Influence of Large Renewable Energy Integration on Insular Grid Code Compliance

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Abstract. Large-scale deployment of renewables in island energy systems attracts local attention of grid operators as a way of reducing fuel fossil consumption. Planning a grid based on renewable power plants poses serious challenges to the normal operation of a power system, namely on frequency and voltage stability. In past grid code compliance, wind turbines did not require services for supporting grid operation. To shift to large renewable energy integration, the island grid code should incorporate a new set of requirements in order to regulate the inclusion of these services, which is the aim of this paper. The paper also discusses additional requirements such as "virtual" wind inertia.

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

1 Introduction

Renewable integration (especially wind energy) on mainland energy systems has been increasing significantly in the last decade [1]. However the penetration rate in insular energy systems is still low. Presently, high penetration of renewables is considered extremely challenging for normal grid operation by the local grid operators. Typically the islanded energy system has a small size, low interconnections and not a high short-circuit ratio (SCR). Therefore, it is more vulnerable to frequency and voltage stability issues [2] and since the generation units cannot be very large, its robustness is ensured by maintaining large reserve capacity, which raises electricity generation costs. Local grid operators are now aware that there is a significant potential for exploring renewable energy resources, which could reduce external dependency on imported fossil fuel [3]. However, it is well known that the intermittent nature of wind and solar energy cannot be controlled. This variability on seasonal and daily basis has been seen as a serious obstacle for large scale installation of renewable power plants. This paper discusses grid code requirements for large-scale integration of renewables in an island context as a new contribution to earlier studies.

2 Contribution to Cloud-based Engineering Systems

Future insular power systems that rely on a heavy mix of distributed energy resources (DER) will require managing tools based on real-time monitoring, controlling and high computational power resources. Cloud computing proposes advances services which allow to use its massive computation power ability and the scalabilities relying on large scale servers that host the web services and web application. Similarly, cloud computing can provide physical or virtual resources on which the insular power system applications can run. On the DER point of view, local hardware facilities for executing specific software programs become practically residual. Thus, it reduces the installation and maintenance costs. Via a cloud structure each client can always access its respective applications or data, out from anyplace and by a connected device to the network. In addition, it provides a common platform for sharing data which drives increased cooperation between insular grid parties. On the other hand, for the network operator side, cloud-based grid management services create a unique framework for the design and implementation of a centralized structure for their distributed monitoring and control tasks. Therefore, by integrating cloud-based engineering systems in the insular power grid infrastructure, an efficient, reliable and secure energy distribution can be accomplished.

3 Island Power Generation System Overview

The island power generation infrastructure typically consists of diesel generators, small groups of thermal power plants, and may include natural hydro or thermal sources based production. Basically there are two types of units. One class of generators runs at constant output, known as base load units, while another group of generators has the function of adapting its output following the load needs. Wind and solar generators do not fit in any of these two groups because they are not flexible load following units. Generators like load following units are designed to operate with variable output. Moreover, this type of flexible generation must maintain a considerable amount of active power reserve for frequency regulation. In an island energy system this reserve is much more critical because conventional plants have a smaller size when compared to power installations in the mainland energy system. Replacing flexible load following units by renewable generating units implies that there will likely be less kinetic energy exchange to support grid power balance, resulting in a degradation of frequency regulation capability, which in turn may imply larger and faster frequency deviations [4]. Hence, the minimum level of conventional generation and concerns about grid stability creates a practical restriction on planning more renewables integration [5]. Even in low penetration scenarios, it is not uncommon to see power curtailment actions by the system operator to face renewable power excess on the grid, or even shutting down the wind farm due to a grid disturbance. However, the revenue lost due to curtailment or disconnection may be greater than the cost of maintaining conventional generation. To accelerate renewable integration, wind and solar farms should replicate conventional power plants during and after network faults [6]. To become effective, island regulations must be updated to impose this strict operation profile. Grid code requirements have been studied for large wind farms integration in mainland systems [7]-[10]. Yet, technical literature focusing on island grid codes requirements is still very scarce and, therefore, this paper provides a new contribution to this issue. In essence, present insular regulations do not allow the grid operator to control distributed energy resources (DER). The coordination between transmission system operator (TSO) and distribution system operator (DSO) is insufficient for the effective DER integration. The lack of adequate regulation for DER systems connection is also a reality. Further, DER does not have any economic incentive to take part in the network operation. All these issues are taken into account in this paper.

4 Grid Code Requirements for DER

A grid code serves the mission of defining the physical connection point requirements to be followed by energy production equipment in order to connect to the grid. In addition it should provide rules for renewable power plants to support grid stability.

4.1 Regulations for Continuous Operation

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 DER system to cope with these issues through a well-defined specifications-based behavior.

Voltage and Frequency Operation. Renewable power plants must stay connected to the grid and able to withstand voltage and frequency variation limits established by the island grid system operator. Voltage range is related to the size of the transmission system, which is characterized by different voltage levels. Frequency nominal range is determined by the electrical characteristics of the insular energy system, such as overall inertia of the installed power generation infrastructure. Renewable power sources must also face voltage and frequency deviations outside the conventional range during a short time period and without being tripped.

Active Power Regulation. It is a set of power control strategies that gives freedom and flexibility to the system operator to manage the power output injected into the grid by renewable power plants. Wind and solar power plants should comply with this requirement. As the renewable generation is increased, active power regulation requirements become indispensable on island grid codes.

a) Maximum power limitation
This parameter has the purpose of setting the maximum power output of renewable generation below its power rating. By restricting the maximum amount of power injection, the system operator has a way to prevent more instabilities of active power balance due to the unpredictable nature of wind and solar resources.

b) Active power range control
Renewables cannot deliver dispatchable power on demand. The goal is to replicate traditional power sources that are fully controllable. Renewable generating units should be prepared to curtail artificially the power production to maintain power balance and also, if necessary, to contribute to the stabilization of grid frequency. Both requirements have different implementation scopes. The first one permits the TSO to introduce output power dispatch flexibility on wind power plants (WPP) and on solar power plants (SPP). The second is basically extending primary control function to the renewable plants.

c) Ramp rate limitation
Limiting the power gradient of renewable power through a set-point can be a very effective way to minimize the impact of a sudden rise of renewable generation. Ramp rate is defined as the power change from minute to minute (MW/min). The idea of this concept is to filter faster variations of wind power output by imposing a ramp rate according to the changes observed on power demand.

d) Delta control

It is a way of securing spinning reserve based on renewable power generation. Power output is artificially lowered, below the available power at the moment of generation. The difference is kept as reserve to be used like a conventional generation does (primary and secondary control). However, the curtailed power depends on available wind or solar power. Thus, the level of reserve is not constant. The curtailed power can be released not only for frequency regulation, but also to maintain the voltage of the overall system through the injection of reactive power to grid.

Power-Frequency Response. When an energy unbalance occurs the frequency deviates from its nominal value. As the unbalance grows a large deviation of frequency is expected to happen, threatening normal power network operation. In order to confine deviation extension to safe levels, frequency surveillance and corrective actions are performed by conventional generators (primary control) along with grid operator supervision and, if necessary, authorizes spinning reserve release (secondary control). For the specific case of European islands, frequency regulation capability compliance is not specified by local grid codes. Wind farms able to restore generation/demand balance are already required in some European countries. Typically, a mainland TSO imposes a frequency regulation strategy through a power frequency curve specification only addressing wind power plants operation. Nevertheless, no compliance is directly demanded for solar power plants on these regulations. Since insular grid codes in European space didn't yet evolved to require this behavior, formal analyses have to be carried out observing the most advanced specifications at non-insular territories. Fig. 1 shows power-frequency response curves required in Ireland, Germany and Denmark [11]-[13]. It is clear that frequency support behavior differs from country to country. The range for frequency correction is higher on Danish and Irish grids. Both regulations set a dead band range where active power production remains independent of frequency variation. Beyond this band both codes show different interpretations on how a wind farm should react to frequency deviations. According to the German regulation, a renewable power plant has to curtail active power by starting at 50.2 Hz with a gradient of 40% of available generation at the moment per Hertz. As for the Irish code, when in the presence of over-frequency excursions, a renewable power plant reacts according to a power curtailment gradient set by the grid operator. Afterwards, if necessary, curtailment rate is updated to the grid operator needs. With respect to frequency events, the wind farms response in German networks is limited when compared to Danish and Irish requirements, because the regulations establish that energy production can be artificially kept lower to provide secondary control at lower frequencies. Furthermore, Danish rules also allow the grid operator to smooth wind power output of each wind power plant, adapting individually power frequency response to the needs. For this purpose, three curtailment gradients that reproduce a droop controller action can be configured over the Danish curve. In Fig. 1, droop regulation areas are identified as d1, d2 and d3. Similar flexibility is provided by Irish regulation.

Reactive Power Control. Traditionally, synchronous generators had the exclusive task of ensuring bulk system voltage regulation at transmission level. As for the distribution network, voltage regulation still remains under distribution substation control. Since their introduction, wind farms were built to generate only active power. Thus, they were operated to keep the power factor at unity. In the last decade this trend has changed. Most of the European grids on mainland context have introduced new regulatory conditions, extending reactive power capability along with active power generation to wind and solar power. Likewise, the growing dissemination of renewables-based DER systems in insular systems will force the incorporation of this ancillary service for security reasons as a result of strong technical constraints. Since an isolated power network is different from island to island, reactive power needs have to be addressed to meet local interconnection issues. This requirement comes in three different ways: by assuming a Q set-point, by power factor control or by managing power reactive flow as a function of grid voltage. The insular approach, for now, relies basically on power factor band specification that must be provided by the wind farm under normal operation. Again, instructions concerning solar power plants are completely absent in the regulations under analysis. Common range goes 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 unity power factor.

Given that the alternative ways to express reactive power support are not imposed by insular grid operators, it is necessary to conduct the analysis relying on mature standards, such as occurs in continental Europe. The Q set-point related to active power generation is one of the strategies adopted in Danish code. It distinguishes the support level according to the wind farm global rating power. Fig. 2 indicates that at power levels above 20% of the rated power, the wind farm whose rating exceeds 25MW has to provide an additional 33 % of reactive power, as maximum, to the instantaneously available active power output. Whereas, smaller wind power facilities have to provide an additional 23% of reactive power. The criterion for reactive range requirement must cover Q capability over the full output range through the specification of Q-P diagrams. However, it should be pointed out that during periods of reduced wind or solar production the reactive power capability is lower.

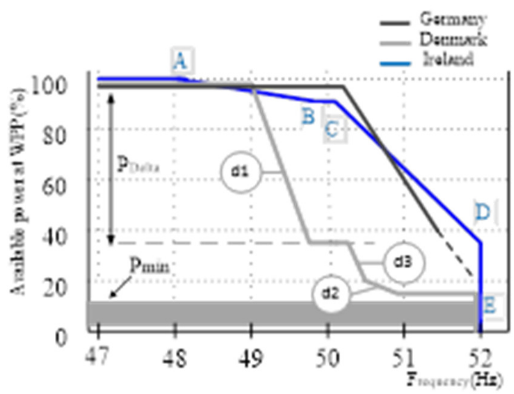

Fig.1. Power-frequency response required by mature grid codes in mainland networks.

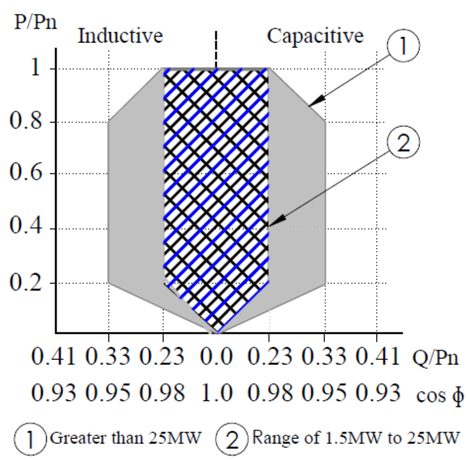

Fig. 2. Danish P-Q interconnection requirements for wind power plants.

When the active power output is low and doesn´t surpass a certain threshold, a less strict reactive power range could be imposed to solar or wind power plants under the grid code requirement. The third way of reactive power compensation is illustrated in Fig. 3, using as example the framework directives of the German regulator. The reactive power compensation range targets diverse voltage levels on the power system, from distribution to transmission networks. Renewable generation units must meet the reactive power capability within the area specified by the TSO, which is free to choose between three variants on the basis of relevant network requirements. In addition, the grid operator may alternate between the Q-V variants over time, whenever it is required. Reactive power compensation acting directly on grid voltage deviation has some merits when compared to the other reactive power compensation approaches. The strongest argument relies on terminal voltage limitations that could affect reactive power generation of variable generators, including renewable power sources [14]. The criterion for reactive range requirement must cover Q capability over the full output range through a specification of Q-P diagrams. Since grid voltage level has a direct impact on renewable power source ability to provide reactive power, the Q-V diagram could also be required as a grid code specification in order to minimize its effect [15].

Emulating Inertia of Conventional Power Plants. “Virtual” wind inertia is a relatively new concept that can expand power-frequency response capability of a wind turbine to further improve grid frequency stability. The concept relies on using the kinetic energy stored in rotating masses of the wind turbine. Despite wind turbine technologies have different inertial response performances [16] 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 [17]. This requirement should be seen as an additional reinforcement of primary power-frequency response of a wind turbine.

4.2 Special Requirements under Network Disturbances

While conventional power plants, such as based on synchronous generators, have strong strength capabilities to resist to symmetrical and asymmetrical faults without being disconnected, wind power plants were not initially designed to handle grid faults. From an insular grid stability point of view, an unexpected shutdown of a wind farm may slow power system recovering because there is less generation to support it. For grid security reasons, renewable power plants should be tolerant to faults, at least during a short time, enough for fault clearance.

Fault Ride through Capability. It is the ability of a generator to survive a transient voltage dip without being tripped. Compliance with this requirement means the generator must be able 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 capability is normally specified through a voltage-against-time profile, which establishes minimum phase-to-phase voltages at PCC for a maximum time frame. Typically a FRT requirement defines three main areas of response depending on voltage deviation severity and time duration of the anomaly. Voltage drop down to 90% of the voltage in the point of connection is not considered significant enough to damage the generator. Dropping below this value a generic FRT requirement establishes a maximum voltage drop at which a generator is forced to stay connected to the grid for a maximum exposure time, independently of the grid fault severity level and the number of faulty phases involved on the grid voltage anomaly. Between the maximum and minimum voltage drop, the exposure time to grid fault is extended as voltage deviation is lower. For voltage-time value pairs below the FRT line, the generator may be instructed to show a specific behavior before being tripped. Two grid codes were chosen to highlight a typical FRT curve. Fig. 4 shows mandatory profiles described on Danish and German regulations. It should be noted that only the German regulatory framework aims to implement the requirement on a global sense, without targeting a specific renewable power source type. German grid code is in comparative terms the most demanding one. A full short-circuit at PCC must be supported by the wind turbine for a time window of 150 ms, which is a typical operation time of the protection relays while for the Danish network the anomaly tolerance is extended to 500 ms, but it is less severe in terms of voltage drop. It should be noticed that for the German case, wind farms may prolong their connection below the blue area upon agreement. As regards the insular European codes, low voltage ride-through compliance is already imposed in large insular systems such as the Canary archipelago (Spain) or the Crete Island (Greece), where renewable power penetration has grown over the last decade. Fig. 5 presents FRT specifications for Canary Islands, Crete and French Islands [18]-[21]. Comparatively to the mainland grid codes previously analyzed, insular voltage-time curves look very similar. Of the three codes analyzed, only in the Canary Islands wind power plants have to withstand instantaneous voltage drop down to zero for a time duration of 150ms. Extensive research concerning the ride-through control capability of wind turbine systems, and other DG systems as well, have showed that with adequate strategy control it is feasible.

Reactive Power Response. Since voltage recovering is a critical point, an additional effort is also required to the non-dispatchable power sources: a reactive current injection mechanism has to be activated as long as fault recovering is underway, followed by a progressive re-introduction of active power after the fault clearance. This capability is seen as crucial for a faster power system recover. This issue is even more critical if we consider that for an insular power network, due to its size and the absence of strong connections, any disturbed operating condition is immediately observed in every corner of the network.

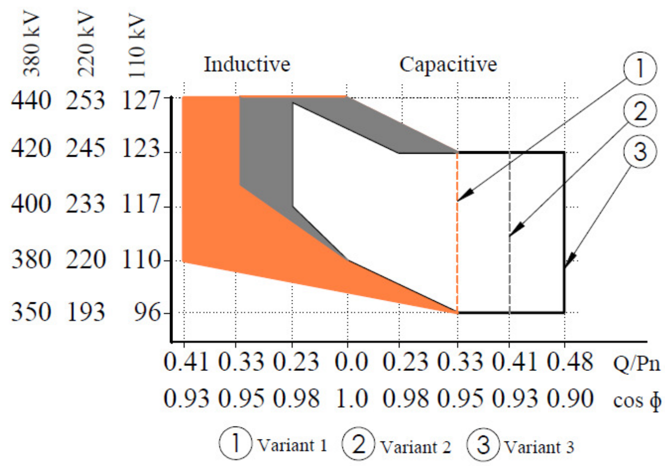

Fig. 3. Reactive power capability requirements for German case.

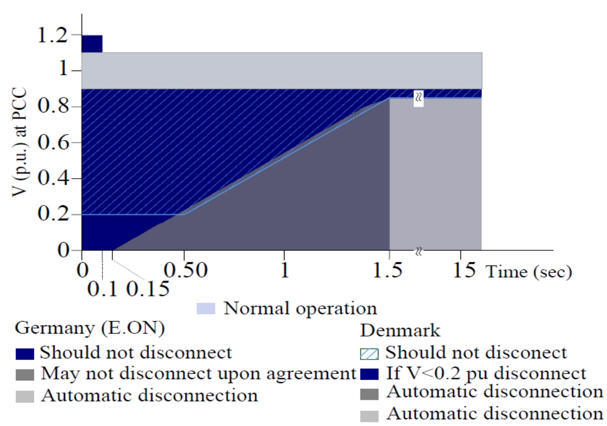

Fig. 4. FRT interconnection requirements for German and Danish codes.

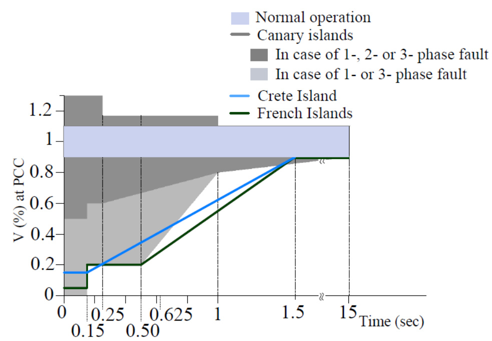

Fig. 5. FRT curve examples required in European insular power systems.

Moreover, island grids are characterized by low short circuit power, which exacerbates the instability, contributing for example to a high variation of voltage when a defect appears. Therefore, a quick mitigation of the under–voltage phenomena is essential to normalize active power generation in order to ensure the power balance within the grid, consequently keeping the frequency in a normal range. Insular grid codes evolution on this topic is still scarce. However, the starting point for the introduction of this requirement has already been taken.

In Fig. 6, the rules in effect for the Canary Islands (Spain) are depicted, along with two non-insular equivalent specifications. For the insular Spanish grid code the wind turbine consumes reactive power as long as the voltage recover is underway. Also, for a drop voltage higher than 50% of the nominal voltage, reactive current does not surpass 90% of the global current injected on the grid. Moreover, the figure reveals that there is no reactive power absorption until full voltage recovery. These constraints prevent additional instability on the voltage line. A visual comparison with the other two requirements leads to the conclusion that the German grid code is by far the most severe in terms of reactive power injection, forcing the wind power turbine to delivery only pure reactive current.

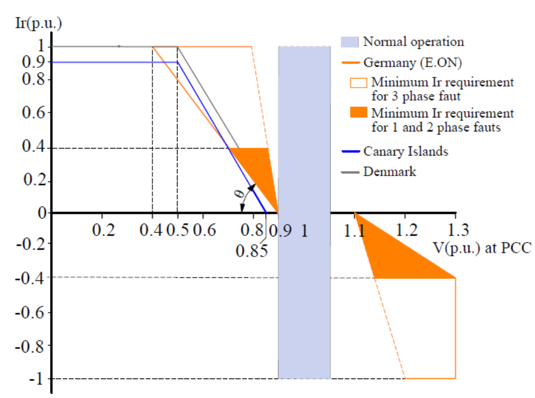

Fig.6. Comparison of reactive power requirements during a voltage disturbance.

5 Insular Smart Grid

A large renewable integration means a considerable dispersion of variable power production (VPP) of small scale, scattered across the island landscape. A complete change from a traditional organization to a network based on DER requires a new whole concept to operate the bulk electricity power. The smart grid concept embraces a set of advanced features, among them, monitoring and controlling of each grid element, whatever is the production entity or the physical distribution link, including real-time consumption tracking as well. Isolated networks being prone to stability issues are well suited to evaluate smart grid technologies. Smart grid operating strategies are today being studied in diverse insular regions in detriment of pilot projects on large interconnected systems. The successful implementation of insular Smart Grids implies meeting two key milestones: reinvention of grid operator's role and the establishment of a reliable and efficient communication backbone.

5.1 Transmission/Distribution System Operators

Grid agents will have to evolve to adapt their role with the development of a Smart Grid related infrastructure, as well as their interactions with new players of the energy system, which are the renewable DER systems. The nature of the interactions can be described as key services to enable a reliable, secure and efficient exploration of the insular grid (Table 1).

Table1. Grid agent's role toward smart grid integration for an insular power system.

Power network optimizer	*Contributor to system security*	*Data manager*	*Smart meter manager*	*Grid users / Suppliers relationship manager*	*Neutral market facilitator / Enabler*
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.	Cooperate with the grid actors by offering new contributions to ensure the system security.	Gaining ability to manage large amounts of data and process them to produce relevant internal/external services.	Promote, operate and maintain smart meters in a cost-efficient way, while providing consumers with new services.	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.	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.

5.2 Communication and Supervisory Control

The information exchange between the VPP control center and the power plant is critical, promoting a successful change from centralized generation to distributed generation based paradigm. The link should be permanent, dependable and providing bi-directional communication capabilities. From system operator side through the control center, customized dispatch orders are sent to renewable power plants. On the other side, every distributed generation (DG) unit reports its operating conditions to the island operator system. Then, according to the received information, dispatch orders are updated to meet power demand and to stabilize grid electrical parameters.

6 Conclusions

In this paper, the technical requirements for large-scale integration of renewable energy sources were discussed regarding their incorporation in island grid codes, as a new contribution to earlier studies. By adding control and regulation capabilities to renewable systems, they change from a passive participation on the grid to an active role, providing services only normally found in conventional power plants. Insular power grid reform into a smart grid infrastructure was also addressed in this paper. Emphasis was given to the grid agents/operators new role and to the distributed communication network, as a catalyst of the renewable revolution alongside grid code evolution.

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