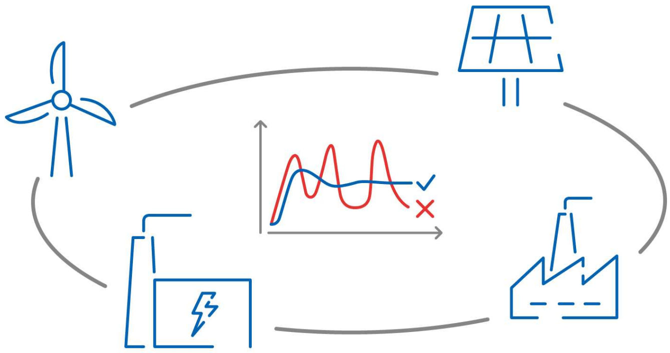


Future requirements for power system stability

The fulfilment of the European climate protection targets under the Fit for 55 agreement until 2030 will lead to a reduction in synchronous power generation modules (SPGM) throughout Europe. Non-synchronous inverter-based generation will fill this gap. Synchronous generators provide high short circuit power and inertia as a by-product of electricity generation. So far, these capabilities have determined the design and operation of transmission and distribution systems. However, the high penetration of power park modules (PPM) in transmission and distribution systems brings new challenges for the power system stability such as a decreasing system inertia and short circuit power. As a consequence, the future power system will not be able to cope with disturbances in the same way as the current system, which is based mainly on the grid-forming capabilities of synchronous generation. Therefore, grid-forming capabilities provided by non-synchronous inverter-based generation play a key role in the transformation of the power system to ensure a safe and robust grid operation.

This VDE FNN Info paper:

- Specifies general requirements for generators for operation under normal conditions and abnormal conditions
- Introduces the concept of fictitious island operation as an essential requirement for power system stability
- Proposes a definition of system-supporting and grid-forming capabilities for generators
- Outlines capabilities to be included in the European Connection Network Codes (i.e. voltage control, active power control)

This document provides a comprehensive concept to inform current and future discussions on grid-forming capabilities at European level.

About the Forum for Network Technology & Network Operation in the VDE (VDE FNN)

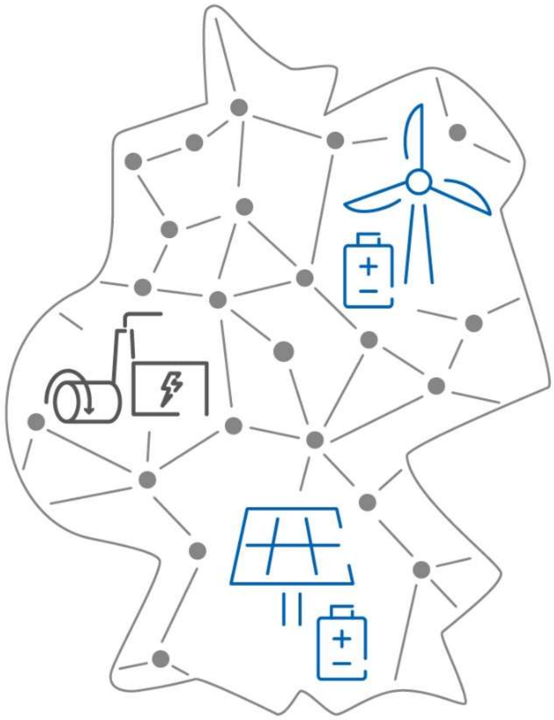
VDE FNN develops technical requirements for the operation of electricity grids in a forward-looking manner. The aim is to always ensure a secure system operation with increasing consumption of electricity from renewable energies.

General requirements for generators

The Network Code Requirements for Generators (NC RfG) defines requirements for power-generating modules (PGMs) at the connection point. However, the requirements and compliance procedures described in the NC RfG do not consider real-life characteristics at the network side of the connection point. The given parameters define only the maximum and minimum short circuit power limits and a defined system frequency. It is therefore critical to consider normal and abnormal operating conditions in the requirements for power system stability, such that the interaction between the PGMs and the power system is taken into account.

Operation under normal conditions

Normal operating conditions are characterized by a steady-state operation with small perturbations around an operating point. Here, the system is able to properly dampen frequency and voltage deviations within the operating margins as defined in the grid codes of each EU Member State.



The replacement of grid-forming synchronous generation with non-grid-forming (grid-following) inverter-based generation leads to a reduction of the short circuit ratio (SCR) in the system. This jeopardizes the stability of grid-following inverters, which require a defined SCR level at the connection point. As the short circuit power defined by the SCR ($SCR = S_k"/P_{\mathrm{Nom\ PPM}}$) is also "utilized" by other grid-following PPMs (and inverter-based loads) in the vicinity of the connection point, the SCR at this connection point decreases resulting in a potentially unstable system. However, a sufficiently high SCR is a basic prerequisite for non-grid-forming PPMs to remain connected to the grid during normal and abnormal operating conditions, in accordance with the relevant specified network connection rules in that region. The SCR can be maintained by limiting the share of grid-following PPMs and by installing grid-forming generation on a regional basis, which can be operated independently from the SCR and even may contribute to it.

Another aspect of power system stability under normal operating conditions is the ability of a national power system to continuously maintain the essential capability for island operation. A power system must perform standard island operation tests according to particular requirements before its connection with the Continental Europe Synchronous Area (CESA), like with the Ukrainian power system in 2022. However, after the synchronization of each national power system to the CESA, the requirement for island operation practically disappears due to cross-border power exchanges. Consequentially, the stability margin of the entire system decreases when neglecting this requirement after the synchronization. To counteract this, each national power system must maintain sufficient inertia and primary control capability to fulfil the stability conditions of the "fictitious island", which is further elaborated below.

Operation under abnormal conditions

Frequency and voltage deviations may significantly exceed limits defined for normal operating conditions thus entering abnormal operating conditions. Sufficient and fast active and reactive power control must be supplied throughout the system to avoid the propagation of faults, exceeding of frequency limits, voltage collapse or angular separation.

Different from voltage deviations which are local phenomena, frequency deviations are seen globally at all connection points. In order to keep frequency and rate of change of frequency (RoCoF) within reasonable boundaries, the system must have sufficient inertia and as many units as possible must participate in frequency control.

Stability in a fictitious island

Current requirements for PGMs in most national grid codes assume a stable grid with a rigid frequency for PGMs, energy storage modules, loads and assets from system operators. Active and reactive power control must satisfy stability requirements only in an explicitly defined island scenario. However, during contingencies with occurring power imbalances, the power control systems of all PGMs operating simultaneously in LFSM-O/U mode according to NC RfG requirements, must satisfy stability requirements in the same way as in an explicitly defined island scenario. In this way, these PGMs contribute to frequency control with sufficient damping. This is equivalent to the operation in a “fictitious island”, which is defined by the operation of the PGM at the connection point (signalling a closed circuit breaker), behind which a proportionate share of the system’s load is supplied by the PGM.

Stability criteria for the LFSM-O/U(*) power speed control (SPGM) or power frequency control (PPM) are defined for the fictitious island scenario. These criteria are critical for determining the inertia in the system and the performance of the actuator of the power generating unit. Whenever frequency deviations exceed the FSM range (e.g. ± 200 mHz) during abnormal operating conditions, the system enters the fictitious island scenario for which speed and frequency control stability requirements must be defined.

(*) *It is suggested to replace the term “limited frequency sensitive mode” with the more appropriate term “security based primary control”. Please note that a closed loop system with defined stability criteria must be described.*

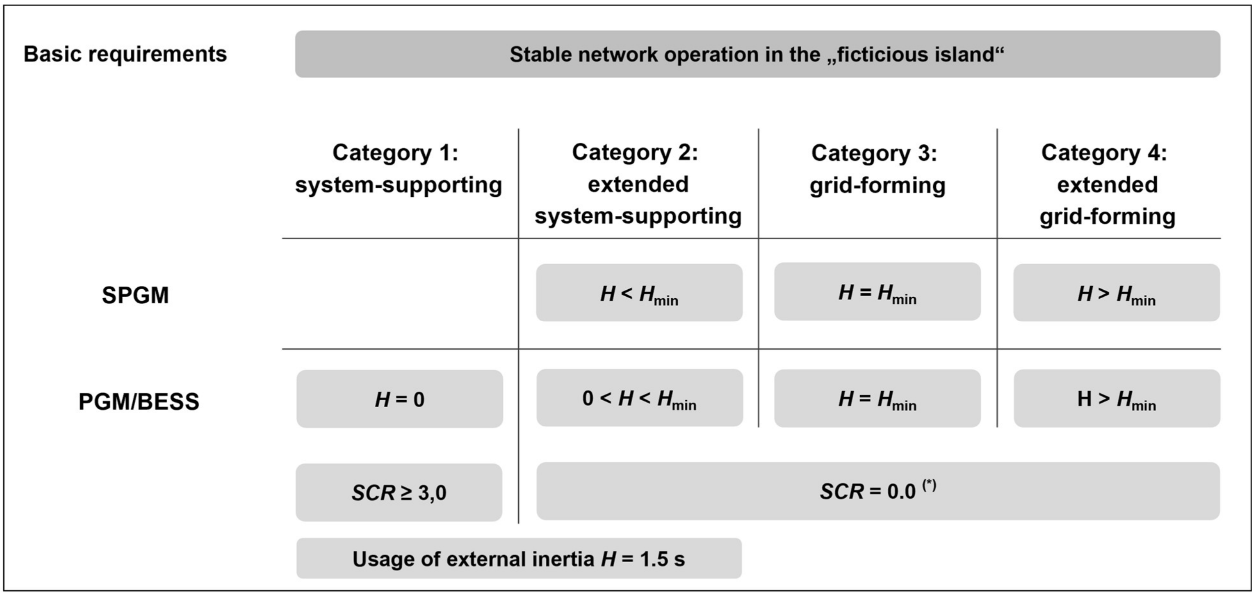
Definition of grid-forming capabilities

A definition of grid-forming capabilities for PGM considering the stability criteria in the fictitious island as an underlying minimum stability requirement is proposed as follows:

> *“The grid-forming properties of a PGM or energy storage module mean the elementary ability, in fictitious island operation as well as in parallel operation with SPGM, PGM and energy storage modules in both, grid-forming and grid-following mode, to maintain a stable operating point at constant voltage and frequency, as well as to ensure a stable behaviour during defined disturbances with steady-state and dynamic deviations from the operating point”.*

Four principal categories of PGM can be derived from this definition as shown in Figure 1. The minimum inertia H_{min} of a PGM should be defined considering the PGM´s specific characteristics for releasing active power so as to establish a defined damping of the primary control (FSM and

LFSM-O/U) and to comply with frequency-related boundary conditions for defined contingencies during fictitious island operation. In any other case, the PGM has “system-supporting” capabilities.



(*) the device is able to create a voltage at its own terminal without requiring external short circuit power

Figure 1 - Classification of system-supporting and grid-forming capabilities of PGM

Category 1

System-supporting PGMs require the parallel operation of an SPGM which enables the PGM to stabilize active and reactive power balance when falling into the fictitious island and to operate in a stable manner with sufficient damping of the frequency and voltage control (H_{PPM} = 0, *SCR* ≥ 3, H_{SPGM} = 1.5s, minimum *SPGM/PGM-ratio* = 30/70).

Category 2

Extended system-supporting PGMs do not rely on external short circuit power (*SCR* = 0) but are not able to provide sufficient inertia to keep frequency and damping within defined limits ($0 < H < H_{min}$, *SCR* = 0, minimum *SPGM/PGM-ratio* = 30/70).

Category 3

Grid-forming PGMs are capable of controlling voltage and frequency in the fictitious island scenario without external support (see definition for “grid-forming”).

Category 4

Extended grid-forming PGMs provide an excess of inertia for the fictitious island scenario which helps to cope with system needs exceeding the fictitious island scenario and allows for system-supporting PGMs to operate in the fictitious island scenario.

Capabilities to be included in NC RfG

A stable behaviour of the frequency and voltage control must be demonstrated in the closed control loop for grid-forming PPMs. The requirements for fictitious island operation according to the FNN Technical Guideline “Grid-forming and system-supporting behaviour of PGMs” [1] without the use of external inertia and short circuit power from synchronous generators apply for this purpose.

Active power control

The FSM and LFSM-O/U requirements according to the FNN Technical Guideline [1] without the use of external inertia and short circuit power from synchronous generators apply for the LFSM-O/U characteristics.

Voltage control

Two basic prerequisites must be fulfilled for stable voltage regulation:

1. In case of a jump in the amplitude of the terminal voltage, an instantaneous change of the reactive current counteracting the voltage change must occur. This enables a contribution to balancing the reactive power in the event of a disturbance.
2. The stability of the closed voltage control loop must be ensured according to a defined rise time and sufficient damping.

Note A: prerequisite 1 is analogous to a sudden change of the active power in case of an angular jump of the terminal voltage (“phase jump power”) and enables the grid-forming capability with respect to the reactive power ("amplitude jump power"). This behaviour is achieved, for example, by a voltage source behind an impedance.

Note B: prerequisite 2 is fulfilled by a suitable design of the voltage control. In particular, it must be ensured that the voltage setpoints in each operating state are limited such that they cannot lead to tripping of the protection system.

The requirements of the power-generating unit (PGU) voltage control refer to the terminals of the PGU in island operation as well as in parallel operation. The requirements for the superimposed PPM control refer to the connection point of the PPM in parallel operation.

Specific properties of grid-forming PGMs

1. The behaviour of the PGMs when the current limit is reached must be specified (e.g. prioritisation of active or reactive current).
2. The phase jump ride-through capability must be specified along with the released active power and its properties. Furthermore, the dimensioning of the synthetic inertia H must take into account the actuator characteristic of the PGM on the basis of the requirements for small-signal stability during fictitious island operation.
3. The damping settings for the active power control of a PGM with regard to the connection point (rigid frequency) must be specified.

[1] VDE FNN, „Grid-forming & system-supporting behaviour of power-generating modules“ January 2022, https://shop.vde.com/de/netzbildendes-und-systemst%C3%BCtzendes-verhalten-von-erzeugungsanlagen-download-2

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