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Grid Integration Issues for Large Scale Wind Power Plants (WPPs)

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Abstract— **The penetration level of wind power into the power system over the world have been increasing very fast in the last few years and is still keeping the fast growth rate. It is just a matter of time that the wind power will be comparable to the conventional power generation. Therefore, many transmission system operators (TSOs) over the world have come up the grid codes to request the wind power plants (WPPs) to have more or less the same operating capability as the conventional power plants. The grid codes requirements from other TSOs are under development. This paper covers the steady state operation and low voltage ride through (LVRT) for the WPPs. The discussion of coping with the grid codes requirements is presented to come up with the grid codes complied WPPs solutions.**

***Index Terms*— Wind Power, Transmission System Operators (TSOs), Grid Codes, Wind Power Plants (WPPs), Grid Integration Issues, PQ Capability, Low Voltage Ride Through, Voltage Control, Frequency Control**

I. INTRODUCTION

The wind power capacity over the world has achieved a dramatic growth in the last few years. Till the end of 2008, the installed wind power capacity of the whole world reaches 121,188 MW, out of which 27,261 MW was installed in 2008 [1]. The new installed wind power capacity from 1998 to 2008 is illustrated in Figure 1. The US installed a record 8.4 GW in 2008 and became the number one in terms of the total installed wind power capacity for the first time. China doubled its installed capacity in 2008 again and has more than 12 GW installed wind power capacity. European wind power industry continues to broaden and deepen.

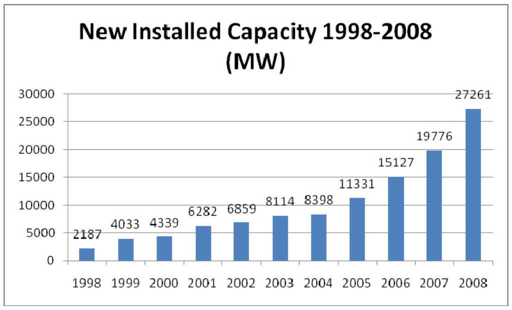

Figure 1 New Installed Wind Power Capacity from 1998 to 2008

With the rapid growth of installed wind power capacity, the wind power is going to have a big share of the whole system installed capacity. The wind power will have a big impact on the system steady state and dynamic operation. In the past time, the wind power plants (WPPs) are allowed to be disconnected under system disturbances. But with the high penetration of wind power into the power systems, the disconnection of WPPs will make it difficult for the system to withstand the system disturbances. Therefore, the grid codes have specified the requirements for the WPPs under the steady state and dynamic conditions. The WPPs have to have the voltage and frequency regulation capabilities under the steady state condition. Under the specified voltage dip conditions caused by the faults within the grid, the WPPs have to stay connected and to fulfill the recovery requirements.

The analysis of large scale integration of wind power in Europe was carried out in [3] regarding the power and energy balancing, grid connection and system stability, grid infrastructure extension and reinforcement, power system adequacy, market design, demand side management and storage. In the end, the recommendations for the power system operation with high amount of wind power were presented. The main problems regarding connecting wind farms to the grid were reviewed in [4] and the suggestions for the amendment of the grid codes were presented in order to integrate the wind power to the power systems without affecting the quality and stability of the system. The analysis of the grid codes of Canada, Denmark, Ireland, Scotland, Germany and UK was implemented in [5] regarding the technical requirements for integrating the wind power to the grid.

In this paper, a more comprehensive review of the grid codes was carried out with the latest grid codes and detailed discussions were implemented to come out the grid codes complied WPP solution.

II. STEADY STATE OPERATION REQUIREMENTS

Basically, the steady state operation requirements comprise power factor requirement, voltage operating range, frequency operating range and voltage quality. Normally, the steady state operation requirements for the WPPs are specified at the point of connection (POC).

1) Reactive Power/Power factor Requirement

The power factor regulation concerns the reactive power capability of the WPPs within the specified voltage range at the POC under the steady state condition. With the development of the wind turbine technology, the doubly fed induction generator (DFIGs) based wind turbine has both

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inductive and capacitive reactive power capabilities as per the active power output. The reactive power can be consumed or supplied by the grid side converter. For the full scale converter wind turbine, the range of reactive power capability is bigger because of the increased rating of the grid side converter.

The requirements for the reactive power and the power factor are similar in the different Grid Codes. The specific requirements are illustrated in Table 1.

Table 1 Reactive Power/Power factor Requirement

Country or Region	PF requirements
UK	0.95 lagging to 0.95 leading [6]
Scotland	from 100% production to 50% production, the reactive power is requested to be -32.87% to +32.87% of the rated MW, from 50% production to 20% production, it is requested to be from -32.87% to -12% for the leading part and at +32.87% of the rated MW, from 20% production to 0% production, it is requested to be -5% to +5% of the rated MW [7]
Ireland	0.95 lagging to 0.95 leading at full production, 32.6MVAr per 100MW installed for active capacity from 100% production to 50% production, 0.95 lagging to 0.95 leading from 50% production to idle [8]
Germany	0.95 lagging to 0.95 leading for a rated active power capacity <100MW, For a rated active power capacity > 100 MW the power factor is voltage dependent [9]
Denmark	Q/Prated = 0 to Q/Prated = 0.1 at full production and through a straight line to Q/Prated = -0.1 to Q/Prated = 0 at zero production [10,11]
Spain	0.98 leading to 0.98 lagging without any penalty [12]
Sweden	the reactive exchange can be regulated to zero [13]
US	0.95 leading to 0.95 lagging [14]
Quebec	the generator facilities must be designed to supply or absorb at the generating unit outlet (system side) the reactive power that corresponds to an overexcited or under excited rated power factor equal to or less than 0.95. The reactive power must be available over the entire active power generation range [15]
Alberta	0.90 lagging to 0.95 leading [16]
China	0.97 lagging to 0.97 leading [17]
Australia	Constant power factor mode:100 % power at PF_{ind} = 1.0 and PF_{cap} = 0.95; 50 % power at PF_{ind} = 1.0 and PF_{cap} = 0.95 [18]

The grid codes specified reactive power and power factor requirements in UK, Sweden, Denmark, US, Alberta, Quebec and China are very straightforward. The WPPs are requested to be able to operate within the area specified by the inductive and capacitive power factor.

The reactive power requirement in Scotland is quite complex which is illustrated in Figure 2. From 100% to 50% active power production, the WPPs are requested to have reactive power capability from -32.87% to +32.87% of the rated MW, from 50% to 20% active power production, the range of the reactive power requirement is from -32.87% to -12% for the leading part to +32.87% of the rated MW, from 20% to 0% active power production, it is requested to be -5% to +5% of the rated MW.

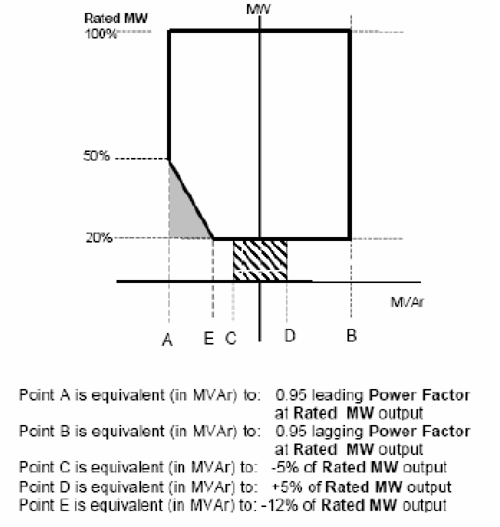


Figure 2 Reactive Power Requirement in Scotland [7]

The reactive power requirement in Ireland is illustrated in Figure 3. From 100% to 50% active power production, the WPPs are requested to have reactive power capability from -32.87% to +32.87% of the rated MW, from 50% to 0% active power production, the range of the reactive power requirement is to be within the range of 0.835 inductive power factor to 0.835 capacitive power factor, from 10% to 0% active power production, the black area indicates that the reactive power has to be adjusted as per the voltage limits.

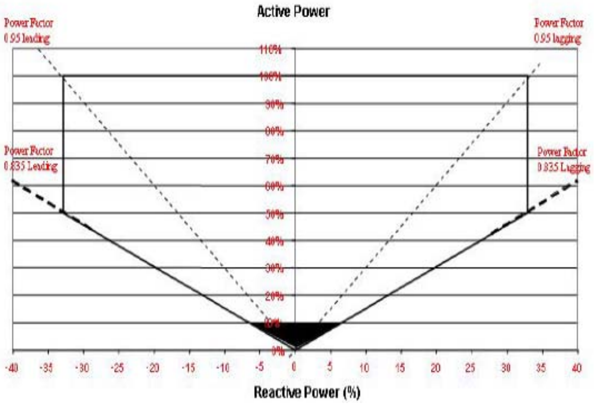


Figure 3 Reactive Power Requirement in Ireland [8]

For the WPPs in Germany, the reactive power requirements consist of two parts. For WPPs with size less than 100 MW, the reactive power requirement is same as the one in other grid codes which requests the WPPs can operate within the range specified by 0.95 inductive power factor to 0.95 capacitive power factor. But for the WPPs with size over 100 MW, the reactive power requirement is voltage dependent. The reactive power requirements for WPPs with size over 100 MW are illustrated in Figure 4. It is shown that when the voltage at the POC increases from the minimum operating level to the voltage with full power factor range, the power factor range changes from the capacitive part of 0.925 to 0.95 to the full power factor range of 0.95 inductive to 0.925 capacitive, the middle part is the voltage range with the full power factor requirement, when the voltage at the POC is above the maximum voltage with full power factor requirement, the power factor requirement is moving to the left, at the maximum operating voltage, the power requirement is reduced to inductive power factor of 0.95 to 1.0.

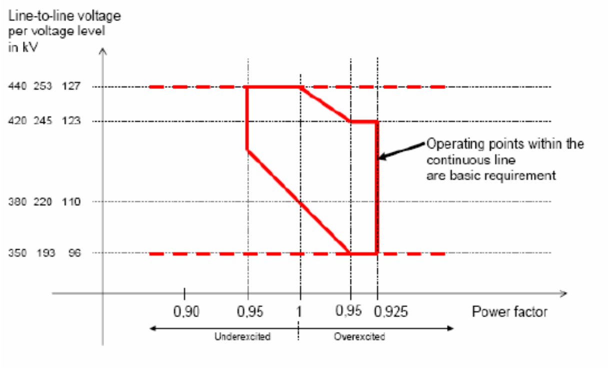


Figure 4 German power factor requirements for P_{rated} above 100MW [9]

In order to fulfill the reactive power and power factor requirements at the POC, it is recommended to use the reactive power capability of the wind turbine generators (WTGs) as much as possible.

The reactive power capability of the DFIG based and full scale converter wind turbine increases when the active power output decreases from the 100% active power output to a specified active power output. After the specified active power level, the reactive power capability of wind turbines will keep the maximum reactive power capability within a range of active power output level. When the active power output of the wind turbine is lower than the minimum active power level with the maximum reactive power, the reactive power capability of the wind turbines is kept in the range specified by an inductive power factor and a capacitive power factor.

Therefore, in order to ensure that WPPs can fulfill the reactive power requirements throughout the range of active power output range of WTGs, the power flow study at the 100% active power output is needed to be carried out. In most cases, it is good enough for the requirement within the range specified an inductive power factor and a capacitive power factor. If the reactive power requirement range at low active power output level is quite big, it is advised to carry out power flow study at the low active power output to check the power factor requirement compliance.

If the WPPs can not fulfill the reactive power requirements, the shunt reactive power compensation equipments are needed to install at the MV side of the substation of the WPPs. If the POC is far from the substation of the WPPs, it is advised to install reactive power compensation equipments at the busbar of the POC too. The size of the reactive power compensation equipments can be determined by implementing the power flow study with the specified voltage operating range and the power factor range at the POC.

2) Continuous Voltage Operating Requirement

The continuous voltage operating requirements are illustrated in Table 2.

Table 2 Voltage Operating Requirement

Country or Region	Voltage operating requirement
UK	132 kV and 275 kV ±10% 400 kV -10% to +5% [6]
Scotland	132 kV and 275 kV ±10% 400 kV ±5% [7]
Ireland	110 kV -10% to +12% 220 kV -9% to +12% 400 kV -13% to +5% [8]
Germany	110 kV -13% to +12% 220 kV -13% to +12% 400 kV -8% to +10% [9]
Denmark	132 kV -5% to +10% 150 kV -3% to +13% 400 kV -10% to +5% [10,11]
Spain	132 kV ±10% [12]
Sweden	-10% to +5% [13]
US	±10% [14]
Quebec	±10% [15]
Alberta	Provided by TSO [16]
China	-3% to +7% [17]
Australia	±10% [18]

The WPPs are requested to be able to operate under the condition when the voltage at the POC is within the continuous operating voltage range.

The reactive power requirement must be coordinated with the voltage control. It must be ensured that when the voltage at the POC is within the specified continuous operating voltage range, the voltages inside the WPPs have to be within the operating voltage range of the electrical equipments. Normally, the operating voltage range of the electrical equipments inside the WPPs is 0.9 to 1.1 pu.

Sometimes, it is difficult to maintain both the voltage operating requirement and the reactive power requirement due to the topology of the WPPs and the grid conditions. It is advised for the WPP owner to liaise with the TSO for a reduced reactive power requirement or a voltage dependent reactive power requirement.

3) Frequency Operating Requirement

The frequency operating requirements for the WPPs specified in the reviewed grid codes are illustrated in Table 3.

Table 3 Frequency Operating Requirement

Country or Region	PF requirements
UK	Continuous operating range 47.5-52 Hz 20 Sec. <47.5 Hz [6]
Scotland	Continuous operating range 47.5-52 Hz 20 Sec. <47.5 Hz [7]
Ireland	Continuous operating range 49.5-50.5 Hz 60 Min. 50.5-52.0 Hz and 49.5-47.5 Hz 20 Sec. <47.5 Hz [8]
Germany	Continuous operating range 47.5-51.5 Hz [9]
Denmark	Continuous operating range 49.5-50.5 Hz 30 Min. 50.5-52.0 Hz and 49.5-47.5 Hz 3 Min. 47.0-47.5 Hz [10,11]
Spain	Continuous operating range 49.5-50.5 Hz [12]
Sweden	Continuous operating range 49.0-51.0 Hz >30 Min. 51.0-52.0 Hz and 47.5-49.0 Hz [13]
US	Not specified [14]
Quebec	Continuous operating range 59.4-60.6 Hz 11 Min. 58.5-59.4 Hz and 60.6-61.5 Hz 1.5 Min. 57.5-58.5 Hz and 61.5-61.7 Hz 10 Sec. 57.0-57.5 Hz

	2 Sec. 56.5-57.0 Hz 0.35 Sec. 55.5-56.5 Hz Instantaneous <55.5 Hz or >=61.7 Hz[15]
Alberta	Refer to WECC requirement [16]
China	Continuous operating range 49.5-50.5 Hz >2 Min. 50.5-51.0 Hz >10 Min. 48.0-49.5 Hz [17]
Australia	Continuous operating range 47.0-52.0 Hz [18]

Normally, the TSOs request the WPPs has the ability for the primary frequency control.

4) Voltage Quality

The assessment of the impact of the WPPs on the voltage quality shall be based on the concepts below.

- Rapid voltage changes or voltage jumps
- Voltage fluctuations and flicker
- Harmonics

In most of the grid codes, the voltage quality requirements are specified by referring to the corresponding IEEE and IEC standards.

The Grid Codes from UK [6] and Scotland [7] refer to the standard ER G5/4 – "Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Loads to the transmission systems and Public Electricity Supply Systems in the United Kingdom". IEC 61000-3-6 "Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems" and IEC 61000-3-7 "Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems" are referred in the Irish Grid Codes regarding the harmonics, the voltage fluctuation and the flicker.

The Canadian Grid Code [16] refers to the IEEE standard 519-1992 "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems". The Chinese Grid Code [17] refers to the GB/T 14549-1993 "Quality of Electric Energy Supply Harmonics in public supply Network" and GB 12326-2000 "Power quality Voltage fluctuation and flicker".

The requirements of the mentioned standards are not included in the paper.

In the Danish Grid Code, the specific requirements on voltage quality are defined. The detailed requirements are presented below.

Rapid voltage changes [10, 11]

- General constraint <3.0%
- Until a frequency of 10 per hour <2.5%
- Until frequency of 100 per hour <1.5%

Voltage variations and flicker

- $P_{st}<0.30$
- $P_{lt}<0.20$

Harmonic voltages

- $D_n<1\%$ for $1<n<51$
- THD<1.5%

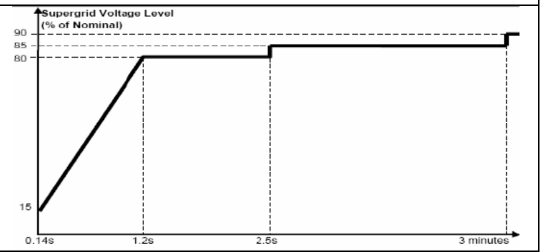
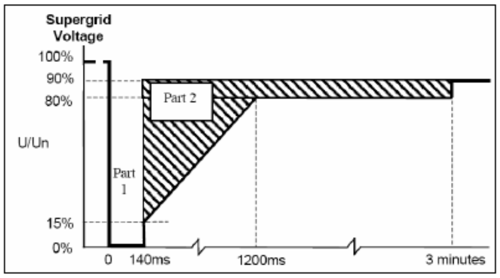
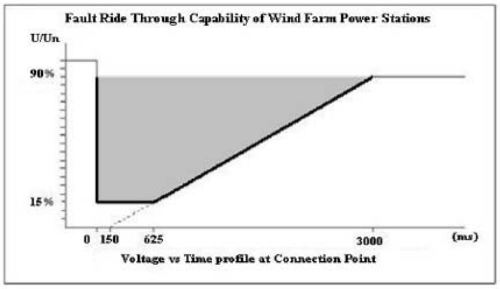
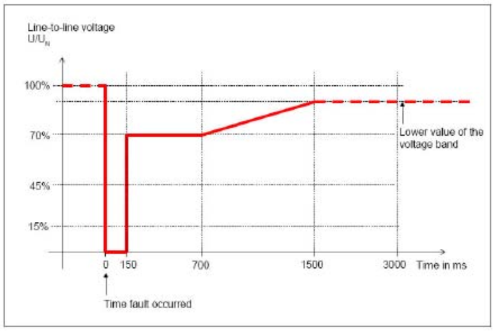
In the rest of the reviewed grid codes, the voltage quality requirements are not mentioned. But the requirements in the IEC or IEEE standard(s) have to be applied.

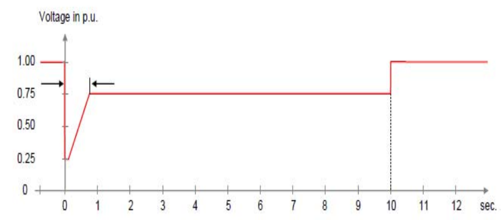
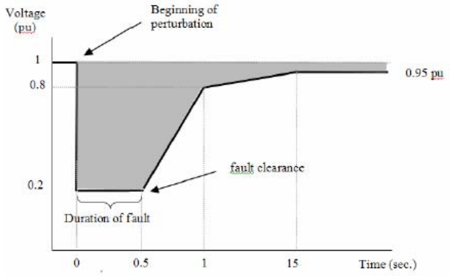
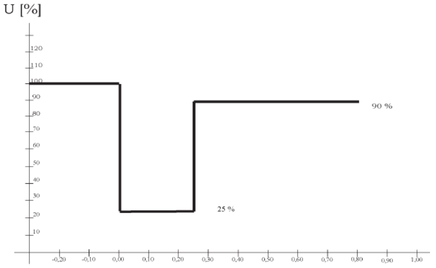
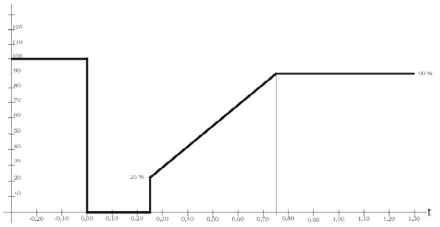
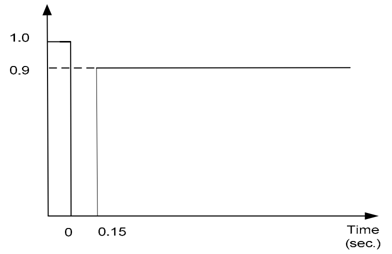
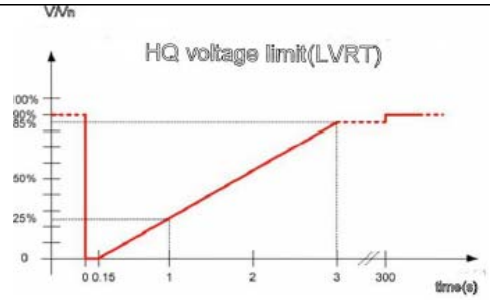
If the voltage quality of the WPPs can not meet the grid code requirements, the active filters can be used to reduce the voltage distortion.

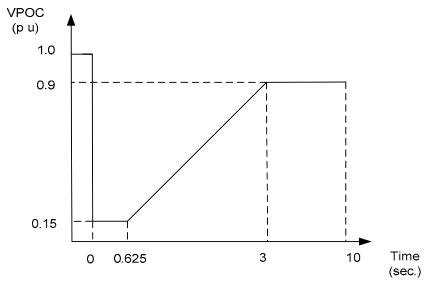
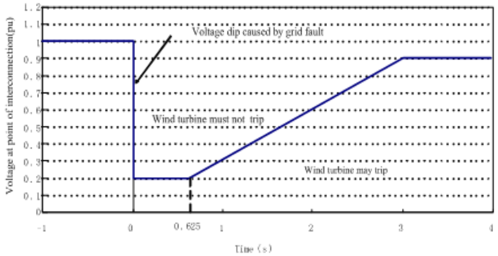
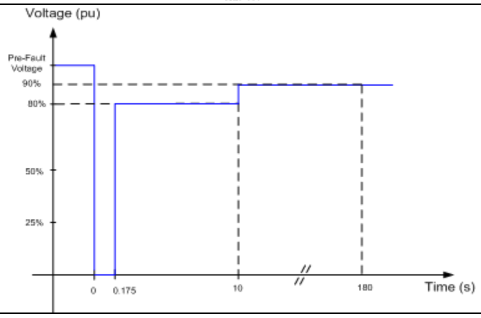
III. LOW VOLTAGE RIDE THROUGH (LVRT) REQUIREMENT

The LVRT requirements for the WPPs refer to the WPPs' capability to stay connected under the specified low voltage conditions at the POC caused by the faults within the grid. In some grid codes, the WPPs are also requested to supply maximum reactive current during the specified low voltage conditions. In the mean time, some grid codes also specify the post fault active power recovery requirement. The specified low voltage conditions at the POC in the reviewed grid codes are illustrated in Table 4.

Table 4 Grid Codes Specified LVRT Requirement [6-18]

Country or Region	Specified low voltage conditions
UK	
Scotland	
Ireland	
Germany	

Denmark	
Spain	
Sweden	 medium and small plant (less than or equal to 100 MW)  large plant (larger than 100 MW)
US	
Quebec	

Alberta	
China	
Australia	

In order to deal with the LVRT requirements requested by TSOs, the wind turbine manufactures have specified the LVRT capability of their products. The LVRT capabilities of wind turbines from different manufactures may differ a little bit to each other. Basically, the LVRT capability of the wind turbines is to change the operation mode of the wind turbines under the specified low voltage conditions and stay connected if the WTG terminal voltage is within its defined low voltage conditions.

The first step of checking the LVRT capability of WPPs is to check whether the WTG terminal voltages are above its defined LVRT capability curve. If the WTG terminal voltages go out of the LVRT capability curve at very low voltage conditions, for example 0 pu voltage at the POC or 0.1 pu voltage at the POC, it is recommended to use STATCOM to boost up the WTG terminal voltages and to keep them above the defined WTG LVRT capability curve. The reason to use STATCOM is due to the fast reactive power response of the STATCOM and its reactive power capability under extremely low voltages.

If the WPPs fail to meet the LVRT requirement due to the long voltage recovery time period at the POC, like the LVRT requirements from UK, Scotland, Ireland, Denmark, Quebec, Alberta and china, the mechanically switched capacitor banks (MSC) can be used to boost up the WTG terminal voltages and to keep them above the WTG LVRT capability curve.

Some grid codes also specify the reactive current requirement under the low voltage conditions at the POC. The reactive current requirement under low voltage conditions from Spain is illustrated in Figure 5.

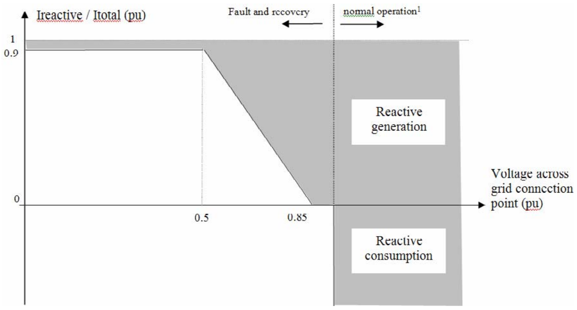


Figure 5 Reactive Current Requirement under Low Voltage Conditions from Spanish Grid Code [12]

It is shown that when the voltage at the POC is less than 0.5 pu, the WPPs are requested supply at least 0.9 pu reactive current. When the voltage at the POC is less than 0.85 pu, the reactive current from the WPPs is the result of the difference between 0.85 pu and the actual pu voltage at the POC timing 2.57.

Some grid codes also specify the active power recovery time after the fault. In the Irish Grid Code, the active power recovery time requirement is stated as the one below.

"WTG must be able to provide at least 90% of its max active power within 1 second of the system voltage recovering to the normal operating range."

The active power of the WPPs has to be checked after the low voltages conditions are cleared.

IV. CONCLUSIONS

The grid integration issues for large scale WPPs are reviewed in this paper. The steady state operation requirements specified by grid codes, like the reactive power requirement, voltage operating requirement, frequency operating requirement and voltage quality requirement, are discussed. The correlation between the reactive power requirement and the voltage operating requirement is analyzed and the suggestion to meet both requirements is presented. The dynamic LVRT requirement is also analyzed. The suggestion for the WPPs meeting the LVRT requirements is also presented.

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