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Advanced Wind Generator Controls: Meeting the Evolving Grid Interconnection Requirements

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<http://dx.doi.org/10.5772/51953>

1. Introduction

1.1. Grid interconnection requirements

Reliable power system operation requires the continuous, instantaneous balance of supply and demand. Traditionally, power system planners have been familiar with a limited, well-understood amount of variability and uncertainty in demand and conventional generation. The large-scale integration of variable generation, such as wind power, gives rise to new challenges, requiring grid planners and operators to modify their traditional activities to maintain a secure, reliable operation of the power system.

1.1.1. Proliferation of wind power

For more than a decade now, wind power has been driving the change in electric grids worldwide. Currently, wind energy serves 22% of the load energy in Denmark, 17% in Portugal, 16% in Spain, 10.5% in Ireland and 9% in Germany. Also, with 86 GW of installed wind capacity in Europe, 42 GW in China, and 40 GW in the United States, it is fair to say that wind power has come to stay.

Each year wind power is increasing its share of the global electricity production, Figure 1. As penetration levels increase to the extent that conventional generators are displaced,

- is there a technical limit on the manageable wind penetration level?
- what are the technical characteristics hindering the integration of wind power?
- what are the needed reforms in technical design or operational trends of the grid to allow further accommodation of wind power?

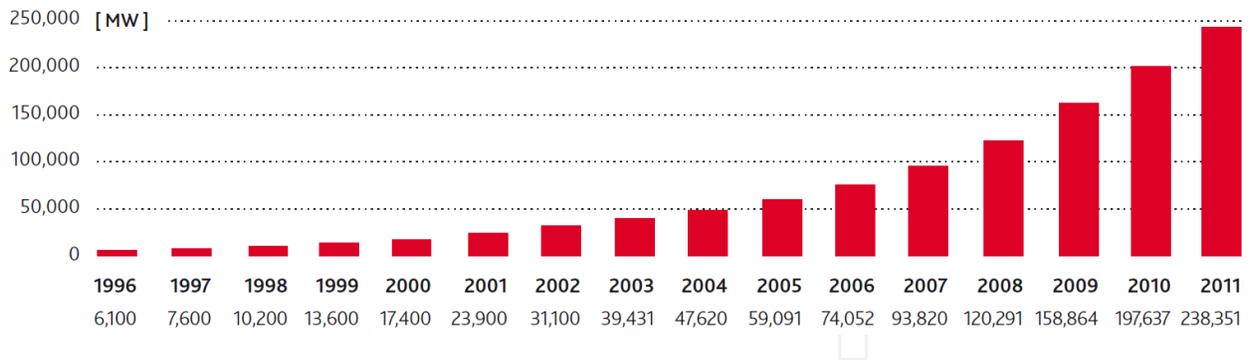


Figure 1. Global cumulative installed wind capacity, 1996-2011 [1].

In this chapter, we attempt at answering these questions to shed light on the main integration challenges that wind power is facing and the opportunities that lie within.

1.1.2. Grid integration challenges & opportunities

The grid impact of the connection of a wind power plant depends on several factors. These include the technology of the turbines, the plant collector system, the required interconnection features/capabilities, and the wind-grid penetration level.

Due to its intermittent nature, wind power blurs the distinction between dispatchable generation resources and variable system load. Since the fuel source of wind plants is uncontrollable and depends on meteorology, it must be dealt with operationally through mechanisms other than the traditional dispatch or commitment instructions. The challenging characteristics of wind power itself can be summarized in the following four elements [2]:

- **Variability:** The output of wind generation changes in time frames that range from seconds to hours
- **Uncertainty:** The magnitude and timing of variable generation output is less predictable than it is for conventional generation
- **Location:** Wind farms are often located in relatively unpopulated, remote regions that require long transmission lines to deliver the power to load centers
- **New technologies:** New technologies are often needed for wind turbines (e.g., doubly fed induction generators), requiring special assessment of their voltage and frequency regulation capabilities, harmonic emissions, contribution to sub-synchronous resonances, and protection coordination.

The nature of wind power, however, is not the only source of challenge. Some power systems attempting at wind integration are already weak, have limited dispatch flexibility and balancing capabilities, or suffer shortage in transmission infrastructure. In some systems, the gap between peak and valley loads is already big and the ramping capabilities are already exhausted,

leading to a tight load-following capability (e.g. China). The situation is exacerbated by wind integration because the wind power peaks typically occur at load off-peak [3].

In order to tackle these technical challenges while responding to the pressure to accommodate wind power, power system planners and operators have to alter their traditional planning methods and operational practices. The dominant philosophy is that wind power plants should have all the technical capabilities needed to contribute to the secure operation of the power system in the same manner as conventional generators do. Thus new grid codes are written, often with supplementary provisions for wind power plants. This is discussed in detail in the following sections.

1.1.3. Grid code development

In the rush of promoting wind energy, little attention was paid to grid interconnection issues in many countries. There were no requirements for wind farms to regulate voltage, ride through grid disturbances, or support the system frequency. Even in regions where interconnection requirements for wind farms were relatively advanced (e.g. Denmark or Germany), the provisions were moderate, reflecting the low wind penetration levels and the technology limitations at the time. At several occasions, these wind farms produced unacceptable voltage fluctuations during normal operation and caused major loss-of-generation events in response to otherwise minor system disturbances [5].

Through extensive experience with interconnection studies, power system operators and planners became increasingly familiar with the concept of a wind power plant; its performance characteristics, capabilities, and limitations. Grid codes were updated, requesting that wind plants exhibit similar operational features as conventional synchronous generators and abide by the same minimum performance criteria. The object of these provisions is to maintain the same level of operational security and reliability while minimizing curtailment of wind power. The main requirements relate to fault ride-through, reactive power and voltage control, dynamic behavior, active power and frequency control, and power quality. These requirements are met (either at the level of the wind turbine or the wind plant) through supplementary control loops that are triggered when specific events occur, such as contingencies resulting from grid faults, instabilities or loss of generation. These topics are treated in detail later in this chapter. Other generation controls not yet required from wind power plants include power system stabilizers (PSS), frequency regulation, and automatic generation control. These controls may in the future be incorporated into the core function or provided as ancillary services.

The technical requirements and performance specifications laid out in grid codes relate to the Point of Interconnection (POI), which is the border of responsibility between the network operator and the wind plant owner. As an example, Figure 2 and Table 1 describe the points of application of the technical rules of the grid operator in the Canadian province of Alberta (AESO). Similarly, Figure 3 shows the points of measurement for voltage ride-through and reactive power requirements according to the grid operator in the Canadian province of British Columbia.

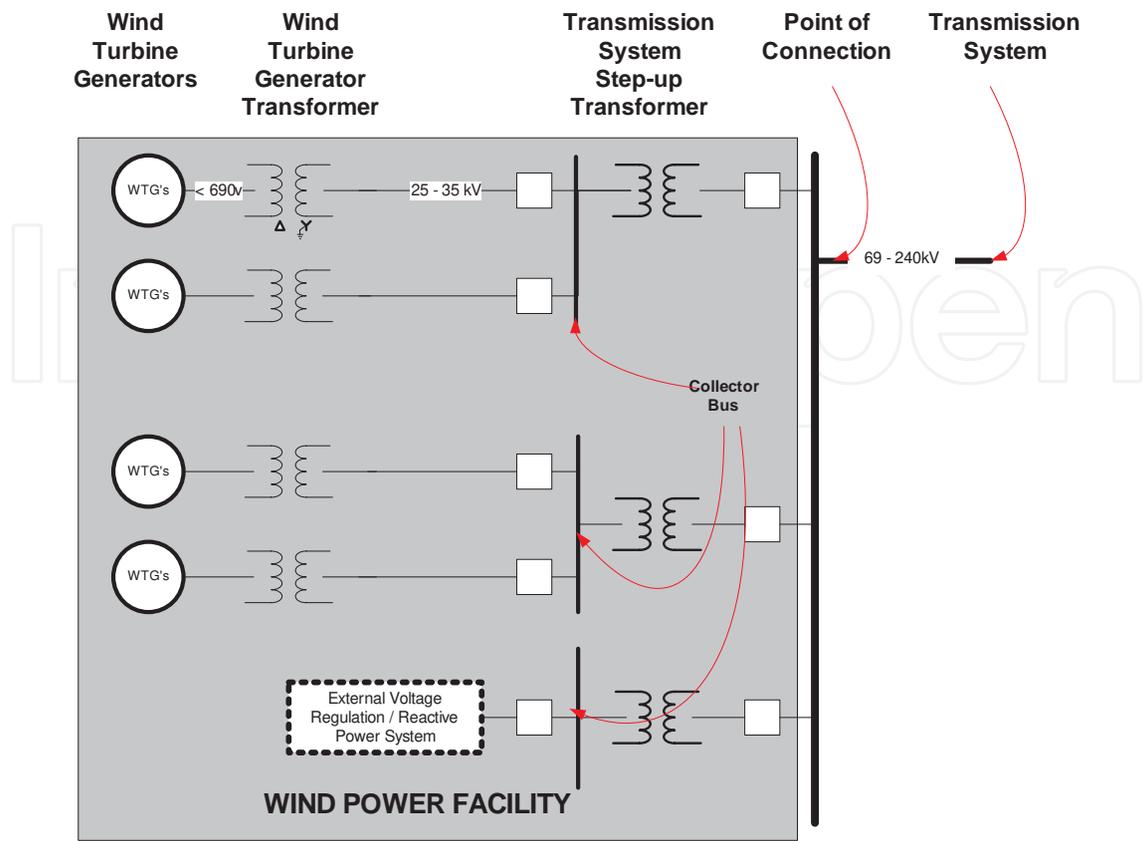


Figure 2. Wind power facility diagram – AESO [7].

Requirement	Performance Point		
	POI	WTG	
Collector Bus			
Maximum authorized MW	X		
Gross MW	X		
MW & ramp rate limiting		X	
Over-frequency control	X		
Off-nominal frequency		X	
Reactive power requirements	X		
Voltage regulation	X		
Voltage operating range	X		
Voltage ride-through		X	
Real-time monitoring	X	X	
Meteorological signals			X

Table 1. Points of measurement of performance criteria – AESO [7].

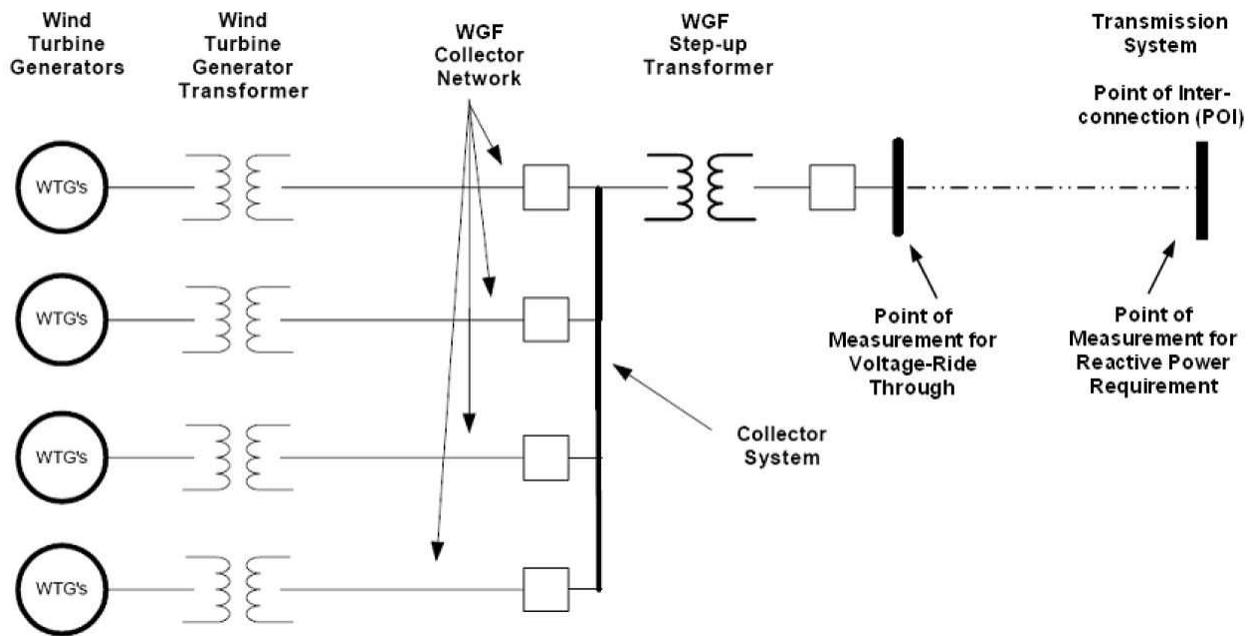


Figure 3. Wind power facility diagram – BC Hydro [24]. WGF: Wind generation facility.

For offshore wind power plants, there are two possibilities for the POI depending on how the grid connection is embedded in the regulatory framework. In some countries (e.g. Germany), the local utility is responsible for extending its transmission network offshore to enable the connection. In this case, the POI is at the offshore substation of the wind plant so all the offshore transmission assets are in the scope of responsibility of the network operator. In other countries (e.g. USA), the wind plant developer is responsible for grid connection up to the onshore POI, thus the submarine cables are within the wind power plant in this case [8].

It is challenging to design a wind plant, consisting of many turbines distributed over a large geographical area, so that it behaves like a conventional power plant as seen by the system at the POI. In the following sections, we discuss the different grid code requirements, design considerations, and industry implementations with reference to provisions from several European and North American grid codes. Emphasis is placed on the more sophisticated codes that come from countries and regions with high wind penetration levels. For each required control function, solutions are cited from the industry and research community.

1.1.4. Power coordination & energy storage

In addition to requiring a behavior similar to conventional generators from wind power plants, grid operators are looking into energy storage and coordinated generation as intelligent solutions to facilitate the connection of wind power. The power coming from conventional generation can be coordinated with the intermittent power from the wind to reduce the minute-to-minute variations. This has been employed in Portugal on multiple occasions where this solution was found technically viable and cost-effective [4]. A recent study performed in Ireland concluded that pumped hydro storage becomes economically attractive at an average annual wind power penetration of approximately 50% [14].

Short-term energy storage facilities (flywheels and batteries) are also gaining momentum in providing ancillary services to assist in power system stabilization and controlled islanding. In one example in the USA [13], a multi-MW battery energy storage system (BESS) was added in the grid to allow a large network to operate as a self-powered “island” in the event of transmission feeder loss. The BESS served radially fed distribution feeder loads for several hours during a permanent fault that was experienced on the grid. The BESS was also employed for peak shaving, thus helping defer costly transmission and substation transformer upgrades. In another example [14], a 21 MW wind power plant in Hawaii is designed to utilize a 4 MW BESS to help regulate the variability of the plant’s output, thus enhanced the stability of the local grid.

1.2. Steady-state tolerance ranges

1.2.1. Frequency & voltage operation ranges

Wind power plants are required to ride through prolonged frequency excursions without disconnection. This is typically defined through tolerance curves and extended time ranges around the nominal operating point of the power system. When the deviations are large, a reduction of the output power or operation for a limited period may be allowed. For example, Figure 4 shows the frequency tolerance curve of the Northeast Power Coordinating Council (NPCC)¹ and that of Hydro-Québec TransÉnergie (HQTE), the system operator in Québec.

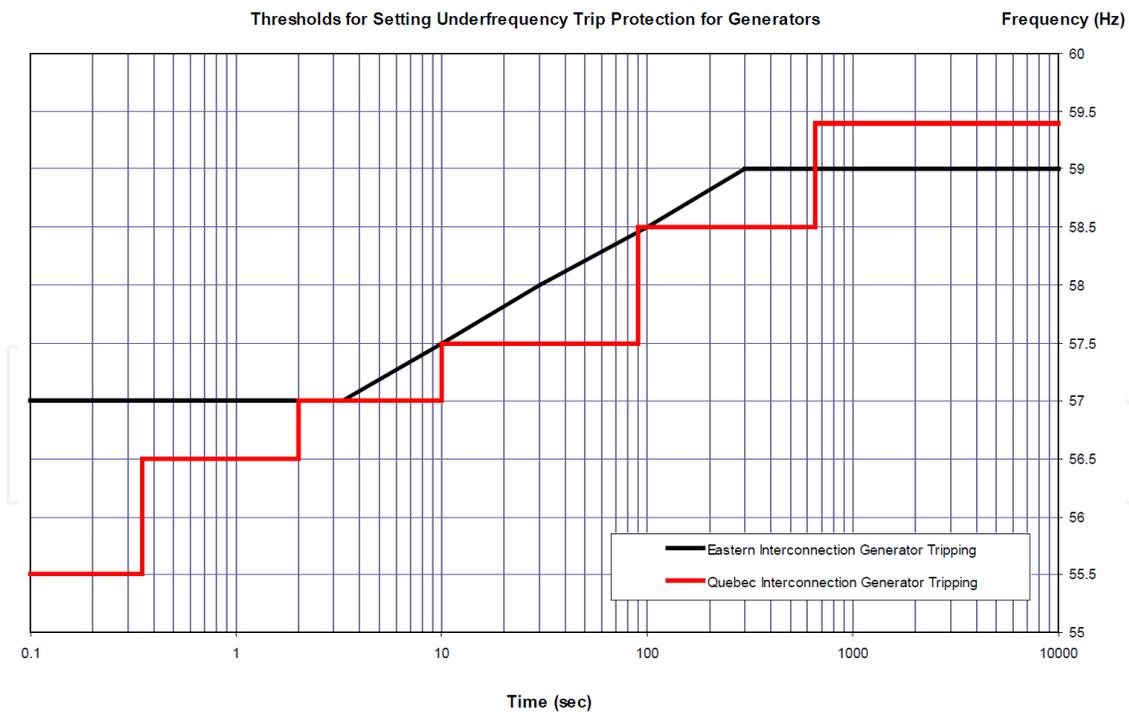


Figure 4. Required settings of under-frequency protection (log scale) – NPCC [18].

¹ NPCC is responsible for the reliability of the bulk power system in Northeastern North America, governing the grids of several American and Canadian provinces.

The stability of the electric grid can be disturbed if a wind plant is disconnected as a consequence of a failure due to a voltage perturbation. Thus, a wind plant must be able to run at rated voltage plus an extended voltage range. In Europe, the required voltage and frequency tolerance ranges are often specified simultaneously. For example, the Nordic code² [19] demands from wind plants to operate in the voltage-frequency regions described in Figure 5.

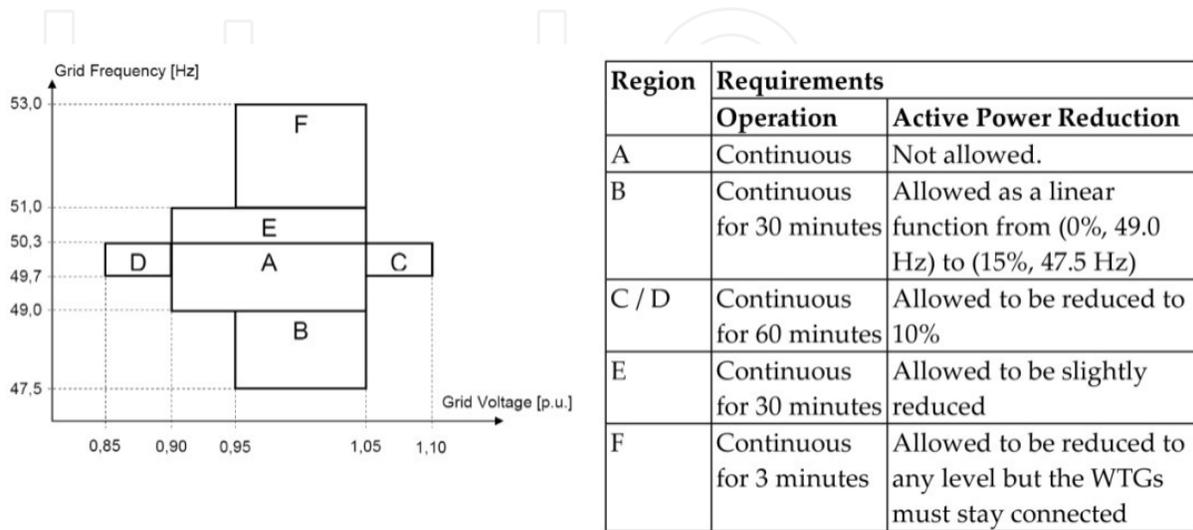


Figure 5. Voltage / frequency regions for wind power plants – Nordic code [20].

Figure 6 shows the different operation regions as specified by one of the German system operators.

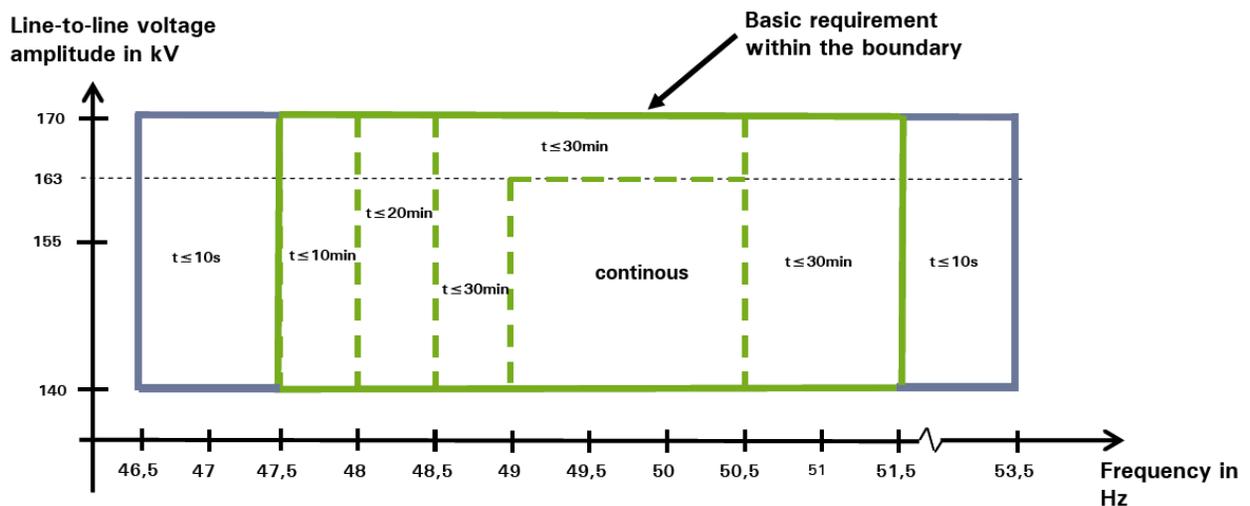


Figure 6. Voltage/frequency tolerance regions of one German system operator. Green: onshore wind plants, Green & blue: offshore wind plants [16], [17].

² Until the publication of the ENTSO-E grid code in Fall 2013 [12]-[13], the Nordic code governs the operation of the transmission systems of Denmark, Finland, Iceland, Norway and Sweden .

In offshore and isolated power systems with weak interconnections, the frequency limits tend to be wider to ensure that wind plants (and other forms of generation) can continue to deliver their power and grid support functionalities. This is evident in the blue section of Figure 6, which shows that offshore wind plants are asked to stay connected between 46.5 Hz to 53.5 Hz ($\pm 7\%$) for up to 10 sec. In Ireland, where the grid is infamous for its wide frequency excursions, wind plants are required to remain connected for frequency deviations down to 47.0 Hz and during a rate of change of frequency up to 0.5 Hz/sec. These are the most extreme frequency limits specified for 50Hz grids.

1.3. Active power control

Wind power plants are required to have an active power control system capable of receiving set-point commands from the grid operator to limit active power and ramp rate. This is typically achieved through pitch angle control and/or by disconnecting some wind turbines.

1.3.1. Set-point curtailment

During periods of transmission congestion or extremely low system loads, constraining conditions can result in deflated (or even negative) market prices, especially in regions with sophisticated wholesale electricity markets. One technique to address the lack of available transmission, or the excess of wind power at any given time, is to curtail wind plants to lower output levels during periods when it is less economic to keep them producing at full capability.

To accomplish this, several system operators have integrated wind energy into their security-constrained economic dispatch (SCED). Within the available power from the wind, the output power can be regulated to a specific MW value or a percentage of the available power. A fast, robust response of the active power control is important during normal operation to avoid frequency excursions and during transient fault situations to guarantee transient and voltage stability.

In one example, AESO specifies that wind plants must be able to limit their active power to real-time MW set-points with an average resolution of 1 MW and accuracy of 2% of rated power on a 1-minute average. It is also specified that wind gusts should not lead to exceeding the active power limit by more than 5% of rated power [18]. One of the German codes requires wind plants to be capable of operating at a reduced power output without exceeding 1% change of rated power per minute across the entire range between minimum and rated power [15]. The Irish code requires wind plants to commence the implementation of any set point within 10 sec of receipt of the signal [26].

1.3.2. Ramp rate limits

Requirements for active power control include the limitation of the ramp rate (rate of change) of active power. Ramp rates are possible for power increase, but operation with a power reserve is necessary in output power decrease, which necessitates sub-optimal economic operation.

For example, wind plants in Québec are required to be able to ramp up rate and down between 0 MW and rated power in an adjustable 2 to 60 second interval [23]. In Alberta, AESO specifies that wind plants must be capable of maintaining their ramp up between 5 and 20 %/min of the rated power, taking into account all losses in cables and transformers [19]. The Irish code requires power curtailment capability with a ramp rate defined project-specifically in the range 1 – 30 MW/min [26]. The Nordic code [20] requires the ability to regulate active power up or down from 100% to 20% of rated power in less than 5 seconds.

1.4. Frequency control

System events that include load-generation mismatches often result in transient fluctuations of the system frequency. This can be caused by mechanical failures of generators, sudden load changes, or line losses in the transmission system. The rate and depth of frequency decline and the time for frequency to return to its target value are all critical bulk power system performance metrics that are affected by the dynamics of the generation mix.

1.4.1. Inertial response

With the increasing penetration of inverter-based generation technologies, such as modern wind plants, the primary frequency response of several North American and European grids has been declining for years. The concern is most pronounced during simultaneous light load and high wind, where economics dictates that fewer synchronous generators will be operating, and the overall grid inertia will consequently be reduced.

This was confirmed by a study performed in late 2010 by the Lawrence Berkeley National Lab and sponsored by the Federal Energy Regulatory Commission (FERC) in USA. The objective of the study was to examine the status of the American grids with respect to frequency regulation capabilities [38]. Among other results, the study concluded that:

- frequency-insensitive wind generation does have an impact on the minimum frequency observed following a loss of major generation
- This influence is not the sole cause for the deteriorated primary frequency response. Other causes include the low quality of the frequency response provided by the conventional generators
- The performance of demand-based primary frequency response reserves was superior to that of conventional governor-controlled generators in arresting the frequency decline due to significant loss of generation.

It was thus concluded that the approach for maintaining adequate frequency responsive reserves should not involve only new requirements for wind generation, but also innovative solutions on the demand side and improvements in the frequency response of the existing conventional generation.

In another case, the integration of wind energy in Québec has triggered an added need for frequency support in order to avoid reaching the low-shedding thresholds under critical

generation loss scenarios. The power system of Québec is connected to its neighboring systems asynchronously, thus it is responsible for its own frequency regulation as an independent region of the North American Electric Reliability Corporation (NERC). With the current inertia of Québec's system, large post-contingency frequency excursions up to ± 1.5 Hz for extended periods can potentially occur. In a recent study [30], HQTE concluded that if 2000MW of hydro generation is replaced by wind turbine generators without inertial response, the frequency nadir will deteriorate by about 0.2 Hz within the first 10 seconds. As a result, HQTE requires wind plants to be equipped with an inertia emulation system to support system frequency following a major frequency event [23]:

- The system should respond to major frequency deviations only
- The performance should be at least as much as that of a conventional synchronous generator whose inertia constant (H) equals 3.5 sec.

The requirement can be satisfied if the active power is increased rapidly by 5% for about 10 sec following a major frequency deviation. A similar provision is stipulated by the Independent Electric System Operator (IESO) of Ontario.

Similar investigations are carried out in Europe. A study by the Irish grid operator forecasts deficiencies in system performance in terms of frequency and voltage control due to the increasing share of non-synchronous generation by 2020 [27]. The analysis concluded that:

- The projected levels of synchronous inertia available in 2020 will be less than the amount needed to meet the statutory system requirements
- At high instantaneous non-synchronous generation, there is a risk of excessive activation of Rate of Change of Frequency (RoCoF) protection relays that shut down wind turbines under certain scenarios.

The solutions that involve the replacement of the RoCoF relays on the distribution networks with alternative protection schemes or increasing the RoCoF thresholds. New commercial mechanisms and financial models are also being studied to allow for advanced ancillary services.

In the UK, the system operator performed a technical assessment of the available options for the management of frequency response with the integration of wind power [22]. The recommendations called for:

- A faster frequency response capability in the first 5 seconds following a load-generation mismatch
- A closer examination of the sensitivity of the frequency response with respect to the ramping capability of the existing generation
- A clearer rephrasing of the grid code provisions addressing frequency control
- A reexamination of the existing RoCoF settings.

In recognition of the grid's need for frequency response, wind turbine manufacturers have developed control functions that temporarily increase power output when frequen-

cy declines by withdrawing energy from the rotating inertia of the turbine. [39]-[46] contain descriptions of several implementations sought in the industry (and in research) with and without auxiliary storage. [47] provides a comprehensive summary and comparison of the different implementations to date. A common aspect among all these implementations, irrespective of the wind turbine generator (WTG) topology or electric concept, is that the amount of power boost is not constant but rather a function of the wind condition. This is because all modern WTGs are variable-speed machines that regulate their rotational speed to optimize power capture from the wind. Another feature is the recovery period that follows the power boost when the WTG is operating at below-rated conditions. During the recovery period, the WTG withdraws active power from the grid to recover its pre-event rotational speed. The design considerations for inertial response emulation include: (a) the optimal amount of power that can be drawn from the rotating masses; (b) the duration of the momentary injection; and (c) the duration of the speed and energy recovery phase.

A long-term overproduction is more challenging for WTGs. Since they are designed to capture the maximum amount of power from the wind at any given moment, it is not possible to maintain an increase in the output power. Leaving “headroom” to increase production would necessitate spilling wind energy when wind speeds are below the turbine’s rating, thereby incurring an economic penalty due to reduced annual production levels. The utilization of such a capability therefore comes down to economics, i.e., the value of primary frequency response relative to the value of the wind energy. This technical option is discussed in the following section in the context of the British frequency control requirements.

1.4.2. Primary reserve for under-frequency

The British grid code contains the most advanced (and complex) frequency control requirements to date. Several operation modes are asked from wind plants whose installed capacity is beyond 50 MW depending on the actual value of the system frequency relative to the system Target Frequency (50 ± 0.1 Hz).

The system operator will send to the wind plant a signal with the Target Frequency and an instruction of whether to operate in the Frequency Sensitive Mode (FSM) or Limited Frequency Sensitive Mode (LFSM). If FSM is specified, the control system has to automatically regulate the active power output as a function of the deviation of the actual frequency from the target frequency, in a direction assisting in the recovery to the target frequency.

When the system operator expects an under-frequency situation, the wind plant is curtailed prior to the frequency drop via a separate command from the system operator. When the frequency drops below the target frequency, the wind plant must exhibit a Primary (P) and Secondary (S) response as defined in Figure 7. The new active power set point can be obtained from Figure 7 for a 0.5 Hz deviation. For smaller deviations, the response should be at least proportional to the requirement specified for the 0.5 Hz deviation [21].

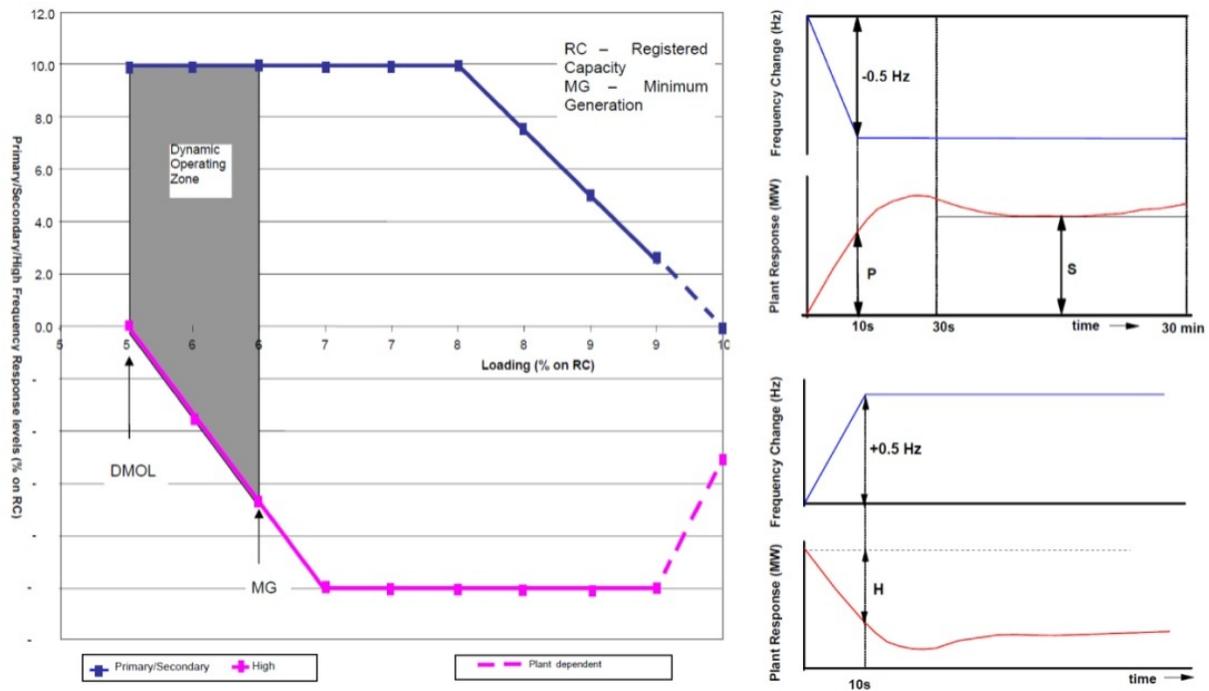


Figure 7. a) Minimum frequency response requirement for 0.5 Hz frequency change from target frequency. (b) Interpretation of Primary (P), Secondary (S), and High-Frequency response values [21].

If the LFSM operation mode is specified by the system operator, only an over-frequency response is required. The active power control system must withhold the output for frequencies in the range between the target frequency and 50.4 Hz. Beyond 50.4 Hz, it must be reduced at a rate of at least 2% of actual active power per 0.1 Hz. The response should last until the frequency drops again below 50.4 Hz, with as much as possible delivered within the first 10 sec from the rise [21].

1.4.3. Over-frequency response

Wind plants are commonly asked to limit their active power as a function of the system frequency in over-frequency situations. For example, wind plants in the Canadian province of Alberta are required to have an over-frequency control system that:

- continuously monitors the grid frequency at a sample rate of 30/sec and a resolution of at least 4 mHz
- automatically controls the active power in a manner proportional to the frequency increase by a factor of 33% per Hz of actual active power output
- responds at a rate of 5%/second of the actual active power output
- has control priority over the other power limiting control functions like ramp rate limitations and curtailment set-point, and must reduce the active power output for an over-frequency condition even when these requirements are in effect

- has no intentional time delay, but may have a deadband of up to 36 mHz.

In Ireland, whose grid is known for its notorious frequency profile due to weak interconnection with the neighboring systems, the grid code demands from wind plants to control active power as close to real-time as possible according to the response curve described in Figure 8. The rate of response should be 1% of rated power per second for each online WTG [26]. Similar requirements exist in other European grid codes.

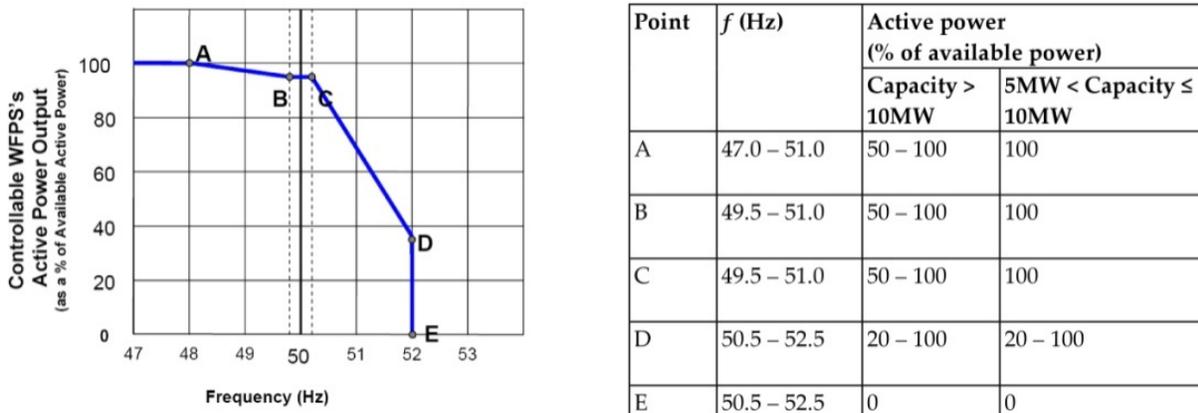


Figure 8. Power-frequency response curve - Irish code [26]. WFPS: Wind farm power station.

1.5. Reactive power & voltage regulation

Voltage regulation in a power system is directly related to the flow of reactive power and is dependent on the short circuit capacity and impedance of the network. Large and quick variations of wind output can cause transient disturbances of the system voltage and tie line flows, both of which can lead to voltage stability issues especially in congested transmission corridors [2].

Conventional generation facilities have traditionally provided reactive power to support system voltage. These facilities have synchronous machines capable of operating in power factor ranges of +/-0.90 or +/-0.95. Voltage regulators on their excitation systems provide the primary voltage control function [6]. Older wind plants have been interconnected without these capabilities; occasionally leading to problems such as depressed voltages, excessive voltage fluctuation, and inability to deliver full power [6].

1.5.1. Steady-state reactive power range

In addition to the capability of operating within an extended voltage bandwidth around unity, modern wind plants are required to offer advanced reactive power and voltage control capabilities. The supplied reactive power should compensate for the reactive power loss and line charging inside the wind plant and up to the POI. It is often also required to regu-

late the POI voltage using dynamic reactive power in-feed, either automatically or in response to real-time instructions from the operator.

According to the British grid code, wind power plants must be capable of operating continuously at any point in the ranges illustrated in Figure 9. They must also be capable of continuous operation between a power factor of 0.95 lag and 0.95 lead when supplying rated MW.

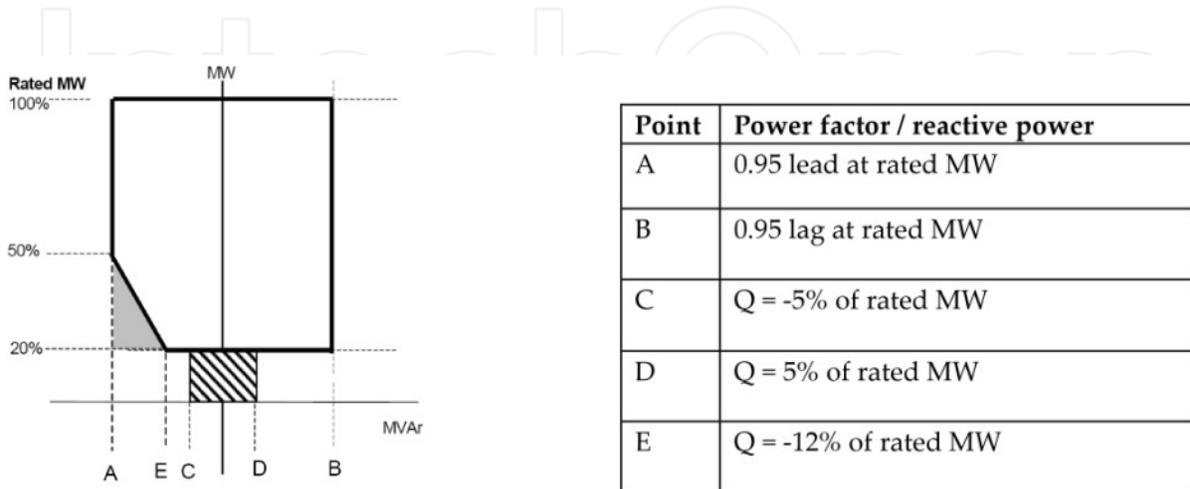


Figure 9. Minimum requirements for reactive power range - British code [21].

Figure 10 shows the reactive power and power factor ranges specified in the Irish code [26].

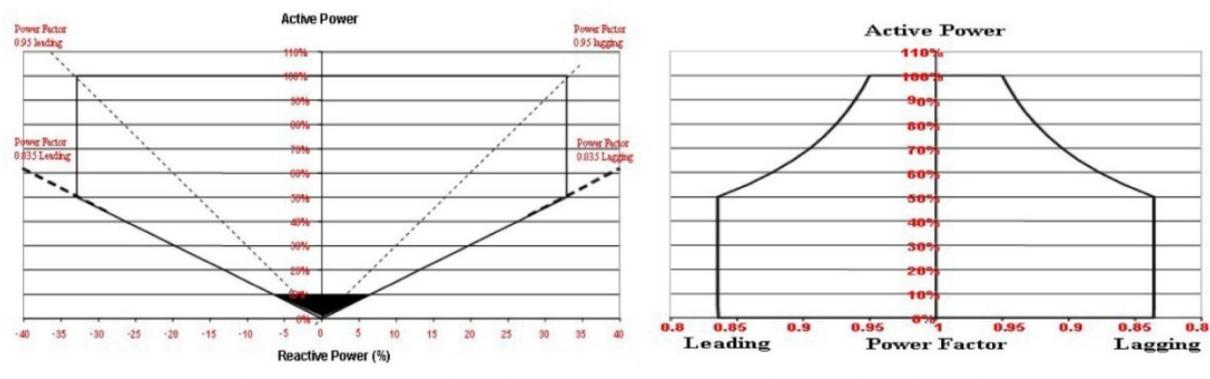


Figure 10. Requirements for reactive power capability of wind plants - Irish code [26].

Figure 11 shows the required static and dynamic reactive power ranges in the Canadian province of Alberta [19]. The requirement applies at the low-voltage side of the transmission step-up transformer. The dynamic capability is defined as the short-term reactive power response in a period of up to 1 second.

A supervisory control is normally present within a wind plant translating the reactive power or voltage demands at the connection point to operational set points for the individual WTGs. In some implementations, identical set points are dispatched to all turbines to keep

the design of the controller simple. In others, the set point is optimized for each individual turbine [6].

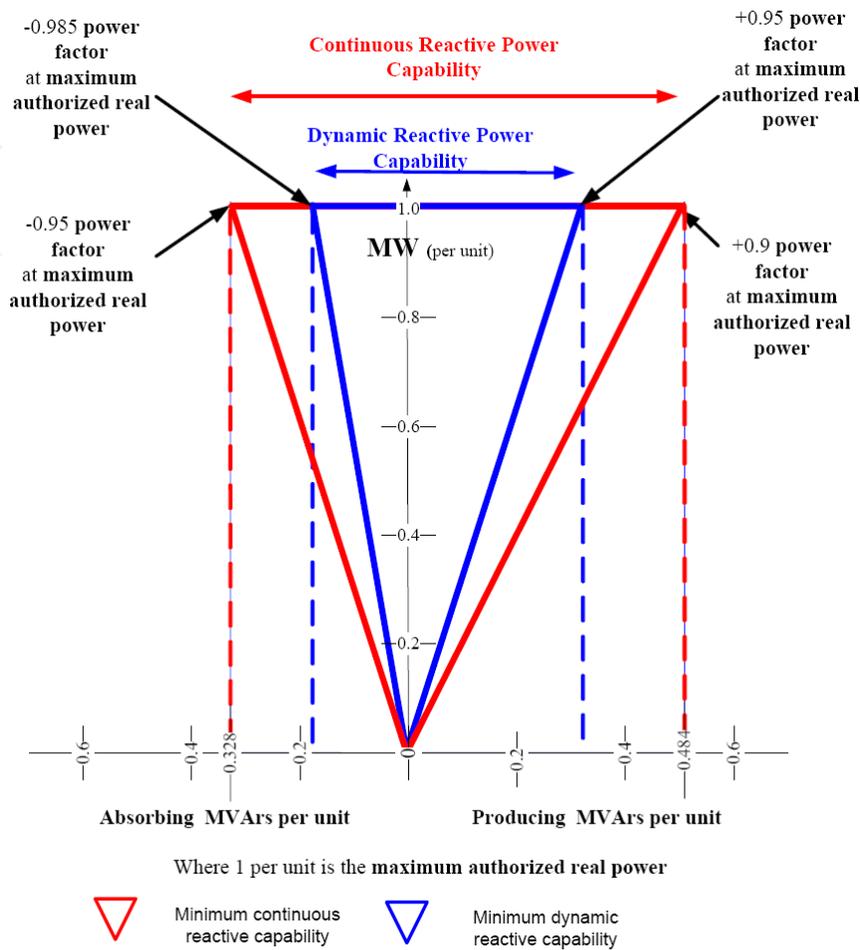


Figure 11. Requirements for reactive power capability of wind plants - AESO code [19].

Power flow calculations are performed to assess if the reactive power capabilities of the WTGs are enough to comply with the steady-state requirements. Although the collector system design work may be considered a separate activity, some iteration will usually be required. Transformers equipped with on-load tap changers are another system component that affects the voltage profile and reactive power flows. The speed of response of the tap changer, the size of the first step and those of subsequent steps are all relevant parameters that need to be optimized for a cost-efficient, grid code compliant wind plant-level control scheme.

Reactive power compensation equipment, such as static var compensators (SVCs) and static compensators (STATCOMs), may also help compliance with grid codes when there is little wind, or when the requirement is beyond the capability range of the WTGs. In offshore wind plants with lengthy submarine ac cables, high charging currents necessitate the injection of a large amount of apparent power. This greatly reduces the reactive power supply

and absorption margin at the on-shore POI under different operating conditions. Therefore, reactive power compensation elements are often needed in these cases at the high-voltage level.

1.5.2. Voltage regulation & dynamic response

Although the main focus is on the quasi-steady-state behavior of the wind plant, system operators also impose certain dynamic performance criteria. In general, there are three common reactive power control modes for wind plants:

1. Fixed reactive power mode, in which a set point reactive power flow is maintained as specified by the system operator
2. Fixed power factor mode, in which the ratio between active and reactive power is maintained. This mode is common for small wind plants or those connected to the distribution system and operated as distributed generation (DG)
3. Voltage control mode, in which the wind plant contributes reactive power to regulate the voltage magnitude at the connection point.

Voltage control is gaining more and more popularity, especially for large wind plants. For instance, wind plants in the UK connected to a line rated 33kV or above are required to contribute to voltage control with a predefined reactive power–voltage droop characteristic, as shown in Figure 12. If a sudden voltage change occurs in the grid, the wind plant is required to start reacting no later than 200 ms after the change and should provide at least 90% of the required reactive power within 1 second. After 2 seconds from the event, the oscillations in the reactive power output may be no larger than $\pm 5\%$ of the target value.

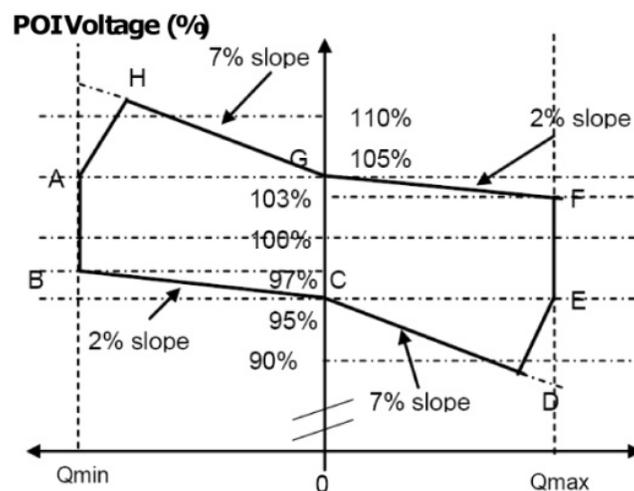


Figure 12. Voltage-reactive power envelope for voltage levels >33kV - British code [21].

The code of the Canadian province of Alberta requires from wind plants to have a continuously acting, closed-loop control voltage regulation system capable of responding to any

voltage set-point sent by the system operator between 95% and 105% of rated voltage. The system must also be able to regulate voltage according to an adjustable droop from 0 to 10%. The dynamic response must be such that a change in reactive power will achieve 95% of its final value no sooner than 0.1 second and no later than 1 second following a step change in voltage [18]. Specific dynamic criteria such as these are becoming more common together with the droop characteristics and steady-state specifications.

1.6. Voltage disturbance requirements

Unsurprisingly, special emphasis is placed in grid codes on the ability of wind plants to survive grid faults and contribute to supporting the grid during and after such events.

1.6.1. Fault ride-through

Although fault ride-through (FRT) profiles for WTGs were introduced more than 15 years ago, the discussions on how they should be established, interpreted and applied in practice are still hot. Early FRT requirements were mere adaptations from those of conventional generators and consisted of specifications of minimum connection durations as a function of voltage drop/rise magnitude. Contemporary provisions evolved to different levels of complexity and degrees of flexibility.

Figure 13 shows the FRT requirements in Québec [23]. Wind power plants are also required to remain in service up to 0.15 seconds for double-phase-to-ground faults and 0.30 seconds for single-phase-to-ground faults.

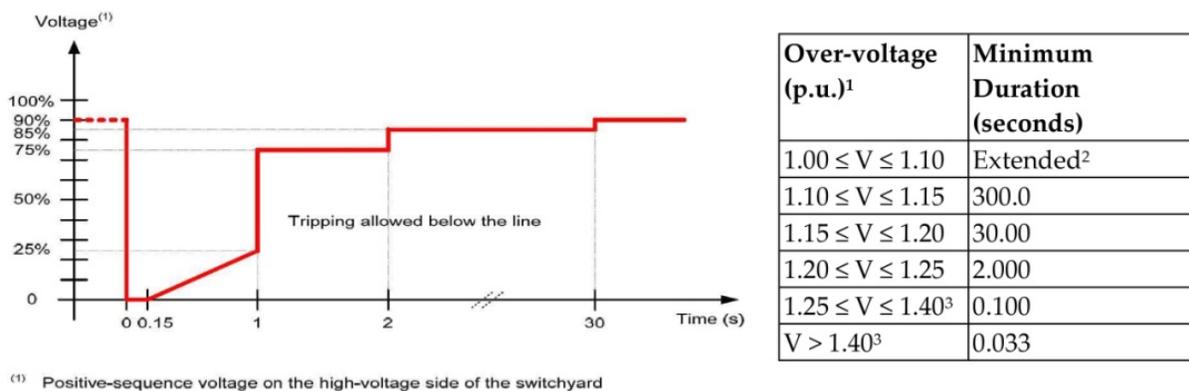


Figure 13. FRT capability required from wind plants - HQTE code [23]; ¹ Positive-sequence voltage on HV side of switchyard; ² Up to hours, depending on time needed to bring grid voltage back to steady-state range; ³ Temporary blocking is allowed beyond 1.25p.u. but normal operation must resume once voltage drops back below 1.25p.u.

Figure 14 shows the FRT curve of one for the German codes [16]. Wind power plants must remain connected without instability above limit line 1 for all symmetrical or unsymmetrical voltage dips. Voltage drops within the area between limit lines 1 and 2 should not lead to disconnection, but short-time disconnection is allowed case of WTG instability. Disconnection is allowed below limit line 2.

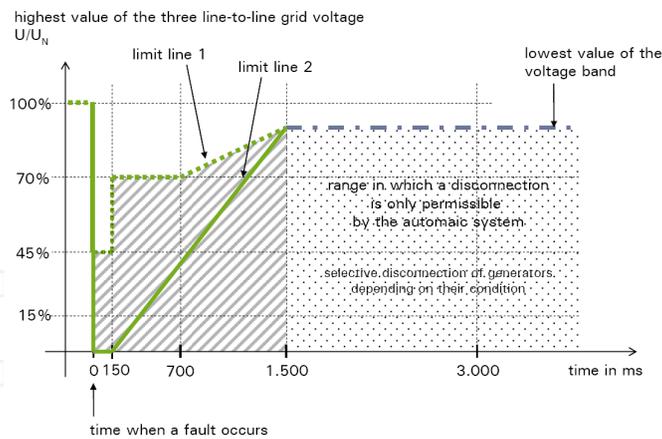


Figure 14. Low-voltage ride-through requirements for wind plants - German code [16].

The Australian grid code stipulates that wind plants must be capable of continuous uninterrupted operation in voltage transients caused by high speed auto-reclosing of transmission lines, irrespective of whether or not a fault is cleared during a reclosing sequence. Thus the wind power plant must be capable of riding through multiple faults as shown in Figure 15, which might be difficult for some FRT implementations due to excess stress on the drive-train of the WTG.



Figure 15. Low-voltage ride-through capability during auto-reclose operation - Western Power [27].

1.6.2. In-fault and post-fault requirements

In addition to remaining connected through the fault, some FRT provisions contain specifications for reactive current in-feed during the fault as well as precise criteria for active power recovery once the fault is cleared.

One German code [16] requires wind plants to support the grid voltage with additional reactive current in proportion to the voltage deviation, as shown in Figure 16. The in-feed must start within 20 msec of the occurrence of the voltage dip and must be maintained for a

further 500 milliseconds after the voltage returns to the 10% voltage dead band. Resynchronization must take place within up to 2 sec and active power must increase with a rate not less than 10% of rated power after fault clearance.

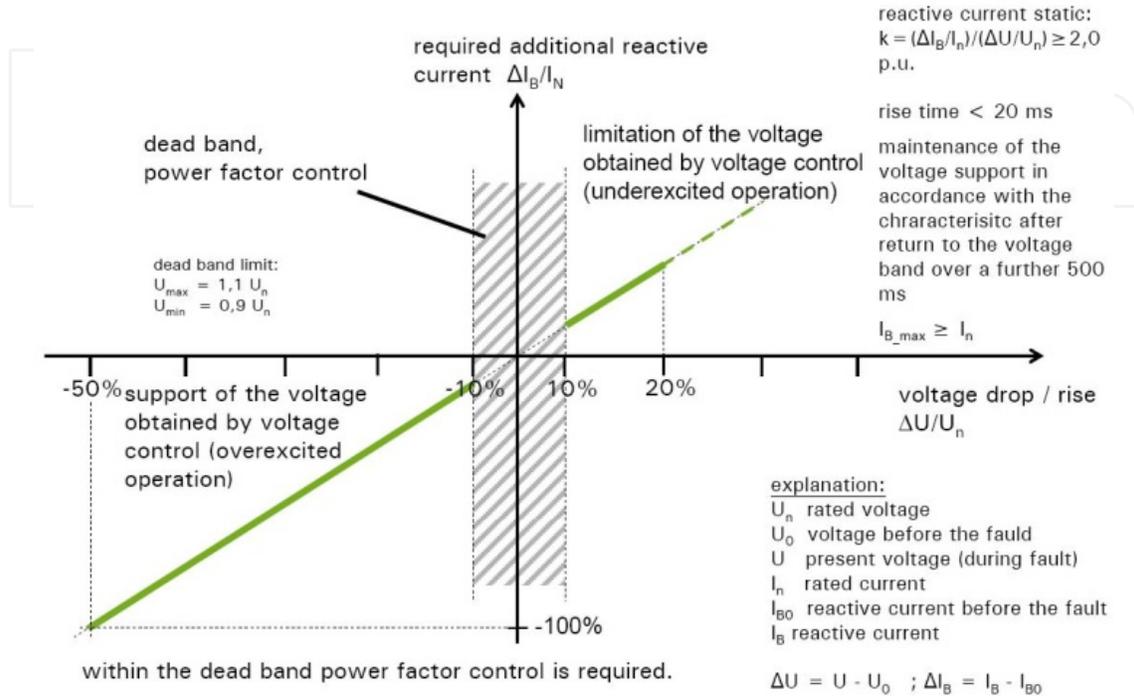


Figure 16. Required voltage support during disturbances in onshore wind plants - German codes [16].

Grid codes of UK and Ireland code [21] requires offshore wind power plants to provide active power output during voltage dips at least in proportion to the retained balanced voltage [26]. The Spanish code [25] has requirements for both active and reactive power consumption during a fault. Wind plants are not allowed to absorb active power during a balanced 3-phase fault or during the voltage recovery period after clearance. Absorption of active and reactive power is accepted for 150 msec interval after the beginning of the fault and 150 msec after clearance, as shown in Figure 17 (a). During the rest of the fault time, active power consumptions must be limited to 10% of the plant rated power. Within the 150 msec, the reactive power injection should be controlled as shown in Figure 17 (b).

Implementing the low-voltage ride-through in WTGs implies a proper management of the power being converted by the machine in the absence of the load or power sink provided by the grid [33]. This power needs to be curtailed, dissipated or stored, to avoid generator overspeeding. A number of technical possibilities are available: (a) acting on the blade capture rate by changing, for example, the blade angles, thus reducing the amount of wind power captured; (b) acting on the generator so that it no longer produces power and that the power does not flow from the stator into the grid; (c) dissipating the power produced by the generator, by means of resistances on the dc bus or using storage devices (seldom implemented). A combination of these solutions can be used concurrently.

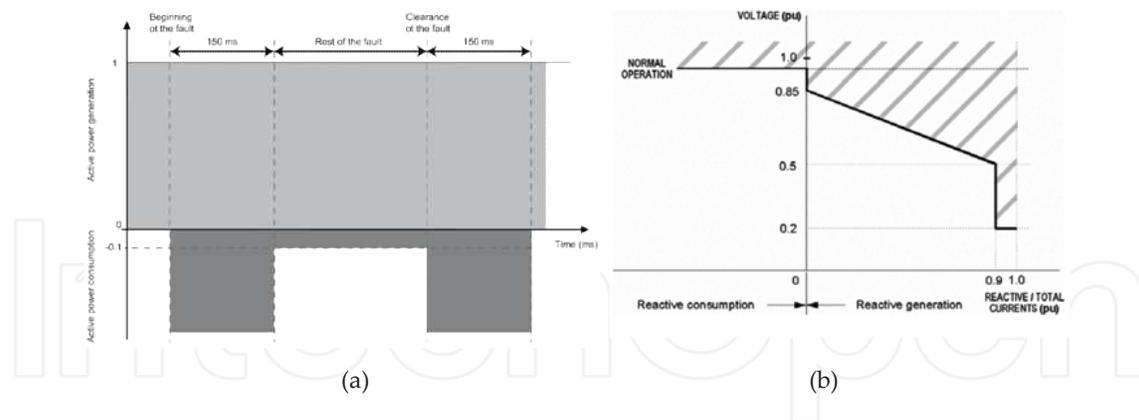


Figure 17. Active power under balanced 3-phase faults - Spanish code [24].

1.7. Harmonic emissions of wind power plants

The influence of a wind power plant on the current/voltage harmonic distortion should be considered in the design process since all system operators have maximum allowed emission levels for single order and total harmonic distortion at the connection point. The three sources contributing to the harmonic levels in a wind power plant are [8]:

1. the wind turbine generators
2. the dynamic reactive power compensation equipment (if any)
3. the collector system feeders, and
4. the electric grid itself

The contribution of each of these four sources to the total harmonic voltage distortion can be determined separately but should not be added arithmetically because they are not in phase. Therefore, summation laws, such as those of the IEC 61400-21 standard, can be applied for a more realistic account for angular differences and randomness of the harmonics.

Reactive power compensation elements will also affect the harmonic performance. SVCs and STATCOMs inject harmonics into the grid just as the wind turbines do. The collector system cables can also act as amplifiers for the harmonic emissions, especially in offshore wind power plants. The long ac submarine cables have frequency characteristics that could trigger critical resonances with the power system at relatively low frequencies.

Adequate modeling of the grid impedance as seen from the wind plant is also very important to quantify the grid's contribution to the harmonic emissions. The grid's impedance is not static; it's rather a function of the switching state and loading level in the grid. The dominant approach is to obtain (through simulation) the network impedance for a wind range of system states and plot them as a set of impedance loci in the complex impedance ($R-X$) plane. An example of this plot is given in Figure 18. For each harmonic frequency corresponds an $R-X$ plane, where the points p_1 through p_4 are usually fixed whereas Z_{max} is different for each harmonic order.

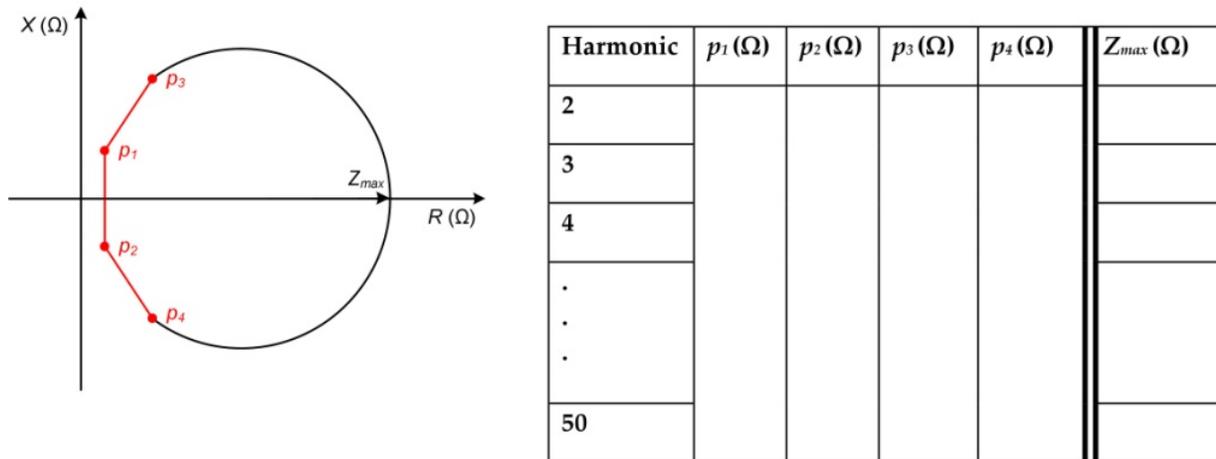


Figure 18. Typical impedance plane as provided by network operators.

The wind plant’s contribution to the harmonic voltage distortion at the POI has to be determined by assuming the worst-case network impedance in terms of resonances, which is generally different from the value resulting in the highest wind turbine contribution. If the harmonic performance analysis indicates that emission limits are likely to be exceeded, mitigation measures must be carried out. In order to mitigate the problem at the WTG level, some vendors equip their turbines with specific control schemes whose objective is to displace the phase angle between turbines to minimize the distortion at the connection point. At the wind plant level, one or more filters can typically be added to the design to diminish the emission at the most critical harmonic frequencies.

1.8. Other interconnection concerns

1.8.1. Power system stabilizers

Some of the recent grid codes include references to the capability of wind power plants in contributing to power oscillation damping in the grid through power system stabilizers (PSS). The grid code of HQTE, for example, stipulates that wind plants must be designed and built so that they can be equipped with a stabilizer in case it was imposed later during the lifetime of the wind power plant.

In synchronous generators, PSSs are used to damp oscillations arising from interactions between generators in a power plant, generators and the network and between generation areas. These functions are implemented using a supplementary control loop acting on the generator excitation system or voltage regulator. Damping is achieved through modulation of the reactive power produced by the generator. Modulating the real power flow through the governor would be slow with cost impacts on the turbine design and performance. However this is easier with wind power plants. The active and reactive power can be modulated independently by means of two separate supplementary control loops on the power converter regulator [48]-[50]. In the case of a DFIG, the control of higher frequency oscilla-

tions is limited by the rating of the rotor side converter, however, in the case of full converters, the control range can be significantly wider and the control can be made more effective.

There are options for implementing and triggering PSS functions in wind plants. One of them is based on the frequency deviation. Studies were carried out to demonstrate that both active and reactive power control could be used effectively to damp inter-machine oscillations and to investigate the impact of the wind plant location on the damping effectiveness [33], [48]. It was found that, in general, active power control is less dependent on location, but still more effective when the point of POI of the wind plant was located close to a synchronous generator plant.

1.8.2. Operational monitoring & communication

Wind plants are required to send a wide range of real-time data points to the control and dispatch centers of the grid operator. These include status indications and measurements collected through the supervisory control and data acquisition (SCADA) system. The data points include:

- electrical measurements the at POI and/or collector system feeders, including: phase and line voltages and currents, actual and available MW and Mvar outputs, and average MW.hr yields
- operating status signals, including: transformer tap positions, status of dynamic compensation systems, and the action of main switchgear and protection systems
- meteorological data at the wind farm, including: wind speed and direction at individual turbines, ambient temperature, atmospheric pressure, and precipitation.

Increasingly, the real-time (electrical and meteorological) data is being used by grid operators/planners for wind power forecasting. In one example, the New York Independent System Operator (NYISO) has developed a program that integrates wind forecast into the real-time dispatch [32]. NYISO uses its wind forecast to predict the output level over the next hour, broken up into 5-minute time steps. At each time step, NYISO determines the output level at which the wind plant is economic to operate by using an economic offer curve supplied by the wind plant. If the wind plant is economic at an output level lower than the forecast level, NYISO will send a curtailment signal to commanding the wind plant to reduce its output. In China, the National Electric Power Dispatching and Communication Center (NEPDCC) uses the real-time wind power operation information from the different regional and provincial grids in China to perform its online transmission reliability and generation adequacy studies [10].

1.9. Grid compliance validation

Studies are performed to investigate the impact of any the new generation added to the grid. The connection of a new wind power plant will be authorized only if the performed connection impact assessments and associated tests show that the integration of new generation does not lead to a deterioration of the reliability and operational security of the system.

1.9.1. System impact studies

In general, the studies performed for the connection of wind plants are similar to those for a conventional thermal or hydroelectric plant. The purpose of these studies is to verify that the coordinated operation of all the units within the plant complies with the general and project-specific requirements stipulated by the grid operator. Those studies typically include [8]:

- Power flow studies to see the impact of the wind plant integration on system steady-state flows, voltages profiles, and transfer capabilities
- Contingency analysis to see the behavior of the wind plant during grid events that involve the loss of transmission circuits, transformers, or other generators so as to ensure that post-contingency flows and voltages are within their respective limits
- Low-voltage ride-through analysis to show compliance with the required durations and fault severities
- Short-circuit studies to ensure that the new plant does not cause over-duty of breakers or other equipment in nearby substations
- Dynamic studies to verify that the wind plant has enough static/dynamic reactive power to meet the requirements of voltage control
- Transient stability analysis to test the response of the wind plant and nearby system to faults occurring on the power system and to ensure that generation remains on synchronism and performs in an acceptable manner.
- Subsynchronous control instability studies addressing the interaction of wind turbines and their control systems with series-compensated lines on the transmission grid
- Load rejection study to evaluate the impact on the wind plant in ac interconnections
- Power quality studies, including harmonic and flicker analysis to determine the potential impact of wind fluctuations on the voltages at nearby substations and load centers.

1.9.2. Wind generator models

System planners and operators use simulations to assess the potential impact of contingency scenarios on system performance and to assess the ability of the power system to withstand such events while remaining stable and intact. As discussed in Sections 1.3–1.8, the wind plant control is composed of several levels with different response characteristics, including the WTGs, wind plant controller, reactive power compensation equipment, and on-load tap changers. Thus, it can be quite challenging to design a collective control scheme for the wind plant to meet the required dynamic response at the POI under all operating conditions. This is typically examined in transient stability studies, where all relevant components and their control loops are modeled. For this type of study, generic simulation models often do not exhibit the necessary level of precision. Thus user-written, validated models are generally needed.

1.9.3. Grid connection testing

Passing the field validation tests is a prerequisite for the permission of interconnection of some grid operators. These tests are performed in order to:

- Demonstrate that the overall wind plant and its constituting elements, including the WTGs, compensating equipment, and substation transformer meet the technical requirements of the grid operator
- Validate the simulation models and the associated parameters by comparing the model behavior to the field measurements.

Figure 19 shows the main areas of wind power plant and wind turbine testing. Type tests are tests of representative equipment performed by the manufacturer in the presence of third party certifiers. The intent is to demonstrate that a particular equipment design exhibits its specific performance that can be generalized to all other equipment of that same design [33]. These include validations of the power performance, load calculations, noise levels, and voltage/frequency operation ranges. Long-term harmonic measurements are also performed to establish the harmonic emission spectrum. These measurements are generally repeated for each wind plant at the POI to account for the emissions of auxiliary equipment and the amplifications caused by the collector system and the grid itself.

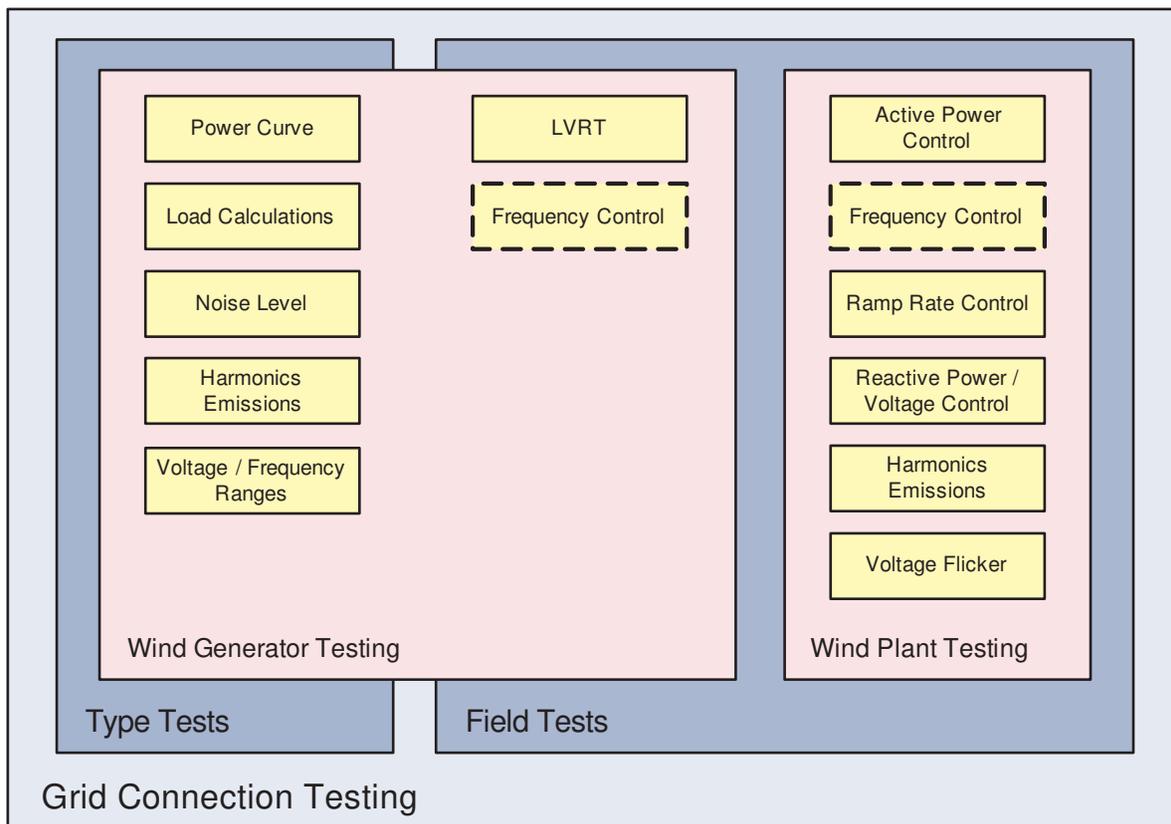


Figure 19. Grid connection tests of wind plants and wind turbine generators.

Other wind plant field tests include active power and ramp rate control. Depending on the approach of the grid operator, frequency control capabilities (including inertia control and over-frequency response) are either tested at the WTG level (e.g. HQTE) or wind plant level (e.g. UK). The reactive power range and voltage control are also tested to verify the capability of the central wind plant controller and any compensation equipment to respond to voltage deviations as quickly and sufficiently as required.

The data gathered through the online monitoring systems during the life-time of wind plants is also used for performance evaluation. This data, including snapshots of the wind plant behavior taken during external and unscheduled events (such as disturbances or large wind changes) is particularly useful in fine-tuning the wind plant parameters for optimal grid compatibility. The large-scale deployment of phasor measurement units (PMU) by system operators would also open the door for a variety of advanced monitoring and control applications.

1.10. Chapter summary

As grid operators worldwide continue to face a rapid growth of the installed capacity of wind power, the following key items should be observed in order to be able to accommodate high penetration levels while maintaining the same level of operational security and reliability:

- Clearer grid codes and standards addressing system issues such as transient stability, voltage collapse, and reactive power support
- Better market practices employing different scheduling periods and incorporating wind power forecasts
- Enhanced interconnections among generation areas with transmission upgrades and optimization of grid utilization
- Wider balance areas and new power exchange mechanisms
- Increased system flexibility through faster response from conventional generation, better demand-side management, and intelligent incorporation of storage technologies
- Improved system operational tools and models for more complex power systems with high wind penetration.

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