An Overview of Grid-Connection Requirements for Converters and Their Impact on Grid-Forming Control

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Keywords

≪Grid forming≫, ≪Virtual synchronous machine≫, ≪Grid-connected converter≫, ≪Converter control≫, ≪Renewable energy systems≫.

Abstract

The increasing share of converters in the power system results in the need to revise grid-connection requirements and a shift in converter control strategies towards grid-forming control. This paper analyzes and compares existing standards and future trends in specifications for grid-connected converters and highlights commonalities and differences. The key consequences for converter control performance requirements are presented to facilitate the selection of the most suitable grid-forming control structures.

Introduction

The transformation towards a sustainable power system will result in fewer synchronous machines in the power system, and grid-forming converters are suggested as one solution for the associated challenges [1]. As the grid-forming concept is still relatively new, discussions between grid operators, legislators and manufacturers on the design and implementation of grid-forming control are still ongoing today. Technical requirements and standards define the functionality required from grid-forming converters and are accordingly an important part of these discussions.

Since the first proposal of the virtual synchronous machine (VSM) concept, a large variety of grid-forming converter controls has been proposed [2], with some relevant selections shown in Fig. 1 and compared in [3]. Analyzing the capability of different control strategies to fulfill the grid-connection requirements is an important part in selecting the most promising designs for further research and development.

This paper compares and analyzes technical requirements for grid-connected converter systems from a selection of different legal regulations, grid codes and standards with focus on grid-forming control. In

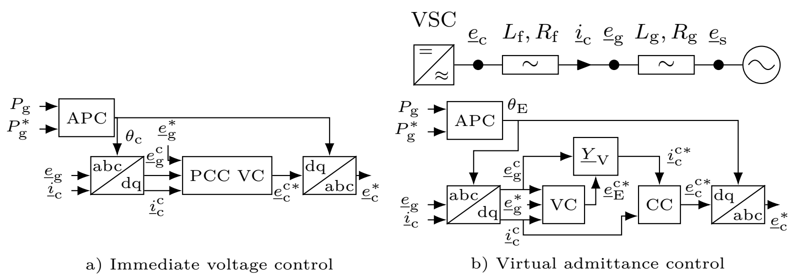

Fig. 1: Single-line diagram of grid-connected converter system and block-schemes for three different types of grid-forming converter control [3]. Quantities with index E refer to the virtual back EMF. APC: Active power controller; VC: Voltage controller; CC: Current controller; $\underline{Y}_V$: Virtual admittance.

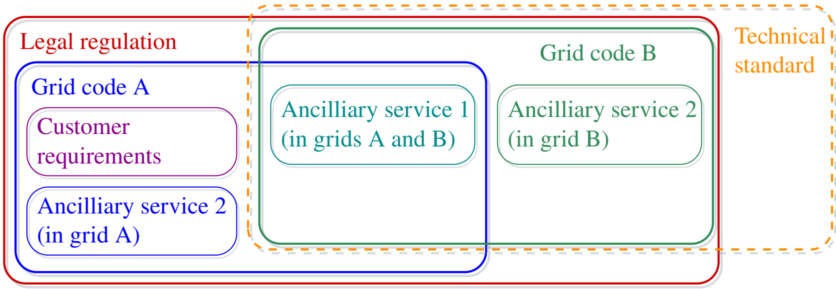

Fig. 2: Illustration of different technical requirement document types and their relation. Grid code A and B serve as examples for two independent grid code documents from different system operators, each also specifying the exemplary ancilliary services 1 and 2.

addition, possible differences and contradictions among the various documents are investigated. The final goal is to highlight implications of the different requirements on converter control strategy and to facilitate the choice of suitable control structures.

Categorization of requirement documents and selection of examples

Documents defining technical requirements for grid-connected converters can be classified according to their author, scope, bindingness and detailedness in the following categories: legal regulations, grid codes, specifications of particular ancilliary services, technical standards and customer requirements. Figure 2 displays how requirements of the different categories are inter-related. Legal regulation is obligatory, but typically less detailed. For connection to a particular grid, additionally the corresponding grid codes have to be followed. The specifications for ancilliary services can be part of the general grid code or provided through additional documents; customers can also provide further requirements. Following technical standards is often voluntary, but can be a requisite for a certain control implementation to be successful.

As illustrated in the figure, the requirements given in different documents are not necessarily the same, but can differ between countries and in some cases even conflict [4]. Moreover standards affect not only the jurisdiction they are valid for, but have an effect on others as well, in particular when concerning development- and testing-intensive equipment such as wind turbines, FACTS and HVDC systems. If one standard explicitly bans a particular implementation, manufacturers are likely to not develop a special solution, but adapt their product to comply with this specification, even if this might result in higher prices and in some cases suboptimal performance for all customers. This is due to the amount of development, testing and tuning needed for these systems, making it uneconomic to maintain a large variety of implementations. While on first glance it might make sense for system operators to tailor requirements to their particular system, a harmonization of requirements could reduce costs, enable share of experience and stimulate innovation by freeing up resources otherwise needed for local adaptations [4]. An exception to this can be certain limits, thresholds, settings or ratings. In conclusion, a harmonization of requirements with option for small local adaptions (as in [5]) is not only in the interest of manufacturers, but even academia and system operators. Consequentially, the regulations shown in Fig. 2 would ideally all coincide or at least be subsets of others. The ENTSO-E network codes for generators [5] and HVDC [6] are recent examples of successful harmonization efforts. However, specifications and requirements for grid-forming converters are still under discussion and development, starting with the definition of grid-forming properties itself. This presents a challenge for all involved parties to find a generally accepted set of required functionalities for grid-forming converters.

The following paragraph describes the grid codes and standards selected for the overview in this paper. The European Commission's network code with requirements for generators (NC RfG) [5] and HVDC systems and DC connected generation (NC HVDC) [6] are drafted by ENTSO-E and are the underlying legal regulation for grid codes in the European Union. They are concretized in national laws and regulations, e.g. in the case of Sweden [7] for RfG (SE RfG) and [8] for HVDC (SE HVDC), or national standards such as the VDE standard VDE-AR-N 4131 for HVDC in Germany [9]. A relevant technical standard

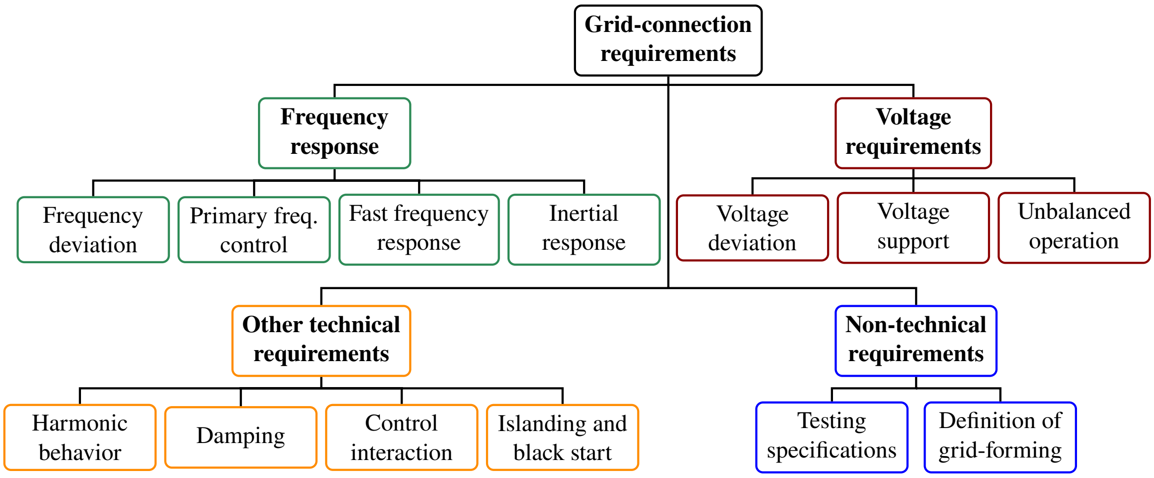

Fig. 3: Categories of typical requirements in regulation, grid codes and standards.

for DC interfaced generation is the draft IEEE P2800 [10]. The UK grid code modification GC0137 (NG GC0137) [11] containing requirements for grid forming capability is an example for an ancilliary service specification. The final investigated document is the ENTSO-E report on the contributions of grid-forming converters [12]. It is not a technical standard but reflects the debate about which features are discussed as a part of grid-forming capabilities. These documents have been chosen due to their relevance to the current and future state of requirements for grid-forming converters and to represent different countries and the categories mentioned above. It should be noted that the used standards in some cases apply to HVDC systems, in some cases to power-electronic interfaced generation and in some cases to either. None of the selected documents is formulated exclusively for FACTS, but often they partly follow HVDC regulations. Different systems such as e.g. wind power parks, grid-connected battery energy storage and HVDC systems will have different purposes and capabilities and comparing the requirements they have to fulfill is consequently meaningful only up to a certain degree. However, as all of these are grid-connected converter systems, they can all be equipped with grid-forming control, which motivates a comparison of the required capabilities.

Comparison of requirements

To facilitate the comparison and analysis, the categorization of a selection of the requirements included in the investigated documents is suggested as shown in Fig. 3. This section describes how the requirements belonging to these categories are treated in the selected documents, with Table I presenting a summary.

Frequency response

Frequency deviation. Nearly all of the compared standards contain a range of steady-state frequency deviations from nominal frequency with corresponding minimum operating times, which are summarized in Table II. The frequency range and times given for NC RfG & HVDC are minimum requirements, which can be further increased by the relevant system operator. Observe that NG GC0137 and the ENTSO-E report do not explicitly indicate low-frequency ride-through, but provide requirements for grid-forming behavior in case of frequency deviations, which implicitly requires operation at lower frequencies. The compared standards provide the requirements in a similar format, but there are significant differences in the required time spans, with the low-inertia systems Great Britain and Ireland placing highest requirements. Apart from steady-state variations, some standards also define the transient conditions which the converter system has to be able to ride through in the form of maximum phase-angle jump and rate of change of frequency. As detailed in Table II, NC HVDC, VDE-AR-N 4131 and IEEE P2800 give requirements for maximum rate of change of frequency, where the IEEE norm is considerably stricter than the others. IEEE P2800 even contains the requirement to withstand sub-cycle phase-jumps of 30°. The ability to withstand high frequency gradients can be affected by requirements for high virtual inertia, as the inertia emulation will slow the ability of the converter to track changes in the system frequency.

Table I: Selection of requirements from the documents. Green: explicitely specified, required by standard or on demand of the TSO; Yellow: unspecific/implicitly specified; Red: not mentioned.

Type of requirement	NC RfG & HVDC	SE RfG & HVDC *	VDE-AR-N 4131	IEEE P2800	NG GC0137	ENTSO-E report
Frequency response						
Frequency deviation	✓	✓	✓	✓	○	○
Primary frequency control	✓	✓	✓	✓	✗	✗
Fast frequency response	✗	✗	✓	✓	✗	✗
Inertial response	✓	✗	✓	✗	✓	✓
Voltage requirements						
Voltage deviation	✓	✓	✓	✓	○	○
Voltage support	✓	✗	✓	✓	○	○
Unbalanced operation	✗	✗	✓	○	✗	✓
Other technical requirements						
Harmonic behavior	✗	✗	✓	✓	○	✓
Damping	✓	✓	✓	○	✓	✓
Control interaction	○	○	✓	○	✓	✓
Islanding and black start capability	✓	✗	✓	✗	✗	○
Non-technical requirements						
Testing specifications	✓	✗	✓	✓	✓	○
Definition of grid-forming capability	✗	✗	✗	○	✓	✓

*: As SE RfG & SE HVDC are national implementations of NC RfG & NC HVDC, respectively, they include the requirements mentioned there. Here is indicated where these documents contain substantial concretizations or additions.

Primary frequency control. All investigated documents require the capability to control active power in dependency of the deviation of the system frequency from nominal with the exception of NG GC0137 and the ENTSO-E report. In case of NC RfG, the requirements vary with converter rating, with smaller generators only required to act in case of overfrequency. All specifications are based on a deadband around nominal frequency and a proportional gain and take the fluctuating character of renewable resources into consideration, allowing for adjustments based on the availability of primary energy.

Fast frequency reserve. Converters are capable of controlling their active power output significantly faster than required for primary frequency control. This can be used to counter the effects of the decline in synchronous inertia caused by the replacement of synchronous machines with converter interfaced generation [13]. In consequence, requirements for fast frequency reserve (FFR) are contained in VDE-AR-N 4131 in general terms and in IEEE P2800 with details about performance and possible FFR variants. Even though NC RfG & HVDC do not contain FFR, it has in the meanwhile been defined by ENTSO-E as an auxiliary service in a separate document and is procured as a service e.g. in Sweden [14].

Inertial response. To counteract the effects of the reduction of mechanical inertia synchronously connected to the grid, converters can emulate inertia by modulating the active power output to counteract either changes in the frequency or phase angle of the voltage at the point of common coupling (PCC). NC RfG & HVDC as well as VDE-AR-N 4131 specify that the TSO can require inertial response capability from connected converter system with the relevant control principle and parameters to be agreed upon by TSO and owner of the converter system in that case. In the case of NG GC0137, both frequency-derivative proportional inertial support as well as a response to grid voltage phase jumps are obligatory requirements. Finally, in the ENTSO-E report inertial response is discussed as one of the key capabilities constituting grid-forming control.

Provision of primary frequency control, fast frequency reserve and inertial response requires active power, but none of the investigated documents stipulates the availability of energy storage or prime energy. This means that the control system needs to be able to provide the response, but additional requirements not currently covered by the standards need to be fulfilled for the active participation in this services.

Table II: Minimum connection time for specific frequency ranges according to selected example requirements. "Gen." denotes requirements for generation, while "HVDC" is for HVDC converter stations.

Frequency range	NC RfG Con. Europe, Nordic & Baltic [5]	NC RfG Great Britain & Ireland [5]	NC HVDC [6]	SE HVDC [8]	VDE AR-N 4131 [9]	IEEE P2800 [10]
0.94 p.u. – 0.95 p.u.	$-^{a}$	$20\,\text{s}^{b}$	$> 20\,\text{s}^{c}$	60 s	$60\,\text{s}^{c}$	$-^{a}$
0.95 p.u. – 0.97 p.u.	$30\,\text{min}^{c}$	90 min	$90\,\text{min}^{c}$	100 min	$90\,\text{min}^{c}$	$5\,\text{min}^{c}$
0.97 p.u. – 0.98 p.u.	$30\,\text{min}^{c}$	$90\,\text{min}^{c}$	$90\,\text{min}^{c}$	100 min	$90\,\text{min}^{c}$	$5\,\text{min}^{c}$
0.98 p.u. – 1.02 p.u.	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
1.02 p.u. – 1.03 p.u.	$30\,\text{min}^{d}$	90 min	$90\,\text{min}^{c}$	100 min	$90\,\text{min}^{c}$	$5\,\text{min}^{c}$
1.03 p.u. – 1.04 p.u.	$-^{a}$	$15\,\text{min}^{b}$	$15\,\text{min}^{c}$	30 min	$15\,\text{min}^{c}$	$-^{b}$
Minimum RoCoF	$-^{e}$	$-^{e}$	2.5 Hz/s	$2.5\,\text{Hz/s}^{f}$	2.5 Hz/s	5 Hz/s

[a]: No connection requirement is given; [b]: Great Britain only, no connection requirement given for Ireland.; [c]: To be specified by the relevant TSO, but not less than the shown time; [d]: In Baltic region, [c] applies; [e]: To be specified by the relevant TSO; [f]: Not explicitly stated, but as national implementation of NC HVDC those requirements apply.

Voltage requirements

Voltage deviation. This category includes the behavior required from the converter system by some standards during transient disturbances such as faults and voltage dips. These fault ride-through (FRT) requirements are commonly provided as a voltage-time-profile, which represents a minimum requirement, i.e. the converter system must be able to stay connected when subject to a voltage than does not go below the defined curve. This way of defining low-voltage ride-through requirements is common to the European standards, but is not present in IEEE P2800, where instead minimum connection times for different voltage ranges are defined. The FRT requirements from a selection of standards are listed in Table III, with the shape of the corresponding voltage profile given in Fig. 4. For the summary in Table III, the IEEE requirements have been rearranged as shown in the dashed profile in Fig. 4.
In some standards FRT is not only a connection requirements, but contains even the obligation of fast fault current injection. NC RfG & HVDC provide the possibility for the TSO to define such requirements. The national implementations SE RfG & HVDC do not concretize this further, while VDE-AR-N 4131 states priority for reactive current and contains specifications for voltage support and unbalanced operation, which can even have an impact on fault current injection. IEEE P2800 contains a very detailed description of different fault modes and expected fault current contributions. None of the mentioned standards provide fault current magnitudes, but place this responsibility on the relevant system operator. In NG GC0137, no minimum connection times are given as they are part of the main grid code, but requirements for grid-forming behavior are mentioned in terms of fast fault current and reactive power injection in case of grid voltage magnitude transients. Emphasis is put on the immediate response, reflecting the voltage source behavior of the grid-forming converter. The same is true, even though less specific, for the analysis in the ENTSO-E report, where fault current contribution is defined as one of the characteristics of grid-forming converters. All fault current requirements take the limited over-current capability of converters into account and allow for appropriate over-current limitation and protection.
Apart from the fault ride-through in response to transient disturbance, the standards also specify connection requirements regarding steady-state voltage deviations. These are summarized in Table IV.

Voltage support. Converter systems are commonly required to contribute to the control of the voltage magnitude at their PCC by exchanging reactive power. For NC RfG & HVDC and their national implementations, this requirement is given in the form illustrated by Fig. 5. The standard defines an outer envelope. The TSO then determines an inner envelope within it, and with a predetermined maximum voltage and reactive power range. Within that envelope, the TSO specifies a profile for the exchange of reactive power in dependence of the voltage. The converter system is required to have the capability of providing the desired reactive power exchange non-withstanding the active power operating point. The reactive power exchange can either be controlled in voltage, reactive power or power factor control

Table III: FRT requirements.

Quantity	NC RfG < 110 kV[a]	NC RfG ≥ 110 kV[a]	NC HVDC[a]	SE HVDC	VDE AR-N 4131	IEEE P2800[b]
V_{ret}	0.05 p.u. – 0.15 p.u.	0 p.u.	0 p.u. – 0.3 p.u.	0 p.u.	0 p.u.	0 p.u.
V_{clear}	V_{ret}	V_{ret}	V_{ret}	V_{ret}	V_{ret}	0.25 p.u.
V_{rec1}	V_{clear}	V_{clear}	0.25 p.u. – 0.85 p.u.	0.85 p.u.	0.85 p.u.[c]	0.5 p.u.
V_{rec2}	0.85 p.u.	0.85 p.u.	0.85 – 0.9 p.u.	0.85 p.u.	V_{rec1}	0.7 p.u.
t_{clear}	0.14 s – 0.15 s[d]	0.14 s – 0.15 s[d]	0.14 s – 0.25 s	0.25 s	0.15 s	0.32 s
t_{rec1}	t_{clear}	t_{clear}	1.5 s – 2.5 s	2 s	3 s	1.2 s
t_{rec2}	t_{rec1}	t_{rec1}	t_{rec1}	t_{rec1}	t_{rec1}	3 s
t_{rec3}	1.5 s – 3.0 s	1.5 s – 3.0 s	t_{rec1} – 10 s	10 s	–	6 s

[a]: TSO determines parameters within specified range; [b]: Only requirements for voltages < 0.9 p.u. given here. Requirements are shown for plants without auxiliary equipment limiting FRT and rearranged to comply with the form in Fig. 4; [c]: 0.894 p.u. (340 kV) if rated voltage is 380 kV; [d]: Can be 0.14 s – 0.25 s if required by system protection and secure operation.

Table IV: Minimum connection time for specific voltage ranges according to selected requirements.

Voltage range	NC RfG Con. Europe[a]	NC RfG Nordic[a]	NC RfG Great Britain[a]	NC HVDC Con. Europe[a]	NC HVDC Nordic[a]	NC HVDC Great Britain[a]	VDE AR-N 4131	IEEE P2800[b]
0.85 p.u. – 0.90 p.u.	60 min	–[c]	–[c]	unlimited	–[c]	–[c]	unlimited[d]	–[c]
0.90 p.u. – 1.05 p.u.	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
1.05 p.u. – 1.10 p.u.	20 min – 60 min[e]	< 60 min[e]	15 min	60 min[f]	< 60 min[e]	15 min	unlimited	30 min
1.10 p.u. – 1.20 p.u.	–[c]	–[c]	–[c]	–[c]	–[c]	–[c]	60 min[g]	1 s

[a]: Applies for a rated voltage of 300 kV to 400 kV, and in case of NC RfG type D power park modules only; [b]: Connection requirements for voltage of 0.9 p.u. and above are shown here, lower voltages in Table III; [c]: No connection requirement is given, see Table III for FRT; [d]: For rated voltage of 380 kV, this applies for $V > 0.894$ p.u. (340 kV); [e]: To be specified by the TSO withing the stated range; [f]: To be specified by the TSO as not less than 60 min for 1.05 p.u. $< V <$ 1.0875 p.u., 60 min for 1.0875 p.u. $< V <$ 1.1 p.u.; [g]: Requirement of 60 min applies for 1.1 p.u.<V<1.158 p.u.

mode, which are further specified in NC RfG & HVDC. While SE RfG & HVDC do not add any further requirements regarding voltage support, VDE-AR-N 4131 contains detailed specifications of the control mode and performance requirements as well as inner envelopes for the voltage control profiles. In IEEE P2800, a reactive power requirement is established, which lies within the outer envelope from NC RfG. It also includes detailed control mode and performance requirements for voltage, reactive power and power factor control. NG GC0137 does not add any further specifications regarding voltage support beyond general grid code apply. However, both here and in the ENTSO-E report the capability to create a system voltage is required, i.e. the ability to behave as a voltage source independent of a grid voltage.

Unbalanced operation. Of the studied standards, NC RfG, NC HVDC, SE RfG & SE HVDC do not make any specifications regarding the expected behavior under unbalanced operating conditions apart from FRT during asymmetric faults to be detailed by the TSO. In IEEE P2800, no requirements for unbalanced but otherwise normal operating conditions are given, but negative sequence current injection is required during asymmetric faults. NG GC0137 does not contain requirements of unbalanced operation. In VDE-AR-N 4131 on the other hand, voltage control is required not only for positive, but also for negative and zero sequence, and the ENTSO-E report demands the converter system to act as sink for unbalances, i.e. provide a low-impedance path for negative sequence currents. This indicates a paradigm shift towards more system responsibility, similar to the one described below for harmonic behavior.

Other technical requirements

Harmonic behavior. Neither NC RfG & HVDC nor SE RfG & HVDC include requirements for the harmonic behavior of the converter system. In VDE-AR-N 4131, maximum values for the total harmonic distortion as well as the magnitude of each of the relevant harmonics in the PCC voltage are specified

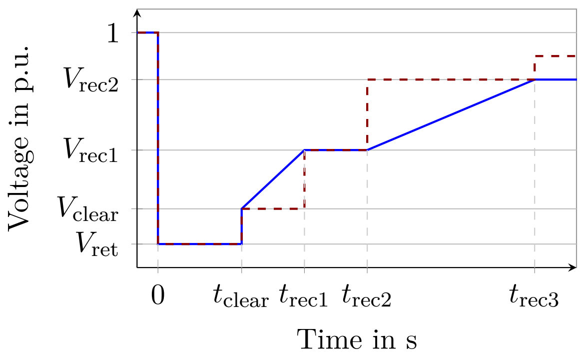

Fig. 4: Structure of FRT minimum voltage profile. Solid blue: European standards ([5]–[9]); dashed red: IEEE P2800 minimum connection times.

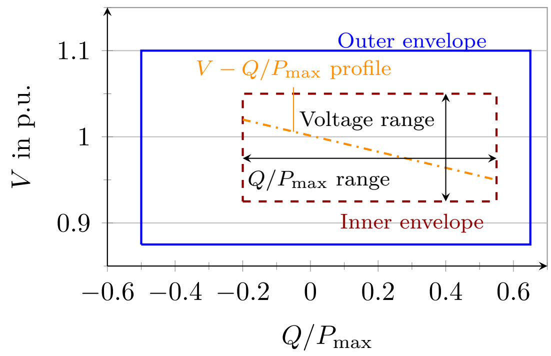

Fig. 5: Reactive power capability as defined by NC RfG. The outer envelope is as shown in the standard, the inner and $V-Q$ profile are indicative.

for DC connected generation, but not for HVDC. In contrast, IEEE P2800 gives requirements for the harmonic distortion of the current, but explicitly does not limit the voltage harmonics. The standard contains a detailed discussion of converter voltage harmonics and liability in the annexes. NG GC0137 does not specify harmonic behavior explicitly, but the required behavior as a voltage source behind a reactance will affect this. In the ENTSO-E report, the ability to act as a sink for harmonics is named as a key capability of a grid-forming converter. This means that the converter should provide an inductive or resistive-inductive path for harmonic current components, improving the quality of the voltage at its PCC. Here, a paradigm shift becomes visible, which already has started to come into effect e.g. in VDE-AR-N 4131: Instead of only being responsible for their own harmonic pollution as previously, converters and grid-forming converters in particular can be expected to be required in the future to increasingly act as sinks for harmonics, actively improving the grid voltage quality.

Damping. This category includes requirements regarding the damping of power oscillations and subsynchronous resonances. Specifications of control actions involving active power (frequency and inertial response) or reactive power (voltage support) can also contain requirements regarding the damped behavior of the control action, but are not considered here. Contribution to the damping of power oscillations is required in NC RfG & HVDC but not specified further, which is complimented with requirements for damping capability for subsynchronous torsional interaction in NC HVDC. The effective range for the required power system stabilizer is further specified for generation in SE RfG. In VDE-AR-N 4131, HVDC systems are required to contribute to the damping of subsynchronous and power oscillations. While not a formal requirement in IEEE P2800, power oscillation damping and subsynchronous instability are discussed in the annex. The supply of damping power analogous to synchronous machines is a requirement for grid-forming converters in NG GC0137 and the ENTSO-E report.

Control interaction. Adverse control interaction is not a new concern, but before the focus has been on interactions in the sub-synchronous frequency range. However, the increasing amount of converter systems in the grid and the decreasing electrical distance between them has resulted in a much wider frequency range for possible interactions, up to several kHz. This is reflected by the increasing amount of detail in requirements of this category, when compared to earlier versions of the investigated documents. IEEE P2800 does not name control interactions as part of the requirements, but contains an in-detail discussion of control instability in its informative annexes. VDE-AR-N 4131 requires a study about possible interactions of the HVDC system with other grid components. The study's method is not prescribed explicitly, but measurement or simulation of grid and HVDC system input admittance as well as frequency domain and EMT studies are suggested as examples. The ENTSO-E report includes a in-depth discussion of control interactions and the same study methods as in VDE-AR-N 4131 are suggested. Two contradictory viewpoints are discussed; one deeming general specifications able to rule out harmonic interaction in any situation as too conservative and unrealistic, calling for specific case studies instead; the other prescribing a bandwidth limitation with a frequency range in which the converter has to behave as a

Thévenin source behind an impedance. The latter perspective is incorporated in NG GC0137, specifying that the grid forming system must appear passive above a frequency of 5 Hz. Even though none of the studied documents accept adverse interaction between the converter system to be connected and any other component of the grid, NG GC0137 is the only one specifying concrete requirements for how the absence of control interactions should be demonstrated. The discussions of this topic contained in VDE-AR-N 4131, IEEE P2800, NG GC0137 and the ENTSO-E report demonstrate that methods and requirements for ensuring absence of control interactions during high penetration of power electronics in the grid are still under investigation and development.

Islanding and black start capability. According to NC RfG, HVDC and VDE-AR-N 4131, the TSO can request islanding capability and ask for a quotation for black start capability. This capability is not a requirement in IEEE P2800 or NG GC0137, but in the latter grid-forming capability is mentioned as a prerequisite for converters wanting to provide black start capability. The ENTSO-E report does not mention islanding or black start capability explicitly, but places a great emphasis on the ability to create a system voltage as a core capability of grid-forming converters.

Non-technical requirements

Testing specifications. The provision of testing specification is not only crucial for ensuring compliance of constructed converter systems with the requirements, but also assists researchers and industry in developing and testing prospective design ideas beforehand in simulation and under lab conditions. NC RfG & HVDC describe compliance test in detail regarding the functions to be tested and the responsibilities of the different actors in these tests. However, no concrete testing scenarios are provided. The same applies for VDE-AR-N 4131, but in this case a supplementary document is available that provides a large number of simulation scenarios for the required capabilities [15]. IEEE P2800 contains a verification matrix listing the type of test and the responsible party for each of the requirements. However, no details are given how simulations and tests are to be conducted. In NG GC0137, simulation, testing and online monitoring are specified as compliance requirements, with three simulation scenarios provided to test compliance with specific parts of the grid-forming capability. Testing and benchmarking, as well as simulation studies for some requirements, are discussed in detail in the ENTSO-E report, but due to the general character of the document no concrete scenarios are suggested.

Definition of grid-forming capability. As discussed in the ENTSO-E report, not all converter systems need to fulfill the same requirements, and grid-forming capability might only be required by a small share of must-run units. For this reason it is instrumental to divide converters in different classes, each coming with a specific set of requirements. The report defines classes 1, 2A, 2B, 2C and 3, where the first four correspond to the type A, B, C and D in NC RfG. Each class or type should fulfill all requirements of the ones below, with further control requirements added subsequently. Common criteria for assigning the class are power and voltage rating of the converter system. In the definition given in the ENTSO-E report, class 3 corresponds to full grid-forming capability on top of the requirements applying for class 2C, which are in essence those specified in NC RfG for type D power park modules or in NC HVDC for HVDC. In this definition, grid-forming means the ability to create system voltage, contribute to fault level, act as a sink for harmonics and unbalances, contribute to inertia, support system survival to enable under-frequency load shedding and prevent adverse control interaction. NG GC0137 likewise defines grid-forming capability as fulfillment of a number of technical requirements, but puts an even stronger emphasis on the voltage-source-behind-a-reactance character of the converter. From the other investigated documents, only IEEE P2800 contains a discussion of the concept grid-forming capability in the annex, while the others do not mention the concept. This is even the case for VDE-AR-N 4131, which contains most of the capabilities typically associated with grid-forming control (e.g. inertial response) as optional requirements.

Qualitative comparison of the requirements

As visualized in Table I, the extent and detail of the studied documents vary widely. While the high-level, legally binding documents such as NC RfG & HVDC remain vague in a lot of aspects and rely on underlying standards and agreements for concretion, low-level norms such as VDE-AR-N 4131 and

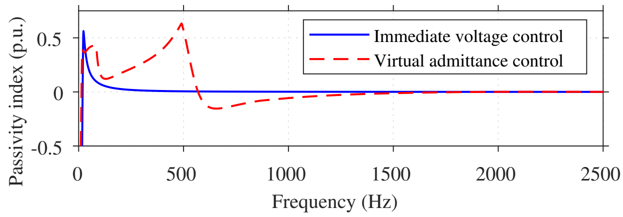

Fig. 6: Passivity index over dq-frequency for immediate voltage control (blue) and virtual admittance control (dashed red) [18].

IEEE P2800 contain an extensive description of requirements with great detail. Additionally there are specifications for specific ancilliary services such as NG GC0137, which contain detailed requirements for the service they concern, but otherwise rely on the underlying grid code. Finally, the ENTSO-E report is a report reviewing and discussing challenges, practices and research and has therefore a different character than the normative documents. It serves as an indication for trends emerging in the standards and shows very clearly in which areas development in the requirements is discussed the most.

Demand for grid-forming capabilities in existing and future standards

Table I shows that none of the obligatory requirements currently in effect mention grid-forming converter control or contain a definition of it. IEEE P2800 discusses grid-forming control in its informative appendices, and only NG GC0137 and the ENTSO-E report define the concept.

When discussing grid-forming converter control as an emerging concept, it is important to be aware of how the meaning of this term has shifted. In 2012, grid-forming control defined a control strategy solely determining the grid voltage in magnitude and frequency, like it is the case in micro- and island grids [16]. Converters with these properties have been in operation for more than 20 years [17]. In the current discussion however, the term grid-forming is commonly not longer used for converters serving as a slack bus, but instead for converters participating in voltage and frequency control by acting as a voltage source behind an impedance [1], [11], [12].

Even though none of specifications currently in effect requires grid-forming converter control, VDE-AR-N 4131 contains a number of optional requirements that are part of the definition of grid-forming capabilities in the ENTSO-E report and typically associated with grid-forming converters, such as inertial response, acting as a sink for harmonics and islanding capability, albeit without utilizing the label grid-forming. To a lesser extent, this also applies to IEEE P2800. With the introduction of NG GC0137, grid-forming capability has become an ancilliary service in Great Britain. Even though standards do not yet require full grid-forming capability, step by step more of the capabilities associated with grid-forming control are becoming part of them as optional or mandatory requirements.

Impact of requirements on grid-forming control topologies

It is important to underline that the compared standards in general are technology agnostic, i.e. not prescribing how the requirements have to be implemented in hard- and software, but instead posing performance requirements to be fulfilled. This allows for the development of different solutions and drives a competition of ideas leading towards the most efficient implementation. However, there can still be consequences for which control strategies are suitable, as not all implementations might be able to comply with the given performance requirements. One notable exception from this is NG GC0137, which explicitly excludes the usage of a virtual impedance with reference to the high bandwidths required.

Even though not explicitly ruled out, some control topologies might not be able to fulfill specific performance requirements. One example for this is non-passive behavior caused by a current controller, as demonstrated by [18] and shown in Fig. 6. In consequence this means that the grid-forming control schemes shown in Fig. 1 (b) and (c) cannot fulfill the passivity requirements formulated in NG GC0137, and that the topology from (a) cannot rely on a current controller for FRT if this requirement is to be met. This illustrates how the grid code requirements currently in place or under discussion can be very challenging to fulfill with existing grid-forming converter control topologies.

Conclusions

This paper has compared and analyzed current technical requirements for grid-connected converters and future trends. It has shown qualitative differences between different standards and discussed the need for harmonization. Furthermore, the impacts of specific requirements on the control topology of converters were demonstrated. Grid-forming control is not a requirement in any of the existing standards, but has been recently included as an ancilliary service in the UK grid code and specific capabilities associated with grid-forming control are appearing as optional requirements in other standards currently in effect as well. This demonstrates the importance of further development of grid-forming converter control as well as the need for harmonized specifications in line with both capabilities of existing control structures and the grid operator's needs.

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