform analyses of their grid impact before allowing the farm grid connection.

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