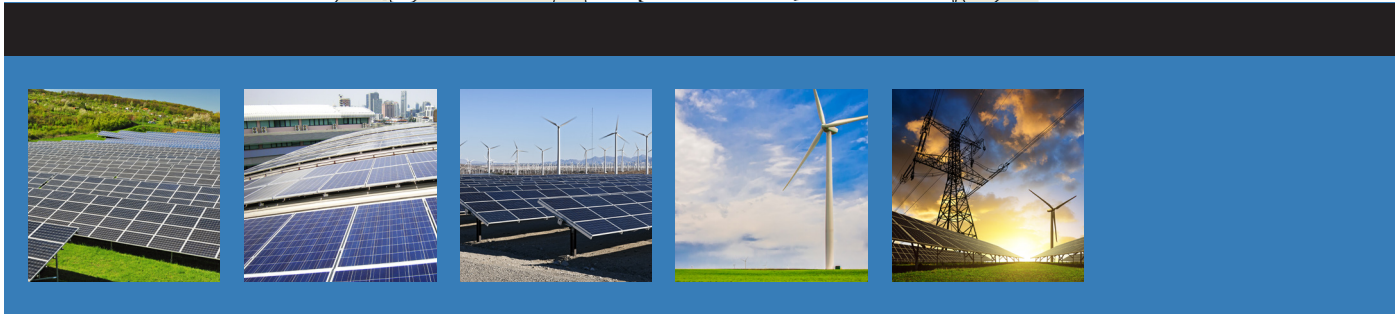
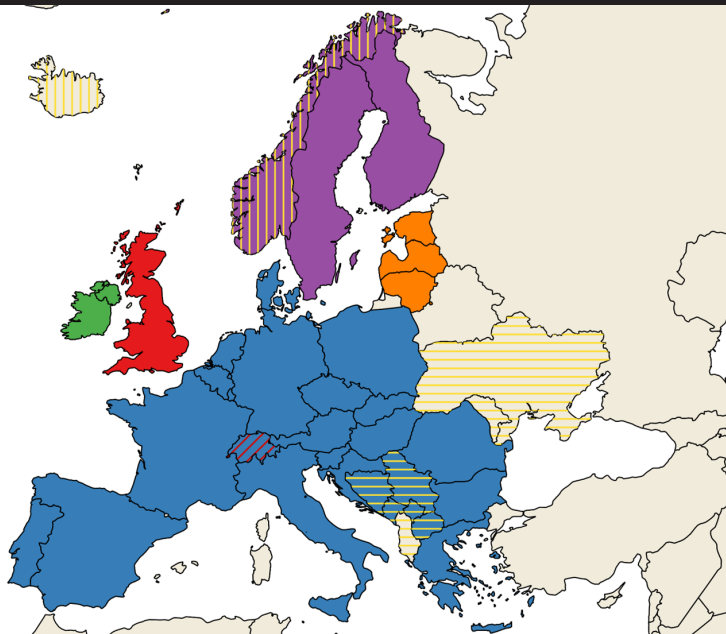


ADVANCED GRID SUPPORT FUNCTIONS FOR SMART INVERTERS

Toward a Unified Regulatory Framework in Europe



November 2016

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Executive Summary

Functions of smart inverters that support the grid have received much attention in recent years as a key component of the future electricity grid with higher penetration of distributed energy resources (DER). In Europe, most of the requirements currently applicable to inverter-based resources were drawn up nationally and in response to local needs. As a result, a comparative analysis across Germany, France, Spain and Italy shows significant variations from one country to another. These differences constitute a limiting factor in an environment where national networks are increasingly interconnected and interdependent.

This white paper provides an introduction, commentary, and selected verbatim excerpts of the *Network Code on Requirements for Generators* (NC-RfG)¹, a new regulation of the European Union (EU) that intends to address these differences by setting harmonized interconnection rules, including unified requirements for smart inverter functions. The code, which took effect in May 2016, will be applicable to all newly connected energy resources in 40+ European countries, including non-EU members, starting May 2019. It will supersede any existing or new national legislation and prevail over any standard.

While setting a common regulatory framework, the NC-RfG recognizes that differences in local network characteristics prevent the development of one-size-fits-all requirements. For this reason, the code uses extensively the concept of a “non-exhaustive” requirement. Non-exhaustive requirements do not provide for a full harmonization of their specifying parameters. Instead, a common methodology describing how these parameters shall be set is defined, and binding ranges, within which values must be chosen, are specified.

The code also introduces four different categories of grid-connected generators to address the wide range of generator characteristics. These categories, or “types,” are based on voltage level at the connection point and maximum active power capacity. To provide greater flexibility, the network code specifies only binding ranges within which each transmission operator is to formally define the four categories for its own control area.

¹ European Commission, Regulation (EU) 2016/631, April 14, 2016.

The sections of the code pertaining specifically to advanced functions for inverter-based generation resources encompass the areas of active and reactive power control and grid fault response. Depending on generator categories, the advanced functions required include remote active power control, active power response at over- and under-frequency, and various reactive power control modes ($Q=f(V)$, Q fix, $\cos \phi$ fix). Functions related to grid fault response include voltage and frequency ride-through, post-fault active power recovery, reactive current support, and the provision of synthetic inertia. This paper provides a technical summary of the NC-RfG, including selected verbatim excerpts for each of the inverter functions required under the new code². Additional provisions on communication and simulation models are also discussed.

² *Ibid.*

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This white paper is primarily directed to decision-makers involved in the process of developing requirements for interconnecting DER to the grid, including the ongoing revision of IEEE Standard 1547. It also provides insights relevant to any stakeholder concerned with the emerging distributed capabilities of the future electricity grid.

Introduction

In recent years, the deployment of distributed energy resources (DER) has noticeably increased in Europe, especially in the form of solar and wind power generation. Between 2008 and 2014, the European Union (EU) doubled its wind power capacity, reaching 130.4 GW in 2014; during the same period, the EU photovoltaic (PV) power capacity rose from 10.4 GWp to 86.7 GWp (Figure 1). This rapid expansion resulted in part from the EU commitment to fulfil at least 20% of its total energy needs with renewables by 2020³, to be achieved through the attainment of individual national targets. As of 2014, five countries—Germany, Spain, Italy, the United Kingdom, and France—represented together 72% of the total wind power capacity installed across the EU, and 83% of the total PV capacity.

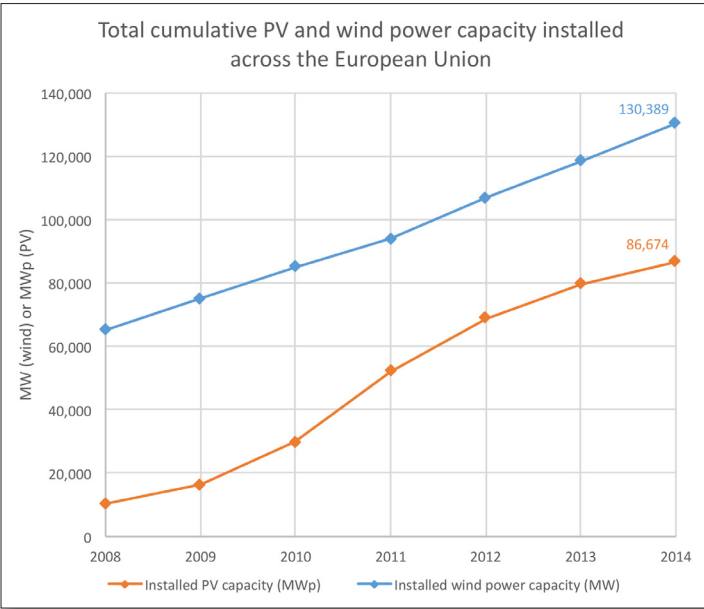


Figure 1. Total cumulative PV and wind power capacity installed across the European Union, 2008-2014. Data from EurObservER database.

From a grid operations standpoint, this fast growth of DER has created a number of integration challenges for distribution and transmission system operators (DSO and TSO) across Europe. First, the intermittent nature of solar and wind generation requires the development of new technical and operational rules to guarantee power reliability and quality of supply. Second, while in the past grid-connected distributed generators were commonly instructed to disconnect at the first sign of trouble, they are now progressively expected to actively support the grid during normal and certain types of abnormal voltage and frequency conditions. This paradigm shift requires the specification of new inverter functions. Third, in an environment where national networks are becoming more and more interconnected, it becomes increasingly important to ensure consistency in the way each network is operated. These, among other factors, motivated the development of a new and unified set of interconnection requirements⁴ applicable to all grid-connected generators across Europe. This white paper provides an overview of these requirements, including selected verbatim excerpts, with a particular focus on advanced functions for inverter-based DER.

Similar efforts to harmonize interconnection requirements for DER are currently undertaken in North America with the full revision of IEEE Standard 1547. While the original 1547 standard, published in 2003, assumed low DER penetration, an amendment known as IEEE Standard 1547a-2014 was adopted in May 2014 that removes some restrictions against DER from actively participating in grid voltage regulation. This amendment allows broader inverter support functions but *does not require nor specify* these functions. The goal is to ensure that an eventual *common* standard can be both effective and actionable in interconnecting next-generation DER equipped with “smart” functions in ways that are beneficial to the power system. The IEEE 1547 revision process involves a wide range of stakeholders among the industry, and the grid-support functions currently being specified as part of this process are similar to the ones specified in the EU Network Code.

³ Directive 2009/28/EC of the European Parliament and of the Council of April 23, 2009 on the promotion of the use of energy from renewable sources.

⁴ European Commission, Regulation (EU) 2016/631, April 14, 2016.

Toward a Pan-European Network Code on Interconnection

Current Scenario in Europe: A Wide Range of Country-Specific Requirements

Most of the grid-connection rules currently in place in European countries were drawn up nationally and in response to local needs. As a result, the existing requirements pertaining to smart inverter

functions vary greatly from one country to another. These inconsistencies constitute a limiting factor in an environment where national networks are increasingly interconnected and interdependent. Tables 1 and 2 illustrate these differences by comparing the smart inverter functions currently mandated in Germany, France, Spain, and Italy, for both the low- and medium-voltage (LV and MV) networks.

Table 1. Comparison of the grid-support functions currently required in Germany, France, Spain, and Italy for inverter-based generators connected to the low-voltage (LV) network.

LOW VOLTAGE		Germany	France	Italy	Spain	Europe ≤16A	Europe >16A
		VDE AR N 4105:2011 National Standard LV: ≤1kV	Arrêté 04/23/2008 Arrêté 02/15/2010 Ministerial decrees LV: 50V-1kV	CEI 0-21:2014 National Standard LV: ≤1kV	UNE 206007-2 IN:2014 National Standard LV: ≤1kV	EN 50438:2013* (applicable 11/2016) European Standard LV: ≤1kV	CLC/TS 50549-1:2015 (non-binding) CENELEC Specification LV: ≤1kV
Active Power Control	Remote ON/OFF	>100kW, optional		>6kW			all
	Remote control of P	>100kW		>6kW	>100kW		all
	P(f) at overfrequency	all	>5MW	all	>100kW for mainland	all	all
	Minimum capability to uphold P in-feed with falling frequency					all	all
	P(f) at underfrequency						
	P(U)					optional	optional
Reactive Power Control	cos φ fix	all		>3kW	all	all	all
	cos φ (P)	>3.68kVA		>3kW		all	all
	cos φ (V)						all
	Q fix				all		all
	Q (V)	optional		>6kW	>100kW	all	all
	Q (P)						all
Grid Fault Response	LVRT			>6kW	all		all
	HVRT						all
	LFRT [‡]	47.5Hz	47.0Hz, >5MW	47.5Hz	47.5Hz	47.5Hz	47.5Hz
	HFRT [‡]	51.5Hz	52.0Hz, >5MW	51.5Hz	51.5Hz	51.5Hz	51.5Hz
	Reactive current support						

Notes:

all indicates requirement is applicable to all generator sizes.

*EN 50438:2013 has been transposed as national standard in the four countries considered: Germany (DIN EN 50438), France (NF EN 50438), Italy (CEI EN 50438) and Spain (UNE EN 50438).

[‡]Frequencies indicate the frequency thresholds beyond which disconnection is permitted.



Table 2. Comparison of the grid-support functions currently required in Germany, France, Spain, and Italy for inverter-based generators connected to the medium-voltage (MV) network.

MEDIUM VOLTAGE		Germany	France	Italy	Spain	Europe
		BDEW MV Guideline (2008, 2013) Industry guideline MV: 1kV-60kV	Arrêté 04/23/2008 Arrêté 02/15/2010 Ministerial decrees MV: 1kV-50kV	CEI 0-16:2014 National Standard MV: 1kV-150kV	UNE 206007-2 IN:2014 National Standard MV: 1kV-36kV	CLC/TS 50549-2:2015 (non-binding)
Active Power Control	Remote ON/OFF	all		>100kW		CENELEC Specification
	Remote control of P	all		>100kW	>100kW	MV: 1kV-36kV
	P(f) at overfrequency	all	>5MW	all	>100kW for mainland	all
	Minimum capability to uphold P in-feed with falling frequency		>5MW			all
	P(f) at underfrequency					all
	P(U)					optional
Reactive Power Control	cos φ fix	all		all	all	all
	cos φ (P)	all		all		all
	cos φ (V)					all
	Q fix	all		all	all	all
	Q (V)	all		all	>100kW	all
	Q (P)					all
Grid Fault Response	LVRT	all	>5MW	all	all	all
	HVRT			all		all
	LFRT [‡]	47.5Hz	47.0Hz, >5MW	47.5Hz	47.5Hz	47.5Hz
	HFRT [‡]	51.5Hz	52.0Hz, >5MW	51.5Hz	51.5Hz	51.5Hz
	Reactive current support					all

Note:

all indicates requirement is applicable to all generator sizes.

‡Frequencies indicate the frequency thresholds beyond which disconnection is permitted.

Initial efforts to address these differences across countries primarily focused on developing unified norms as part of the European *standardization* process. Harmonized standards and technical specifications were developed through the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC). These efforts resulted in

the release of EN 50438:2013 and CLC/TS 50549-1:2015 for LV networks (both shown in Table 1) and CLC/TS 50549-2:2015 for MV networks (shown in Table 2). Once finalized, European standards (EN) are *voluntarily* adopted by the participating countries as national standards, while technical specifications (TS) can be seen as pre-standards.

Grid Codes versus Standards: What Are the Differences?

Over the past decade, two distinct processes, often confused, have contributed to the development of requirements pertaining to smart inverter functions: *rule-making* and *standardization*.

Rule-making refers to the various regulations, decrees, and orders issued by governments and/or regulatory agencies. When related to interconnection, these requirements are referred to as “network codes” or “grid codes.” Network codes are *legally binding* for the DSO, TSO, and power plant owners; they sometimes further authorize the DSO and/or TSO to specify additional rules within their jurisdiction. Other actors, although not explicitly mentioned in these codes, are indirectly impacted: equipment manufacturers, installers, and certification bodies.

Standardization is a distinct process related to the relevant norms and technical specifications developed by standard, industry, and other professional organizations. This standardization process, deliberative and open to any interested parties, is *non-binding*: Only the parties affiliated with the relevant organizations voluntarily commit to develop and possibly adopt these specifications.

In recent years, these harmonization efforts were further extended as part of the EU *rule-making* process to develop EU-wide *binding* rules governing the way power generators gain access to the grid. This white paper provides an overview of the recently approved EU *Network Code on Requirements for Generators* (NC-RfG), which resulted from these efforts, with a particular focus on advanced functions for inverter-based DER.

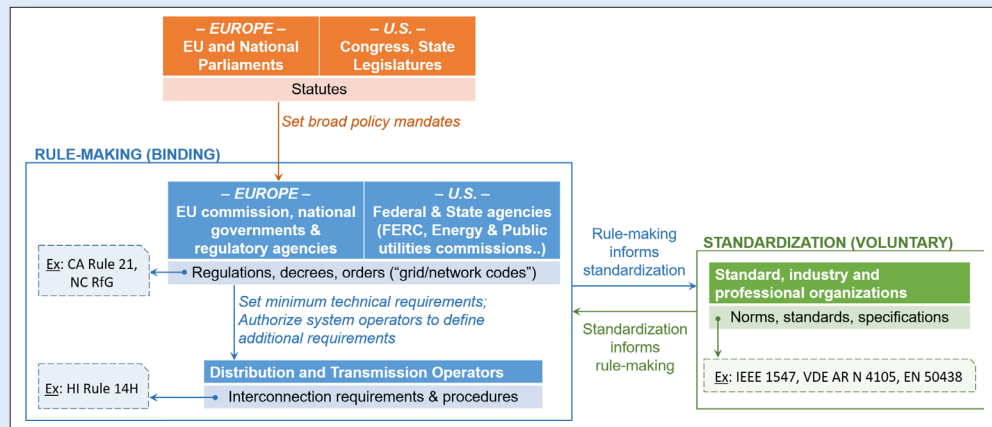


Figure 2. Relationships between the various types of requirements pertaining to smart inverter functions.

Both processes—rule-making and standardization—inform each other over time. A norm might be developed to standardize the implementation of an existing requirement mandated through rule-making. Conversely, a regulation might refer explicitly to an existing norm and make its implementation mandatory. However, network codes such as the NC-RfG always *prevail* over any conflicting standard due to their legally binding nature. Figure 2 illustrates the relationships between the various types of grid-connection requirements and the processes that generate them.

Inception, Goals, and Benefits of a Unified Code

The need for EU-wide grid connection requirements was identified as part of the Third Energy Package of 2009⁵, which is a legislative package aiming at further opening up the gas and electricity markets in Europe. More specifically, Regulation (EC) 714/2009 provides the legal basis for developing a network code harmonizing the technical and operational rules that new power generators must follow to connect to the electric grid. The goal is to support the

⁵ Official Journal of the European Union, L 211, August 14, 2009.



creation of a reliable, efficient, and fully integrated energy market across Europe, in an environment with more intermittent generation and increasingly interconnected national networks. Manufacturers of grid technologies will also see fewer differences between national rules.

Drafting Process

Regulation (EC) 714/2009 established an *ad hoc* institutional setup for developing the new network code on grid connection requirements. The Agency for the Cooperation of Energy Regulators (ACER) first issued a set of principles, referred to as “framework guidelines,” for developing the code⁶. Based on these principles, the European Network of Transmission System Operators (ENTSO-E) was mandated to develop an initial version of the code in cooperation with national experts and relevant stakeholders. This panel included experts from CEN and CENELEC⁷. The resulting draft, titled *Network Code on Requirements for Generators (NC-RfG)*, was assessed by ACER to ensure consistency with the framework guidelines and was submitted to the European Commission. The EU-member states approved a revised version of the ENTSO-E draft in July 2015, which was formally adopted in April 2016.

Scope of Application

The NC-RfG was published in the form of an EU regulation in May 2016. Regulations are legal acts of the European Union that become immediately binding and applicable in all EU member states. The network code therefore supersedes any existing or new national legislation concerned with grid connection requirements for power generators and will also prevail over any standard. Although the new code is directly applicable at the national level, each country may adjust its national rules and standards accordingly to provide for consistency and clarity. An implementation period of three years, from May 2016 to May 2019, will allow for updating the national regulatory frameworks, as well as any existing contractual arrangements conflicting with the new code (Figure 3).

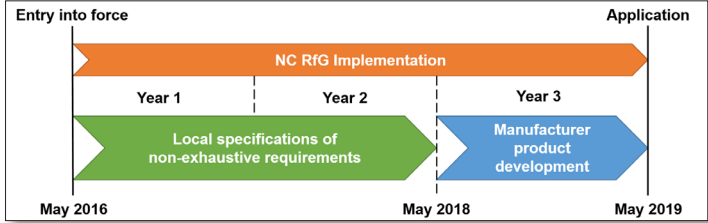


Figure 3. Implementation timeline for the NC-RfG. Source: Adapted from ENTSO-E.

In addition to the 28 member states of the European Union, several non-EU countries will also implement the NC-RfG (Figure 4). These include the three non-EU countries that are parties to the European Economic Area agreement (Iceland, Liechtenstein, and Norway), as well as the eight contracting parties to the Energy Community Treaty (Albania, Bosnia and Herzegovina, Kosovo, Macedonia, Moldova, Montenegro, Serbia, and Ukraine). Supplemental adoption procedures may apply for the code to become fully applicable in each of these countries. Switzerland is also expected to voluntarily introduce part or all of the new NC-RfG rules under the Swiss law.

⁶ ACER, “Framework Guidelines on Electricity Grid Connections,” July 20, 2011.
⁷ CEN-CENELEC, “Enhanced Cooperation with ENTSO-E Should Contribute to More Efficient and Reliable Electricity Distribution in Europe” in CEN-CENELEC Newsletter, Issue 14, Fall 2013.

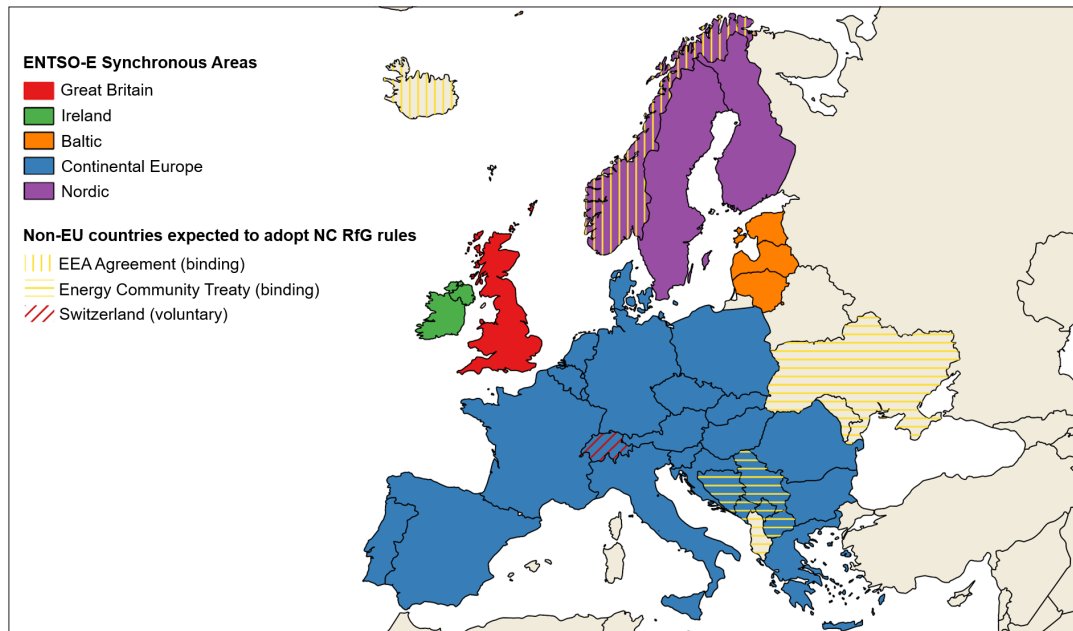


Figure 4. ENTSO-E synchronous areas and non-EU countries that are expected to adopt the EU network code on grid connection requirements for power generators (NC-RfG).

Only *new* power generators will be subject to the NC-RfG requirements. However, existing generators may also be subject to part or all of the requirements at the discretion of the relevant regulatory authorities. In particular, when equipment impacting the technical capabilities of a generating unit is modernized, the relevant regulatory authorities may decide to re-qualify the unit as new.

NC-RfG Approach: Common Framework, Flexible Implementation

Requirements regulating the connection of power generators to a national yet interconnected network have cross-border impacts. This was one of the factors motivating the development of harmonized connection rules across Europe. However, network characteristics such as topology, dynamic system response, or stability differ across countries and synchronous areas. The use of identical interconnection requirements across the European Union would not be sound technically and result in unreasonable financial impacts. The diversity across grid-connected generators (such as size, voltage at the connection point, and technology) also prevents the development of one-size-fits-all requirements.

The NC-RfG recognizes the differences in local system needs through the concept of “non-exhaustive” requirements. A non-exhaustive requirement does not require full harmonization of the parameters specifying the technical terms of the requirement. Instead, a common methodology describing how these parameters shall be set is defined, and binding ranges, within which values must be chosen, are specified. Typically, the *relevant system operator* (to whose system the generator is directly connected) and/or the *relevant transmission operator* (managing the relevant control area) are responsible for rendering each non-exhaustive requirement exhaustively defined through a transparent and non-discriminatory process. Non-exhaustive requirements of general application are to be fully specified and submitted to the relevant regulatory authorities for approval by May 2018 or a date that is no later than two years after the new code enters into force (Figure 3).

Additionally, four different categories of generators, referred to as “types,” are defined to address the wide range of generator characteristics. These generator categories are specified based on (1) voltage level at the electrical connection point (ECP) and (2) maximum real power capacity of the generator. Under the NC-RfG, the term *connection point* refers to “the interface at which a power generating module is connected” to a distribution or transmission system. A power-generating facility consists of “one or more power generating modules connected to the network at one or more connection points.” In the following sections, the terms “generator” and “power generating module” are used interchangeably.

Generators of type A, B, and C require a connection point below 110 kV, while generators of type D are connected at 110 kV or greater. Maximum capacity thresholds are defined to further distinguish between types A, B, and C. For each of the five

ENTSO-E synchronous areas (Figure 4), the NC-RfG sets area-specific binding limits for these maximum capacity thresholds (Figure 5). Two identical generators located in two different synchronous areas may therefore qualify under two different generator types.

Finally, within each synchronous area, each transmission system operator sets the maximum capacity thresholds for its own control area at or below the binding limits set by the network code for that synchronous area. Two identical generators located in two distinct control areas that are part of the same synchronous area may therefore qualify under two different types. Figure 6 illustrates this possibility for two hypothetical TSOs, each controlling an area within the Nordic synchronous area. Under this scenario, a 24-MW generator connected at 55-kV voltage would be classified as Type D in control area #1 but as Type C in control area #2.

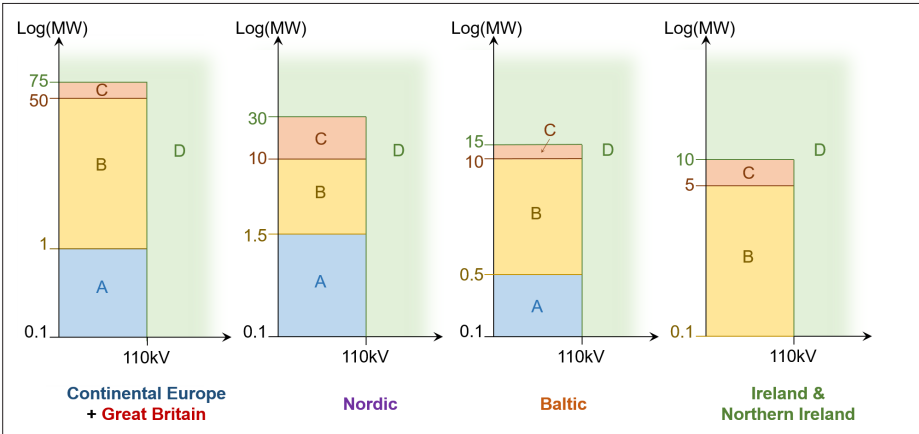


Figure 5. Generator types A, B, C, and D as defined in the NC-RfG for each of the five ENTSO-E synchronous areas as a function of (1) the voltage level at connection point (kV) and (2) the area-specific binding limits for the maximum capacity thresholds (kW). Type A requires a maximum capacity of 0.8 kW or more (not shown in this figure). For the Ireland and Northern Ireland area, Type B begins at 0.1 MW.

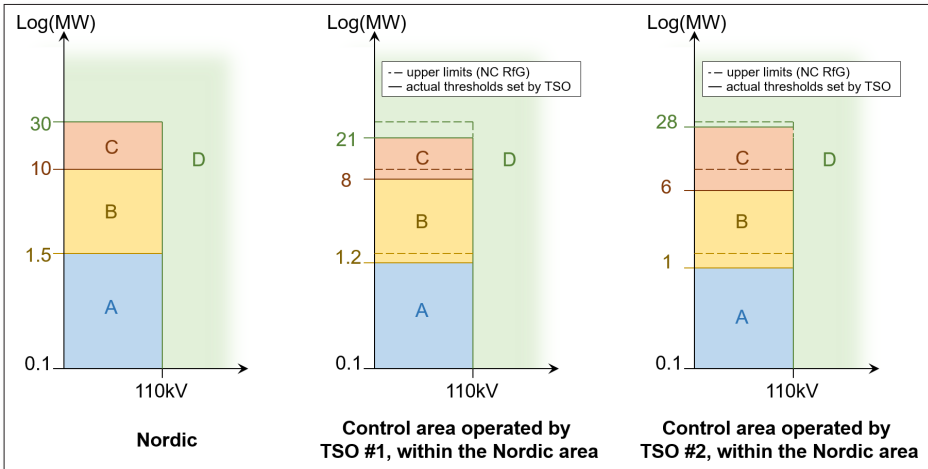


Figure 6. Example of fully defined generator types A, B, C, and D for two hypothetical control areas operated by TSO#1 and TSO#2, both located within the Nordic synchronous area. Left: binding limits for the maximum capacity thresholds as set by NC-RfG for the Nordic area. Middle and right: fully defined thresholds set by TSO#1 and TSO#2 within the NC-RfG binding limits.

The scope of application of each of the NC-RfG requirements is specified in terms of generator types (A, B, C, and/or D) and technology types (rotating machines and/or inverter-based generation). For example, a given requirement may only apply to generator types C and D, regardless of the technology, while another requirement will be only applicable to inverter-based generators qualifying

under types A and B. In practice, the set of requirements is minimal for the smallest generators (type A) and gradually builds up as generation size increases.

The rest of this white paper focuses on the NC-RfG requirements pertaining specifically to advanced functions for inverter-based generators. A technical summary—including selected verbatim excerpts—is provided for each requirement. Table 3 provides exact references to the corresponding sections of the code.

Table 3: Summary of the main NC-RfG requirements pertaining to smart inverter functions.

		Scope of application				Decision-maker responsible for fully specifying the requirement (● primary, ○ secondary)			References	
		A	B	C	D	Relevant System Operator	Relevant Transmission System Operator	Power Generating Facility Owner	NC-RfG*	ENTSO-E Guidelines**
Active Power Control	Remote ON/OFF	✓	✓	✓	✓	●			13(6)	
	Remote control of P		✓	✓	✓	●	● (C/D only)		14(2), 15(2)(a-b)	
	P(f) at overfrequency	✓	✓	✓	✓		●		13(2)	3-1
	Minimum capability to uphold P in-feed with falling frequency	✓	✓	✓	✓		●		13(4-5)	3-3
	P(f) at underfrequency			✓	✓		●		15(2)(c)	3-4
	P(f), combined mode over/under frequency			✓	✓		●		15(2)(d)	
Reactive Power control	cos φ fix			✓	✓	●	○	○	21(3)(d)(vi)	
	Q fix			✓	✓	●	○	○	21(3)(d)(v)	
	Q=f(U)			✓	✓	●	○	○	21(3)(d)(ii-iv)	
Grid Fault Response	LVRT		✓	✓	✓		●		14(3), 16(3)	3-5, 3-9
	LFRT and HFRT	✓	✓	✓	✓	●	○	○	13(1)(a)	
	Post-fault active power recovery		✓	✓	✓		●		20(3)	3-10, 3-12
	Reactive current support		✓	✓	✓	●	○		20(2)(b-c)	3-13
	Synthetic inertia			✓	✓		●		21(2)	

* European Commission, Regulation (EU) 2016/631, April 14, 2016.

** ENTSO-E, *Implementation Guideline for Network Code: Requirements for Grid Connection Applicable to All Generators*, October 16, 2013.

Active Power Control Functions

Remote Active Power Control

All generators, regardless of type, shall have the capability to bring their real power output down to zero no later than 5 seconds after such a request is received from the system operator. In addition, generators of type B must be able to “reduce” their active power output, while types C and D must be able to “adjust” to a given setpoint. The time limit by which the adjusted output level must be reached is to be defined by the relevant system operator or the relevant TSO.

$P(f)$ at Overfrequency

All generator types shall have the capability to provide real power frequency response at over-frequency, as defined in Figure 7. The relevant TSO is to set the threshold frequency between 50.2 Hz and 50.5 Hz and the droop settings between 2% and 12%. This frequency response mode must be activated within 2 seconds after reaching the frequency threshold (“initial delay”) unless technical evidence justifying a greater response time is provided to the TSO. The relevant TSO, with approval from the relevant regulatory authority, may exempt generators of type A from this requirement and choose instead to allow for automatic disconnection and reconnection at randomized frequencies above the frequency threshold.

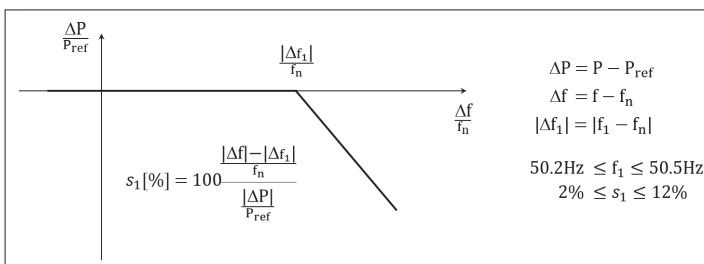


Figure 7. Active power frequency response capability of grid-connected generators at over-frequency. f_n is the nominal frequency; f_1 is the threshold frequency; Δf is the frequency deviation in the network; P_{ref} is either the actual real power when the frequency threshold is reached, or the maximum real power capacity, as defined by the relevant TSO; ΔP is the change in active power output; s_1 is the droop. Source: Adapted from Figure 1 in NC-RFG

Minimum Capability to Uphold P In-Feed with Falling Frequency

For each control area, the relevant TSO is to specify an acceptable real power reduction from the generator’s maximum output when frequency is falling. This requirement, applicable to all generator types, is expressed as a rate of reduction that must remain within the shaded area represented in Figure 8. When fully specifying this requirement, the TSO must clearly delineate the “ambient conditions” applicable and “take account of the technical capabilities of the power generating modules.”

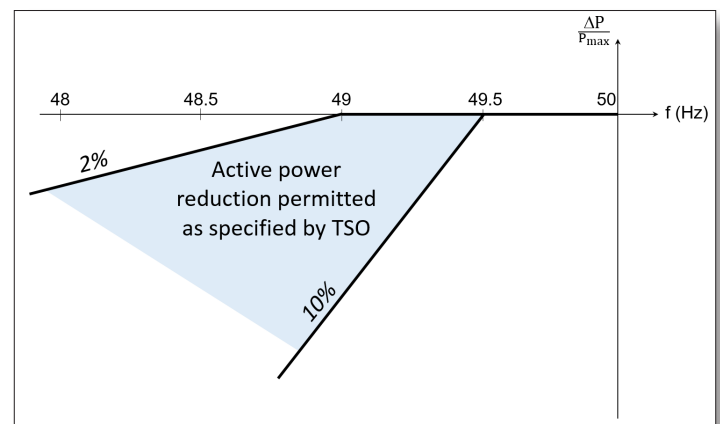


Figure 8. Minimum capability to uphold P in-feed with falling frequency. The boundaries delineating the shaded area are to be specified by the relevant TSO. Each boundary line tagged “X%” corresponds to a reduction rate of X% of the generator’s maximum real power output at 50 Hz per 1 Hz frequency drop. Source: Adapted from Figure 2 in NC-RFG.

Simulation Models

NC-RFG authorizes the relevant system operator or the relevant TSO to request that owners of generator types C and D provide simulation models reflecting the behavior of their power modules in transient, steady-state, and/or dynamic simulations. These simulation models must include voltage control, power generating module protection, and converter sub-models. Recordings of the actual performance of the generator may also be requested to compare the response of the models provided with those recordings. Any request for simulation models must include the format in which the models are to be provided, the specification of the model structure including block diagrams, and an estimate of the minimum and maximum short-circuit capacity at the connection point, expressed in MVA, as an equivalent of the network.

P(f) at Under-Frequency

This requirement is only applicable to generators of type C and D, which shall have the capability to provide real power frequency response at under-frequency as represented in Figure 9. Each TSO is to set for its own control area the threshold frequency between 49.5 Hz and 49.8 Hz and the droop settings between 2% and 12%. The frequency response mode must be activated within 2 seconds unless technical evidence justifying a greater response time is provided to the TSO. In addition, the actual delivery of real power support at under-frequency must take into consideration the “ambient conditions” at the time that frequency response is to be provided, the “operating conditions” of the generator, and the availability of the generator’s energy source.

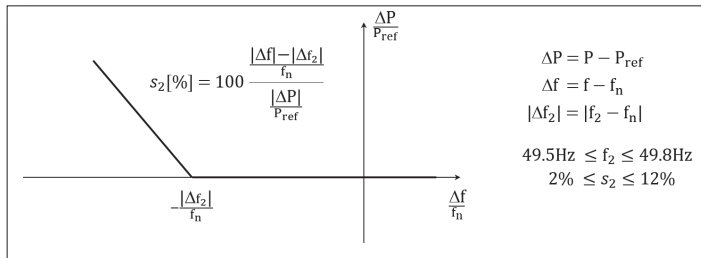


Figure 9. Real power support capability at under-frequency for grid-connected generators of type C and D. f_n is the nominal frequency; f_2 is the threshold frequency; Δf is the frequency deviation in the network; P_{ref} is **either** the actual real power when the frequency threshold is reached, **or** the maximum active power capacity, as defined by the relevant TSO; ΔP is the change in active power output; s_2 is the droop. Source: Adapted from Figure 4 in NC-RfG.

Frequency Sensitive Mode

The active power frequency response modes at over-frequency and under-frequency discussed above are understood as distinct modes independent from each other. In addition to these modes, NC-RfG requires generator types C and D to provide a third “frequency sensitive mode” (FSM) as defined in Figure 10. Table 4 shows the corresponding parameters to be set by the relevant TSO.

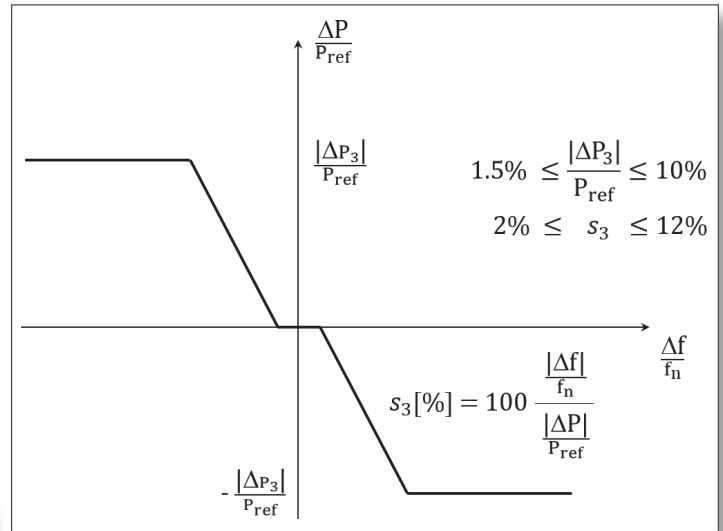


Figure 10. Real power support capability of grid-connected generators of types C and D in frequency response mode (FSM). f_n is the nominal frequency; Δf is the frequency deviation in the network; P_{ref} is **either** the actual real power when the FSM threshold is reached, **or** the maximum active power capacity, as defined by the relevant TSO; ΔP is the change in real power output; s_3 is the droop. Source: Adapted from Figure 5 in NC-RfG.

Table 4. Parameters for active power frequency response in FSM mode. Source: Adapted from Table 4 in NC-RfG.

Parameter	Description	Binding Range
$\Delta P_3 / P_{ref}$	Active power range related to maximum capacity.	1.5–10%
$\frac{\Delta f_i}{f_n}$	Frequency response insensitivity.	10–30 mHz
$\Delta P_3 / P_{ref}$	Frequency response insensitivity.	0.02–0.06%
-	Frequency response deadband.	0–500 mHz
S_3	Droop	2–12%
t_1	Maximum admissible initial delay unless otherwise justified.	$\leq 2\text{s}$
t_2	Maximum admissible time for full activation. Longer activation times accounting for system stability may be permitted by the relevant TSO.	30 s

Implementation shall make it possible to reselect repeatedly both the deadband of frequency deviation and the droop. Figure 11 shows the boundary above which the full power frequency response mode shall be activated during a frequency step change event. The relevant TSO shall keep the settings shown in Figure 11 consistent with the ranges specified in Table 4. Those settings must consider that the actual delivery of real power support at the time it is to be delivered depends on a number of ambient and operating conditions, including limitations on operation near maximum capacity at low frequencies and the availability of the generator's energy source.

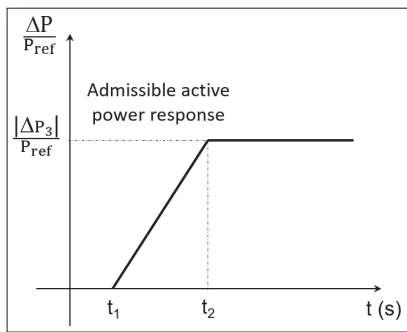


Figure 11. Real power support capability of grid-connected generators of types C and D in frequency response mode (FSM). The generator has to provide a change in real power output ΔP up to level ΔP_3 that is consistent with times t_1 and t_2 . Source: Adapted from Figure 6 in NC-RfG.

Advanced Functions Specific to Storage Systems

All inverter functions required under NC-RfG (see Table 3) are fully applicable to inverter-based storage systems acting as generators (discharging). In addition, storage systems acting as loads (charging) must be capable of “disconnecting their load” (stop charging) in case of an under-frequency. Italian standards CEI 0:21-V1:2014 (LV networks) and CEI 0:16-V1:2014 (MV networks) also require that any storage system connected to the Italian grid be equipped with a bi-directional converter to absorb active power from the network at over-frequency.

Reactive Power Control Functions

Reactive Power Capability

NC-RfG requires grid-connected generators of type C and D to provide reactive power capability. System operators are permitted to develop additional requirements for generators of type B as needed. Type A generators are not subject to this requirement. The rest of this section focuses on types C and D.

The relevant system operator, together with the relevant TSO, must specify for types C and D a V - Q/P_{max} profile **at maximum real power capacity** that shall verify the following:

- The V - Q/P_{max} profile shall stay within the inner envelope shown in Figure 12.
- The dimensions of the inner envelope shall be consistent with the Q/P_{max} and voltage ranges defined in Table 5 for each synchronous area.
- The inner envelope shall be positioned inside the fixed outer envelope shown in Figure 12.
- Consideration shall be given to the costs of providing reactive power support capability at high voltages (production) and low voltages (consumption) when specifying the V - Q/P_{max} profile.

For V - Q/P_{max} profile specified is not rectangular, the voltage range shown in Figure 12 defines the profile highest and lowest voltage values. Full reactive power range capability is not expected across the range of steady-state voltages.

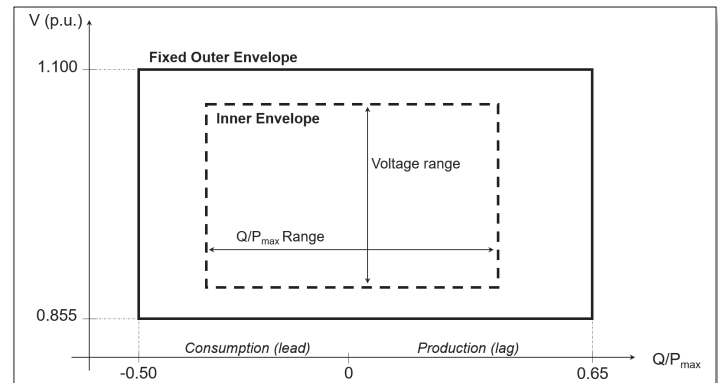


Figure 12. V - Q/P_{max} profile of a type C or D inverter-based generator at maximum active power. The V - Q/P_{max} profile shall be within the boundaries of the inner envelope, which shall itself be contained in the fixed outer envelope. The inner envelope shown is only illustrative. Source: Adapted from Figure 7 in NC-RfG.

Table 5. Parameters for the inner envelop in Figure 12. Source: Adapted from Table 8 in NC-RfG.

Synchronous Area	Maximum Q/P _{max} Range as defined in figures 12 and 13	Maximum voltage Range (p.u.) as defined in figure 12
Continental Europe	0.75	0.225
Nordic	0.95	0.150
Great Britain	0.66	0.225
Ireland and Northern Ireland	0.66	0.218
Baltic	0.80	0.220

Below maximum active power capacity, the relevant system operator, together with the relevant TSO, must specify for types C and D a V-Q/P_{max} profile that shall verify the following:

- The P/P_{max}-Q/P_{max} profile shall stay within the inner envelope shown in Figure 13.
- The dimensions of the inner envelope shall be consistent with the Q/P_{max} range defined in Table 5 for each synchronous area.
- At zero reactive power, the real power range of the inner envelop shall be P=P_{max}.
- The P/P_{max}-Q/P_{max} profile can be of any shape and shall include conditions for reactive power capability at zero active power.
- The inner envelope shall be positioned inside the fixed outer envelope shown in Figure 13.

Note that the NC-RfG does not state any voltage range applicable to Figure 13.

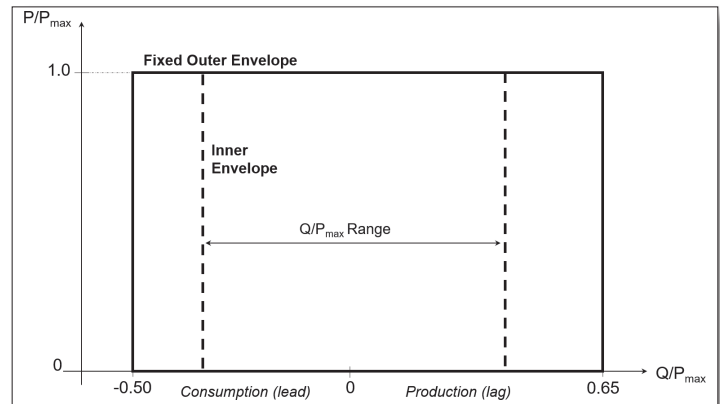


Figure 13. P/P_{max}-Q/P_{max} profile of a type C or D inverter-based generator below maximum active power capacity. The P/P_{max}-Q/P_{max} profile shall be within the boundaries of the inner envelope, which shall itself be contained in the fixed outer envelope. The inner envelope shown is only illustrative. Source: Adapted from Figure 9 in NC-RfG.

Reactive Power Control Modes

With regard to reactive power control modes, an inverter-based generator of type C or D shall have capability to provide reactive power support through at least one of the following modes: voltage control (Q=f(V)), reactive power control (Q fix), or power factor control (cos φ fix).

In voltage control mode, the Q=f(V) characteristic shall be defined from 0.95 to 1.05 p.u. in steps no greater than 0.01 p.u.; its slope shall have a range of at least 2 to 7% in steps no greater than 0.5%. When grid voltage equals the voltage setpoint, the reactive power injected at the connection point shall be zero. An optional deadband selectable shall be available in a range from zero to +5% of reference 1 p.u. network voltage in steps no greater than 0.5%. Finally, following a step change in voltage, the generator shall achieve 90% of the change in reactive power as specified by the Q=f(V) characteristic within 1 to 5 seconds and 100% of the change within 5 to 60 seconds. The relevant system operator is responsible for specifying the exact response times along with the steady-state reactive tolerance that shall be no greater than 5% of P_{max}.

In reactive power mode (Q fix), the generator must be capable of setting the reactive power setpoint anywhere in the reactive power range discussed above with setting steps no greater than 5 MVar or 5% of full reactive power, whichever is smaller, with an accuracy within +- 5MVar or +-5% of the full reactive power, whichever is smaller.

In power factor control mode ($\cos \phi$ fix), the generator must be capable of controlling the power factor at the connection point within the required reactive power range with a target power factor in steps no greater than 0.01. The relevant system operator shall specify the target power factor value, its steady-state tolerance, and the maximum response time permitted following a sudden change of active power output.

Grid Fault Response Functions

Low-Voltage Ride-Through

With regards to low-voltage ride-through (LVRT) capability, each TSO is to specify a voltage-against-time profile at the connection point for fault conditions. LVRT capability is required for generator types B, C, and D. The profile specified by the relevant TSO must be consistent with Figure 14, which defines the lower voltage limits above which a generator must remain connected to the network and operate stably. As with prior inverter functions, the piece-wise linear curve shown in Figure 14 is configurable to fit local system characteristics, with points M_1 and M_2 to be set within the binding ranges shown in Table 6.

Frequency Ride-Through

NC-RfG also specifies low- and high-frequency ride-through (L/HFRT) requirements applicable to all generator types. Table 7 and Figure 15 summarize the minimum L/HFRT capability required for each ENTSO-E synchronous area. In addition, NC-RfG provides that the relevant system operator, in coordination with the relevant TSO, and the power generating facility owner may agree on wider frequency ranges and/or longer minimum times if required to preserve and/or restore system security.

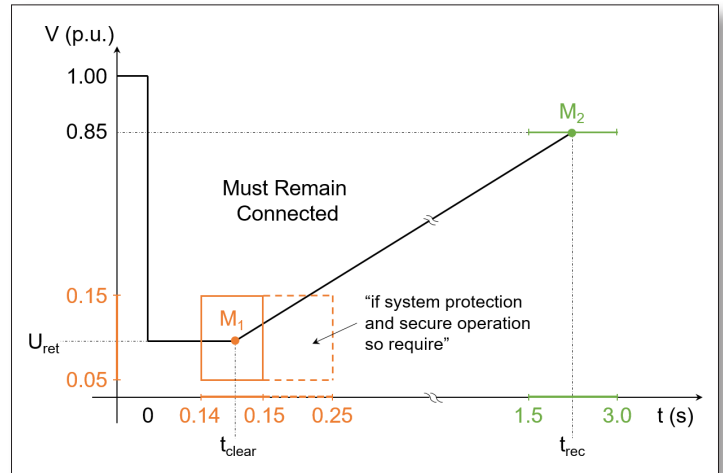


Figure 14. Low-voltage ride-through profile as defined in NC-RfG for inverter-based generators of types B, C, and D. The diagram represents the lower limit of a voltage-against-time profile of the voltage at the connection point before, during, and after the fault and the binding ranges within which points M_1 and M_2 are to be defined.

Table 6. Parameters for Figure 14 for LVRT capability of inverter-based generators. Source: Adapted from Table 3.2 in NC-RfG.

Parameter	Description	Binding Range
U_{ret} (p.u.)	Retained voltage at the connection point during a fault	0.05 to 0.15
t_{clear} (s)	Instant when the fault has been cleared	0.14 to 0.15 (or 0.14 to 0.25 "if system protection and secure operation so require")
t_{rec} (s)	Instant when voltage reaches 0.85 p.u after fault clearance	1.5 to 3.0

Table 7. L/HFRT capability of grid-connected generators as required in NC-RfG. Source: Adapted from Table 2 in NC-RfG.

(Hz)	47	47.5	48.5	49	51	51.5	52
Continental Europe	-	$\geq 30\text{min}^*$	$\geq 30\text{min}^{*\ddagger}$	unlimited	30min	-	-
Nordic	-	30min	$\geq 30\text{min}^*$	unlimited	30min	-	-
Great Britain	20s	90min	$\geq 30\text{min}^*$	unlimited	90min	15min	-
Ireland and Northern Ireland	-	90min	$\geq 90\text{min}$	unlimited	90min	-	-
Baltic	-	$\geq 30\text{min}^*$	$\geq 30\text{min}^{*\ddagger}$	unlimited	$\geq 30\text{min}^*$	-	-

Notes:

*To be specified by relevant TSO; \ddagger not less than the period for 47.5 Hz to 48.5 Hz.

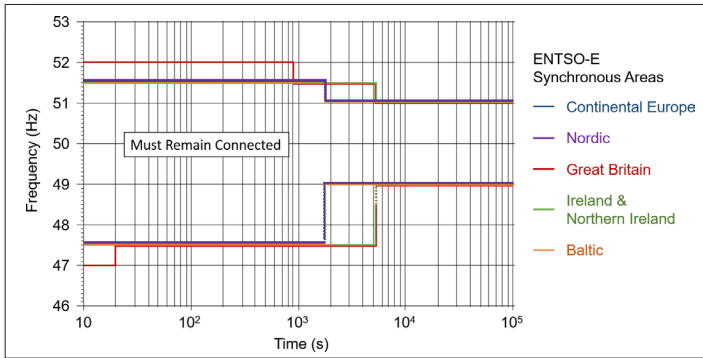


Figure 15. L/HFRT capability of grid-connected generators as required in NC-RfG. Dotted lines indicate minimum, non-exhaustive requirements that are to be fully specified by the relevant TSO. Exact values are shown in Table 7.

Finally, NC-RfG authorizes the relevant TSO to specify additional grid-support functions, including post-fault active power recovery, reactive current support during faults, and synthetic inertia. For these functions, NC-RfG provides only general guidelines, leaving the detailed specification to the TSO.

Conclusion

This document provides an introduction, commentary, and selected verbatim excerpts of the *Network Code on Requirements for Generators (NC-RfG)*⁸, an important EU regulation that establishes requirements for advanced grid-support functions in the areas of active and reactive power control and grid fault response. The new code, which took effect in May 2016, will be applicable to all newly connected energy resources across Europe, including inverter-based generation, starting May 2019. It supersedes any existing or new national legislation and prevails over any standard. While setting a common regulatory framework that facilitates convergence of all the national codes, the new EU code leaves flexibility for managing and making best use of local system characteristics. Even then, the code provides a unified list of parameters to be specified at the local level and ensures that actual specifications are set in a consistent manner from one country to another and by the same actors—the relevant system operator and/or the relevant TSO.

⁸ European Commission, Regulation (EU) 2016/631, April 14, 2016.

Similar efforts to harmonize grid-connection requirements for DER are currently undertaken in North America with the full revision of IEEE Standard 1547. However, and in contrast to any other interconnection requirements in the world, the latest draft of the standard (IEEE P1547/Draft 5) is structured around DER “performance categories” and not DER technology types. State laws and utility interconnection agreements in North America would ultimately have to assign these performance categories to specific DER technology types based on an impact assessment and stakeholder process. In that respect, the revised IEEE Standard 1547 may give even more flexibility than the European NC-RfG to account for local system characteristics. Yet, the revised 1547 harmonizes the requirements across a limited set of two or three performance categories that DER vendors can choose to design their equipment for.

Given the strategic importance of well-specified grid-connection requirements for the reliability and safety of integrating DER into the power system, EPRI will continue facilitating the revision process of IEEE Standard 1547 while monitoring the upcoming implementation of the new EU code.

Communications

NC-RfG requires DER to be equipped with a communication interface allowing the relevant system operator to send control signals, including ON/OFF commands (all generator types), active power setpoints (B, C, and D only), and Q or cos φ setpoints (C and D only). The relevant system operator or the relevant TSO may also define a list of data to be provided by generators in real time or periodically with time stamping. In particular, during active power frequency response, generator types C and D must have the capability to transfer in real time the following information: status signal of frequency sensitive mode (ON/OFF); scheduled real power output; actual value of the real power output; actual parameter settings for real power frequency response; actual droop value; and actual deadband value.

Key Reference Documents

Additional information on the European code discussed in this paper can be found in the following references:

- The EU regulation “Establishing a Network Code on Requirements for Grid Connection of Generators,” in its final version adopted on April 14, 2016⁹;
- The “Implementation Guideline,” a companion document published by ENTSO-E on October 16, 2013¹⁰, which discusses in greater details some of the non-exhaustive requirements.

Table 3 maps the NC-RfG requirements pertaining specifically to inverter functions to both their scope of application and the decision-maker(s) responsible for their full specification that shall be completed no later than two years after the code enters into force. While this paper focuses specifically on inverter-based DER, other NC-RfG requirements, not discussed in this paper, also apply to synchronous generators.

⁹ European Commission, Regulation (EU) 2016/631, April 14, 2016.

¹⁰ ENTSO-E, Implementation Guideline for Network Code: Requirements for Grid Connection Applicable to All Generators, October 16, 2013.

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Integration of Distributed Energy Resources