Grid Code Reinforcements for Deeper Renewable Generation in Insular Energy Systems

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Abstract

Introduction of renewable energy sources (RES) in insular areas is growing on different islands of various regions in the world and the large-scale deployment of renewables in island power systems is appealing to local attention of grid operators as a method to decrease fossil fuel consumption. Planning a grid based on renewable power plants (RPP) presents serious challenges to the normal operation of a power system, precisely on voltage and frequency stability. Despite of its inherent problems, there is a consensus that in near future the RES could supply most of local needs without depending exclusively on fossil fuels. In previous grid code compliance, wind turbines did not required services to support grid operation. Thus, in order to shift to large-scale integration of renewables, the insular grid code ought to incorporate a new set of requirements with the intention of regulating the inclusion of these services. Hence, this paper discusses grid code requirements for large-scale integration of renewables in an island context, as a new contribution to earlier studies. The current trends on grid code formulation, towards an improved integration of distributed renewable resources in island power systems, are addressed. The paper also discusses advanced grid code requirement concepts such as virtual wind inertia and synthetic inertia for improving regulation capability of wind farms and the application of energy storage systems (EES) for enhancing renewable generation integration. Finally, a comparative analysis of insular grid code compliance to these requirements is presented in the European context.

Keywords: Grid codes; renewables penetration; insular energy systems; smart grid; energy storage.

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1. Introduction

When compared with the progression of renewables on mainland grids insular power systems seem perfect candidates for this energy mix revolution. A preliminary assessment points to large share of RES capacity is possible to integrate due to their higher RES potential [1] [2]. However from a conventional viewpoint, insular power grids must keep their balance through resource management and demand prediction for a given time horizon. When elements that their behaviour is not easy to predict are introduced to the power system, keeping the balance of the system becomes a more complex task since the energy balance between the injected and consumed energy should be stable.

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RES belong to this type of category providing irregular power due to meteorological and atmospheric conditions. The issue of fluctuations in generated power, caused by variability in wind speed and solar intensity, becomes more pronounced as the penetration of these renewables into the electricity grid increases [3]. Therefore, their stochastic nature will become visible on the power quality of the grid, namely generating transient and dynamic stability issues within the system. Power quality concerns generally associated with RES include voltage transients, frequency deviation, and harmonics. Therefore maintaining the reliability, stability and efficiency of an electrical system becomes a complex issue for insular grids with highly variable energy resources [4].

Despite the aforementioned concerns, a significant presence of RES based installed capacity has already taken place in insular energy grids since these regions are preferable due to high availability of RES [5]. However, moving further towards an increasing share of RES in the generation mix of insular power systems presents a big challenge in the efficient management of the insular distribution network and a serious threat to its normal operation [6].The implications for non-dispatchable energy resources integration in insular systems can be mitigated through several operational techniques and grid infrastructure enhancement measures such as expanding and planning the island power grid in order to minimise technical constraints brought about the effects of variation in renewable energy generation, by balancing fluctuations with flexible forms of generation (e.g. gas turbines) or as last resort imposing curtailment actions on extreme wind and solar power generation peaks when variable renewable production surpasses significantly the electricity demand. While the first option promotes the grid stability, the other two impose significant financial risk on generation developers [4].

Successful exploitation on mainland grids has proved that it is possible to expand the penetration with reduced wind power curtailment levels under the introduction of new regulations for grid code compliance [7]. A grid code has a particular role in this integration paradigm. Grid codes are basically a set of technical conditions and requirements to be followed when connecting generators to the grid. By complying with these rules the power plant ensures system stability when connected to the grid.

In this context, renewable energy participation on the continental European power grid system, especially with the wind generation, has already considerable penetration which has forced advances on this technology and broader changes on the rules, for its integration through grid codes for the last decade [8]. On a global scale, the most demanding grid code requirements are in the continental Europe, especially for higher penetration levels of renewables, hence, it is considered extremely challenging to respect grid codes during the normal and faulty grid operation by the local grid operators [9] [10] [11].

In [12] an in depth analysis on islanded European network situations like UK and Ireland is made, where they have no access to the large interconnected continental network. The study results show that, the grid code requirements are even stricter than the requirements for the continental Europe; driven by the rising level of penetration of wind generation.

In [13] a review of recent grid codes issued in different years for different countries is examined – codes which underline that the wind power plants (WPP) should participate in frequency and voltage control under normal conditions. Meanwhile, during failure – additional requirements and supply of reactive power are considered. In addition, considering the incessant growth of penetration level of wind energy, the requirement of grid codes should be revised and enhanced continuously [13].

In [14] has been presented and informative clarification related with the usual confusion between fault tolerance and grid codes. It has been stated that "in large interconnected power grids, it is incumbent on each generating plant to do its fair share in maintaining the security and reliability of the grid. The ability of a power plant to continue operation after a grid disturbance is governed by: 1) the ability of its generator to recover voltage and remain in synchronism with the power grid after the disturbance (i.e., transient stability) and 2) the ability of its turbine generator and auxiliary systems to remain in operation during and after the disturbance.

A lesson learned from these experiences in islands situation, like Ireland and UK indicates that there are basically two main reasons to put in place stricter grid code requirements in Island systems: the first is the absence of robust grid interconnection comparable to the continental Europe and the second is the need for higher level of wind penetration [12].

In smaller scale insular systems grid code evolution is even more necessary. Typically the power network has limited robustness, poor interconnections and limited short-circuit ratio (SCR). Consequently, these systems are innately prone to frequency and voltage stability problems which can be aggravated with the integration of large share of RPPs [15]. Conversely, small islanded systems are entirely dependent on imported fossil fuels to meet its energy demand. Local grid operators are now aware that there is a significant potential for exploring natural renewable energy resources, which could reduce external dependency on imported fossil fuel [5].

As an example in [16] is presented a review of a small insular grid, namely, the French Reunion Island, located in an ultra-peripheral region of Europe. It was described that this island is deeply dependent (over than 85%) on imported fossil fuels for electricity production and is estimated that in 2030 Reunion Island will have over than 1 million of inhabitants. Like other islanded systems, the development of different solutions to mitigate the fuel dependency, namely, the implementation of renewable energies such as wind, photovoltaic, ocean energy, among others, are a priority to achieve energetic independence, namely by governmental incentives and highest private investments. Furthermore, the proposed work presented the major achievements of policies and the future goals in the construction of innovates renewable energy programs with perspective of a net zero energy island versus the pressure of the population size, including the barriers related with the integration of renewable energy in a small-scale grid.

This paper discusses grid code requirements for large-scale integration of renewables in an island context, as a new contribution to earlier studies. These requirements are, either related to the continuous operation of the RES, called static requirements (voltage, power factor, frequency, active power etc.) or regarding the operation of wind turbines during fault sequences and disturbances in the grid; the so called dynamic requirements (fault ride through and fault recovery capability).

In section II an overview about insular grids current situation is presented, in section III these requirements are thoroughly discussed for the continuous operation and under grid faults. The concept of inertia emulation is included in this analysis. Next, in Section IV, insular Smart Grid concept is introduced. In this regard, attention is given to the communication infrastructure issue for guarantying effective coordination of distributed generation (DG). Then, in Section V, the role of the EES is covered as an advanced requirement for deeper renewable generation. Finally, some island grid codes in European context are studied and compared in Section VI, in order to verify their accordance to these requirements. Finally the conclusions are presented in Section VII.

2. Current Status for Insular Energy Systems

In contrast to large interconnected power networks, generation in smaller island systems comprises small thermal power units based on diesel generators [6]. In addition, exploitation of endogenous resources derived from geothermic and hydro sources is also common when available. The typical small size of generators is preferable to large units because loads are normally small and predictable in islands. On the other hand, smaller generator selection has also to do with transportation and installation cost since they are imported. Another aspect that justifies this option refers to demand evolution at a slow pace. Therefore, extra power capacity to be added can be fulfilled with low size power stations [17].

Large frequency ranges are expected in isolated systems with weak interconnection, to accommodate a variety of distributed energy sources, where the system stability is more vulnerable to disturbances compared to large interconnected systems.

Essentially there are two types of units: one class of generators that runs at constant output – also known as base load units and another group of generators that has the function of adapting its output according to the needs of the load.

Solar and wind generators do not fit in any of the above two groups since they are not flexible load following units. Generators like load following units are planned to work with variable output. Besides, this type of flexible generation has to retain a significant amount of active power reserve for frequency regulation. In an island energy system this reserve is far more critical since conventional plants have a smaller size when compared to mainland power installations. As a consequence, the available rotational kinetic energy is usually low [18]. In order to reduce flexible load following units by renewable generating units implies that there will likely be less kinetic energy exchange to support grid power balance, causing a degradation of frequency regulation capability, which may in turn imply higher and faster frequency deviations [19].

With an increased penetration of renewable generation the capability of conventional generators to reduce the output turns into a challenging issue, specifically when base loads output cannot be lowered. Even forcing down a load following unit output, the unit should respect a minimum load ratio, if not respected it may compromise its long-term reliability [20]. For example, coal power plants have to be operated in the range of 50-100% of full capacity while generators based on diesel have a minimum limit of 30%. Therefore, the conventional generation minimum level and concerns related to grid stability creates a practical restriction when it comes to planning more renewables integration. Even in low penetration scenarios it is not unusual to witness power curtailment actions made by the system operator so it could tackle renewable power excess in the grid, or in extreme situations to shut down the wind farm in case of grid disturbance. The curtailment amount is dependent on the installed capacity, the location, the wind forecasting reliability and the scale of revenue losses, which cannot be outlined precisely.

Yet, the revenue lost caused by curtailment or disconnection may be higher than the cost of maintaining the conventional generation. To accelerate the renewable integration, solar and wind farms must replicate conventional power plants during and after network faults [21].

Island regulations have to be updated to impose this strict operation profile, thus becoming effective. Grid code requirements have been studied for renewables integration in mainland systems for quite some time [7] [12] [18] [22] [23] [24] [25] [26] [27] [28] [29]. Yet, research concerning island grid codes requirements is still very scarce, so this paper provides a major contribution to this issue.

For all intents and purposes, the grid operator is not allowed by the present insular regulations to control distributed energy resources (DER). For the effective DER integration the coordination between transmission system operator (TSO) and distribution system operator (DSO) is unsatisfactory. The absence of adequate regulation for DER systems connection is also a reality. Furthermore, DER does not benefit from any economic incentive for taking part in the network operation. Previous discussions indicate that in insular context, further updates of grid code require the following elements to consider [13], [10], [12].

1- A robust control, with the shortest possible time response that will guarantee reconnection and continuation of power generation of wind farms.
2- Wind farms and individual turbines with an integrated ancillary service to control voltage and frequency to enable the operation in insular mode.
3- Establishment of fast fault tracking and continuous monitoring system to satisfy the grid code requirements.
4- Establishment of intelligent protection system to selectively separate critical wind turbines during disturbances to ensure the minimum loss of wind power and fast recovery of a wind farm.

3. Grid code requirements

A grid code serves the mission of defining the physical connection point requirements to be followed by energy production equipment in order to be connected to the grid. In addition, a regulatory framework defines the requirements for permanent connection and the relevant network parameters to be supported, in a way to secure system operation. A grid code has a particular role in this integration paradigm. By complying with these rules all RPPs may contribute to the system stability.

3.1 Static Requirements

Perfect balance between generation and demand is hard to achieve since consumption-side is inherently variable, on the one hand, and conventional power generation structures require time to change their output, on the other hand. Thus, a residual balance mismatch is fairly normal, which may result in over-frequency as well as under-frequency. With intermittent generation at larger-scale, the balancing game becomes more complex and less predictable. A proactive attitude is required regarding renewable based DER system to cope with these issues through a well-defined specifications-based behaviour.

3.1.1 Voltage and frequency

The voltage variation sensed at PCC is related to the short circuit impedance and the real/reactive power output of the RPP. Therefore keeping the voltage stable within an acceptable range of values under different operating conditions may be challenging for the permanent operation of RPPs. In this way, the weaker the insular electric power grid more troublesome becomes the introduction of additional renewable generation. Moreover, the different nature of each isolated system either in terms of size or grid strength translates into different requirements on the part of each insular grid system operator.

In turn, grid frequency operating limits are dictated by the power connections strength, extension and size of power reserve services and grid inertia which may vary significantly from island to island.

Fig. 1 shows, as example, the operating area for simultaneous values of voltage and frequency with regards to French islands grid code [30].

"See Fig. 1 at the end of the manuscript".

3.1.2 Active power control

The active power control is a set of power control strategies that enables freedom and flexibility to the system operator in order to able to manage the power output – injected into grid by RPPs. Solar Power Plants (SPP) and WPPs must comply with this requirement by incorporating within active power control capabilities, as well as by allowing to be remotely controlled. As the renewable generation grows active power regulation requirements will become essential.

a) Maximum power limitation

This parameter is intended to set the renewable generation maximum power output below its power rating. Thus, by restricting the power injection maximum amount, the system operator is allowed to prevent additional instabilities of active power balance caused by the unpredictable nature of wind and solar resources.

b) Operating range

RES cannot deliver dispatchable power on demand and as so, the goal is to replicate traditional power sources that are entirely controllable. Thus, renewable generating units need to be prepared to artificially curtail the power production in order to maintain power balance and also, if necessary, to contribute to the stabilisation of grid frequency. Both requirements have different implementation purposes. The first one allows the TSO to introduce output power dispatch flexibility on SPPs and on WPPs. The second simply extends the primary control function to the renewable plants. Therefore, RPPs have to be equipped and prepared to modulate their active power production between the minimum and maximum of its rated capacity.

c) Ramp rate limitation

A very effective way to minimise the impact of a sudden rise of renewable generation is to limit the power gradient of renewable power through a set-point. Ramp rate is defined as the power changes from minute to minute (MW/min). The general idea is to filter faster variations of wind power output trough the imposition of a ramp rate according to changes observed on power demand. If not implemented, there is a genuine risk of installed conventional generation not decreasing their power output as fast as necessary and in extreme cases leading to severe grid frequency issues.

d) Delta control

Delta control is a method of securing spinning reserve based on renewable power generation. Power output is artificially pulled down until below the available power at the moment of generation. The difference is kept as reserve to be used imitating a conventional generation (primary and secondary control). However, the curtailed power depends on the available solar or wind power. Thus, the level of reserve is not constant. The curtailed power can be released for frequency regulation and to support grid voltage through the injection of reactive power to grid.

3.1.3 Power-frequency response

In cases when an energy unbalance occurs in the power system the frequency deviates from its nominal value. A large deviation of frequency is expected to occur as the unbalance grows, thus, threatening normal power network operation. With the intention of confining deviation extension to safe levels, frequency surveillance and corrective actions are performed by conventional generators along with grid operator supervision – known as primary control and, if necessary, authorizing spinning reserve release –

known as secondary control. If the issue for large-scale integration of renewables is to be taken seriously in insular territories, this type of ancillary service needs to be standardised and mandatory for renewable power generating units. Yet, for the particular case of European islands, frequency regulation capability compliance is not specified by local grid codes. Wind farms that are able to restore generation/demand balance are required in some European countries already [31] [32] [33] [34] [35]. Usually, a mainland TSO imposes frequency regulation strategy through a power frequency curve specification only when addressing WPPs operation.

However, no compliance is directly required for SPPs on these regulations. Since insular grid codes in European space didn't yet evolved to require this behaviour, proper analyses have to be carried out by observing the most advanced specifications at non-insular territories. Fig. 2 depicts the power-frequency response curves required in Ireland, Germany and Denmark [31] [33] [36]. It can be observed that frequency support behaviour differs from country to country as each respective regulation establishes a frequency range for primary control intervention. It can also be seen that the range for frequency correction is higher in Irish and Danish grids - regulations which set a dead band range where active power production remains independent from frequency variation. Outside from this band both codes show different interpretations on how a wind farm should react to frequency deviations. Looking at the German regulation, a RPP must curtail active power starting at 50.2 Hz with a gradient of 40% of available generation at the moment per Hertz. Concerning the Irish code, when over-frequency excursions occurs a RPP responds according to a power curtailment gradient set by the grid operator. Subsequently, if necessary, curtailment rate is updated to the grid operator requirements. Regarding frequency events and when compared to Danish and Irish requirements the wind farms response in German networks is limited since the regulations enunciate that energy production can be artificially kept at low levels in order to provide secondary control at lower frequencies. In addition, Danish directions also allow the grid operator to smooth wind power output of each WPP by adapting specific power frequency response to the needs. As so, three curtailment gradients that replicate a droop controller action can be configured over the Danish curve. In Fig. 2, droop regulation areas are labelled as d1, d2 and d3. Analogous flexibility is provided by Irish regulation through specific points.

3.1.3 Reactive power control

Normally, synchronous generators had the particular task of ensuring bulk system voltage regulation at transmission level. As for the distribution network, voltage regulation still remains controlled by the distribution substation. Since their implementation, wind farms were only built to generate active power. Thus, they were operated to maintain the power factor at 1.

However, this trend has changed in the last decade. The majority of mainland European grids have introduced new regulatory conditions by extending reactive power capability along with active power generation to solar and wind power [23]. Likewise, the growing propagation of renewables-based DER systems in insular grids, and as a result of strong technical constraints, will force the incorporation of this ancillary service for security reasons.

"See Fig. 2 at the end of the manuscript".

WPPs are usually deployed in remote areas, often being connected at weak points in the insular network. Consequently, grid vulnerability to voltage drop as a result of energy transit at point of common coupling (PCC) is high. Besides, in order to secure grid voltage stability within acceptable limits, variable renewable production introduces more complexity.

While an isolated power network is different from island to island, reactive power needs must be addressed in order to meet local interconnection issues. This requirement is separated in three different ways: by power factor control, by assuming a Q set-point or by managing power reactive flow as a function of grid voltage. For insular cases, for now, it is relied essentially on power factor band specification that must be provided by the wind farm under normal operation. Once more, instructions concerning SPPs are completely absent in the regulations under analysis. The common range comprises values from 0.95 lag to lead at full active power, having voltage range within 90% to 110% of nominal value. Other ranges may be found, such as 0.86 inductive to the power factor of 1.

Since the alternative ways to express reactive power support are not imposed by insular grid operators, it is indispensable to conduct the analysis relying on mature standards, such as the ones occurring in continental Europe. One of the strategies adopted in Danish code is the Q set-point related to active power generation. It separates the support level according to the wind farm global rating power. Fig. 3 shows that at power levels above 20% of the rated power the wind farm of whose rating exceeds 25MW has to provide an additional 33% of reactive power, as maximum, to the instantaneously available active power output, while smaller wind power facilities have to provide an additional 23% of reactive power.

The condition for reactive range requirement must cover Q capability over the full output range through the specification of Q-P diagrams.

Modern wind generators of doubly fed induction generator (DFIG) type and permanent magnet synchronous generator (PMSG) type are capable of injecting or receiving reactive power while at same time active power output is generated. Likewise, this capability is also available in solar plants as they share the same power electronics technology as power interface to grid. Moreover, the increased performance doesn't require additional costs from insular implementation point of view. The capability is now available from most manufactures [37] [38].

However, it should be pointed out that during periods of reduced wind or solar production the reactive power capability is lower.

"See Fig. 3 at the end of the manuscript".

Thus, when the active power output is low and does not exceeds a certain threshold, a less strict reactive power range could be imposed to SPPs or WPPs under the grid code requirement.

The third and final method of reactive power compensation is shown in Fig. 6 by using as example the framework directives of the German regulator. The reactive power compensation range targets various voltage levels in the power system, from transmission to distribution networks. Renewable generating units have to meet the reactive power capability contained by the area specified by the TSO, which is free to choose between three variants on the basis of relevant network requirements. Additionally, whenever it is required, the grid operator may alternate between the Q-V variants over time.

When compared to the other reactive power compensation methods reactive power compensation acting directly on grid voltage deviation displays some qualities. The strongest factor relies on terminal voltage limitations that may influence the reactive power generation of variable generators, including RES [39]. The criterion for reactive range requirement has to cover Q capability on top of full output range through a specification of Q-P diagrams.

Whereas grid voltage level has a direct impact on RES ability to deliver reactive power, the Q-V diagram might also be required as grid code specification in order to minimise its effect [40].

3.1.4 Inertia emulation and fast primary reserve

When there is a sudden failure in generation or a new set of loads are connected grid frequency starts to droop at a rate dictated by inertia sum of all generators. In other words the fall in grid frequency is decelerated as function of the inertia available in the network. Therefore a slow decay rate enables the activation of the power reserve services to help in restoring system frequency [41].

Small insular systems are characterised by having lower grid inertia comparable to mainland situation [4]. But with further introduction of electronically controlled and/or connected power plants inertia availability is expected to decline further. Modern wind and solar power generation belongs to this category. Wind technology comprises typically two types of wind generators: DFIG and PMSG. Both have inherent capability to provide inertia to the system. However when the wind turbine is operated with variable speed contribution toward system inertia is null. This occurs because the generator is connected to the grid via inverter decoupling the rotor speed from changes in the grid frequency. Therefore, an inverter-coupled generating device does not provide frequency stabilisation based on wind turbine inertia as found on constant speed synchronous generators operated power production plants. From an small insular energy system view point the reduction of conventional petroleum-fuelled combustion power plants in favour of wind power production brings with it considerable risks for the grid frequency stability. That is, increasing wind power presence in a power system with the overall reduced grid inertia has the effect of soaring frequency oscillations.

It is established that a power system, independently of the system size, needs some amount of inertia, but it is complex to determine just how far away it is situated today from a critical threshold. This subject has already been addressed in recent years, particularly in island power system such as Ireland and UK. The discussion in the UK about grid code review on that matter came to the conclusion that for the time being, a clearer definition of the requirements and a quicker primary response is enough [26].

Knowing that large scale integration is creating operating difficulties continental grid operators are studying emulated inertia response as mandatory for wind turbines operation. Synthetic inertia expresses the capability of a variable-speed wind turbine to provide emulated inertia through additional control loops [42]. This is achieved using the kinetic energy stored in rotating masses of a variable-speed wind turbine [43]. An alternative method for generating emulated inertia is raising wind turbine torque that allows a reduction in the system load generation imbalance. Despite wind turbine technologies having different inertial response performances [44] [45] a recent study has shown that “virtual” wind inertia can exceed the inertial power response of a synchronous generator with the same amount of inertia [46]. This is a new trend for the solution approaches through simulated control schemes – detecting grid frequency and command according to active power feed-in similar to the behaviour of synchronous generators. This control scheme, also considers a recovering strategy for the wind park to lead the turbines back to their initial operating point, however, the details has not been clearly defined as yet [12]. In the near future, according to the European Network of Transmission System Operators for Electricity (ENTSO-E) WPPs may be required to provide a synthetic inertia. In effect, ENTSO-E draft code concerning requirements for grid connection is proposing the inclusion of this requirement as an additional capability to supply additional active power to the network by its inertia [47].

To cope with this future requirement some wind turbine manufacturers have already introduced this capability, as optional feature, in their most recent family of wind turbines [48].

With regards to insular scenarios specific requirement have to be introduced in such a way that wind turbines can respond to frequency variations in a manner that is beneficial to the system [26] [49]. However the technical constraints of each islanded network have to be taken into account and properly evaluated to identify required capabilities need to be translated into specific requirements. For this purpose, physical terms need to be defined, which have not been required to define at all so far. Clearly speaking, the amount of energy employed during an inertial occurrence has to be determined. Furthermore the allowed impact on the post-event generation needs to be assessed. In any case, when the response to a frequency incident is acquired closely to the speed of physical inertia, the response would have to be given in ms. Each island power system operator could then set in its grid code the balance between precision and response speed according to its very specific physical needs [26].

Below in Fig. 4 is shown as example the frequency response requirement on a large islanded system. The frequency curve refers to British power network.

"See Fig. 4 at the end of the manuscript".

Primary reserve is triggered with a response delay of approximately 2 s after the generation loss event and completely released in 10 s. Secondary frequency response follows primary response timescale. This reserve must be maintained up to 30 min. To quantify the future frequency response requirement with high, average, and low wind penetration in relation to this grid, recent studies provided by [50] suggest that a fast frequency response scheme should be adopted in detriment of synthetic inertia services in order to minimise the risk of additional power reductions with wind turbines in the recovery period. To be effective the primary control must be enabled in less than 1 s of a -0.5Hz change in frequency and released to the grid in the next 5 s, allowing frequency response to be reduced significantly [51].

Next in Fig. 5 is presented the frequency response requirement applied to French isolated grids. The insular grid code [32] requires the activation of frequency control immediately after the occurrence. As opposed found on a large islanded system secondary control is inexistent. As can be seen frequency regulation is executed by the primary control reserve which is enabled within a time frame of 10 s. Primary reserve contribution must last up to 15 min. The current frequency requirement presented is only mandatory in respect of conventional generators (frequency trace following an in-feed loss at dark green trace). On the other hand, French islands have been receiving an increasing wind and solar power penetration. Therefore their impact on frequency control is becoming a real concern and a maximum penetration limit of renewables production is in place [52]. That is to say, system security is ensured by disconnecting temporarily the RPPs whenever the penetration is higher than 30%. To face this limitation advanced studies are being carried related to the French Islands. In [52] is proposed a fast-acting storage scheme working as a backup conventional generation assets, providing immediate energy during primary reserve system start-up.

"See Fig. 5 at the end of the manuscript".

3.2 Dynamic grid support

The impact of the wind power generation has become a serious concern in a scenario of large penetration of renewable generation. It is well known that synchronous generators based conventional power plants can handle symmetrical and asymmetrical faults without being disconnected and at the same time injecting short-circuit currents during voltage dip. This characteristic property of the synchronous generators is crucial in a power system by raising the voltage around location of the fault [53]. However when WPP started to be deployed the issue of withstanding grid faults was not critical. Therefore RPPs generating units were disconnected during grid faults. However with increasing installations of WPP and SPPs this measure has become counterproductive [26]. Normally when a grid fault occurs the fault impact can be sensed in a wide are surrounding the fault epicentre. Consequently several RE units are automatically tripped. In turn, disconnection in series of RPPs translates into considerable loss of electricity generation and wind farms shutdown not planned may slow power system recovering since there is less generation to support it. For example, in an islanded scenario a mix of energy sources comprises a considerable RE generation based power capacity and a large wind power generation fall down due to a trip, it may have a major impact on grid frequency stability. In other words the overall result can be a severe drop in grid frequency. Additionally, with the conventional power reserves reduced to a minimum due to the progressive decommission of diesel power plants there is an aggravated risk of grid blackouts. In sum, a fault localised in a single place can induce a significant grid frequency deviation. In addition, another aspect to be taken into account refers to higher fault severity in insular energy systems arising from high impedance grid connection at the point of common coupling (PCC).

For reasons of security since the insular power system will become more sensitive to grid faults the voltage sag tolerance must be included within the limits of RPPs operation.

"See Fig. 6 at the end of the manuscript".

3.2.1 Fault Ride Through Capability

To withstand a transient voltage dip without been disconnected the RPP must have the capability to ride through system fault, and at the same time to support voltage during the deviation. The ability to stay connected with under voltage events for a specified time frame without tripping as known as fault ride through (FRT) capability. To satisfy this requirement the WPP is designed to ride through all kinds of grid faults, including faults with very low remaining voltage levels and unsymmetrical (1-phase and 2-phase) faults. FRT requirement is presented in the form of a voltage vs time curve.

A FRT diagram normally describes three regions of response related to voltage deviation level and event exposition time. The region concerning a voltage drop between the 90% and 100% at PCC is acceptable since the probability to impair the generator is low. Below the 90% a FRT diagram defines a maximum voltage drop that a RPP must be exposed as function of time, independently of the grid fault severity level and the number of faulty phases involved on the grid voltage anomaly. In this region the exposure time to grid fault is determined by voltage deviation level. For higher voltage dip values the connection time is pretty reduce while for less severe voltage sags the RPP remains connected for longer. For voltage-time value pairs below the FRT line, the generator may be instructed to show more than one behaviour before being tripped.

Presently there are not many examples where the existence of grid codes for mainland areas and islanded territories allow the evaluation of the differences between them. Therefore for comparison purposes two mainland grid codes were chosen to highlight FRT curve state of art.

Fig. 7 presents FRT requirement related to Danish and German regulations. The Danish specification aims directly wind turbine operation while the German regulatory framework does not address any particular renewable generation technology.

"See Fig. 7 at the end of the manuscript".

According to Fig. 7 the grid codes of these countries have different interpretation for a FRT implementation. In comparatively terms German grid code reveals to be most challenging for WPP operation.

In the German case the RE unit must withstand a full short-circuit at PCC for a time frame of 150ms. Surpassing this time the renewable generator is tripped by the under voltage protection relay. Moreover, it is necessary to point out that this code allows upon agreement (below blue area) to extend their grid support for longer periods of time.

On the other hand, in the Danish case the voltage drop severity level for sustaining the connection within this time-frame is lower compared to German requirement. However, as can be seen, the exposure time is higher and reaching 500 ms.

In relation to insular European codes low FRT compliance is present in large insular systems. Canary archipelago (Spain) and Crete Island (Greece) are two examples where due to significant RE integration this requirement is mandatory. Fig. 8 presents FRT requirement concerning Canary Islands, Crete, French Islands and Cyprus [32] [35] [54] [55] [56]. It can be seen that FRT requirements vary from insular region to islanded system. When compared to non-insular codes the insular FRT versions have a similar shape. On evaluating the three insular regulations is clear that the Canary Islands code requires the most exigent specification. That is, an instantaneous voltage drops down to zero for time duration of 150ms. This can be explained with the local government strategic plans to accelerate the introduction of RE sources along with the weakness of its electrical grids.

With an increasing interest by local insular system operators to shift the paradigm of the present power mix the issues of grid stability that arise from RE power sources must be first mitigated, by preparing them to be resilient to faults for a certain amount of time. Advanced control strategies are available on the literature for achieving the FRT compliance. These approaches are aimed at improving the FRT performance on doubly fed induction generator (DFIG) and synchronous generator (SG) based wind turbines.

In [57] an adaptive strategy to obtain technically justified FRT specifications is unveiled and discussed considering progressive penetration of wind power level and key characteristics of the system.

A parallel capacitor dc-link scheme enhancing FRT capability of DFIG designed for power evacuation is proposed in [58]. The configuration studied is evaluated in terms of asymmetrical grid faults and three phases to ground fault in order to remain connect to grid even at full voltage dip.

In [59] a low-voltage ride-through (LVRT) strategy for a doubly fed induction generator (DFIG) with a switch-type fault current limiter (STFCL) is presented and compared with a crowbar circuit based classic solution. A fault-tolerant distributed control system has been proposed in [60] for a wind turbine grid during normal operation and grid fault ride through.

In [61] a novel protective scheme to protect small-scale synchronous generators against transient instability is researched. In [62] a hybrid control scheme for ESS and braking choppers for fault ride-through capability and a suppression of the output power fluctuation is proposed for permanent-magnet synchronous generator (PMSG) wind turbine systems.

In [63] FRT capability enhancement for self-excited induction generator-based wind parks by installing fault current limiters is explored while in [64] is proposed a static synchronous compensator sizing for enhancement of FRT capability and voltage stabilisation of fixed speed wind farms.

In [65] a single stage single phase solar inverter with improved fault ride through capability is proposed. A FRT for solar inverters is researched in [66].

As for existing PV inverters a shunt-connected power electronics scheme that adds FRT functionality is proposed in [67]. When the voltage disturbance is detected the PV installation is isolated from the grid fault through the device providing reactive power to help grid voltage restoration.

"See Fig. 8 at the end of the manuscript".

3.2.2 Reactive power response

Restore grid voltage level to normal levels is only possible if power system generators contribute in that aim. By norm this function is carry out by fossil-fuel power plant. However, in order to reduce the contribution from these sources this role as to be assumed by the non-dispatchable power sources.

For this reason, a reactive current injection service has to be provided by RPP as long as fault recovering is underway, followed by a progressive re-introduction of active power after the fault clearance. This requirement is fundamental for accelerating power system restoration.

And when it comes to an insular power system, the small scale factor and typical weak grid connection means that abnormal operating condition is immediately sensed in the network. To complicate this scenario islanded systems have normally low short circuit power promoting even more the issue of instability. For example, a simple defect can originate a significant variation of the voltage value by the combination of these factors.

As the under-voltage event loses strength via reactive energy support, it is necessary at the end of the recovering process to change the RE unit output. That is to say, to secure the power balance within the grid the renewable generator must inject active power into grid, helping this way to keep the frequency within acceptable range.

In general, from the insular grid codes point of view (European insular regions) the adoption of this requirement is still to be done. At least one implementation is already mandatory. This is the case of Canary Islands (Spain). Fig. 9 shows the performance profile in effect along with two non-insular equivalent specifications.

As shown in figure the insular Spanish grid code requires the wind turbine to supply reactive power as long as the voltage recover is underway. In case of voltage sag above 50% of the reactive current generated corresponds to 90% of the global current value.

The analysis also reveals that consumption of reactive power is not permitted without a complete recovery of the voltage. These operational constraints help to minimise instability issues on the voltage line.

On the other hand, when compared with the non-insular codes in the same figure it is clear that the German grid code is the most demanding concerning reactive power injection. For this regulation the wind turbine must provide only pure reactive current if necessary. But to satisfy such demanding capability it requires also active power as part of the power output. In other words, to provide reactive capability at rated power the power converter is forced to be sized according to the active and reactive current maximum parameters. It should also be noticed, the German system operator has also at its disposal flexibility on defining the level of reactive current to be generated by the RPPs. Finally, the

German regulation also allows choosing between two maximum reactive current settings bearing in mind the number of phase faults.

"See Fig. 9 at the end of the manuscript".

In [68] has been proposed a reactive power injection strategy for a photovoltaic system, considering different grid codes: 1) constant average active power control; 2) constant active current control; 3) constant peak current control; and 4) thermal optimised control strategy. Furthermore, the proposed reactive power injection model was tested by simulations and with real case study, namely on a 1-kW singe-phase grid-connected system in low-voltage ride-through operation mode showing the effectiveness and feasibilities of the proposed strategy. Furthermore, it has been shown the design of used constraints for those strategies under study, providing as results the benchmarking of the proposed strategies, offering feasible way to select the appropriate power devices for the new inverters with the specific control strategy.

4. Insular Smart Grid

Power generation through renewable energy exploitation is usually much smaller than traditional electrical generation plants. Therefore, a large renewable integration is translated into a considerable dispersion of variable power production (VPP) of small scale, dispersed across the insular landscape. A complete change from a typical organisation to a network based on DER requires a whole new concept to operate the bulk electricity power. The smart grid concept is considered to be the key feature in order to promote the operating performance needed to DER-based generation.

The concept includes a set of advanced features and among them the monitoring and controlling of each grid element, whatever may be the production entity, or a physical distribution link including real-time consumption tracking as well [34]. Insular grids that are susceptible to stability issues are well equipped in order to evaluate smart grid technologies which make available a perfect testing environment to evaluate non typical loads such as electric vehicles (EV) of which increased penetration provides an opportunity to support the integration of non-dispatchable power sources, such as RES. Contrariwise, the proliferation of EVs creates new challenges concerning their integration into the electric grids [69] [70].

Nowadays smart grid operating strategies are being studied in diverse insular regions [71] [72] [73] in detriment of pilot projects on large interconnected systems. The successful implementation of the Smart

Grid concept implies meeting two key milestones: the establishment of a reliable and efficient communication backbone and reinvention of grid operator's role.

In [74] has been presented a case study where it was evaluated the complexity and salience of a smart grid with a public and private domain, showing the advantages and disadvantages in the development of a smart grid infrastructure under existing socio-political systems adapted to a new rule of making, evaluate and regulate the new energy decisions and its usage. It is also stated that smart grid development allows smarter usage of energy in appliances, plug-in hybrid and electric vehicles, renewable energy and microgrids, allowing also a smarter flows of electricity production and consumption in real time and giving a sustainable management and grow-up of overall grid.

In [75] an analysis of policies, pilot projects, achievements and barriers of developing smart grids in China is made. In proposed study was found that one of a lack or barrier to improve or integrate a smart grid is related with an unclear local governmental strategy. It was also stated that the industrial structure of electrical framework, the oldest vertical integration of power systems are also institutional barriers to integrate a smart grid, namely when the solution of smart grids are related with DG, micro-grids and intelligent demand management or ultra-high voltage transmission systems.

In [76] has been presented a brief characterisation of some smart grid projects adding new perspectives related with selection criteria which allowed identify the benefits that the system stakeholders should expect by the innovation of distribution operation and planning. Also, it has been described all regulatory environment suited for smart grids, defining all essentials rational and transparent regulation mechanisms based on different levels of smartness and the identification of some suitable indicators that allowed the governmental entities to establish the expected performances, penalties and reward that can be included in novel smart grids operation.

In [77] has been proposed an islanded control architecture tool for an island operation considering a smart grid, based on islanding security region. The islanded control architecture tool covered three stages: monitoring, supervision and islanding security assessment stage; controlling and coordination of islanding security re-assessment stage, and the post-islanding transition stage. It was used as case study a system composed by controllable units such as synchronous generators (thermal units), wind turbines and demand as frequency controlled reserve, revealing feasibility, faster and flexibility results in the security and coordinated assessment for a transmission system operator increasing the security and robustness of islanded grid.

4.1 Transmission/distribution system operators

It will be required for grid agents to evolve in order to adapt their role with the development of a Smart Grid related infrastructure, as well as their collaborations with new players of the energy system – the renewable DER systems. The essence of the interactions can be described as key services that will allow a secure, reliable and efficient insular grid exploration.

A. Power network optimiser

Optimizing the development, operation, and maintenance of the distribution network by managing constraints, emergency situations and faults in a cost-efficient way, through planning, scheduling and forecasting tools.

B. Power network optimiser

Cooperate with the grid actors by offering new contributions to ensure the system security.

C. Data manager

Gaining ability to manage large amounts of data and process them to produce relevant internal/external services.

D. Smart meter manager

Promote, operate and maintain smart meters in a cost-efficient way, while providing consumers with new services.

E. Grid users/ suppliers relationship manager

Respond to regulatory changes and expand the range of smart-related services offered to the actors of the energy system (grid users, local authorities, etc.) and other third parties.

F. Neutral market facilitator/enabler

On a short-term basis: comply with regulation and facilitate the exchange of information between the insular power grid players. On a medium-term basis: experiment and demonstrate the island system operator ability to play an active role in the proper functioning of market mechanisms, if applicable.

4.2 Communication and supervisory control

The exchange of information between the power plant and the VPP control centre is critical and promotes a successful change from centralised generation to the DG paradigm. The link has to be permanent, dependable and providing bi-directional communication capabilities. From the system operator side through the control centre, customised dispatch orders are sent to RPPs. On the other hand, every DG unit reports its operating conditions to the island operator system. Then, in line with the received information, dispatch orders are updated in order to meet power demand and to stabilise grid electrical parameters. Fig. 10 illustrates typical data exchange concerning VPP Control Centre and DER units.

5. Energy storage as a grid code requirement

Although a wind farm supports grid recovery during fault conditions and has power regulation capability, in some situations these issues are insufficient. For example, when renewable production has a peak at times of low consumption the excess power is easily curtailed. The same occurs when the system needs to reduce the wind power ramp rate. Yet, if a high consumption period starts and the tendency is more growth, then there will be situations when momentary weather conditions will not allow more power output. Thus, the grid operator has no means to shift up the ramp rate output, unless sufficient conventional spinning reserves exist at his disposal. This type of strategy cannot represent a cost-effective solution since it requires the maintenance of large power capacity based on fossil fuel plants [78]. EES is broadly seen as a potential technology to overcome technical problems intrinsic to the massive renewable production. Numerous megawatt hour capacities are already being deployed and new technologies are tested in pilot installations all over the world. EES technologies vary in design, cost and technological maturity. The best EES technology is not available and defined but there are many and each with its own worthy characteristics. Additionally there are differences in energy and power capabilities. EES technologies display the potential of solving many issues concerning the renewables integration issue, as well as most of grid support services carried out by conventional generation [79].

The purpose of storage applications can be categorised based on the nature and duration of events that take place in the grid.

"See Fig. 10 at the end of the manuscript".

In an insular energy system, the main concern is related to power balance mismatch, as well as frequency and voltage issues. Additionally, large scale integration of renewables could create power quality issues. Although these are short time events, power fluctuations on RPPs could create a negative impact on the grid stability that may possibly last minutes or even hours. Issues that can be addressed by the bi-directional power flow characteristics of EES devices. This property has the possibility to boost the integration of renewables. For instance, it has potential to minimise power fluctuations by smoothing the output supplied power. Additionally, the surplus energy can be stored in high generation periods, where it can be released when the output of the generator drops due to a fall in wind speed or caused by the passage of clouds. It could also permit the peak shifting, by storing energy during high generation periods and discharging it during peak load periods. EES technologies appear to be better suited to replace most of the services provided by the conventional generation, such as regulation or spinning reserve. It becomes clear that there is a growing consensus among insular system operators regarding the potential benefits of transferring such services to EES systems. Certainly it would only make sense if the EES system meets the energy and power requirements, which are determined by the type of application, charge/discharge frequency and discharge time duration.

Fig. 11 provides the type of services that might be supported by EES to increase renewables integration. Furthermore, it shows the most common ancillary services that could be performed by EES facilities as a function of discharge time profile.

Regardless of all potential positive benefits discussed, EES still obliges to careful analysis on the costs and benefits issues. The introduction of EES as a grid code requirement should be done in order to give freedom of choice to the power plant owners or the grid operator as regards to the technology that matches the desired application. It is also necessary for a reliable weather forecasting tool to be available to support the decision process of specifying power and energy requirements of EES. At the present time, EES technologies display some drawbacks such as limited life-cycle and being too expensive on a level needed for helping large-scale penetration of solar and wind power. Consequently, in the upcoming years high costs will prevent the adoption of EES as a requirement for insular grid codes.

"See Fig. 11 at the end of the manuscript".

6. Island grid codes comparison

Relying on the information available by system operators, some European insular grid codes were examined with the intention to assess the compatibility to advanced technical requirements. The collected information was compared to the one country grid code with the highest renewables share on the European mainland territory, as shown in Table I.

"See Table I at the end of the manuscript".

The aforementioned comparative study of insular grid codes in the European space has shown that the existing regulations do not stipulate specific requirements to connect solar or wind plants. Consequently, insular systems may not be fully prepared yet to manage large renewables share.

7. Conclusions

Progressive introduction of renewable energy source in insular power networks has gained more relevance as their advantages are being disclosed. However, the shift towards sustainable energy requires a major updating of the current grid codes. Due to the absence of advanced regulations in insular context, the source for this discussion relays on mainland directives. To this end, main non-insular codes with significant renewable penetration were considered as a reference for this research work. It is clear that adding regulation and control capabilities to RES is critical and necessary to ensure future grid stability. The insular grid code reinforcement is a process that generally cannot be uniformed with a single approach. Due to the technical difference between the insular systems, it is necessary to analyse and specify the level of requirements and their restrictions for each of the insular system. The possibility for an insular power grid upgrade into a smart grid infrastructure was also explored in this paper. Emphasis was given to the distributed communication network and to the grid agents/operators new role, both as a catalyst of the renewable implementation in conjunction with grid code evolution. The study also analysed the potential benefits that could be resultant from renewable integration based on EES support. A survey was conducted to assess insular grid codes compliance to these requirements. The survey scope reported only to European islands. The results showed that significant steps have to be made for promoting a secure integration of increased renewable generation. Wind power is slightly ahead, while for solar PV interconnection the regulation is still scarce or absent.

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References

[1] [1] S. V. Papaefthymiou, S. A. Papathanassiou and E. G. Karamanou, “Application of Pumped Storage to Increase Renewable Energy Penetration in Autonomous Island Systems,” in *Wind Energy Conversion Systems*, Springer London, 2012, pp. 295-335.

[2] [2] C. K. Simoglou, E. G. Kardakos, E. A. Bakirtzis, D. I. Chatzigiannis, S. I. Vagropoulos, A. V. Ntomaris, P. N. Biskas, A. Gigantidou, E. J. Thalassinakis, A. G. Bakirtzis and J. P. Catalão, “An advanced model for the efficient and reliable short-term operation of insular electricity networks with high renewable energy sources penetration,” *Renewable and Sustainable Energy Reviews,* vol. 38, pp. 415-427, 2014.

[3] [3] A. Ntomaris, E. Bakirtzis, D. Chatzigiannis, C. Simoglou, P. Biskas and A. Bakirtzis, “Reserve quantification in insular power systems with high wind penetration,” in *2014 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Istanbul, 2014.

[4] [4] T. B. Tsuchida, “Chapter 24 - Renewables Integration on Islands,” in *Renewable Energy Integration*, L. E. Jones, Ed., Boston, Academic Press, 2014, pp. 295-305.

[5] [5] K. Kavadias, D. Zafirakis, E. Kondili and J. Kaldellis, “The Contribution of Renewables on Reducing the Electricity Generation Cost in Autonomous Island Networks,” in *International Conference on Clean Electrical Power, 2007. ICCEP '07.*, Capri, 2007.

[6] [6] C. Kayser-Bril, C. Liotard, N. Maizi and V. Mazauric, “Power Grids on Islands: from Dependency to Sustainability?,” in *IEEE Energy 2030 Conference, 2008. ENERGY 2008.*, Atlanta, GA, 2008.

[7] [7] B. Rona and Ö. Güler, “Power system integration of wind farms and analysis of grid code requirements,” *Renewable and Sustainable Energy Reviews,* vol. 49, pp. 100-107, 2015.

[8] [8] Global Wind Energy Council, “Global Wind Report - Annual market update 2010,” GWEC, Brussels, 2011.

[9] [9] E. Rodrigues, A. Bizuayehu and J. P. Catalão, “Analysis of requirements in insular grid codes for large-scale integration of renewable generation,” in *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, USA, 2014.

[10] [10] A. Arulampalam, G. Ramtharan, N. Jenkins, V. Ramachandaramurthy, J. Ekanayake and G. Strbac, “Trends in wind power technology and grid code requirements,” in *International Conference on Industrial and Information Systems, 2007. ICIIS 2007.*, Penadeniya, 2007.

[11] [11] E. M. G. Rodrigues, R. Godina, T. D. P. Mendes, J. C. O. Matias and J. P. S. Catalão, “Influence of Large Renewable Energy Integration on Insular Grid Code Compliance,” in *Technological Innovation for Cloud-Based Engineering Systems*, Caparica, Portugal, Springer International Publishing, 2015, pp. 296-308.

[12] [12] F. Díaz-González, M. Hau, A. Sumper and O. Gomis-Bellmunt, “Participation of wind power plants in system frequency control: Review of grid code requirements and control methods,” *Renewable and Sustainable Energy Reviews,* vol. 34, pp. 551-564, 2014.

[13] [13] X. Liu, Z. Xu and K. P. Wong, “Recent advancement on technical requirements for grid,” *J. Mod. Power Syst. Clean Energy,* vol. 1, no. 3, p. 216–222, 2013.

[14] [14] R. Piwko, N. Miller, R. Girad, J. MacDowell, K. Clark and A. Murdoch, “Generator Fault Tolerance and Grid Codes,” *IEEE Power and Energy Magazine,* vol. 8, no. 2, pp. 18-26, 2010.

[15] [15] P. Wang, Z. Gao and L. Bertling, “Operational Adequacy Studies of Power Systems With Wind Farms and

Energy Storages," *IEEE Transactions on Power Systems,* vol. 27, no. 4, pp. 2377-2384, 2012.

[16] [16] J. P. Praene, M. David, F. Sinama, D. Morau and O. Marc, "Renewable energy: Progressing towards a net zero energy island, the case of Reunion Island," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 1, pp. 426-442, 2012.

[17] [17] G. Notton, "Importance of islands in renewable energy production and storage: The situation of the French Islands," *Renewable and Sustainable Energy Reviews,* vol. 47, pp. 260-269, 2015.

[18] [18] N. Hamsic, A. Schmelter, A. Mohd, E. Ortjohann, E. Schultze, A. Tuckey and J. Zimmermann, "Increasing Renewable Energy Penetration in Isolated Grids Using a Flywheel Energy Storage System," in *International Conference on Power Engineering, Energy and Electrical Drives, 2007. POWERENG 2007.*, Setubal, Portugal, 2007.

[19] [19] J. Morren, J. Pierik and S. W. d. Haan, "Inertial response of variable speed wind turbines," *Electric Power Systems Research,* vol. 76, no. 11, pp. 980-987, 2006.

[20] [20] S. A. Papathanassiou and N. G. Boulaxis, "Power limitations and energy yield evaluation for wind farms operating in island systems," *Renewable Energy,* vol. 31, no. 4, pp. 457-479, 2006.

[21] [21] J. C., "Stability and Control of Wind Farms in Power Systems - Ph.D. dissertation," Risø National Laboratory, Univ. Aalborg, Roskilde, Denmark, 2006.

[22] [22] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 6, pp. 3876-3890, 2012.

[23] [23] A. Etxegarai, P. Eguia, E. Torres, A. Iturregi and V. Valverde, "Review of grid connection requirements for generation assets in weak power grids," *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 1501-1514, 2015.

[24] [24] I. M. d. Alegría, J. Andreu, J. L. Martín, P. Ibañez, J. L. Villate and H. Camblong, "Connection requirements for wind farms: A survey on technical requierements and regulation," *Renewable and Sustainable Energy Reviews,* vol. 11, no. 8, pp. 1858-1872, 2007.

[25] [25] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renewable Power Generation,* vol. 3, no. 3, pp. 308-332, 2009.

[26] [26] E. Quitmann and E. Erdmann, "Power system needs – How grid codes should look ahead," *IET Renewable Power Generation,* vol. 9, no. 1, pp. 3-9, 2015.

[27] [27] T. Ackermann, A. Ellis, J. Fortmann, J. Matevosyan, E. Muljadi, R. Piwko, P. Pourbeik, E. Quitmann, P. Sorensen, H. Urdal and B. Zavadil, "Code Shift: Grid Specifications and Dynamic Wind Turbine Models," *IEEE Power and Energy Magazine,* vol. 11, no. 6, pp. 72-82, 2013.

[28] [28] J. Wright, P. Tuson and J. Van Coller, "Studies for wind energy facility grid code compliance in South Africa," in *2012 IEEE Power Engineering Society Conference and Exposition in Africa (PowerAfrica)*, Johannesburg, 2012.

[29] [29] W. Jarzyna and P. Lipnicki, "The comparison of Polish grid codes to certain European standards and resultant differences for WPP requirements," in *2013 15th European Conference on Power Electronics and Applications (EPE)*, Lille, 2013.

[30] [30] Électricité de France (EDF), "Référentiel Technique – SEI REF 01 - Systèmes Énergétiques Insulaires - Referentiel technique HTB," EDF, 2008.

[31] [31] H. Berndt, M. Hermann, H. D. Kreye, R. Reinisch, U. Scherer and J. Vanzetta, “Transmission Code 2007 - Network and System Rules of the German Transmission System Operators,” Verband der Netzbetreiber, Berlin, 2007.

[32] [32] Électricité de France (EDF), “Référentiel Technique SEI REF 04 (V5) – Protection de decouplage pour le raccordeent d’une production decentralisee en HTA et en BT dans les zones non interconnectees (in French),” EDF, 2010.

[33] [33] EirGrid, “EirGrid Grid Code - Version 5.0,” Dublin, 2013.

[34] [34] J. Jorgensen, S. Sorensen, K. Behnke and P. Eriksen, “EcoGrid EU — A prototype for European Smart Grids,” in *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011.

[35] [35] Red Eléctrica de Espana, “Procedimientos de operación non peninsulares,” [Online]. Available: http:// www.ree.es. [Accessed 22 05 2015].

[36] [36] Energinet.dk , “Technical regulation 3.2.5 for wind power plants with a power output greater than 11 kW,” Energinet.dk, Fredericia, 2010.

[37] [37] Alstom, “A STATCOM that helps wind to meet grid codes,” *Alstom Grid,* pp. 28-31, Spring/Summer 2013.

[38] [38] H. Knopf, “International Grid Codes and Local Requirements - the Evolvement of Standards for Distributed Energy Resources and Inverter Technology,” in *5th International Conference on Integration of Renewable and Distributed Energy Resources*, Berlin, 2012.

[39] [39] A. Ellis, R. Nelson, E. Von Engeln, R. Walling, J. MacDowell, L. Casey, E. Seymour, W. Peter, C. Barker, B. Kirby and J. Williams, “Reactive power performance requirements for wind and solar plants,” in *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2012.

[40] [40] A. Ellis, R. Nelson, E. V. Engeln, R. Walling, J. McDowell, L. Casey, E. Seymour, W. Peter, C. Barker and B. Kirby, “Reactive power interconnection requirements for PV and Wind plants – Recommendations to NERC,” Sandia National Laboratories, Albuquerque, New Mexico & Livermore, California, 2012.

[41] [41] F. Teng, V. Trovato and G. Strbac, “Stochastic Scheduling With Inertia-Dependent Fast Frequency Response Requirements,” *IEEE Transactions on Power Systems,* vol. PP, no. 99, pp. 1 - 10, 2015.

[42] [42] W. He, X. Yuan, J. Hu, X. Xiong, N. Chen and L. Zhu, “Providing inertial support from wind turbines by adjusting phase-locked loop response,” in *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014.

[43] [43] Y. Wang, G. Delille, H. Bayem, X. Guillaud and B. Francois, “High Wind Power Penetration in Isolated Power Systems—Assessment of Wind Inertial and Primary Frequency Responses,” *IEEE Transactions on Power Systems,* vol. 28, no. 3, pp. 2412-2420, 2013.

[44] [44] R. de Almeida and J. Peas Lopes, “Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation,” *IEEE Transactions on Power Systems,* vol. 22, no. 3, pp. 944-950, 2007.

[45] [45] J. Conroy and R. Watson, “Frequency Response Capability of Full Converter Wind Turbine Generators in Comparison to Conventional Generation,” *IEEE Transactions on Power Systems,* vol. 23, no. 2, pp. 649-656, 2008.

[46] [46] P.-K. Keung, P. Li, H. Banakar and B. Ooi, “Kinetic Energy of Wind-Turbine Generators for System Frequency Support,” *IEEE Transactions on Power Systems,* vol. 24, no. 1, pp. 279-287, 2009.

[47] [47] ENTSO-E, “ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators,”

ENTSO-E AISBL, Brussels, 2013.

[48] [48] E. Q., "Ancillary Services from Wind Turbines and Related Grid Codes," in *Proc. 5th International Conference on Integration of Renewable and Distributed Energy Resources*, Bremen, 2012.

[49] [49] J. Brisebois and N. Aubut, "Wind farm inertia emulation to fulfill Hydro-Québec's specific need," in *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011.

[50] [50] P. Ashton, C. Saunders, G. Taylor, A. Carter and M. Bradley, "Inertia Estimation of the GB Power System Using Synchrophasor Measurements," *IEEE Transactions on Power Systems,* vol. 30, no. 2, pp. 701-709, 2015.

[51] [51] UK National Grid, "Firm Frequency Response Information," National Grid, London, 2014.

[52] [52] G. Delille, B. Francois and G. Malarange, "Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia," *IEEE Transactions on Sustainable Energy,* vol. 3, no. 4, pp. 931-939, 2012.

[53] [53] Z. Rather, Z. Chen, P. Thogersen and P. Lund, "Dynamic Reactive Power Compensation of Large-Scale Wind Integrated Power System," *IEEE Transactions on Power Systems,* vol. PP, no. 99, pp. 1-11, 2014.

[54] [54] Ministerio de Industria, Turismo y Comercio, "P.O. 12.2 – SEIE: Instalaciones conectadas a la red de transporte de energia eléctrica: Requisitos mínimos de diseño, equipamiento, funcionamento y seguridad y puesta en servicio (in Spanish)," Boletín Oficial del Estado, 2009.

[55] [55] Red Eléctrica de España, "P.O. 12.3. Requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas," Red Eléctrica de España, 2006.

[56] [56] A. Armenakis, "Grid code compliance test for small wind farms connected to the distribution grid in Cyprus," in *8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012)*, Cagliari, 2012.

[57] [57] C. Rahmann, H.-J. Haubrich, A. Moser, R. Palma-Behnke, L. Vargas and M. Salles, "Justified Fault-Ride-Through Requirements for Wind Turbines in Power Systems," *IEEE Transactions on Power Systems,* vol. 26, no. 3, pp. 1555-1563, 2011.

[58] [58] L. Huchel, M. El Moursi and H. Zeineldin, "A Parallel Capacitor Control Strategy for Enhanced FRT Capability of DFIG," *IEEE Transactions on Sustainable Energy,* vol. 6, no. 2, pp. 303-312, 2015.

[59] [59] W. Guo, L. Xiao, S. Dai, Y. Li, X. Xu, W. Zhou and L. Li, "LVRT Capability Enhancement of DFIG With Switch-Type Fault Current Limiter," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 1, pp. 332-342, 2015.

[60] [60] M. Parker, L. Ran and S. Finney, "Distributed Control of a Fault-Tolerant Modular Multilevel Inverter for Direct-Drive Wind Turbine Grid Interfacing," *IEEE Transactions on Industrial Electronics,* vol. 60, no. 2, pp. 509-522, 2013.

[61] [61] R. Razzaghi, M. Davarpanah and M. Sanaye-Pasand, "A Novel Protective Scheme to Protect Small-Scale Synchronous Generators Against Transient Instability," *IEEE Transactions on Industrial Electronics,* vol. 60, no. 4, pp. 1659-1667, 2013.

[62] [62] T. H. Nguyen and D.-C. Lee, "Advanced Fault Ride-Through Technique for PMSG Wind Turbine Systems Using Line-Side Converter as STATCOM," *IEEE Transactions on Industrial Electronics,* vol. 60, no. 7, pp. 2842-2850, 2013.

[63] [63] M. El-Moursi, "Fault ride through capability enhancement for self-excited induction generator-based wind

parks by installing fault current limiters," *IET Renewable Power Generation,* vol. 5, no. 4, pp. 269-280, 2011.

[64] [64] M. Mahfouz and M. A. El-Sayed, "Static synchronous compensator sizing for enhancement of fault ride-through capability and voltage stabilisation of fixed speed wind farms," *IET Renewable Power Generation,* vol. 8, no. 1, pp. 1-9, 2014.

[65] [65] J. Arya and L. M. Saini, "Single stage single phase solar inverter with improved fault ride through capability," in *2014 IEEE 6th India International Conference on Power Electronics (IICPE)*, Kurukshetra, India, 2014.

[66] [66] K. Fujii, N. Kanao, T. Yamada and Y. Okuma, "Fault ride through capability for solar inverters," in *Proceedings of the 2011-14th European Conference on Power Electronics and Applications (EPE 2011)*, Birmingham, 2011.

[67] [67] J. Roldán-Pérez, A. García-Cerrada, J. Zamora-Macho and M. Ochoa-Giménez, "Helping all generations of photo-voltaic inverters ride-through voltage sags," *IET Power Electronics,* vol. 7, no. 10, pp. 2555-2563, 2014.

[68] [68] Y. Yang, H. Wang and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," in *2014 Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, 2014.

[69] [69] J. de Hoog, T. Alpcan, M. Brazil, D. Thomas and I. Mareels, "Optimal Charging of Electric Vehicles Taking Distribution Network Constraints Into Account," *IEEE Transactions on Power Systems,* vol. 30, no. 1, pp. 365-375, 2015.

[70] [70] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renewable and Sustainable Energy Reviews,* vol. 34, pp. 501-516, 2014.

[71] [71] D.-H. Yoon, B. Shin, C. S. Song, H. Lee and G. Jang, "Study on Jeju Island power system considering multiple HVDC," in *2010 IEEE Power and Energy Society General Meeting*, Minneapolis, MN, 2010.

[72] [72] T. Kim, S. K. Park and B. G. Lee, "What Is Appropriate Strategy for Smart Grid Business?: A Case Study of Test Bed in Korea," in *2010 Proceedings of the 5th International Conference on Ubiquitous Information Technologies and Applications (CUTE)*, Sanya, 2010.

[73] [73] E. Rodrigues, R. Godina, S. Santos, A. Bizuayehu, J. Contreras and J. Catalão, "Energy storage systems supporting increased penetration of renewables in islanded systems," *Energy,* vol. 75, pp. 265-280, 2014.

[74] [74] C. Koliba, M. DeMenno, N. Brune and A. Zia, "The salience and complexity of building, regulating, and governing the smart grid: Lessons from a statewide public–private partnership," *Energy Policy,* vol. 74, pp. 243-252, 2014.

[75] [75] J. Yuan, J. Shen, L. Pan, C. Zhao and J. Kang, "Smart grids in China," *Renewable and Sustainable Energy Reviews,* vol. 37, pp. 896-906, 2014.

[76] [76] M. Coppo, P. Pelacchi, F. Pilo, G. Pisano, G. Soma and R. Turri, "The Italian smart grid pilot projects: Selection and assessment of the test beds for the regulation of smart electricity distribution," *Electric Power Systems Research,* vol. 120, pp. 136-149, 2015.

[77] [77] Y. Chen, Z. Xu and J. Østergaard, "Islanding Control Architecture in future smart grid with both demand and wind turbine control," *Electric Power Systems Research,* vol. 95, pp. 214-224, 2013.

[78] [78] M. Swierczynski, R. Teodorescu, C. Rasmussen, P. Rodriguez and H. Vikelgaard, "Overview of the energy storage systems for wind power integration enhancement," in *2010 IEEE International Symposium on Industrial*

Electronics (ISIE), Bari, 2010.

[79] [79] J. Leadbetter and L. G. Swan, “Selection of battery technology to support grid-integrated renewable electricity,” *Journal of Power Sources,* vol. 216, pp. 376-386, 2012.

[80] [80] EPRI, “EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications,” Electric Power Research Institute, Inc., Palo Alto, California, 2003.

[81] [81] EPRI, “Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits.,” Electric Power Research Institute, Inc., Palo Alto, California, 2010.

[82] [82] IEC, “Electrical Energy Storage,” International Electrotechnical Commission, Geneva, 2011.

Figure captions

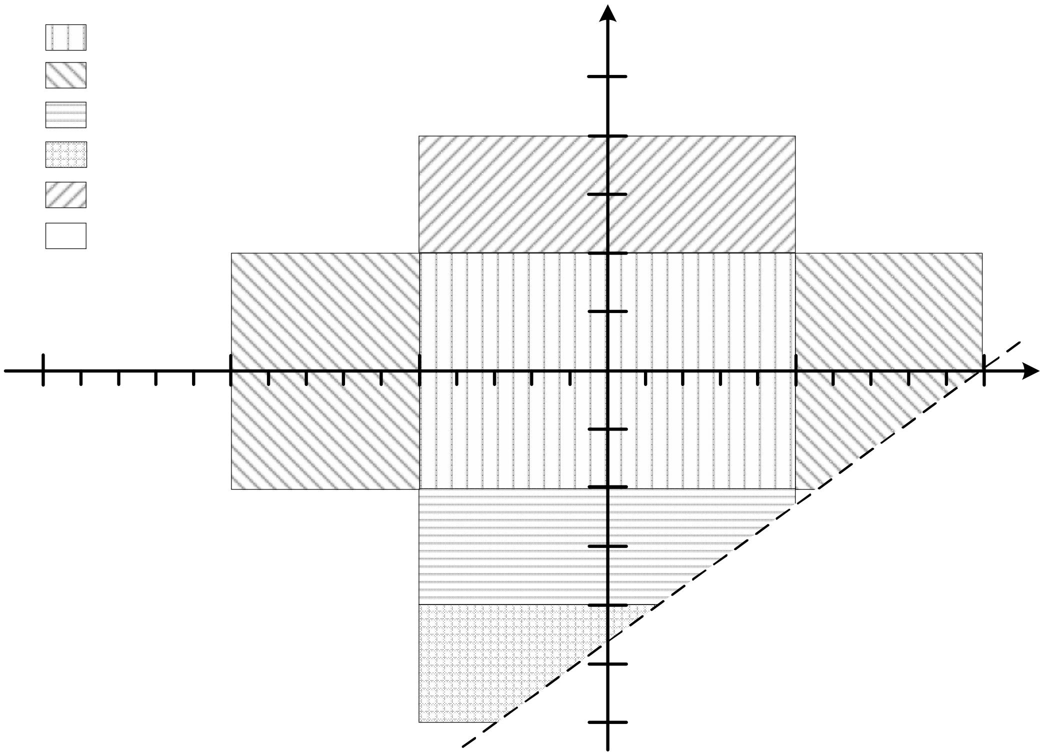

Fig. 1. The operating area of voltage and frequency for French insular grid code.

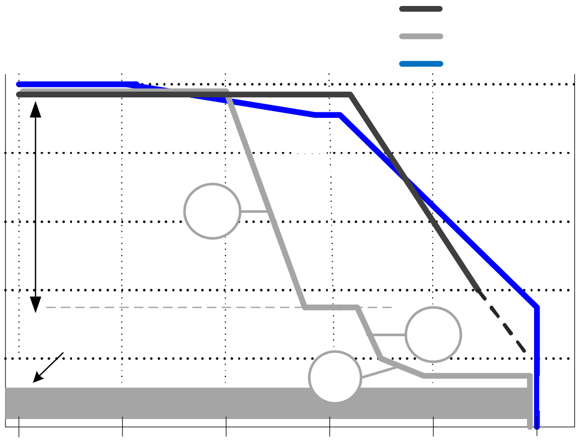

Fig. 2. Power-frequency response required by mature grid codes in mainland networks.

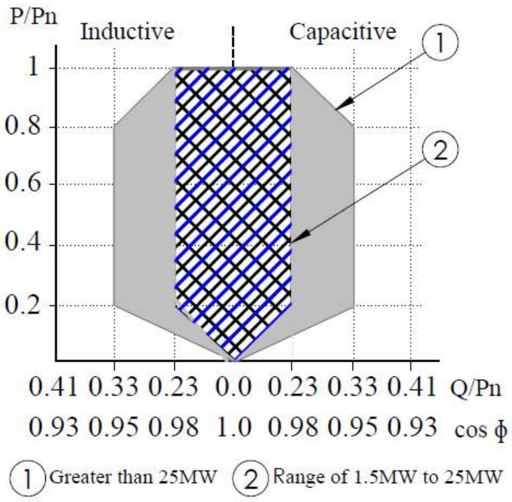

Fig. 3. Danish P-Q interconnection requirements for wind power plants.

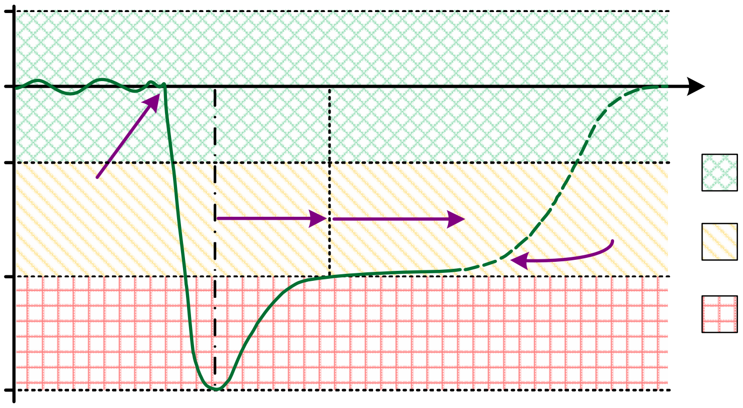

Fig. 4. Frequency response requirement for British islanded system.

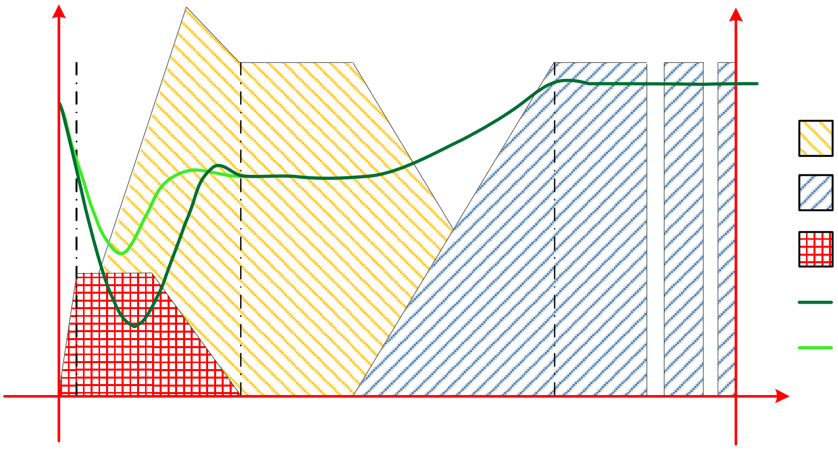

Fig. 5. The frequency response requirement applied to French isolated grids.

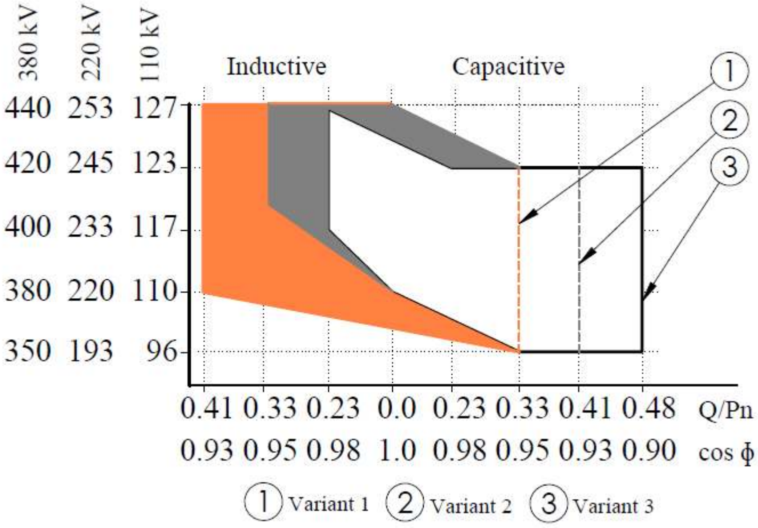

Fig. 6. Reactive power capability requirements for German case.

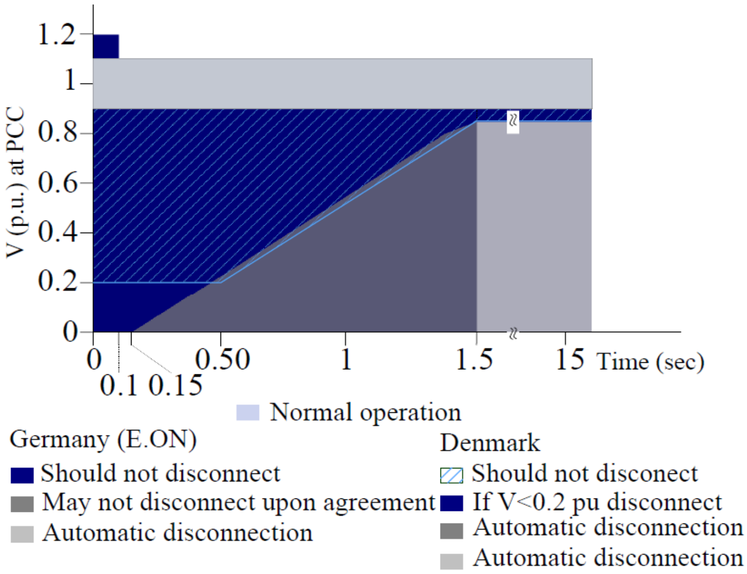

Fig. 7. FRT interconnection requirements for German and Danish codes.

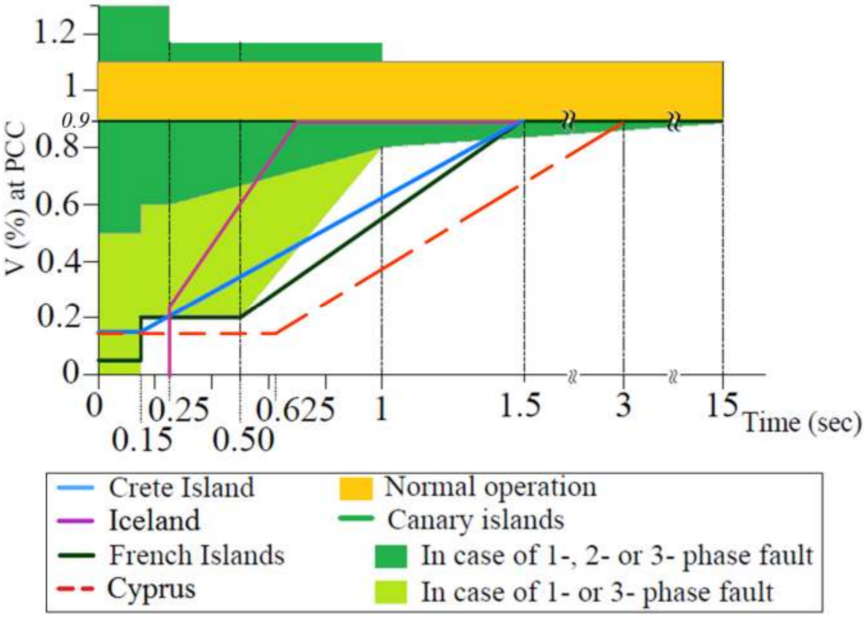

Fig. 8. FRT curve examples required in European insular power systems.

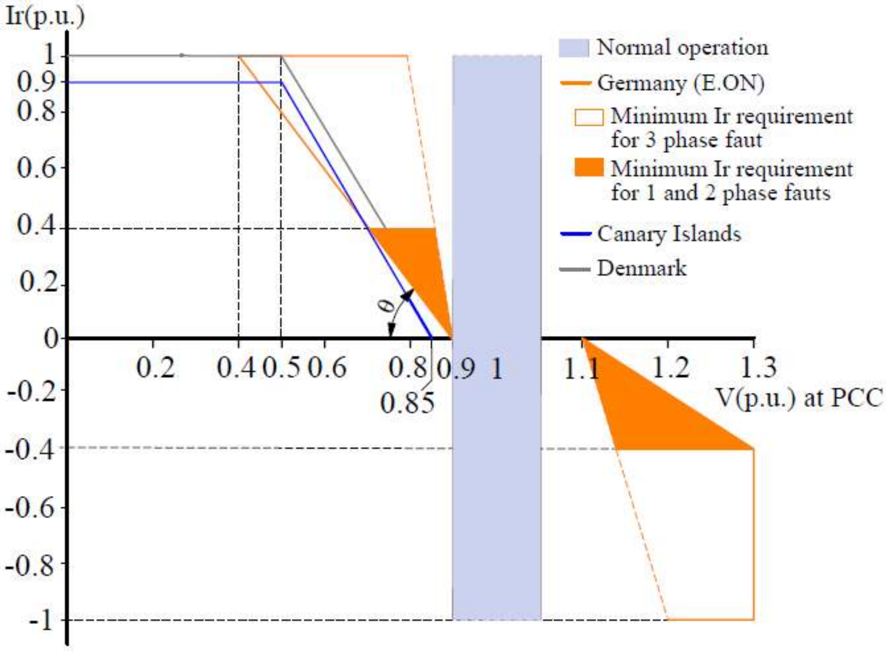

Fig. 9. Comparison of reactive power requirements during a voltage disturbance.

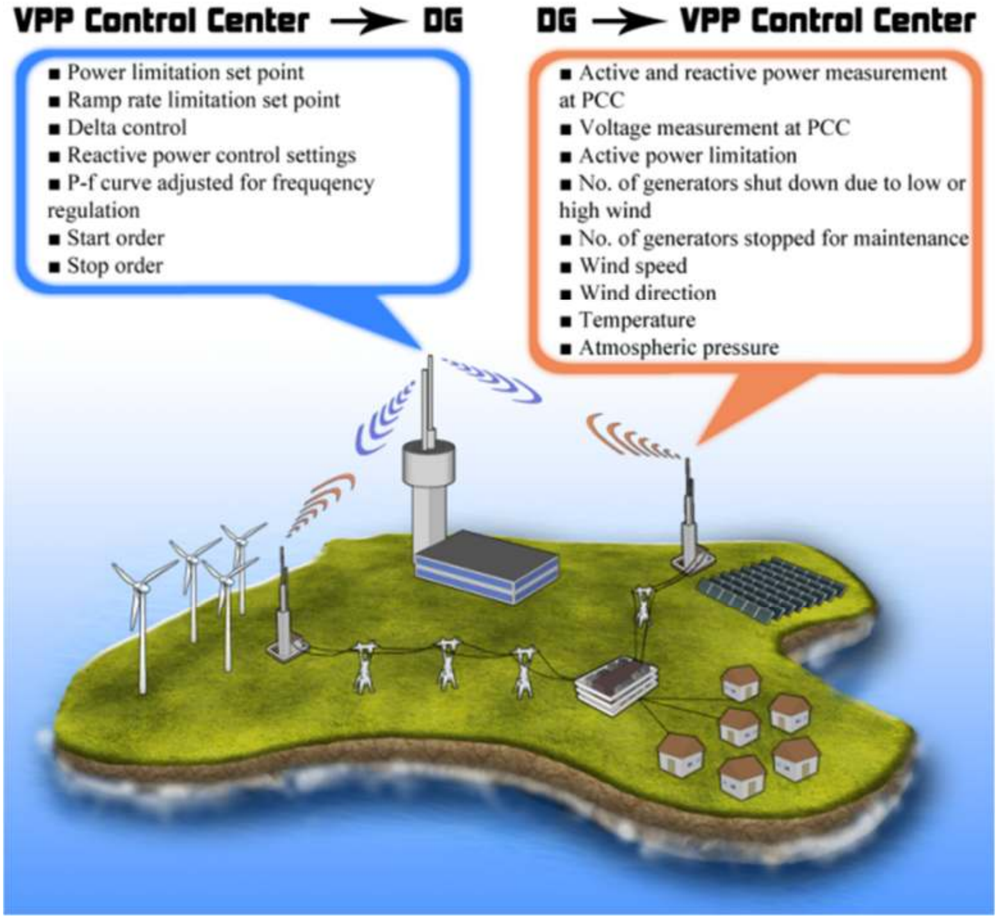

Fig. 10. Typical Information flux between VPP Control Center and DG units.

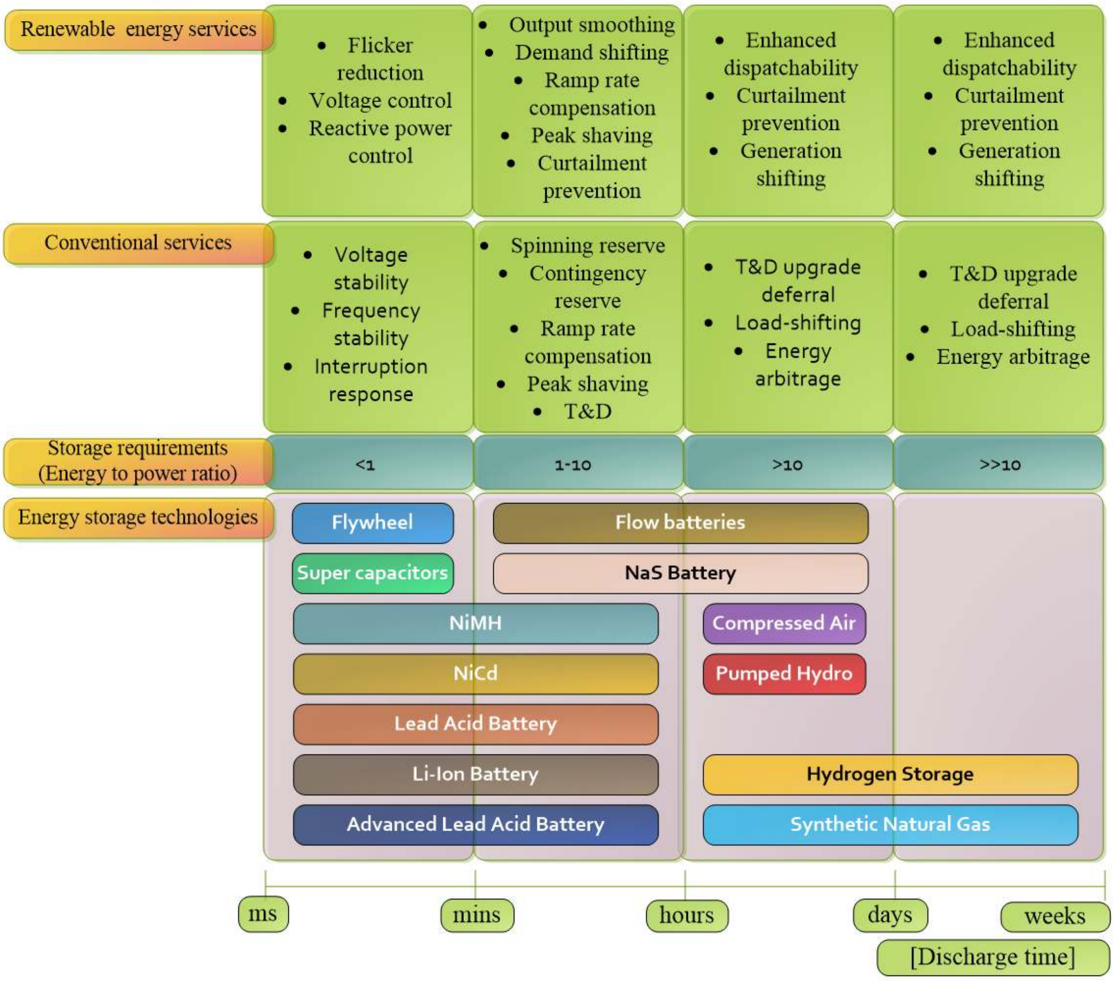

Fig. 11. Energy storage technologies as a function of discharge time [80] [81] [82].

Tables

Table 1.

Grid codes comparison.

	Azores Islands		*Canary Islands*		*Crete Island*		*Pantelleria Island*		*French Islands*		*Denmark*	
VARIABLE PRODUCTION PLANT REQUIREMENTS												
Voltage												
Nominal (tolerance range)	6kV, 6.9kV, 10kV, 15kV, 30kV, 60kV (±10%)		220 kV (0.93 – 1.11 pu) 132 kV (0.93 – 1.1 pu) 66 kV (0.91 – 1.09 pu)		6.6kV,15kV and 20kV (±10%)		10.5 kV (0.85-1.10 pu)		63kV and 90kV (±10%)		400kV (0.90-1.05 pu) 150kV (0.97-1.13 pu) 132kV(0.95-1.1 pu)	
Limited time period									57kV-70kV [20min] 55kV-72kV[5min] 81kV-98kV[20min] 79kV-99kV[5min]		400kV (0.80-1.10 pu) 132kV(0.90-1.18 pu) 150kV (0.90-1.20 pu) (1 hour)	
Frequency												
Nominal Temporary range	50Hz±1.5% 50Hz±2%(95% of time)		49.85Hz-50.15Hz 49.85Hz-50.25Hz[5min] 47.5Hz-51Hz [5min]		42.5 Hz-57.5 Hz 49 Hz-51 Hz (95% of time)		47.5 Hz - 51.5 Hz		48Hz-52Hz 47Hz-48Hz[3min] 46Hz-47Hz[1m] 44Hz-46Hz[0.4sec] 52Hz-53Hz[5sec]		49.5Hz-50.2Hz 50.2Hz-52Hz [15min] 49Hz-49.5Hz [5min] 48Hz-49Hz [30min] 47.5Hz-48Hz [3min] 47Hz-47.5Hz [20 sec]	
Active Power Control												
Max output	Not specified		Not specified		Not specified		Not specified		Full curtailment if combined wind farms production surpass 30% of instant consumption (upon agreement)		Defined by the TSO	
Output range	Not specified		Not specified		Not specified		Not specified				40% - 100%Pn (3) 20% - 100%Pn (4)	
Ramp rate	Not specified		Not specified		Short discon. <2 sec with a rate of 10% and 20% of the nom. power		Not specified				From 10% to 100% of rated power per minute	
Delta control (reserve)	Not specified		Not specified		Not specified		Not specified				Specified by TSO(1)	
Power Frequency Capability												
	Not specified		Not specified		Not specified		Not specified		Not specified		Programmable P-f curve	
Reactive Power Capability to Grid Fault Condition												
	Vmin (U/Un)	Ireact (Ir/It)	Vmin (U/Un)	Ireact (Ir/It)	Vmin (U/Un)	Ireact (Ir/Itl)	Vmin (U/Un)	Ireact (Ir/t)	Vmin (U/Un)	Ireact (Ir/t)	Vmin (U/Un)(2)	Ireact (Ir/It)(2)
During a voltage dip	Not specified		≤0.5	0.85	Not specified		Not specified		Not specified		≤0.5	1
			0.5-0.85	Negative gradient							0.5-0.9	Negative gradient
After recovering	Not specified		≥0.85	Variable	Not specified		Not specified		Not specified		≥0.90	Variable
Steady State Reactive Power Capability												
Power factor P-Q diagram V-Q diagram	Not specified		0.95 ind to 0.95 cap (± 0.05 pu)		1-0.85 inductive $P_{\text{Wind Farm}}$> 2MW:		0.2Pn<P<Pn 1-0.8 inductive		U-Q diagram		0.2Pn<P<Pn (4) 0.975 ind to 0.975 cap P-Q / V-Q charts	
Low Voltage Fault Ride-Through Capability												
	Vmin (U/Un)	Time (s)	Vmin (U/Un)	Time (s)	Vmin (U/Un)	Time (s)	Vmin (U/Un)	Time (s)	Vmin (U/Un)	Time (s)	Vmin (U/Un)(2)	Time max(s)(2)
During fault	0.2	0.5	0	0.5	0.15	0.15	Not specified		0.05	0.15	0.2	0.5
Fault clearance	≤0.8	2	≤0.8	1	≤0.9	1.5			≤0.9	1.5	0.9	1.5
Inertia Emulation												
	Not specified		Not specified		Not specified		Not specified		Not specified		Not specified	
Communication and Supervisory Control												
Reporting operating conditions to TSO (1)	Not Specified		Only if Pn>10MW		Not Specified		Not Specified		Specified		Specified	
Operating orders from TSO (1) to VPP	Not specified		Only if Pn>10MW		Not Specified		Not Specified		Specified		Specified	
ENERGY STORAGE REQUIREMENTS												
Frequency regulation	Not specified		Not Specified		Not specified		Not specified		Not specified		Not specified	
Load shifting	Not specified		Not Specified		Not specified		Not specified		Not specified		Not specified	
Peak shaving	Not specified		Not Specified		Not specified		Not specified		Not specified		Not specified	
Back-up reserve	Not specified		Not Specified		Not specified		Not specified		Not specified		Not specified	
Power rating (MW)	Not specified		0.70*$P_{\text{Wind Farm}}$(5)		Not specified		Not specified		Not specified		Not specified	
Capacity (MAh)	Not specified		14h*0.5* $P_{\text{Wind Farm}}$ (5)		Not specified		Not specified		Not specified		Not specified	

1-Transmission system operator
2-Wind power plant with a power output greater than 1.5MW
3-Wind power plant with a power output range of 1.5MW to 2.5MW
4-Wind power plant with a power output greater than 2.5MW
5-Wind power plant up to 15MW rating