4-TSO Paper on
Requirements for Grid-Forming Converters

1. A common 4-TSO position on requirements for grid-forming converters

1.1 Why grid-connected converters?

The fulfillment of the European climate protection targets under the Green Deal will lead to a reduction in synchronous generation capacity throughout Europe. In Germany the significant reduction in synchronous generation capacity has already been initiated by the coal phase-out based upon the German act KVBG ("*Gesetz zur Reduzierung und zur Beendigung der Kohleverstromung"*) together with the exit from nuclear energy. Therefore, synchronous generation capacity will be consistently replaced by converter-based generation to an increasing extent.

The high penetration of non-synchronous generation in future energy transmission systems simultaneously leads to a wide range of challenges concerning stability aspects. Those challenges are significantly caused by the decrease in system inertia and short-circuit power and have to be managed. Secure grid operation and conceptual resolution of grid disturbances, even under the increasing influence of non-synchronous generation power, are the superordinate and legally binding objectives of the transmission system operators (TSOs). One technical approach to meet these future challenges of the changing generation structure is the use of converters with so-called grid-forming characteristics.

In order to ensure stable grid operation even with a high share of converter-based generation from 60% to 100%, the four German transmission system operators have agreed on seven basic characteristics of grid-forming converters, the so-called *grid forming capabilities*.

In principle, grid-forming characteristics can be provided by all plants with self-controlled grid converters or synchronous generators. This comprises synchronous as well as converter-based generation and other TSO facilities like HVDC links, STATCOM and synchronous condensers. In this context, the provision of grid-forming characteristics must also be evaluated based upon application-specific technological limitations and cost involved. These considerations are out of this document's scope. Furthermore, the regional distribution of future grid-forming converters is not addressed as well and needs to be considered separately.

1.2 Motivation for a joint 4-TSO paper

Though each individual transmission system operator is responsible for the stable grid operation in its control area, the future technical challenges regarding system stability, security and availability of the transmission grid in total can only be jointly solved.

The four German TSOs pay great attention to future grid-forming converters in the non-synchronous generation structure, which will be clarified and detailed in this jointly developed paper.

The objective is to motivate the importance of grid-forming converters for the stability of the German and European interconnected grid in order to address the fundamental characteristics of grid-forming converters in the revised European connection network codes NC RfG (Network code on requirements for grid connection of generators) and NC HVDC (Network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules). It is intended to draft the definition of requirements for grid-forming converters in the German transmission grid at national level for the next revision of the Technical Application Rules (TAR) right now.

2. Basic requirements for grid-forming converters

In the recent past various studies on grid-forming converters have been performed. The technical report HPoPEIPS (High Penetration of Power Electronic Interfaced Power Sources) of ENTSO-E is probably one of the most important and best-known preliminary publications among Europe on the definition of the conceptual characteristics of grid-forming converters. The report was published at the beginning of 2020 as part of the interdisciplinary cooperation between ENTSO-E and other manufacturers' associations [1].

The HPoPEIPS report identifies seven capabilities which characterize a grid-forming converter. In the following, these capabilities are classified from the perspective of the four German TSOs into mandatory capabilities and capabilities which can be additionally demanded by the relevant TSO. Depending on the local grid situation and grid requirements, the basic requirements can be parameterized and complemented by optional capabilities.

This new class of grid-forming converters is only fulfilled by the simultaneous integration of all mandatory capabilities. If one or various mandatory capabilities are not implemented, the whole system does not meet the requirements for grid-forming converters.

2.1 Mandatory capabilities of grid-forming converters

In the following, with reference to the HPoPEIPS report, the characteristics of grid-forming converters are listed which are mandatorily demanded from the point of view of the four German TSOs.

1. **Creating system voltage analogous to the induced rotor voltage of synchronous generators *(Creating System Voltage)*:**

   Each grid-forming converter behaves like a voltage source behind an impedance. For grid-forming converters, the fundamental oscillation component (50 Hz component) of the provided source voltage must be limited in the short-time range (a few grid periods after a grid disturbance) with respect to its rate of change. As a consequence, stabilizing equalizing currents occur between the grid connection voltage and the supplied voltage.

   Supplementary note: Outside the short-time range, set points can also be tracked for a grid-forming converter. An analogy to a synchronous machine does not necessarily mean that the control behaviour of the grid-forming converter reflects the equation of motion of a synchronous machine.

   Fast converter protection is permissible if it does not lead to a shutdown (e.g. current limitation) − e.g. in the event of faults with low residual voltage or large grid disturbances.

2. **Instantaneous short-circuit current contribution *(Contribution to Fault Level):***

   In the event of a short circuit (step change in voltage), the compensation current described in point 1 contributes to the short-circuit current. The time constant, the phase position and the amplitude of the short-circuit current are determined in the short-time range by the effective grid impedance and fault impedance as well as other impedances of the overall system. Outside the short-time range, if a fault condition is still present, the positive sequence of the converter current can be provided in a controlled manner according to a characteristic curve or an adjustable system characteristic. The transition between the first response and a higher-level characteristic must be uninterrupted and as shock-free as possible. Alternatively, outside the short-time range, the converter can continue behaving as a voltage source behind an impedance. Fast current limitation to protect the system − e.g. in the event of faults with low residual voltage (short circuit close to the system) − is permissible and must not lead to loss of synchronism. The current limitation must be parameterizable with regard to its prioritization (e.g. true-angle or with prioritization on active or reactive current). In the case of asymmetrical grid faults, a defined system behaviour for the counter system is also required.

3. **Provision of electrical inertia *(Contribution to Inertia) within the design limits:***

   In the event of a load or feed-in change in the system (abrupt angle change of the voltage), the compensation current described under point 1 with its effective component leads to a contribution to the instantaneous reserve (in the short-term range). If there is a continuous angle change beyond the short-time range, the compensation current described in point 1 leads to an effective component proportional to the frequency gradient (according to an adjustable virtual inertia of the inverter). A fast current and power limitation (please compare to the following paragraph) in order to protect the plant, e.g. in case of major disturbances, which would lead to a power supply outside the design limits, is permissible and must not lead to a loss of synchronism.

The maximum energy that can be exchanged with the connected grid is limited by the inherent energy storage capability of the plant components. A dedicated energy storage device to provide instantaneous reserve is not a mandatory requirement. If the plant has an asymmetric energy storage capability in the positive or negative direction, this asymmetric energy storage capability must be used depending on the grid event (e.g. power reduction for renewable energies).

The behaviour described causes the voltage provided by the converter to synchronize with the grid voltage in its phase angle and frequency with a certain inertia. This behaviour limits the frequency of the system in the gradient and adjusts the frequency proportionally to the power imbalance at the same time. This ensures that higher-level emergency functions (e.g. the frequency-dependent load shedding LFDD or LFSM-O) take effect in accordance with the concept in case of active power imbalance.

4. **Preventing adverse control interaction:**

   The converter should behave passively for frequency components not equal to the fundamental frequency (50 Hz) and contribute to the stable parallel connection of several converters and other network components. For quasi-stationary processes (with frequency components around 50 Hz), a defined damping contribution must be provided for active and reactive power control so that passive, best possible damping behaviour of the system is ensured.

5. **Controller stability**

   Controller stability (based on operation in a virtual island) is required for grid-forming generation facilities as well as grid-forming HVDC systems that connect non-synchronous generation facilities to a transmission or distribution grid.

2.2 Other characteristics of grid-forming converters that can be demanded

In the following, with reference to the HPoPEIPS report, the characteristics of grid-forming converters are listed which can be demanded by the TSO if necessary from a grid planning point of view.

1. **Limiting the contribution to harmonics *(Sink for Harmonics):***

   In principle, according to chapter 2.1, grid-forming converters must be designed in such a way that a positive real part of the converter impedance results for frequency components not equal to 50 Hz. This corresponds to a harmonic sink with impedance to ground and must be fulfilled for all relevant time ranges and operating modes.

   Furthermore, self-guided converters additionally offer the possibility to actively attenuate selected harmonics by means of dedicated control loops. A resistive component should dominate, especially for the 5th, 7th, 11th and 13th order harmonics. This additional functionality can be parameterized and executed according to the specified limits.

2. **Regulation of the negative sequence *(Sink for Unbalance):***

   In principle, grid-forming converters must be designed in such a way that a positive real part of the converter impedance results for the negative sequence. This corresponds to a sink with impedance to ground and must be fulfilled for all relevant time ranges and operating modes.

   Furthermore, self-guided converters additionally offer the possibility of active damping of the negative sequence by means of dedicated control loops. A resistive component should dominate (restricted angle range if necessary). This additional functionality can be parameterized and executed according to the specified limits.

3. **Provision of additional electrical inertia *(Contribution to Inertia)* by means of extended energy reserve:**

   In addition to the requirements according to point 3 in chapter 2.1, an additional energy storage is provided. The maximum energy that can be exchanged with the connected grid can be taken from this dedicated energy storage facility, in accordance with the specific requirements of the responsible TSO, up to a duration and amount of a defined active power contribution.

2.3 Optional features of grid-forming inverters

Grid-forming converters can be designed with black-start capability.

3. Summary

This paper on the requirements of grid-forming converters has been jointly prepared by the four German transmission system operators, due to the need of future grid-forming converters and their importance for secure grid operation.

The presented characteristics of grid-forming converters are oriented towards the corresponding requirements of the published technical report HPoPEIS (High Penetration of Power Electronic Interfaced Power Sources) of ENTSO-E.

An essential part of this document is the differentiation between mandatory, additional, TSO-requested and optional properties of grid-forming converters. Mandatory characteristics are obligetory and must always be fulfilled by grid-forming converters. Depending on the requirements of the transmission grid at the specific point of connection, further capabilities can be additionally demanded by the relevant TSO in the individual project.

In addition, there are other optional features of grid-forming converters. Their need must be evaluated in the specific project.

The listed capabilities initially represent exclusively technical definitions as a starting point for the description of grid-forming converters. These definitions must be implemented in control concepts, threshold specifications and characteristic curves of the system in technically detailed investigations.

Bibliography

[1] ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources, "High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters", 2020.