Overview of Recent Grid Codes for Wind Power Integration

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***Abstract*- As wind power penetration level increases, power system operators are challenged by the penetration impacts to maintain reliability and stability of power system. Therefore, grid codes are being published and continuously updated by transmission system operators of the countries. In this paper, recent grid codes, which are prepared specially for the large wind power plants, are analyzed and compared. Also, harmonization of different grid codes in a common manner and future trends are assessed.**

I. INTRODUCTION

Wind power penetration to power systems increases in large amounts worldwide. The transmission system operators (TSO) have revised their grid codes which are technical interconnection requirements for the wind power plants (WPP). There are also different requirements for the distribution system operators (DSO) however, the grid codes, which are surveyed in this paper, are related only for transmission systems.

The grid codes are significant due to the following statements:

- TSOs must maintain stability and reliability of power dispatch regardless the generation technology.
- The technical negotiations between TSOs and power plant operators must be clear, transparent and reduced as much as possible.
- On the power plant manufacturer side, they must design equipments and controllers considering these grid codes, and they should not make changes without the TSO's permission.

Conventional power plants, which are composed of synchronous generators, are able to support the stability of the transmission system by providing inertia response, synchronizing power, oscillation damping, short-circuit capability and voltage backup during faults. These features allow the conventional power plants comply with the grid codes, thus today TSO have a quite stable and reliable grid operation worldwide.

Wind turbine generator technical characteristics, which are mainly fixed and variable speed induction generators, doubly fed induction generators and synchronous generators with back to back converters, are very different to those of the conventional generators. As the installation of WPPs, which consist of these wind turbine generators, has reached important levels that they have a major impact on the characteristics of the transmission system [1]. Therefore, the grid codes demand WPPs to behave as much as similar to the conventional power plants for maintaining power system stability and reliability. Simultaneously the wind turbine manufacturers have been challenged by the new grid codes as they must adapt their technology to satisfy these grid codes. After adaptations and developments in the wind turbine technology, TSOs and WPP developers will work together and revise the grid codes in order to assist the future WPP connections without destabilizing the transmission system [2]. This is an iterative process regarding TSOs, WPP developers and operators.

As grid codes have evolved especially in the countries with already or planned high wind power penetration, technical analyses of the main issues related to the WPP connection are provided in the literature [3], [4]. This paper provides first, main requirements of the WPP connection in different countries and then, compares the resent available grid code versions. The current grid codes of these countries are listed in Table I.

In Section II, the common technical issues for connection of WPPs are described briefly. Section III compares the latest available versions of the grid codes listed in Table I. Grid codes harmonization and future trends are discussed in Section IV.

TABLE I
GRID CODES IN COUNTRIES WITH HIGH WIND POWER PENETRATION

Country	TSO	Release Date	Ref
Denmark	Energinet.dk	December 2004	[5]
Germany	E.ON, EnBW, Vattenfall, RWE	August 2007	[6]
		2009	[7]
		2008	[8]
Spain	Red Electrica	March 2006	[9]
		October 2008	[10]
		2007	[11]
		2000	[12]
UK	NGET	June 2009	[13]
Ireland	EIRGRID	April 2008	[14]
US	FERC, WECC	June 2005	[15]
		July 2009	[16]
China	CEPRI	July 2009	[17]

II. COMMON TECHNICAL REQUIREMENTS IN GRID CODES

According to the grid codes, the technical requirements are defined for the connection and operation of WPPs in the transmission system. The following requirements, which are common in most of the grid codes, have been considered in this paper:

- Normal operation:
  - Frequency and voltage ranges
  - Active power (P) control
  - Reactive power (Q) control
- Behavior under grid disturbances
  - Voltage ride through (VRT)
  - Reactive current injection (RCI)

WPPs must be required to operate within a range around the rated voltage and frequency at point of common coupling (PCC) to avoid instabilities due to the grid disturbances. Typically this requirement can be described as the following frequency/voltage operation zones:

- Continuous operation in a limited range below and above the nominal point.
- Time limited operation with possible reduced output in extended ranges.
- Immediate disconnection.

For normal grid operations, active power control requirement is defined as an ability to adjust the active power output with respect to the frequency deviations and the orders coming from the TSO. According to this requirement, WPPs can participate both in primary and secondary frequency control.

Reactive power control in normal operation is generally reactive power regulation in response to the PCC voltage variations. The reactive power requirement is related to the characteristics of each grid as a voltage changing capability, which depends on the grid short-circuit power. There are three different ways for this requirement; reactive power set point control, power factor (PF) control, and voltage control.

Grid disturbances in the form of voltage sags or swells can typically lead to WPP disconnections that may cause instability and yield in blackouts. To avoid this, the grid code requires continuous operation even if the voltage dip reaches very low levels (in some cases 0 pu), support the voltage recovery by injecting reactive current and active power restoration after the fault clearance with a limited ramp values. These typical features are generally defined in grid codes as follows

- VRT in terms of minimum (low VRT) and maximum (high VRT) voltage ride through and recovery slope for symmetrical and asymmetrical faults that WPPs must be able to withstand without disconnection from the grid.
- Active power and reactive power limitation during faults and recovery.
- RCI for voltage support during fault and recovery.
- Restoration active power with limited ramp after fault clearance.

III. COMPARISON OF THE GRID CODE REQUIREMENTS

A. Frequency and voltage deviations under normal control

The voltage-frequency operational window for grid codes is graphically represented in Fig. 1 and Fig.2. The strictest continuous operation limits for frequency appear in the British code [13] (47.5-52 Hz) and for voltage in the Chinese grid code [17] (90-110% nominal voltage). It is obvious that the most extreme frequency limits 46.5 Hz and 53.5 Hz are for EON offshore [8].

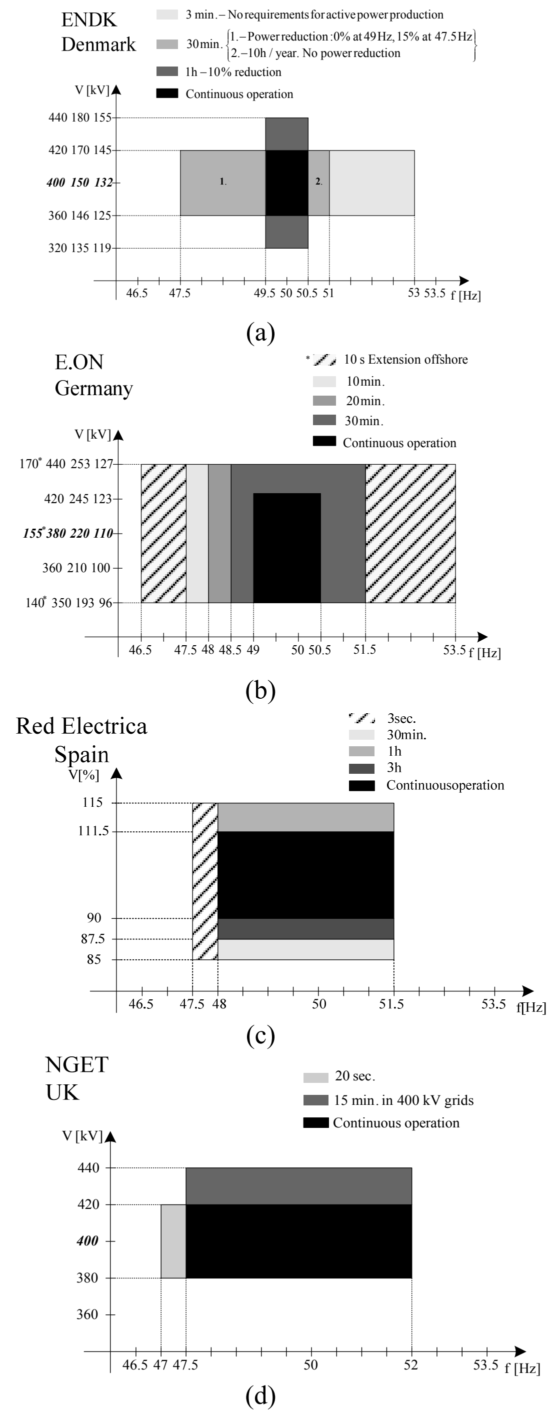
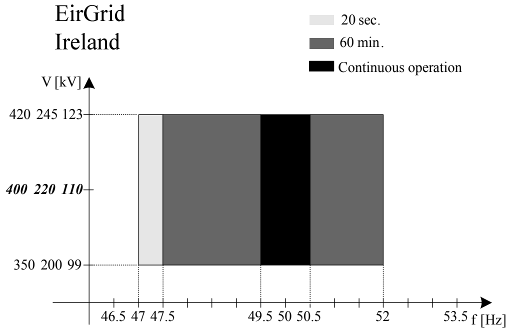
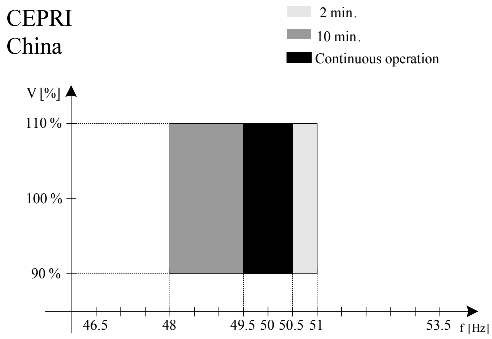


Fig. 1. Limit Voltage-frequency operation window for Denmark (a), Germany (b), Spain (c), UK (d) grid codes.



(e)



(f)

Fig. 2. Limit Voltage-frequency operation window for Ireland (e), China (f) grid codes.

B. *Active Power Control in Normal Operation*

Active power curtailment requirements are different across the countries as given in Table II.

As a particularity in Denmark, various types of power curtailment are requested [5].

The frequency control participation is varying with respect to transmission system characteristics.

According to the German code [7] when frequency exceeds the value 50.2 Hz, wind farms must reduce their active power with a 0.4 pu/Hz gradient (WPP 40% of the available power).

The British code [13] requires that wind farms larger than 50 MW to have a frequency control device capable of supplying primary and secondary frequency control, as well as over-frequency control. It is remarkable that it also prescribes tests, which validate that wind farms indeed have the capability of the demanded frequency response.

In Spanish grid code, WPPs must be able to give active power increase or decrease active power output proportional to the frequency deviation at the connection point. The frequency control must work as a droop controller of which values vary between 0.02 and 0.06 pu based on wind power plant ratings. Speed of the response will be adjustable 10% of the rated capacity in 250 ms.

The Irish code [14] demands a frequency response as described in the curve in Fig. 3.

TABLE II
ACTIVE POWER CURTAILMENT RATES

Country	Active Power Ramp Rate Range		
Denmark	20 – 100% with accuracy of 5% (5 min average)		
Germany	At least 10% of grid connection capacity per 1 min. (to a set level higher than 10%)		
Spain	-		
UK	-		
Ireland	over 1 min 1–30 MW per min. (activation time less than 10 s)	over 10 min 1–30 MW per min. (activation time less than 10 s)	
China	Inst. capacity <30 MW	Inst. capacity 30-150 MW	Inst. capacity >150 MW
	over 1 min. max ramp: 6 MW	over 1 min. max ramp: inst. cap. / 5	over 1 min. max ramp: 30 MW
	over 10 min. max ramp: 20 MW	over 10 min. max ramp: inst. cap. / 1.5	over 10 min. max ramp: 100 MW

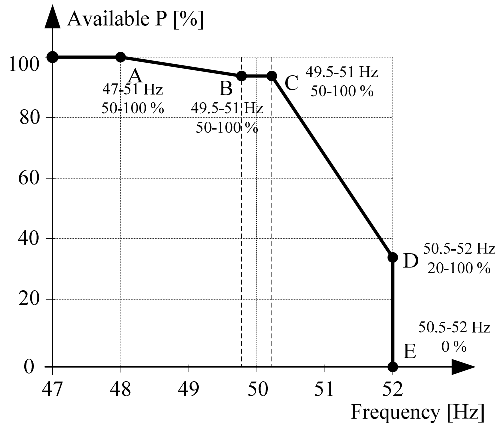


Fig. 3. Irish P-f curve.

The values for the power and frequency of ABCDE points should be online modified by the TSO within the ranges shown in the Fig. 3. This is due to the fact that in order to obtain a smooth participation of WPP in the TSO frequency control, the active power ramp should be imposed by TSO in harmony with the frequency response of the other participants to the balancing act.

C. *Reactive Power Control in Normal Operation*

1. *Germany*

The minimum requirements for reactive power generation [7] are given in the form of areas as function of voltage at nominal active power and as function of active power for the cases when the WPP is working at derated power for different ranges of voltages inside the normal operation range. The requirement can be given as a reactive power requirement or a power factor requirement. As the characteristics of the grid may differ depending on location and strength, three variants are defined by the Germans TSO's as depicted in Fig. 4 and Fig. 5.

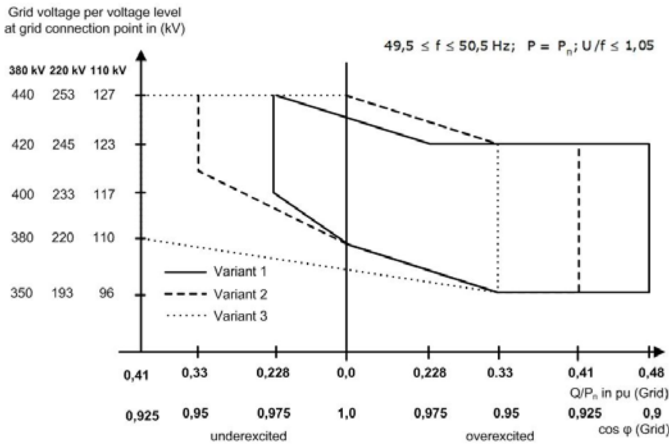


Fig. 4. Three variants of V-Q dependencies defined in Germany grid code.

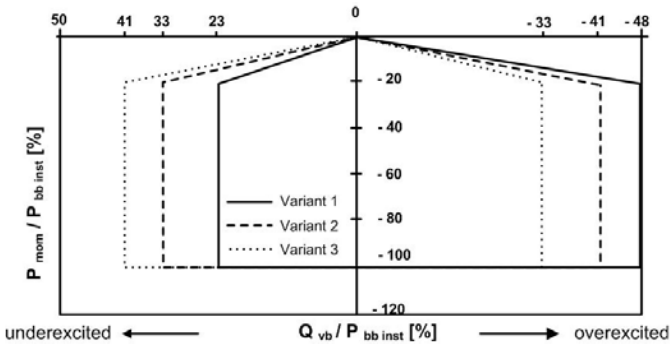


Fig. 5. Three variants of P-Q dependencies defined in Germany grid code.

2. Spain

The reactive power requirements during normal operations are defined by the directive [12], which applies to all generation on high voltage (HV) level both conventional and renewable. The following requirements are defined as a function of active power and transmission voltages as follows:

- Min. range 0.15 inductive - 0.15 capacitive for all technical active power range and nominal voltage
- Min. range 0.30 inductive - 0.30 capacitive as a function of the voltage shown in Fig. 6

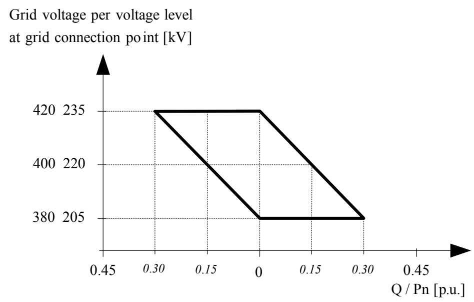


Fig. 6. V-Q dependence in Spain grid code.

3. Denmark

In the Danish grid code [5], the 10 s average PQ diagram is given as shown in Fig. 7 which applies for the whole range of voltage during normal operation. Basically it defines a control

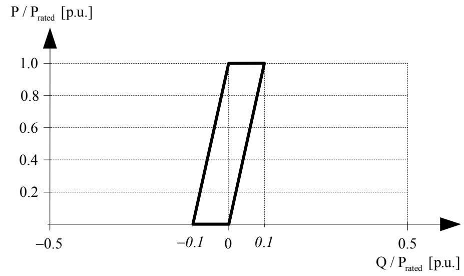


Fig. 7. P-Q dependence in Denmark grid code.

band of 0.1 pu. In comparison with the Germany and Spanish grid codes, the minimum required reactive power is lower.

4. UK

The British [13] code is specifically formulated for non-synchronous embedded generation and requires a power factor in the range 0.95 inductive to 0.95 capacitive at 1 pu active power for connection to the HV system (132/275/400 kV). This requirement equivalent to 0.33 pu reactive power should be maintained for active power down to 0.2 pu for lagging power factor and down to 0.5 pu for leading power factor. The grey area in Fig. 8 is an extension of the reactive power requirements in the dashed are for active power lower than 0.2 pu a lower band of pu of reactive power is required at low power leading power factor that can be required after agreement with the TSO (NGET).

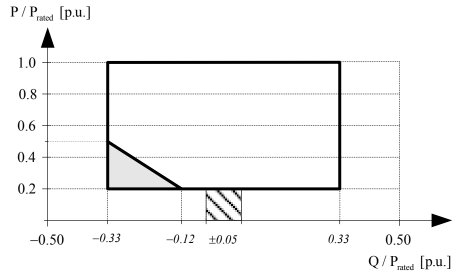


Fig. 8. P-Q dependence in UK grid code

5. Ireland

The Irish code [14] is quite similar but with 0.33 pu reactive power for both lagging and leading power factor as shown in Fig. 9 and with the reactive power requirements decreasing linearly to zero proportional to active power for lower than 0.5 pu.

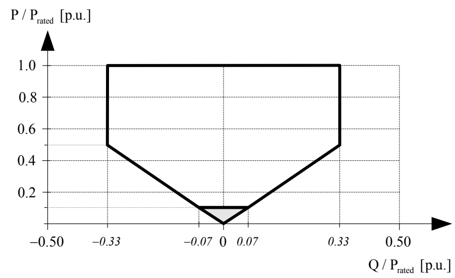


Fig. 9. P-Q dependence in Ireland grid code.

6. *US*

The US FERC 661 code [15] is specifying that reactive power in the power factor range 0.95 inductive to 0.95 capacitive can be required by TSO on a situation, which is not permanent operation but dynamically employed.

D. *Behavior Under Grid Disturbance*

1. *Germany*

The VRT and RCI are described in Fig. 10 and Fig. 11, respectively.

VRT

- Within the black area no interruptions is allowed. The WPP must stay connected even when the PCC voltage is zero. The 150 ms accounts for typical operating time of protection relays.
- Within the dark grey area, if the facility is facing stability issues, short time interruptions (STI) with resynchronization in maximum 2 s are allowed.
- The voltage value in Fig. 10 refers to the highest value of all three phase grid voltages measured at the low voltage side of the transformer in each wind turbine.

P and Q limitation during faults and recovery

- During faults, the active current can be reduced in order to fulfill the reactive current requirements

Minimum reactive current injection

- In case of significant deviation of the voltage, proportional reactive current has to be injected/absorbed as shown in Fig. 11, which indicates that rated reactive current can be requested for a voltage deviation of 10%.
- The response time of reactive current controller should be max 30 ms and the control band should be between –10% and +20% of the rated current.

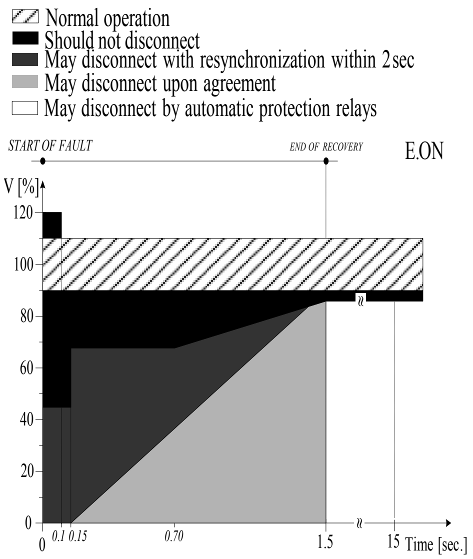


Fig. 10. VRT requirements in German grid code.

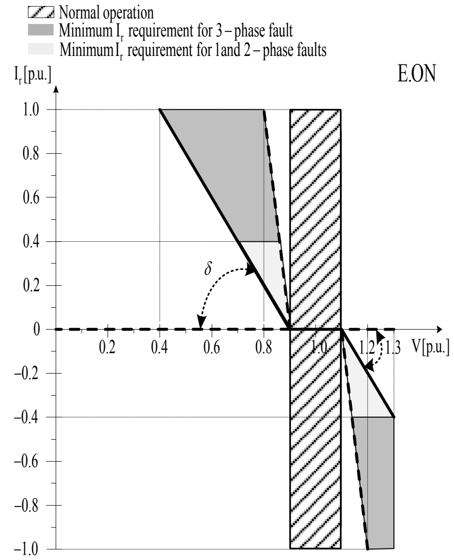


Fig. 11. Reactive Current Injection Requirements in German grid code.

- The reactive current requirements in Fig. 11 apply for the highest value of the three phase voltages in case of faults within the black area.
- For 1 and 2-phase faults, the maximum reactive current can be limited to 40% of the rated current.
- After fault clearance, the reactive current reference should not change stepwise in order to avoid stability issues.
- For voltages below 0.85 pu, if the facility is unable to supply the reactive power required for voltage support, the so called “Safeguard I” implemented in PCC will trip the wind farm after 0.5 s. “Safeguard II” at the wind turbine level is implemented as system protection acting after 1.5 s and includes the stepwise tripping of wind turbines.

Resuming Active power

- After fault clearance without disconnection, the active power feed-in must be continued immediately after fault clearance and increased to the original value with a gradient of at least 20%/s.
- In case of short disconnection, the active power feed-in must be resumed immediate after fault clearance with a gradient of at least 10%/s.

2. *Spain*

The VRT and RCI requirements of Spain are described in Fig. 12 and Fig. 13, respectively.

VRT

- During the whole transient regime, the facility must be able to inject to the grid at least the nominal apparent current.

P and Q limitation during faults and recovery

- The facility might not consume active and reactive power at the grid connection point during both, fault duration and the duration of voltage recovery following fault clearance.

- Momentary active or reactive power consumption (<0.6 pu) is allowed during just the first 40 ms after the start of the fault and the first 80 ms after the clearance of balanced (three-phase) faults.
- Momentary active or reactive power consumption (<0.4 pu) is allowed during just the first 80 ms after the start of the fault and the first 80 ms after the clearance of unbalanced faults (single-phase and two-phase).

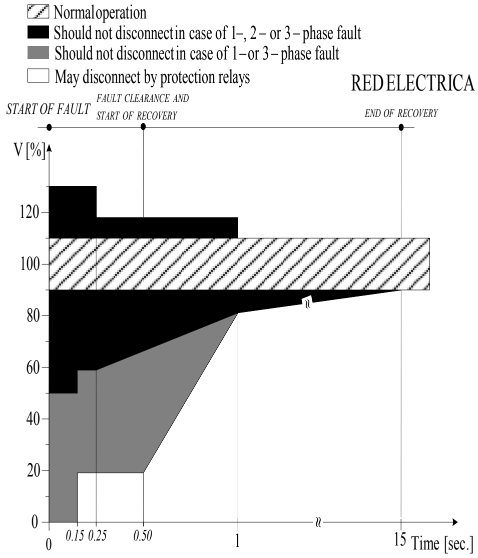


Fig. 12. VRT requirements in Spain grid code.

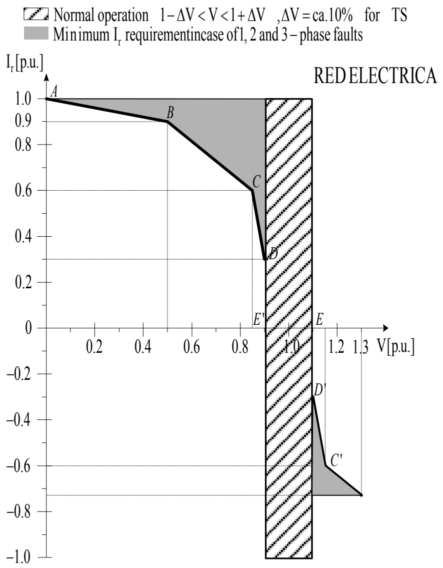


Fig. 13. RCI requirements in Spain grid code.

Reactive current injection

The requirements of reactive power generation under voltage faults (V<0.85 pu) are implemented similarly as for the case of automatic voltage regulation (AVR) in conventional synchronous generation, i.e. in the form of a PI voltage controller with reactive current reference I_r as output, as shown in Fig. 14. V_c is the voltage set point (rms), V is the PCC voltage (rms) and I_r is the instantaneous reactive current reference. The saturation levels are voltage dependent as explained in Fig. 14.

The following particularities apply:

- The controller will be enabled for any voltage outside the normal operation range.
- If the WPP was working in voltage control mode in normal operation, the voltage set point during fault will remain unchanged.

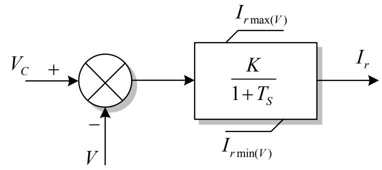


Fig. 14. Reactive current injection requirements in Spain during FRT.

- If the WPP was working in reactive power or power factor control mode, during the disturbance the voltage set point will be the voltage prior to the fault if the normal operation set to reactive power or power factor allocation.
- During the fault, the facility should inject/absorb positive sequence reactive currents based on the action of the voltage controller with minimum saturation levels defined by the polygonal curve ABCDE as shown in Fig. 13. In case of overvoltage, the saturation levels are mirrored but for voltages higher than 1.3 pu, disconnection is required by protection relays.
- These levels should be implemented as saturation levels for the voltage controller that runs in both normal and faulty operation.
- For the range 0.85≤V≤1.15 pu, the injected reactive current will react according to the voltage control, possibly saturating the regulator limits.
- Once the fault is cleared, the voltage controller will keep be enabled for at least 30 s after voltage level reenter the normal operation range. Afterwards, the voltage controller will be disabled and the reactive power requirements for normal operation will apply

Active current injection

- During faults, the facility should limit the active current within the grey area as shown in Fig. 15 (excluding the active current increments/reductions due to frequency control or, if applicable inertia emulation).

As it can be seen, the active current limitation is a function of P_{ao}, the active power that the facility was generating prior to the disturbance and voltage level.

- For voltage levels lower than 0.5 pu, the active current can be reduced to zero.
- Any possible violation of these active current limits must be corrected before 40 ms.

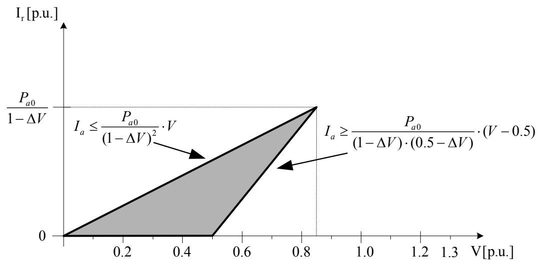


Fig. 15. Active power limitation in Spain during FRT.

- In case of current saturation, reactive current limitation given by voltage controller saturation has priority over active current limitation.
- For voltages higher than the normal operation, the facility will seek if possible, to maintain the active power level prior to the disturbance.
- The gain of the active current controller should ensure dynamic response (90% rise) in less than 40 ms for V<0.85 pu and 250 ms for V>0.85 pu

Resuming Active power

- The voltage dependent active current control previous mentioned ensures that after the fault clearance without disconnection, the active power level prior to disturbance will be restored smoothly within 250 ms.

3. Denmark

The VRT requirement for Danish grid code is as shown in Fig. 16, which is valid only for three-phase faults. For single or double-phase faults, wind power plant should be able to withstand unsuccessful reclosures in the transmission network [5].

During the voltage dip the wind farm must as a maximum take a reactive current measured in at the grid connection point corresponding to 1.0 times the nominal current of the wind farm.

1. US

The recent WECC LVRT standard [16] is an effort to create compliance with the federal regulation FERC Order

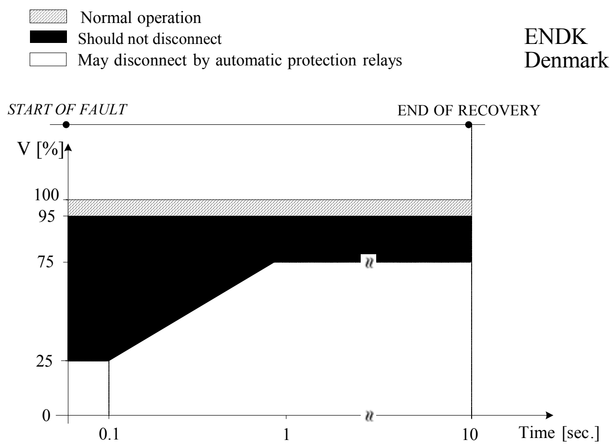


Fig. 16. VRT in Denmark Grid Code.

661-A [14] in terms of fault voltage level and duration (0V for 9 cycles) and boundaries for time of voltage recovery for both LVRT (until voltage became higher than 90%) and HVRT (until voltage became lower than 110%) shown in Fig. 17.

VRT

- All generators are required to remain in-service during three-phase faults with normal clearing (for a maximum of 9 cycles) unless clearing the fault disconnects the generator from the transmission system
- The voltage is measured at high voltage side of the WPP step-up transformer
- For single-phase faults, delayed clearing times apply unless clearing the fault disconnects the generator from the transmission system
- TSO should provide to the WPP owner the normal breaker clearing time for three-phase faults and delayed clearing time for single-line-to-ground faults at the high voltage side of the generating plant step-up transformer
- There is no requirement for power limitation during fault or reactive power injection during fault or recovery.

IV. Discussion of Harmonization of Grid Codes

From the survey presented above, it can be observed that the interconnection regulations vary considerably from country to country. It is often difficult to find a general technical justification for the existing technical regulations that are currently in use worldwide due to the different wind power penetration levels in different countries and operational methodology of power systems.

For instance, countries with a weak power system, such as Ireland, have considered the impact of wind power on network stability issues, which means that they require fault ride-through capabilities for wind turbines already at a lower wind power penetration level compared with countries that have very robust systems. The inclusion of FRT regulations for DFIG noticeably increase overall cost by 5%. The European Wind Energy Association (EWEA) recommends that regulations for the European grid connection (or other nations) are to be developed in a more consistent and harmonized manner [18].

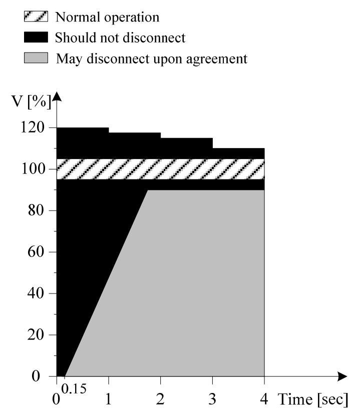


Fig. 17. VRT in US-WECC.

Harmonized technical requirements will bring maximum efficiency for all parties and should be employed wherever possible and appropriate. While this applies to all generation technologies, there is a particular urgency in the case of wind power. As wind penetration is forecasted to increase significantly in the short to medium term, it is essential that grid code harmonization should be tackled immediately. It will help manufacturers to internationalize their products/services, developers to reduce cost, and TSOs to share experience, mutually, in operating power systems. It is also important that the national grid code should aim at an overall economically efficient solution, i.e., the costly technical requirements such as ''fault ride through'' capability for wind turbines should be included only if they are technically required for reliable and stable power system operation. Hence, it can be summarized that grid codes should be harmonized at least in the areas that have little impact on the overall costs of wind turbines. In other areas, grid codes should take into account the specific power system robustness, the penetration level, and/or the generation technology.

V. Future Trends

The following requirements are expected to be included in the future grid codes:

Local Voltage control

Both the Spanish and the German grid codes have increased the complexity of the reactive current injection during fault and recovery and a continuous local voltage control may prove to be necessary, particularly for offshore wind farms [19].

Inertia Emulation

The Spanish grid code [10] mention that even if for the moment the ability to emulate inertia is not yet compulsory it is strongly recommended and it may be introduced as a requirement later.

The implementation of emulated inertia should be in the form of proportional-derivative controller acting on frequency variation as input and outputting the necessary power variation as shown in Fig. 18.

The following particularities apply:

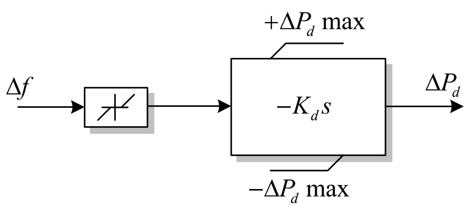


Fig. 18. VRT in US-WECC.

- The gain K_d should be adjustable between 0 and 15 s, and the response time should be such that in 50 ms the active power should increase at least by ΔP=5%.
- In order to be able to generate the required saturation levels: $\pm\Delta P_d$max, energy storage of any technology is required able to inject or absorb at least 10% active power for at least 2 s.
- The deadband of frequency variation will be limited to $\pm$ 10 mHz.
- The Inertia Emulation should be disabled for voltages lower than 0.85 pu.

Power Oscillation Damping (POD)

This is another feature strongly recommended by the Spanish grid code [10], where just like in the case of the synchronous generators, the system should be able to increase or decrease the output power in such a way to reduce the power oscillations in the low frequency range (0.15 – 2.0 Hz). The following specific requirements apply:

- The POD can be implemented by "sharing" the existing power-frequency regulator.
- The POD can "share" the energy storage used for Inertia Emulation.
- The deadband of frequency variation will be limited to $\pm$ 10 mHz.
- The POD should be disabled for voltages lower than 0.85 pu.

VI. Conclusion

In this paper, the grid code technical requirements were presented for the connection of wind farms to the power systems, basically at the HV level. A comparative overview and analysis of the main requirements were conducted, comprising several national codes from many countries where high wind penetration levels have been achieved or are expected in the future. The objective of these requirements is to provide wind farms with the control and regulation capabilities encountered in conventional power plants and are necessary for the safe, reliable and economic operation of the power system. Current wind turbine technology, particularly developed over the last years, has been heavily influenced by these requirements. Modern wind turbines are indeed capable of meeting all requirements set, with the exception of the constant speed machines, which are practically not marketed anymore for large scale applications.

Acknowledgment

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