

Technical requirements for grid-forming capabilities including provision of inertia

Requirements and verifications for grid-forming units

Version 2.0

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Foreword

The expansion of converter-based installations brought by the energy transition and the phase-out of conventional power generation pose new challenges for maintaining system stability at a pan-European level. The main factors leading to system instability are the loss of installations with grid-forming capabilities, which provide the inertia required for the stable operation of grid-following installations, as well as the progressive reduction of the effective short-circuit power ratio also required by grid-following systems. The network development plan for the year 2035 (based on data from 2021) and the network development plan for the year 2037 (based on data from 2023) show the need for additional inertias. Grid-forming capabilities, and particularly the provision of inertia, are therefore essential capabilities of customer installations to ensure system stability.

A market-based procurement of grid-forming capabilities is intended to both counter this loss and cover the additional demand for inertia in the power supply system. In September 2023, the Federal Network Agency initiated a formal procedure in accordance with EnWG, Sections 12h (5) and 29 (1) on the specifications and technical requirements for the transparent, non-discriminatory and market-based procurement of the non-frequency based ancillary service “Inertia of local grid stability” (“inertia”) as required by EnWG, Section 12h (1) Sentence 1 No. 2. In this determination procedure, the exemption for inertia from a market-based procurement scheme, as established by the Federal Network Agency on 18 December 2020, should be revoked as a prerequisite for the inertia market.

Installations participating in the inertia market shall qualify for this purpose, fulfil the suitable requirements and provide the necessary verifications. The requirements are defined in this FNN Guideline and serve as basis for the proof of compliance.

This FNN Guideline was developed by the Project Group “System requirements” of the Forum for Network Technology and Network Operation in the VDE (FNN). The first part of the document pertaining requirements was publicly reviewed as Version 0.1 from 20 February 2024 until 20 March 2024. The second part pertaining the verifications was publicly reviewed from 12 July 2024 to 23 August 2024 also as Version 0.1.

Note to Version 2.0

This VDE FNN Guideline (Version 2.0) describes requirements and verifications for grid-forming units as a prerequisite for participation in the inertia market.

Disclaimer: in case of doubt the German original shall prevail.

1 Introduction

This FNN Guideline describes requirements and verifications as a technical basis for an incentive scheme for the procurement of grid-forming capabilities including inertia and is aimed at grid-forming power-generating units (PGUs) of Type 1 or Type 2¹, grid-forming power-generating and storage units (PGSUs), grid-forming storage as well as grid-forming controllable consumption units (CCUs). These grid-forming customer installations are referred to in this FNN Guideline as grid-forming units.

Customer installations shall comply with defined technical capabilities for the provision of inertia², including voltage source behaviour, start-up time constant behaviour as well as controller stability of the active power³ and voltage control.

From an engineering point of view, there are three categories of grid-forming units:

- 1 Grid-forming units with “symmetric inertia”, which provide both positive and negative inertia
- 2 Grid-forming units with “negative inertia”, which counteract positive frequency gradients (increase in frequency) in particular
- 3 Grid-forming units with “positive inertia”, which counteract negative frequency gradients (decrease in frequency) in particular

NOTE In certain operating conditions, even in the non-procured direction of asymmetric inertia, a small power response in accordance with Section 4.2.1.1 and Section 4.2.1.13 is still required.

The general principles for the provision of verification are detailed in Section 5.1.

¹ [Translator’s note] The Technical Connection Rules distinguish between Type 1 and Type 2 installations (or units) depending on whether they are connected directly to the network connection point or via an internal (customer) network. This classification has no equivalent in the NC RfG (Regulation 2016/631), which categorizes generation by capacity (Types A–D) rather than by connection topology, as is the case with the German Type 1/Type 2 distinction. While the Type 1/Type 2 distinction is not defined by generator technology, Type 1 installations are most often synchronous in practice, whereas Type 2 installations are typically converter-based or hybrid systems.

² [Translator’s note] The term *Momentanreserve* is translated as “inertia”. Consequently, *markgestützten Beschaffung von Momentanreserve* is interpreted as a market for inertia.

³ See also: FNN Guideline - Grid-forming & system-supporting behaviour of power-generating modules, December 2021.

2 Scope

This FNN Guideline applies to grid-forming units participating in the inertia market and shall be used as a supplement to VDE-AR-N 4110, VDE-AR-N 4120, and VDE-AR-N 4130.⁴ Sections in this FNN Guideline replace or supplement the Clauses of the existing VDE application rules as follows:

Table 1 - Overview of Clauses in the Technical Connection Rules to be updated or replaced

FNN Guideline		VDE-AR-N 4110	VDE-AR-N 4120	VDE-AR-N 4130
Type 1 unit	Type 2 unit			
Requirements				
4.1.1.1+ 4.1.2	4.2.1.9 + 0	10.2.4.3	10.2.4.3	10.2.4.3
-	4.2.1.3	10.2.2	10.2.2	10.2.2
-	4.2.1.5	10.2.3	10.2.3	10.2.3
-	4.2.1.4.5	10.2.3.3.4	10.2.3.3	10.2.3.3
4.1.3	4.2.3	8.1 (Prioritisation)	8.1 (Prioritisation)	8.1 (Prioritisation)
Verifications (unit certificate)				
5.2	5.2	12	12	12
5.4.3 + 5.4.5.2	5.5.4 + 5.5.4.4.2	11.2.8	11.2.8	11.2.8
Verifications (system certificate)				
5.6.2.1	5.6.2.1	11.4.1	11.4.1	11.4.1
5.6.2.2	5.6.2.2	11.4.2	11.4.2	11.4.2

NOTE 1 Table 1 will be updated in the next revision of the FNN Guideline regarding requirements for system certification.

In addition, the specifications in this FNN Guideline that deviate from the frequency protection settings in accordance with the relevant Technical Connection Rule shall be taken into account when parametrising the protection equipment of the customer installation.

NOTE 2 Deviations from frequency protection specifications are specified in Section 4.2.1.13 and Section 4.2.2.

The requirements and verifications specified in this FNN Guideline apply to the following units participating in the inertia market:

- Type 1 PGUs (Type 1 PGUs with an additional flywheel mass and/or optional phase-shifter operation)
- Type 2 grid-forming units to be installed
- Existing Type 2 grid-following units (existing installations) to be upgraded to Type 2 grid-forming units
- Grid-forming power-generating and storage units as well as grid-forming storage
- Converter-based grid-forming controllable consumption units (CCUs)

For the purpose of this Guideline, existing installations are those commissioned by 31 December 2027. The underlying technology of the installation is essential for the technical description of inertia. Any technological differences shall be taken into account in the procurement process, as well as in the provision of inertia for network operation processes.

Preliminary notes on the application

The value of the start-up time constant of an individual grid-forming unit is limited by:

⁴ The following versions of the Technical Connection Rules are referenced in this FNN Guideline: VDE-AR-N 4110:2023-09, VDE-AR-N 4120:2018-11, and VDE-AR-N 4130:2018-11. In principle, the current Technical Connection Rules (TCR) apply. However, there might be deviations regarding the references to the TCRs in this Guideline.

- a) the minimum start-up time constant $T_{A,E,\min}$
- b) the maximum start-up time constant $T_{A,E,\max} = 25$ s (maximum value significant from a system perspective), unless higher values are agreed with the network operator

NOTE 3 No minimum requirements for $T_{A,E,\min}$ are specified in this FNN Guideline. However, grid-forming units shall provide at least a T_A at a level that ensures the inherent stability of the unit (sub-network operability or stability in the virtual island network) without an additional flywheel mass in accordance with Section 4.2.2. $T_{A,E,\min}$ may be set to higher values within the framework of technical minimum requirements. Similarly, grid-forming units may provide a maximum T_A which still ensures that they follow the reference frequency-response curve indicated in Figure 4 without restrictions in accordance with Section 4.2.1.13.

Special features of grid-forming Type 1 units

The requirements and verifications specified in this FNN Guideline apply to the following units participating in the inertia market:

- Type 1 units with an additional flywheel mass (generator and prime mover permanently coupled)
- Type 1 units with optional phase-shifter operation (coupling of generator and prime mover)
- Type 1 units with additional inertia for optional phase shifter operation
- Type 1 units without an additional flywheel mass or without optional phase-shifter operation are outside the scope of this FNN Guideline. Rotating phase-shifters (RPS) are also outside the scope of this FNN Guideline.

3 Terms and abbreviations

3.1 Terms

The following terms apply to the application of this document.

3.1.1

start-up time constant of a Type 1 PGU

T_A

time required for a Type 1 PGU with a nominal active power $P_{r,E}$ to bring the turboset (prime mover and synchronous machine with number of pole pairs p) or a synchronous machine with the moment of inertia J_E at nominal torque from rest to nominal speed or nominal frequency f_n , respectively:

$$T_A = \frac{J_E \cdot (2\pi f_n)^2}{P_{r,E} \cdot p^2}$$

Note to entry: The start-up time constant of the Type 1 PGU is a measure for the moment of inertia J_E of the PGU relative to its nominal power and nominal frequency.

3.1.2

start-up time constant of grid-forming units (Type 2, storage or CCUs)

T_A

parameter emulated by the converter control, whose effect on the inertia of the internal voltage angle of the grid-forming unit corresponds to the effect of the start-up time constant of a Type 1 PGU and which is determined as:

$$T_A = \frac{\left(\frac{\Delta P}{P_{r,E}}\right)}{\left(\frac{\Delta f / f_n}{\Delta t}\right)}$$

3.1.3

initial operating state

IOP_X

operating state in X percentage of $P_{r,E}$ relative to the active power output of the PGU, hybrid PGSU, storage or CCU from which a test is performed

Note to entry: The operating state IOP_{\min} refers to the technical minimum power of the unit under test.

3.1.4

rated active power

$P_{r,E}$

active power of the power-generating unit given by the manufacturer for nominal conditions

[SOURCE: VDE-AR-N 4120:2018-11]

Note to entry: The nominal conditions for PGUs with a gas turbine are defined in accordance with ISO 3977-2:1997 (ambient temperature 15 °C, atmospheric pressure: 101.325 kPa, relative humidity: 60 %, height above sea level: 0 m).

3.1.5

maximum active power

$P_{E\max}$

highest 10-minute average of the active power of a PGU or storage

Note 1 to entry: For wind turbines, this value (e.g. as a 600-s maximum) may be taken from FGW TR3, Annex B. If this value is not explicitly stated, the rated electric active power of the power-generating unit is generally used.

[SOURCE: VDE-AR-N 4120:2018-11]

Note 2 to entry: For PV this value is determined by the size of the converter and depends on the actual peak power of the installed PV modules of the PV plant.

3.1.6

maximum active power (consumption)

$P_{E\max,B}$

highest 10-minute average of the active power of storage, a PGSU or a CCU during consumption

3.1.7

technical minimum technical power of the unit (feed-in)

$P_{E\min,E}$

minimum technical power of the unit to which the requirements described here apply permanently

Note to entry: $P_{E\min,E}$ shall be $\leq P_{ub,\min}$ (Table 10), respectively, correspond to the lower limit of the setting range specified in Table 11.

3.1.8

minimum dynamic active power available for the provision of negative inertia

$P_{\min,dyn}$

minimum dynamic active power available for the provision of negative inertia (in the generator sign convention) and which depends on $P_{\text{limitneg,min}}$

$$P_{\min,dyn} = P_{\text{limitneg,min}} - \left(T_A \cdot P_{rE} \cdot \frac{0.04}{s} \right)$$

3.1.9

minimum dynamic active power available for the provision of positive inertia

$P_{\max,dyn}$

minimum dynamic active power available for the provision of positive inertia (in the generator sign convention) and which depends on $P_{\text{limitpos,max}}$

$$P_{\max,dyn} = P_{\text{limitpos,max}} + \left(T_A \cdot P_{rE} \cdot \frac{0.04}{s} \right)$$

3.1.10

minimum active power for the full provision of negative inertia

$P_{\text{limitneg,min}}$

minimum active power for the full provision of negative inertia (in the generator sign convention)

Note to entry: Corresponds to P_{limitneg} for the provision of inertia when $m = 1$.

3.1.11

maximum active power for the full provision of negative inertia

$P_{\text{limitneg,max}}$

maximum active power for the full provision of negative inertia (in the generator sign convention)

Note to entry: Unless technical restrictions are specified by the manufacturer, $P_{\text{limitneg,max}}$ corresponds to the value of $P_{E\max}$.

3.1.12

minimum active power for the full provision of positive inertia

$P_{\text{limitpos,min}}$

minimum active power for the full provision of positive inertia (in the generator sign convention)

Note to entry: Unless technical restrictions are specified by the manufacturer, $P_{\text{limitpos,min}}$ is zero for PGUs and corresponds to $P_{\text{Emin,B}}$ for storage and PGSUs.

3.1.13

maximum active power for the full provision of positive inertia

$P_{\text{limitpos,max}}$

maximum active power for the full provision of positive inertia (in the generator sign convention)

Note to entry: $P_{\text{limitpos,max}}$ corresponds to P_{limitpos} for the provision of inertia when $m = 1$.

3.1.14

damping ratio

D

measure for the damping of an oscillatory system determined as the smallest damping ratio D_i with:

$$D = \min_{(i=1,n)} \frac{|\sigma_i|}{\sqrt{\sigma_i^2 + \lambda_i^2}} = \frac{\Lambda}{\sqrt{(2\pi)^2 + \Lambda^2}}$$

where σ_i and λ_i denote the real and imaginary parts of the eigenvalue i and Λ is defined as the logarithmic decrement with $\Lambda = \ln(x_n/x_{n+1})$ of the oscillation with the smallest damping ratio

Note to entry: In this case, the variables x_n or x_{n+1} denote two consecutive amplitude maxima (or minima) of the considered state variable x , where the subsequent amplitude maximum (or minimum) assumes a lower value relative to the previous one. This means that the damping ratio may be determined not only from the eigenvalues but also directly by means of simulation or measurement. See Appendix A.1 for an illustration of the damping ratio.

3.1.15

power-generating and storage unit (PGSU)

PGU, which is combined with storage on the DC side and which uses AC terminals shared with the storage for connection to the network

Note to entry: Depending on the variant, a PGSU may have different minimum or maximum outputs for the primary side (usually DC) and secondary side (usually AC).

3.1.16

virtual island operation, virtual island network

virtual operation to verify the stability of the primary control based on network security (PCNB), in which the network beyond the NCP exclusively consists of a constant load and, in the case of Type 2 PGM or PGU, PGSU, or storage with grid-following converters, with an additional flywheel mass and short-circuit power and the power-generating module (PGM) or PGU, PGSU, or the storage remains connected to the NCP

Note 1 to entry: A basic prerequisite for stable network operation within the range of the PCNB is for PGMs, PGSUs, or storage that are connected to the network, to be capable of maintaining the network frequency within a stable operating point, regardless of how the operating point of the initial state is reached.

Note 2 to entry: The virtual island network operation whose stability condition corresponds to that of island network operation. There is no signalling of the island network operation situation during the transition from regular parallel network operation to such an operating condition. The status as a virtual island network shall be detected exclusively by determining and monitoring the PCNB frequency limits. The virtual island network is described in the relevant section on verifications.

Note 3 to entry: Virtual island network operation shall be distinguished from the defined "island network operation" in which the circuit breaker at the NCP is open and is also seen as open by the PGM, PGSU, or storage. Therefore, there are no explicit and specific island network operation requirements (such as those specified in ISO 8528) that apply to the "virtual island network" or the "virtual island network operation". Rather, the "virtual island network operation" is an operating condition where the network frequency is exclusively generated by the PGM, PGSU, or storage itself.

Note 4 to entry: For virtual island network operation it is assumed that the PGUs of a PGM that are subject to the relevant requirements shall fully fulfil the aforementioned requirements.

3.1.17

short-circuit ratio (SCR)

SCR_{NCP}

ratio of the initial short-circuit power S''_k available at an NCP to the generation power $P_{inst,NCP}$ installed at the NCP originating from grid-following installations

$$SCR_{NCP} = \frac{S''_k}{P_{inst,NCP}}$$

Note to entry: The initial short-circuit power is to be determined in accordance with the relevant Technical Connection Rule.

3.1.18

market-based primary control (corresponds to FSM, or in short “primary control”)

primary control which is traded on the electricity balancing market and deployed in the frequency range between 49.8 Hz and 50.2 Hz

3.1.19

maximum power point (MPP)

operating point of a PGU without active power limiting

Note to entry: For example, this applies to a wind power plant for less than the nominal wind speed when its feed-in power is not reduced due to market conditions or network security management.

3.1.20

inertia energy

energy for the provision of inertia

Note 1 to entry: The inertia energy of a Type 1 PGU corresponds to the part of the stored kinetic rotational energy, which is stored or released when the frequency changes.

Note 2 to entry: The inertia energy of a grid-forming Type 2 PGU is considered provided by the available primary energy in electrical storage and/or by a suitable control system.

3.1.21

inertia power

power contribution of a grid-forming unit which deviates from the steady-state power both in positive and negative directions due to RoCoF or a phase angle step and by which the unit inherently counters the change of the mains voltage angle or the original power imbalance

3.1.22

grid-forming capability

capability of a PGU, PGUSU, storage or CCU with frequency and voltage control equipment designed to maintain a stable operating point during virtual island network operation and parallel operation at constant voltage and frequency and which ensures stable behaviour in the event of defined disturbances with steady-state and dynamic deviations from the operating point

Note to entry: A prerequisite for this is the capability to provide inertia power and inertia energy.

3.1.23

grid-forming unit

PGU, PGUSU, storage or CCU with grid-forming capabilities

3.1.24 Primary control based on network security or PCNB (collection of terms)

3.1.24.1

primary control based on network security (corresponds to LFSM-O/U)

primary control contribution of PGMs, PGSUs, storage, and continuously CCUs to the primary control required outside the frequency range between 49.8 Hz and 50.2 Hz to ensure network security

3.1.24.2

small-signal stability of the primary control based on network security

stability characteristic of the PCNB of a PGM in virtual island network operation within the unlimited active power setting range

Note to entry: small-signal stability of the PCNB is ensured if the frequency control equipment is able to compensate for small disturbances of the active power balance and maintain stability at the new resulting operating point (also see Appendix A.II).

3.1.24.3

unlimited primary control based on network security

contributions of the PCNB which are not subject to significant type and/or installation-specific limitations of the active power gradient within the agreed active power setting range such that the time response meets the requirements for small-signal stability of the primary control

3.1.24.4

limited primary control based on network security

contributions of PCNB which are limited by type and/or installation-specific limitations of active power gradients for specified active power controlling amplitudes within the agreed active power setting range

3.1.24.5

unlimited setting range of the primary control based on network security

available active power setting range for the PCNB starting from an any permissible operating point and for which no type and/or system-specific limitations exist which would not allow the requirements for small-signal stability of the PCNB to be fulfilled

Note to entry: The unlimited setting range of the PCNB is the setting range for which the dynamic behaviour is generally approximately linear starting from any steady-state operating point in the event of frequency deviations (also see Table 10). The unlimited setting range of the PCNB ensures that an installation is capable of compensating small displacements and keeping a stable operation from any permissible operating point in the virtual island network with defined damping.

3.1.24.6

limited setting range of the primary control based on network security

total available setting range for the PCNB which exceeds the unlimited setting range and is subject to type and system-specific limitations

3.1.24.7

upper power limit in the unlimited setting range of the PCNB

$P_{ub,max}$

technology-specific upper limit of the active power output or active power input in the unlimited setting range of the primary control based on network security

3.1.24.8

lower power limit in the unlimited setting range of the PCNB

$P_{ub,min}$

technology-specific lower limit of the active power output or active power input in the unlimited setting range of the primary control based on network security

Note on entry: Provided that $P_{Emin,E}$ is below $P_{ub,min}$, as defined in Table 10, all requirements for the unlimited setting range of the PCNB shall refer to $P_{Emin,E}$ instead of $P_{ub,min}$.

3.1.24.9

power-related droop of the primary control based on network security

s

slope of the controller characteristic of the PCNB outside the deadband which describes the change of the active power of a PGU as a function of the network frequency change

Note 1 to entry: The droop may be determined as the absolute value of the ratio of the value of the controller input signal Δn or Δf , which either relates to the nominal speed n_n or to the nominal frequency Δf , to the value of the speed or frequency-dependent power change ΔP of the relative to the reference power P_{ref} of the PGU:

$$s = \left| \frac{\frac{\Delta f}{f_n}}{\frac{\Delta P}{P_{ref}}} \right| \quad \text{or} \quad s = \left| \frac{\frac{\Delta n}{n_n}}{\frac{\Delta P}{P_{ref}}} \right|$$

3.1.24.10

step change of the frequency difference

Δf

step change in the control deviation from the frequency setpoint to the actual frequency value or from the speed setpoint to the actual speed value

3.1.24.11

positive step change of the frequency difference in the unlimited setting range of the PCNB

Δf_+

positive step change in the frequency difference Δf , which causes a positive change in the active power output according to technology-specific control ranges in the unlimited setting range of the primary control based on network security

3.1.24.12

positive step change of the frequency difference in the limited setting range of the PCNB

Δf_{++}

positive step change in the frequency difference Δf , which causes a positive change in the active power output according to technology-specific control ranges in the limited setting range of the primary control based on network security, until the maximum possible active power output was reached

3.1.24.13

negative step change of the frequency difference in the unlimited setting range of the PCNB

Δf_-

negative step change in the frequency difference Δf , which causes a negative change in the active power output according to technology-specific control ranges in the unlimited setting range of the primary control based on network security

3.1.24.14

negative step change of the frequency difference in the limited setting range of the PCNB

Δf_{--}

negative step change in the frequency difference Δf , which, based on the minimum technical power, causes a negative change in the active power output according to technology-specific control ranges in the limited setting range of the primary control based on network security, until the maximum possible active power output was reached

3.1.25

bumpless controller switching

changeover or parameter change without initiating a jump of the control variables, so that the same values before and after the changeover shall be used when deriving status parameters for the system

3.1.26

system-supporting capabilities

capabilities of an installation that is designed considering the control equipment for active power control at the NCP so that it supports the stability of the network beyond the NCP without itself having grid-forming capabilities

Note to entry: The installation has no or no sufficient inertia of its own and is therefore dependent on the addition of external inertia to ensure stable behaviour of the active network frequency control in virtual island network operation.

3.1.27

inertia

for a given power imbalance, the inertia determines the rate of change of the angular velocity (frequency) of the voltage phasor of the internal voltage of the grid-forming unit

Note 1 to entry: The inertia of an individual Type 1 PGU is described by the rotational kinetic energy of the turbo-set or, alternatively, by its start-up time constant as a related quantity. This start-up time constant may still be used as an equivalent for describing the inertia if the grid-forming units provide an inertia equivalent in its effect through their control device.

Note 2 to entry: A contribution from an individual unit to the system inertia corresponds to the inertia of the unit.

Note 3 to entry: The system inertia describes the total rotational kinetic energy of the synchronous rotating masses or, alternatively, by the start-up time constant as a related quantity. These quantities may still be used to describe the system inertia provided that converter-based grid-forming units contribute equally to the system inertia through their control. The system inertia defines the frequency change rate in the event of a disturbance with a power imbalance between the consumption (load) and the instantaneous power generated in the system under consideration (instantaneous power output).

3.1.28

transient minimum power

minimum electrical power that can be supplied from a Type 1 PGU or PGM over a limited period of time without taking into account regulatory requirements (e.g. emission limits) and process specifications in case of a disturbance, and therefore different from the minimum technical power at which regulatory requirements shall be fulfilled at all times

3.1.29

power response to a phase angle step

maximum value of the profile that shows the changes of the active power dissipated by the grid-forming unit immediately after a sudden change in the angle of the voltage at the transition to the new operating point

3.1.30

additional flywheel mass

separate rotating mass which is connected to the generator or the turbine either directly or via coupling

3.2 Abbreviations

ESCR	Effective short-circuit ratio (ge: effektives Kurzschlussverhältnis)
PGM	Power-generating module (ge: Erzeugungsanlage, EZA)
PGU	Power-generating unit (ge: Erzeugungseinheit, EZE)
PGSU	Power-generating and storage unit (ge: Erzeugungs- und Speichereinheit, EZSE)
FSM	Frequency-sensitive mode
LFSM-O	Limited frequency-sensitive mode over-frequency
LFSM-U	Limited frequency-sensitive mode under-frequency
MPP	Maximum Power Point
NCP	Network connection point (ge: Netzanschlusspunkt, NAP)
OVRT	Over Voltage Ride Through
UVRT	Under Voltage Ride Through
PCNB	Primary control based on network security (ge: netzsicherheitsbasierte Primärregelung, PRNB; similar to LFSM-O/U)
CCU	Controllable consumption unit (ge: regelbare Bezugseinheit, rBE oder regelbare Last, rL)
SCR	Short-circuit ratio (ge: Kurzschlussleistungsverhältnis)
THD	Total harmonic distortion (ge: Gesamtoberschwingungsgehalt)
VSM	Virtual synchronous machine (ge: virtuelle Synchron-Maschine)

4 Requirements for grid-forming units

4.1 Grid-forming Type 1 units

4.1.1 Basic requirements

4.1.1.1 Response to steep frequency gradients (RoCoF)

Grid-forming Type 1 units shall be capable of riding through fast frequency changes at the NCP without disconnecting from the network. The requirements for “ride through fast frequency changes” specified in Clause 10.2.4.3 of the relevant Technical Connection Rule apply.

4.1.1.2 Specifications for the start-up time constant

The operator of the installation shall specify the capabilities of the installation and provide them as well as the following mass moments of inertia to the network operator, when considering the option for phase-shifter operation and the installation of an additional flywheel mass:

- Mass moment of inertia of the generator
- Mass moment of inertia of additional flywheel mass with the coupled generator
- Mass moment of inertia of the entire shaft train (overall system)

NOTE 1 There are no requirements for the capability to switch between generator operation and phase-shifter operation during operation.

NOTE 2 The deployment of inertia may temporarily exceed the steady-state fed-in power during operation at partial load with a relatively high T_A . In this case, short-term operation with reverse power shall be enabled and the reverse power protection shall be properly parametrised.

There are different cases to be considered when modifying existing installations:

- If an additional flywheel mass is added, its mass moment of inertia shall be indicated.
- If an upgrade to enable phase-shifter operation is made, the mass moment of inertia of the generator shall be indicated.

4.1.2 Requirements for the response to overfrequency and underfrequency

Sections 4.2.2.1, 4.2.2.5, 4.2.2.6 and 4.2.2.7 apply without limitations.

While the requirements in Section 4.2.2.2 apply, the following deviations from the requirements in Section 4.2.2.2 shall also be taken into account:

- Regarding the requirements for **droop and damping** in the area of the PCNB, the installation shall comply with Section 4.2.2.2, **Point 1**, where the effective PCNB shall be designed as a proportional speed control. In addition, P_{ref} shall be used as a reference quantity to determine the droop for Type 1 PGU, $P_{\text{b inst}}$ and a damping ratio of $D \geq 0.06$ shall be maintained for the **structure and parametrisation of the speed control**.
- Regarding the **response during overfrequency and underfrequency events** in the area of the PCNB, the installation shall comply with Section 4.2.2.2, **Point 5**. However, instead of what is specified in the Point 1, the installation shall be capable of managing a spontaneous load disconnection on the lower limit value of the setting range specified in Table 11 but with a maximum of 45 % of $P_{\text{b inst}}$. Furthermore, the installation shall be capable of managing a load disconnection of arbitrary amplitude but no more than 45 % of $P_{\text{b inst}}$, within the operating range of $P_{\text{b inst}}$ and at minimum load.
- The following **special requirements** also apply to grid-forming Type 1 PGUs in the area of the PCNB:
 - Each Type 1 PGU shall be capable of ensuring virtual island network operation based on PCNB between the operating points of transient minimum power and maximum load P_{Amax} according to this section. The system-supporting capabilities of the PGU verified for this purpose shall be activated

within the PCNB control range at any time during network operation. Stable operation of the PGU shall be ensured during changeover of parameters and/or structures of the control equipment when the PCNB is activated (exceeding the 200 mHz deadband) and vice versa.

NOTE 1 Ensure that no isochronous operation occurs when the PCNB is activated.

NOTE 2 The 200 mHz deadband may also be exceeded by using arbitrarily small gradients.

Section 4.2.2.3 applies.

While the requirements in Section 4.2.2.4 apply, the following deviations from the requirements in Section 4.2.2.4 shall also be taken into account:

- The following limitations shall be added at the end of the first paragraph in Section 4.2.2.4: For internal combustion engines and gas turbines, a technology-related reduction of 3 % $P_{b \text{ inst}}$ in the dynamic short-time range is permissible until a value of 49.5 Hz is resumed.
- For gas and steam turbines a reduction of the maximum active power output of the PGUs not exceeding $10 \% \cdot P_{b \text{ inst}} \cdot (49.5 \text{ Hz} - f) / 1 \text{ Hz}$ caused by the gas or steam process is permissible with decreasing speed below 49.5 Hz and below the curve indicated in Figure 5. This also applies to internal combustion engines. If the maximum active power output is reduced further, the operator of the PGM shall document the underlying ambient conditions (e.g. ambient temperature) and technical capabilities and obtain the approval of the network operator.
- Section 4.2.2.7 applies to Type 1 PGUs with frequency measurement.

4.1.3 Prioritisation of the requirements

The prioritisation requirements of Clause 8.1 of the relevant Technical Connection Rule apply.

4.2 Grid-forming units (Type 2, storage and controllable loads)

4.2.1 Basic requirements

4.2.1.1 Behaviour of voltage sources

From the network perspective, the grid-forming unit shall permanently show a behaviour at its terminals equivalent to a voltage source downstream of an effective impedance (Thevenin source) corresponding to the equivalent circuit diagram for the positive sequence indicated in Figure 1, where the internal controlled voltage source shall be a positive sequence voltage source of fundamental frequency. In exceptional cases, a negative sequence voltage may be applied.

The effective impedance is in part physical (e.g. coupling transformer, filter inductance) and may additionally be characterised through control technology.

A voltage source downstream of a predominantly inductive impedance is characterised by its response to a sudden change:

- the voltage amplitude of the network (Figure 1) instantaneously causes an essentially reactive current change, and
- the voltage angle of the network (Figure 1) instantaneously causes an essentially active current change.

The active and reactive components of the positive sequence current, $i_{P1,PGU}$ and $i_{Q1,PGU}$, at the terminals of the grid-forming unit may be described as follows, assuming an approximation of $r_{w,1} \ll x_{w,1}$ using related quantities:

$$i_{P1,PGU} = \frac{p_{1,PGU}}{u_{1,PGU}} \approx -\frac{u_1}{x_{w,1}} \sin(\delta_1) \quad (1)$$

$$i_{Q1,PGU} = \frac{q_{1,PGU}}{u_{1,PGU}} \approx \frac{1}{x_{w,1}} (u_{1,PGU} - u_1 \cdot \cos(\delta_1)) \quad (2)$$

When using

$$\delta_1 = \varphi_{u1,PGU} - \varphi_{u1} \quad (3)$$

Where:

δ_1	is the angular difference between the positive sequence voltage at the terminals and the positive sequence voltage of the internal voltage source of the PGU
$\varphi_{u1,PGU}$	is the voltage angle of the positive sequence voltage at the terminals of the grid-forming unit
φ_{u1}	is the inertia-induced voltage angle of the positive sequence voltage of the internal voltage source of the grid-forming unit
$p_{1,PGU}$	is the positive sequence active power output/input of the grid-forming unit at its terminals
$q_{1,PGU}$	is the positive sequence reactive power output/input of the grid-forming unit at its terminals
$r_{w,1}$	is the active resistance of the positive sequence effective impedance $z_{w,1}$ of the grid-forming unit
$x_{w,1}$	is the inductive reactance of the positive sequence effective impedance $z_{w,1}$ of the grid-forming unit
u_1	is the magnitude of the positive sequence voltage of the internal voltage source of the PGU
$u_{1,PGU}$	is the magnitude of the positive sequence voltage at the terminals of the grid-forming unit

For unsymmetrical network conditions, the negative sequence reactive current $i_{Q2,PGU}$ may be approximated using the following equation and related quantities:

$$i_{Q2,PGU} \approx \frac{1}{x_{w,2}} \left(u_{2,PGU} - u_2 \cdot \cos(\delta_2) \right) \quad (4)$$

When using

$$\delta_2 = \varphi_{u2,PGU} - \varphi_{u2} \quad (5)$$

Where:

- δ_2 is the angular difference between the negative sequence voltage at the terminals and the negative sequence voltage of the internal voltage source of the grid-forming unit
- $\varphi_{u2,PGU}$ is the voltage angle of the negative sequence voltage at the terminals of the grid-forming unit
- φ_{u2} is the voltage angle of the negative sequence voltage of the internal voltage source of the grid-forming unit
- $x_{w,2}$ is the inductive reactance of the negative sequence effective impedance $x_{w,2}$ of the grid-forming unit
- u_2 is the magnitude of the negative sequence voltage of the internal voltage source of the PGU
- $u_{2,PGU}$ is the magnitude of the negative sequence voltage at the terminals of the grid-forming unit

The value of $\cos(\delta_2)$ is typically 1 provided no negative sequence active current is fed.

NOTE 1 This describes the desired behaviour at the terminals and explicitly not a control concept.

The control impedance (of fundamental frequency) shall be kept constant as long as the current limits (Section 4.2.1.4.4) of the grid-forming unit are not reached.

The effective impedance z_w of new installations shall be designed to ensure that, during changes of the mains voltage amplitude, the grid-forming unit does not exceed the following maximum value $z_{w,max}$ without the current limitation being activated:

- a) without unit transformer (or on the low-voltage side of the unit): 0.27 p.u. or
- b) including unit transformer (or on the medium-voltage side of the unit,): 0.35 p.u. or
- c) if applicable, at high-voltage level: 0.50 p.u.

For double-fed asynchronous generators, the upper limit of the impedance may alternatively be determined by the physical transient reactance of the asynchronous generator plus the stator resistance of the asynchronous generator and the impedance of the unit transformer.

NOTE 2 The nominal active power shall be used as the basic value for determination of the impedances in p.u.

Alternatively for retrofitted existing installations, the control-related impedance shall be designed so that it does not exceed a maximum value of 0.2 p.u. within the design limits of the grid-forming unit.

NOTE 3 No requirements for the effective minimum impedance are described in this FNN Guideline.

The negative sequence effective impedance shall generally be designed to be equal to the positive sequence effective impedance in normal operation. For grid-forming units with double-fed asynchronous generator, smaller values of the negative sequence impedance are permissible if a converter of larger rated values would otherwise be required.

NOTE 4 It is recommended to select the smallest possible R/X ratio of the control impedance (approximately 0.1).

In case of a voltage angle step at the terminal of the grid-forming unit, the unit shall respond by adjusting its power response to an angle step at its terminal within its current limits in accordance with the following requirements. The following applies for the maximum value $\Delta i_{P1,PGU,max}$ of the active current response $\Delta i_{P,PGU}$ triggered by a voltage angle step:

$$\Delta i_{P1,PGU,max} = -\frac{1}{Z_{w,max}}(\sin(\delta_{n1}) - \sin(\delta_{v1})) \quad (6)$$

where δ_{v1} and δ_{n1} are the angle of the positive sequence voltage at the terminal of the grid-forming unit before (v) and after (n) the event.

The following applies to the active current response $\Delta i_{P,PGU}$:

- At least 50 % of $\Delta i_{P1,PGU,max}$ shall be provided in the procured direction, where the power change may be limited to values $\geq 45 \% P_{E,max}$
- At least 5 % of $\Delta i_{P1,PGU,max}$ shall be provided in the non-procured direction, where the power change may be limited to values $\geq 5 \% P_{E,max}$. There are no requirements for existing installations regarding the provision of $\Delta i_{P1,PGU,max}$ in the non-procured direction.

Instantaneous values shall be used to evaluate $\Delta i_{P,PGU}$.

NOTE 5 It is assumed that the active power response to a phase angle step is influenced not only by the effective impedance but also, for example, by control measures for damping.

Negative sequence components of the voltage source are permissible, provided they are used to ensure that the voltage at the terminals is as symmetric as possible or to limit any permanent loading caused by unsymmetrical currents to values $> 3 \% I_r$.

The voltage source behaviour of a grid-forming unit is a permanent and fundamental characteristic which shall be maintained even when running into a limitation (current limitation). Upon reaching the current limit (also see Section 4.2.1.4.4), current clipping is permitted up to 40 ms after voltage angle steps and sudden changes in the voltage amplitude. In order to avoid persistent current clipping, it is permissible to regulate the current to 95 % of the current at which current clipping would occur, however, at least to I_r .

NOTE 6 Current clipping is characterized by a significant distortion of the output current of the grid-forming unit.

If the generating unit (PGU) is operating in current limitation mode, it shall respond to system events that tend to relieve the limitation while maintaining voltage source behaviour. In doing so, deviations from the steady-state effective impedance are permitted.

NOTE 7 As it corresponds to a voltage source behaviour (Thevenin source), the current or the electrical power at the terminals of the grid-forming unit adjusts itself instantaneously when an event occurs within the network at or beyond the NCP, according to the impedance (physical and control impedance) effective across the NCP based on physical phenomena (e.g. electromagnetic compensation processes). The changing angular differences (angle of the internal voltage source to the voltage angle at the NCP or at the terminals of the grid-forming unit) shall be counteracted with a correctly signed power change. Verification of voltage source behaviour is considered provided by verifying inherent stability in the virtual island network.

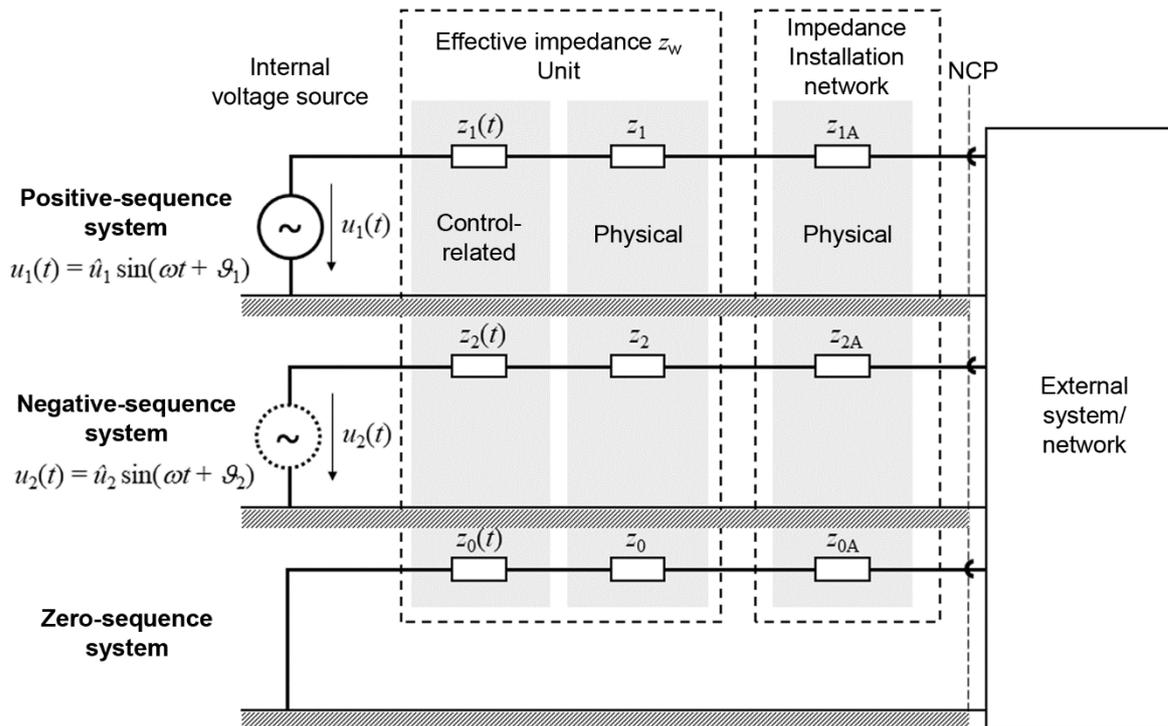


Figure 1 - Schematic representation of the fundamental frequency voltage source behaviour of a grid-forming unit at the NCP with optional negative sequence voltage source

4.2.1.2 Damping behaviour above 10 Hz

The grid-forming unit shall have a damping effect in the range of sub-synchronous torsional interactions above 10 Hz and in particular for frequencies in the range between 100 Hz and 1 kHz.

NOTE The damping behaviour is determined by, among other things, the damping torque and the impedance-related behaviour of the unit.

4.2.1.3 Method for the provision of reactive power at the NCP

Clause 10.2.2.4 of the relevant Technical Connection Rule applies. The first sentence, however, shall be omitted: "The provision of reactive power shall not impair the dynamic network stability."

It shall be replaced by the following: "The steady-state voltage stability shall not impair the continuous voltage control at the grid-forming units and the UVRT/OVRT behaviour of grid-forming units in accordance with Section 4.2.1.5 outside the quasi-steady-state operating range of the PGM for grid-forming units indicated in Figure 4 within the scope of VDE-AR-N 4110 and VDE-AR-N 4120 or in Figure 2 within the scope of VDE-AR-N 4130 and within the respective FRT limit curves."

NOTE 1 This may be achieved, for example, by sufficient time decoupling and limiting the setting value (e.g. to a range between 0.85 and 1.15 U_ρ).

The requirement for reactive power control behaviour for grid-forming installations within the scope of VDE-AR-N 4110 and VDE-AR-N 4120 shall be updated as follows: "The reactive power control behaviour at the NCP in accordance with methods a) and b) described in Clause 10.2.2.4 of the VDE-AR-N 4110 and VDE-AR-N 4120 shall correspond in its quality to the behaviour indicated in VDE-AR-N 4110 and VDE-AR-N 4120, Figure C.2 for all setpoint step changes. Any reactive power value resulting from the control behaviour predefined by the network operator shall be provided by the grid-forming installation and be adjustable between 15 s and 45 s (rise time). If no specific value is predefined by the network operator, then a value of 30 s applies."

NOTE 2 This does not present a restriction for the control dynamics for power-frequency-oscillations specified in Section 4.2.1.11.

The requirement for the reactive power control behaviour for grid-forming installations within the scope of VDE-AR-N 4130 shall be updated as follows: “The maximum permissible rise time for reaching the reactive power setpoint shall be adjusted between 5 s and 60 s by the PGM. In the absence of any concrete values specified by the network operator, a value of 30 s shall apply. The maximum permissible settling time for reaching the reactive power setpoint shall be specified by the relevant network operator between 5 s and 60 s, whereby the tolerance for steady-state reactive power supply shall not exceed 5 % of the maximum reactive power supply.”

4.2.1.4 Continuous voltage control for grid-forming units

4.2.1.4.1 General information

Grid-forming units shall be equipped with a continuous voltage control which is subordinate to steady-state voltage stability and is permanently active. The continuous voltage control encompasses all control processes regarding the amplitude of the voltage source including the effective impedance specified in Section 4.2.1.1.

The voltage control shall be designed to comply with requirements also in conjunction with several grid-forming units connected in parallel at an NCP.

NOTE 1 The superordinate requirements for steady-state voltage stability described in Clause 10.2.2 of the relevant Technical Connection Rule relate to the grid-forming installation.

NOTE 2 An illustrative representation of the steady-state voltage control through continuous voltage control during implementation in the grid-forming unit can be found in Figure 2.

For grid-forming units which, due to the availability of primary energy, only feed active power of $\leq 5\% P_{E_{max}}$, apply requirements for voltage control outside the quasi-steady-state operating range according to ability and capacity.

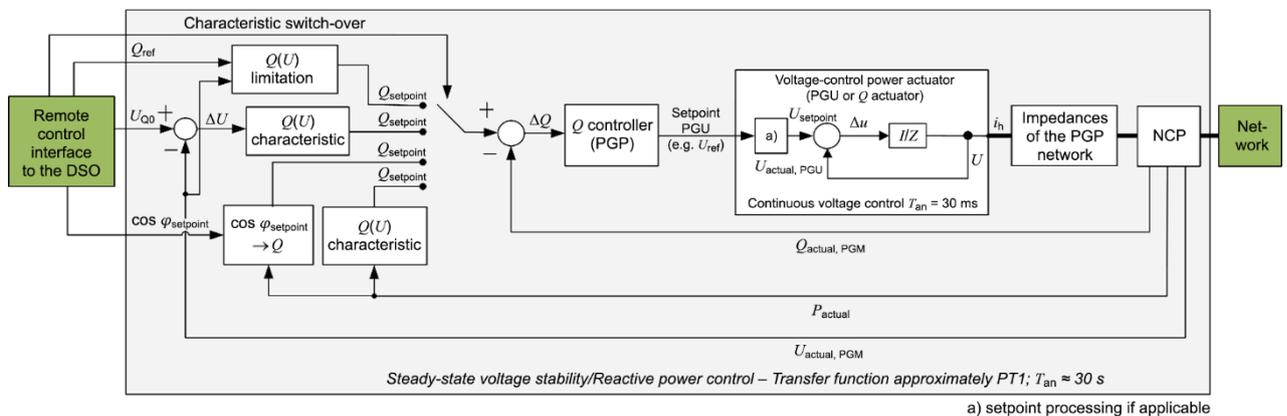


Figure 2 - An illustrative representation of the steady-state voltage control through continuous voltage control during implementation in the grid-forming unit

4.2.1.4.2 Continuous voltage control

A prerequisite for stable voltage control is the stability of the closed-loop voltage control system with a maximum rise time and a minimum damping at an impedance consisting of the impedance of the network of the installation and the impedance of the external network (Figure 1). The voltage control shall fulfil the stability requirements mentioned above for a short-circuit power ratio at the PGU terminal of $SCR \geq 1$. The voltage control shall also fulfil the stability requirements mentioned above when operating in the virtual island network.

This shall be achieved through an adequate design of the voltage control. In particular, the setpoints in each operating states shall be limited in a way to prevent tripping of protection systems.

These requirements only apply if the prerequisites of steady-state voltage stability for transmission of the output power are fulfilled.

The voltage at the terminals of the grid-forming unit is controlled in terms of a controlled voltage source downstream of an effective impedance z_w in accordance with Section 4.2.1.1 and therefore shows a proportionate behaviour without a deadband over the full unlimited working range.

NOTE *The proportional behaviour corresponds to the k-factor used in the context of grid-following installations or the reciprocal value of the effective impedance in steady state.*

A response in the current should follow a step change in the voltage amplitude at the terminals of the grid-forming unit, which indicates a constant voltage source downstream of a constant impedance. This is satisfied if, starting from an operating point in the unlimited working range, the doubling of a voltage step applied at the terminals of a grid-forming unit leads to doubling the reactive current change. The values to be considered here are those of the steady state.

A tolerance of $(\Delta u_I / \Delta i_I) / (\Delta u_{II} / \Delta i_{II}) = 100 \% \pm 15 \%$ applies to linearity. Here, Δu_{II} and Δu_I are the two voltage step changes compared to the original operating point and Δi_I and Δi_{II} are the resulting changes in reactive current.

4.2.1.4.3 Dynamic requirements

In the event of a change of the setpoint for the continuous voltage control of the grid-forming unit, the rise time shall not exceed 1 s within the short-circuit power range specified in Clause 10.2.3.2 of the relevant Technical Connection Rule.

For a sudden change of the amplitude of the voltage at the terminals at a constant setpoint, the following requirements apply to the dynamics of the current resulting from the voltage control:

- Rise time of the apparent current: $T_{\text{rise}_{90\%}} \leq 10 \text{ ms}$
- Settling time of the reactive current: $T_{\text{settling}_{\Delta x}} \leq 60 \text{ ms}$
- Damping of the reactive current: $D \geq 0.3$

The rise time shall be kept as short as possible whilst meeting the requirements for damping over the full short-circuit power range.

The rise time and the settling time are related to the final value. The settling tolerances are +20 % I_r and -10 % I_r for $\Delta i_Q > 0$ or -20 % I_r and +10 % I_r for $\Delta i_Q < 0$, whereby Δi_Q corresponds to the reactive current that is considered provided in addition to the steady-state reactive current during a fault.

The damping shall be evaluated after the settling period for grid-forming units with double-fed asynchronous generators.

NOTE 1 *The onset of a sudden change of the voltage at the terminals amplitude is defined as the moment at which the magnitude of the voltage at the terminals in the $\alpha\beta$ system reaches 10 % of the final value of the voltage change.*

NOTE 2 *Instantaneous values are used to assess compliance with the rise time. The upper limit of 80 ms (settling time) shall be taken into account when evaluating compliance with the settling time and damping, since the positive sequence and negative sequence quantities are determined over a period of 20 ms.*

NOTE 3 *Notwithstanding the requirements of VDE-AR-N 4110, there is currently no defined control specification for limited dynamic network support (or limited continuous voltage control) for grid-forming generation units. To ensure*

that the automatic active power / frequency control (AWE) remains effective (no feed-in to the fault arc) and to prevent measurement values from being distorted by intermediate feed-in, the network operator may require this behaviour via loss of mains protection until a corresponding requirement is specified (e.g. $U \ll: 0.45 U_{1V}$, without delay; $U <: 0.8 U_{1V}$, 300 ms).

4.2.1.4.4 Behaviour when reaching and leaving the current limits

In addition to the requirements described in Section 4.2.1.1, a limitation of the current shall be applied in terms of magnitude when reaching the current limits.

NOTE Direct prioritisation of active or reactive current is prohibited. The division between active and reactive current is determined by the control functions designed to fulfil the requirements for the grid-forming unit specified in this FNN Guideline.

If current limiting is no longer required, the grid-forming unit shall immediately switch to a new operating state without current limitation. This operating state is a result at that point in time of the respective requirements for the dynamic behaviour of the grid-forming unit.

4.2.1.4.5 Behaviour upon return to the voltage range of $U_c \pm 10 \% U_c$

If, after a fault according to Section 4.2.1.5, the mains voltage returns to a value within the voltage range $U_c \pm 10 \% U_c$ and the active current of the PGM was reduced during the network fault, then the active current shall be increased as quickly as possible immediately after the end of the fault until the value pre-fault value of the active current or active power is reached. The rise time should not exceed 1 s, depending on the impact of any inertia provided. Longer rise times shall be justified.

For Type 2 PGUs equipped with a double-fed asynchronous generator, the rise time may be a maximum of 1.0 s for faults during which all three line-to-line voltages have fallen below $25 \% U_n$. In addition, in the event of successive faults in which all three line-to-line voltages have fallen below $25 \% U_n$, the rise time for the active current may be a maximum of 5 s until the end of the second mains fault at the earliest.

Transient overvoltages in the positive sequence of the PGU during voltage recovery shall be limited to 5 % relative to the final steady-state value of the voltage at the terminals. A value of 2.5 % instead of 5 % applies to grid-forming units commissioned after 31 December 2027. Voltage changes attributed to the active power behaviour are exempt from this requirement. The steady-state final value of the voltage at the terminals is determined based on the assumption of a constant voltage setpoint provided by the superimposed static reactive power control.

4.2.1.5 Robustness through short-term overvoltage and undervoltage events (OVRT/UVRT robustness)

The following requirements apply to grid-forming Type 2 installations instead of those specified in Clause 10.2.3 of the relevant Technical Connection Rule regarding riding through network faults which are detected as short-term overvoltages (overvoltage ride through, OVRT) or undervoltages (undervoltage ride through, UVRT):

The objective of the OVRT/UVRT robustness is to prevent any unintentional disconnection of the generation power in the event of short-term voltage dips or rises and with that, the risk of system stability.

NOTE 1 Events that lead to short-term voltage drops or increases are typically network faults (short circuits) but can also have other causes. To facilitate legibility, the term network fault is used hereafter.

Grid-forming units shall fulfil the robustness requirements for OVRT/UVRT. These requirements apply to both symmetrical and unsymmetrical faults in the network. Auxiliary power units, which may not be part of the certified grid-forming unit, but which are required for the operation of the grid-forming unit, shall not compromise the capability of the grid-forming unit to comply with the requirements.

The following requirements apply:

- a) The grid-forming units shall not disconnect from the network at overvoltage or undervoltage events within the predefined limits:
- The grid-forming unit shall maintain stability over its entire operating range and remain connected to the network if the short-circuit power ratio at the NCP after fault clearance is greater than three. This applies as long as all line-to-line voltages at the NCP are within the limit curves indicated in Figure 14 for grid-forming units within the scope of VDE-AR-N 4110 or Figure 12 for grid-forming units within the scope of VDE-AR-N 4120 and VDE-AR-N 4130 (red for three-phase voltage dips, green for two-phase voltage dips and blue for the overvoltage limit curve).
 - When the voltage is reduced, the lowest of the three line-to-line voltages at the NCP shall be used for assessing the OVRT/UVRT limit curves⁵. When the voltage is increased, the highest of the three line-to-line voltages at the NCP shall be used (for details see Appendix B.4).
 - The time of the onset of a fault (and, thus, the reference point $t = 0$ as given in Figure 14 in VDE-AR-N 4110 or in Figure 12 in VDE-AR-N 4120 and VDE-AR-N 4130) is defined during the following event:
 - voltages $> 1.1 U_c$ or $< 0.9 U_c$

The criterion for the end of a fault is defined as the following event:

- return of all line-to-line voltages to the range of $U_c \pm 10\% U_c$

The reference point for this requirement for the robustness towards network faults is the NCP.

- b) The grid-forming units shall be designed to ride through several consecutive network faults.

- Grid-forming units shall be capable of riding through any sequence of network faults, unless the total amount of accumulated energy which could not be fed into the network due to network faults over the last 30 min exceeds the electrical energy equivalent of $P_{E_{\max}} \cdot 2$ s.

NOTE 2 Technical solutions for the implementation of this requirement are not specified in this FNN Guideline. Thus, both thermal considerations (such as the use of chopper resistors) and equivalent criteria are permitted.

Grid-forming units connected to a distribution network with isolated neutral points or to a resonant earthed system shall not disconnect from the network in the event of a single-phase fault (earth fault). If single-phase faults lead to significant dips in the line-to-line voltage (short circuit to earth) due to the neutral point treatment of the medium-voltage distribution network, the characteristic for the two-phase fault in Figure 13 and Figure 14 shall be used for grid-forming units within the scope of VDE-AR-N 4110 or in Figure 11 and Figure 12 for grid-forming units within the scope of VDE-AR-N 4120 and VDE-AR-N 4130.

NOTE 3 The FRT curves indicated in Figure 13 and Figure 14 or in Figure 11 and Figure 12 of the relevant Technical Connection Rule describe the minimum requirements for the PGM to remain connected to the network. These requirements do not specify parameters for undervoltage protection.

After a fault clearance, the dynamic interactions between the grid-forming unit and the network (at the NCP as well as for houseload voltage) result in a voltage equalisation process that lasts beyond the fault duration. Overvoltage and undervoltage events will then occur in no chronological order but may have the same cause. This shall be taken into account in the design of the grid-forming unit.

The requirements specified in Clauses 10.2.3.2 and 10.2.3.3 of the relevant Technical Connection Rule (see Figure 14 in VDE-AR-N 4110, Figure 12 in VDE-AR-N 4120 or VDE-AR-N 4130), do not apply if a short-term increase in voltage Δu_{NCP} (difference between the highest line-to-line voltage at the NCP and its average

⁵ Also referred as “FRT limit curves”.

value over 1 min, $U_{1\min}$, at the onset of the fault relative to the agreed supply voltage) exceeds the limit curve specified in Figure 12 (VDE-AR-N 4110) or Figure 10 (VDE-AR-N 4120 and VDE-AR-N 4130).

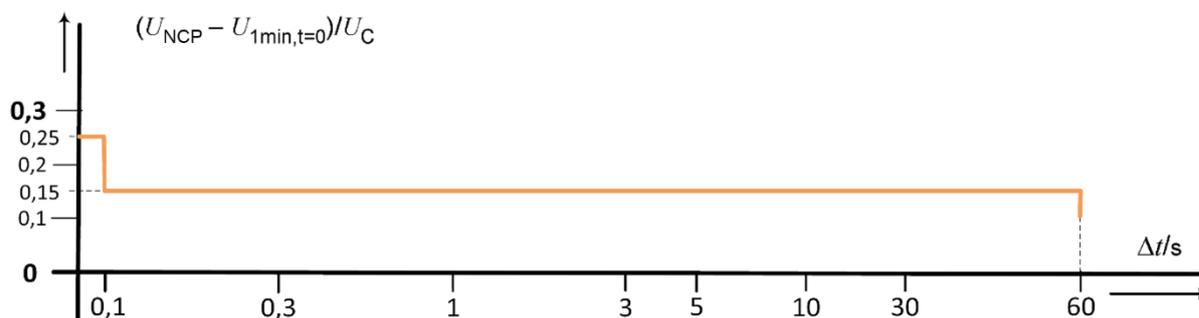


Figure 3 - Limit curve for relative voltage rises (Figure 12 in VDE-AR-N 4110 or Figure 10 in VDE-AR-N 4120)

The requirements for dynamic network stability apply to customer installations with grid-forming units separately for Type 1 or Type 2 units.

The network operator may impose technical requirements for protection of the network, which may reduce the period during which the PGM remains connected to the medium-voltage network. This depends on the conditions of the network and technology used.

4.2.1.6 Fast protection during high voltages

4.2.1.6.1 General information

When galvanically isolating a sub-network with one or more grid-forming units together with a high effective capacitance (e.g. cable or compensation device), this can interact to cause a high temporary overvoltage. This can be critical for other connected network users and the units themselves.

In its own interest, the grid-forming unit will have a permissible internal protection for very high voltages that are above the HVRT characteristic. This internal protection will only provide reliable protection for other grid users if the mentioned disconnection above the HVRT characteristic is supplemented by a disconnection requirement.

4.2.1.6.2 Requirement for fast protection during high voltages

The requirement for fast protection during high voltages only applies to Type 2 grid-forming units that are to be connected in systems with an NCP at medium-voltage (network levels 4 and 5). This requirement does not apply to grid-forming units based on double-fed asynchronous machines.

If a voltage occurs at the terminals of the grid-forming unit that has a half-oscillation RMS value ≥ 1.35 p.u., the grid-forming unit shall be permanently switched within 40 ms to a state in which the half-oscillation RMS value of the current in each conductor is limited to a maximum of 5 % of the rated current. Currents resulting from passive components still connected to the mains are generally permissible. This state may only be reset after the reconnection conditions are fulfilled.

NOTE 1 For example, the interconnecting circuit breaker of the grid-forming unit, on which the loss of mains protection acts, may also be triggered simultaneously.

The requirement relates to the voltage at the terminals of the grid-forming unit on the low-voltage side of the unit transformer.

NOTE 2 This may refer to the voltages (phase-to-earth/phase-to-phase voltage or conductor-to-conductor) in abc or space vector coordinates. The implementation of this requirement is not specified.

Switching off may also occur even if the overvoltage lasts for a shorter period or has a lower amplitude than required.

NOTE 3 There are no requirements for staying connected to the network above the OVRT requirements. The requirement for OVRT robustness in accordance with Section 4.2.1.5 shall not be undermined.

4.2.1.7 Synchronism and angular stability

Synchronism between the internal voltage source of the grid-forming unit and the network shall be maintained continuously during operation as well as for the events relevant to the design of the unit in accordance with this FNN Guideline. This requirement only applies below residual voltages of 20 % at the terminals of the grid-forming unit according to its capability. The requirements specified in Section 4.2.1.5 remain unaffected.

NOTE 1 In quasi-steady-state operation, the dynamics with which the angle between the internal voltage source follows the mains voltage largely depends on T_A .

NOTE 2 Clause 10.5.2 of the relevant Technical Connection Rule applies to Type 2 installations in the event of control instability of the unit or the installation.

4.2.1.8 Design of the network-side converter

No additional requirements for the rated apparent current of the grid-forming unit result from the provision of inertia. It is expressly permitted to use overcurrent capability temporarily above the rated apparent current.

4.2.1.9 Response to steep frequency gradients (RoCoF)

Grid-forming units shall be able to ride through fast frequency changes at the NCP without disconnection from the network. The requirements for “ride through fast frequency changes” specified in Clause 10.2.4.3 of the relevant Technical Connection Rule apply. In addition, Section 4.2.2.7 applies for frequency measurement or RoCoF determination.

NOTE The grid-forming unit shall ride through the frequency-response curve indicated in Section 4.2.1.13 in Figure 4 without disconnecting the installation from the network.

4.2.1.10 Capability of parallel operation

Grid-forming units shall be capable of operating in parallel. In this context, capability of parallel operation means that the grid-forming unit does not exclusively have to fulfil the requirements specified here for a defined NCP, but that it is capable of maintaining stability while operating together with Type 1 PGUs, other grid-forming units, and grid-following Type 2 units (PGUs, PGSUs, storage, and CCU), while providing verifications for the specified requirements relative to a single NCP. This requirement shall be verified for suitable operating conditions with an ESCR (see Appendix A.III) of 1.0, 3.0 and 25.0 at the PGU terminals.

NOTE The capability of the grid-forming unit for operation with SCR or ESCR values approaching zero is covered by the verification of stability in virtual island network in the relevant section on verifications.

4.2.1.11 Damping of power-frequency-oscillations

The power-frequency-oscillations caused by the continuous synchronisation (exchange of synchronising power) of the grid-forming unit with the electrical network at the NCP shall be damped by the grid-forming unit over the entire frequency range between 0.05 Hz and 10 Hz. The grid-forming unit shall have a damping capability which, based on the evaluation of its electrical power, allows it to contribute to the damping of power deviations regardless of its frequency, even if the angle of its internal voltage source remains virtually unchanged. The damping ratio shall be a minimum of 0.5 without taking into account the influence of the PCNB (see Section 4.2.2). The grid-forming unit shall comply with the damping requirements at its terminals with an SCR value equal to or greater than 3. The PCNB shall always have a positive impact on the damping ratio of the power-frequency-oscillations.

NOTE The damping behaviour relates to the ratio of influence of the power synchronisation control of the unit in its fundamental oscillation power.

The permanent provision of synchronisation power or damping power as a response to oscillations occurring on the network-side is specified for grid-forming units only within the limitations of the mechanical structures of the PGU, which shall not be critically excited by the occurring active power-oscillations.

4.2.1.12 Specifications for the start-up time constant

Different values of T_A required for a grid-forming unit in operation shall be indicated and used in all required verifications.

For grid-forming units offering a direction-dependent inertia, the start-up time constant for positive inertia $T_A = T_{A,pos}$ or a start-up time constant for negative inertia $T_A = T_{A,neg}$ shall be taken into account. The resulting T_A shall be maintained in all operating ranges as long as no permissible limitations apply in accordance with Section 4.2.1.13. Grid-forming units offering both positive and negative inertia shall be designed to be symmetric regarding the start-up time constants with $T_A = T_{A,pos} = T_{A,neg}$.

A steady-state reduction (throttling) of the primary energy input may use this power reserve for positive inertia is permissible.

NOTE 1 As long as Section 4.2.1.13 does not specify any permissible limitations, the relationship $T_A \cdot d\omega/dt = p_{gen} - p_{actual} - p_D$ applies, where p_{gen} corresponds to the power generated on the primary side, p_{actual} corresponds to the electrical power output and p_D corresponds to the damping power.

The range of the active power operating points in which the inertia may be fully provided shall be stated.

NOTE 2 This working range is used to determine the availability for the inertia market.

NOTE 3 When providing inertia, operating points with reverse power are permissible for grid-forming PGUs and operating points with active power reversal are permissible for grid-forming PGSUs or storage.

4.2.1.13 Requirements for inertia power and inertia energy

The grid-forming unit shall comply with requirements specified in Section 4.2.1.4 (Continuous voltage control), Section 4.2.1.5 (OVRT/UVRT robustness), and Section 4.2.2 (Behaviour in the event of overfrequency or underfrequency) as well as follow the reference frequency profile at the NCP indicated in Figure 4 in a stable manner where the start-up time constant T_A shall be verified to be maintained at all times in accordance with the sections mentioned above.

The grid-forming unit may temporarily deviate from the effective T_A in the following conditions:

- a) if the current limitation function is active when the design limits of the converter are reached,
- b) if the requirements for voltage control or FRT, PCNB, and the reference frequency-response curve are fulfilled, and the inertia energy would be required in operating conditions beyond these requirements,
- c) if an angle limiting function is enabled to ensure stability (staying connected to the network, transient stability).

Curve (a) shows the reference frequency-response in which applies to the market-based procurement of negative inertia. Curve (b), also in Figure 4, applies to the market-based procurement of positive inertia with an SCR of 3 at the NCP⁶. In both cases, the respective T_A shall be maintained. For the market-based procurement of asymmetric inertia, the PGU shall operate within the curve in the non-procured direction, whereby the requirement to maintain the T_A only applies according to capability. For the market-based

⁶ Upon reaching a frequency maximum or minimum, inertia shall also be provided in the opposite direction with the corresponding start-up time constant to counter the frequency drop or frequency rise in the same way.

procurement of symmetric inertia, curves (a) and (b) shall both be followed in the same way while maintaining the T_A .

NOTE 1 The energy required to provide inertia may be provided through other means other than a dedicated storage. Instead, existing storage, braking resistors or other control functions may be used to avoid the need for additional storage.

In case of events that would lead to the demand for inertia capacity or energy exceeding the design specifications as shown in Figure 4, the unit may temporary deviate from the specified T_A .

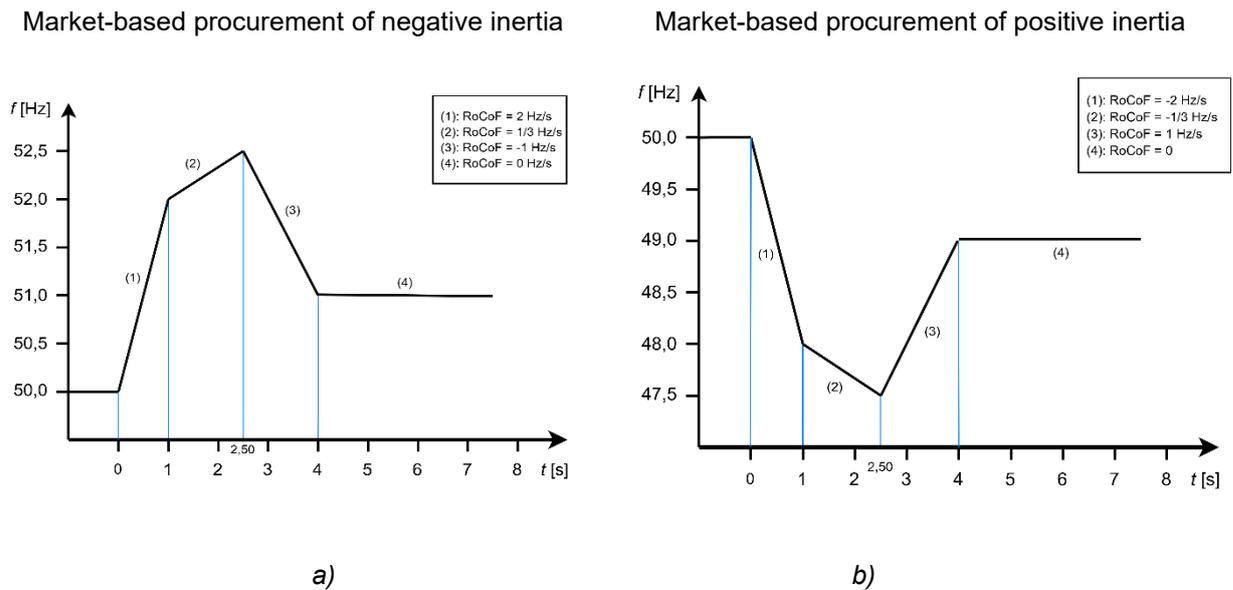


Figure 4 - Reference frequency profiles for the verification of inertia power and energy

NOTE 2 Based on the frequency fluctuations in normal operation (in the frequency range ± 50 mHz), the provision of asymmetric inertia may, due to its active principle, lead to active power losses. This should be taken into account in the design of the control system.

After providing inertia energy, the grid-forming unit may compensate for the energy of the internal storage by drawing energy from the grid. In that case, the following applies to installations providing asymmetric inertia:

- After the provision of positive inertia, the energy input of the internal storage shall not exceed 1.5 times the energy output.
- After the provision of negative inertia, the energy output of the internal storage shall not exceed 1.5 times the energy input.

NOTE 3 When a wind power plant operates at its Maximum Power Point (MPP), the provision of positive inertia causes the system to approach an operating point which subsequently leads to a temporary reduction of the feed-in power.

4.2.2 Requirements for the response to overfrequency and underfrequency

4.2.2.1 General information

All grid-forming units shall participate in the PCNB when the network frequency rises above or drops below the frequency range of 50 Hz \pm 200 mHz.

NOTE 1 Such an event, which causes the system to operate outside the frequency range of 50 Hz \pm 200 mHz, may occur when a large power imbalance is not compensated in a steady state manner by the market-based primary and secondary controls. This frequency range may also be temporarily exceeded due to the limited dynamic capabilities of the market-based primary and secondary controls.

Participation in the PCNB may be subject to limitations depending on the generation technology.

NOTE 2 Limitations arise especially from limited actuating speeds (active power gradients) exceeding a setting amplitude specified for a specific installation.

There are differences in the unlimited and the limited setting range of the actuating speed of the PCNB. The unlimited and the limited setting ranges of the actuating speed are different for each technology based on the parameters in Table 10 and Table 11. Within the respective type-specific active power setting ranges, the unlimited actuating speed range specified in Table 10 refers to the respective steady state applicable at the time of the PCNB requirement. Any additional limitations within designated active power setting ranges apply.

4.2.2.2 Requirements for the PCNB

Grid-forming units shall always be capable of operating in a virtual island network in a stable manner. The following requirements apply to the PCNB:

Droop and damping in the area of the PCNB

- 1) The effective PCNB within the frequency ranges between 47.5 Hz and 49.8 Hz or between 50.2 Hz and 51.5 Hz (temporarily up to 52.5 Hz) shall be designed as a proportional frequency control. The following shall be taken into account for the droop settings:

Grid-forming PGUs

- The droop of the speed or frequency-dependent active power feed-in shall be adjustable between 2.0 % and 12.0 %.
- A droop of 5.0 % shall be specified as a default value for grid-forming PGUs.
- P_{mom} shall be used as the reference quantity P_{ref} for determining the droop for Type 2 PGUs in the overfrequency range and P_{Emax} for the underfrequency range.

P_{mom} corresponds to the active power at the terminals of the PGU at the time of exceeding 50.2 Hz or at the time of falling below 49.8 Hz, as a moving average over a period of 10 s.

Grid-forming PGSUs and Storage

- A droop of 2.0 % in the overfrequency range and of 0.2 % in the underfrequency range shall be specified as the minimum value for PGSUs and storage.
- A droop of 12.0 % in the overfrequency range and of 5.0 % in the underfrequency range shall be specified as the maximum value for PGSUs and storage.
- A droop of 5.0 % in the overfrequency range and of 1.6 % in the underfrequency range shall be specified as the default value for PGSUs and storage.
- The droop of the frequency-dependent active power feed-in shall be adjustable between the respective minimum and maximum values for the overfrequency and the underfrequency ranges.
- P_{Emax} shall be used as the reference quantity P_{ref} for determining the droop for PGSUs and storage.

Structure and parametrisation of the speed or frequency control

The structure and parametrisation of the frequency control shall comply with the following conditions:

- The frequency control shall have a damping ratio of $D \geq 0.2$ for Type 2 PGUs and of $D \geq 0.06$ for PGSUs and storage within the unlimited setting ranges specified in Table 10 between minimum and maximum loading conditions.
- The frequency control for grid-forming units in the closed-loop control system shall be designed so that it complies with damping requirements.
- Deviations from a controller structure with purely proportional effects are permissible only when required by the specified power-related droop settings to maintain the required damping.

NOTE 1 Deviations from a controller structure with purely proportional effects may be implemented through a transient droop acting temporarily or other controller structures corresponding in their effect solely to the frequency control. Point 2 applies in this context.

These requirements apply without any limitation only to the over-frequency range (between 50.2 Hz and 51.5 Hz; transient up to 52.5 Hz) for grid-forming PGUs with supply-dependent primary energy. This requirement applies to the underfrequency range only if an active power reduction of lower priority existed previously.

- 2) If the required damping ratio (in accordance with Appendix B) for the power-related droop within the required setting range (specified in Point 1) may only be achieved using an additional transient droop or supplementary controller structures, then a suitable additional control shall be used to ensure that the maximum possible actuating speed of the actuator or process as a whole is applied in operating states where the frequency gradient exceeds a value of ± 0.5 Hz/s averaged over 400 ms.

Response to overfrequency and underfrequency in the area of the PCNB

- 3) The requirements for the unlimited setting range specified in Table 10 apply to the PCNB. The actuating speeds in the limited setting range specified in Table 11. Actuating speeds higher than those specified in Table 11 are permissible and shall be indicated.
- 4) In the virtual island network, grid-forming PGSUs and storage shall be capable of handling a spontaneous transition from charging to discharging mode and vice versa by at least 100 % (in accordance with Table 10) based on a setpoint step change.
- 5) In virtual island network operation, grid-forming units shall fulfil the following requirements in the event of spontaneous load disconnection (**overfrequency event**):

Grid-forming PGUs:

- A Type 2 PGU shall handle spontaneous load disconnection of 45 % of P_{mom} as long as it does not fall below the lower limit of the setting range specified in Table 11.
- Grid-forming PGUs shall be capable of reducing the active power from the power output value prior to the entry of load disconnection until reaching the minimum or partial load within the temporarily permissible speed or frequency range of 52.5 Hz.
- It shall be possible to reduce the active power output until reaching the technical minimum power. Any further reduction to a value below the technical minimum power is permissible only if the grid-forming PGU maintains a stable operation in compliance with this section. The technical minimum power depends on the respective technology (see Table 10 and Table 11). Values of the minimum power possible technically which are lower than those indicated in Table 10 and Table 11 are permissible.

Grid-forming PGSUs and storage:

- In discharging operation, PGSUs and storage shall be capable of handling a spontaneous reduction of the load from nominal power to any partial load, including power reversal.

- In discharge operation, PGSUs and storage shall be capable of reducing the active power output until a partial load is reached, which corresponds to a permanently permissible frequency value of 51.5 Hz.
- 6) In virtual island network operation, grid-forming units shall fulfil the following requirements in the event of spontaneous power demand (power increase or **underfrequency event**) caused by the network frequency dropping into the range of the PCNB:
- Grid-forming PGUs shall comply with the requirements specified in Table 10 , grid-forming PGUs shall increase their power output within the unlimited as well as in the limited setting range specified in Table 11 . This applies under the assumption that a corresponding power reserve had been planned for operational purposes.
 - In charging operation, grid-forming PGSUs and storage shall be capable of handling a spontaneous reduction of the discharge from the nominal value to any partial load, including power reversal.
 - In charging operation, grid-forming PGSUs and storage shall be capable of reducing the active power input until a partial load is reached, which corresponds to a temporarily permissible frequency value of 48.5 Hz.
- 7) The threshold values for PCNB activation shall be adjustable within the ranges between 49.5 Hz and 49.8 Hz or between 50.2 Hz and 50.5 Hz in steps of 10 mHz. 49.8 Hz or 50.2 Hz shall be used if the network operator does not provide specific values.
- 8) The maximum insensitiveness of the frequency-dependent active power adjustment is ± 10 mHz around the measured frequency value.
- 9) The transition to PCNB as well as the crossing(s) of the threshold values shall be conducted without bumps by the power actuator.
- 10) Grid-forming units shall not disconnect from the network within the frequency range between 47.5 Hz and 51.5 Hz.
- 11) Grid-forming units may automatically disconnect from the network at network frequencies below 47.5 Hz.
- 12) At network frequencies greater than 51.5 Hz, grid-forming units shall remain connected to the network for at least 10 s and may automatically disconnect from the network above 52.5 Hz.

4.2.2.3 Requirements subject to technology-specific restrictions

Characteristic values dependant on the technology of the installation of the active power output within the PCNB shall be used according to Table 10 and Table 11 . Additional limitations may result from technical restrictions. In these cases, the requirements in the following paragraph apply.

In the case of internal combustion engines with carburetion there is a significant dead-time behaviour. This is also caused by the considerable amount of fuel in the path between butterfly valve(s) and engine cylinders. During the transition to virtual island network operation with spontaneous load disconnection, starting from $P_{b \text{ inst}}$ and reaching minimum power, the specification of a maximum transient frequency of 52.5 Hz in the area of the PCNB may therefore not be fulfilled. Therefore, spontaneous load disconnection may be limited to ensure that the maximum frequency of 52.5 Hz is not exceeded. The load disconnection shall be at least 5 % $P_{b \text{ inst}}$. Alternatively, during the transition to the virtual island network operation as well as during operation in the virtual island network, a maximum transient frequency may be greater than 52.5 Hz for load disconnection according to Table 10 . It considers the start from an operating point between $P_{b \text{ inst}}$ and minimum load or temporary minimum power, depending on the capability of the installation.

4.2.2.4 Requirements for frequency deviations in the dynamic short-term range

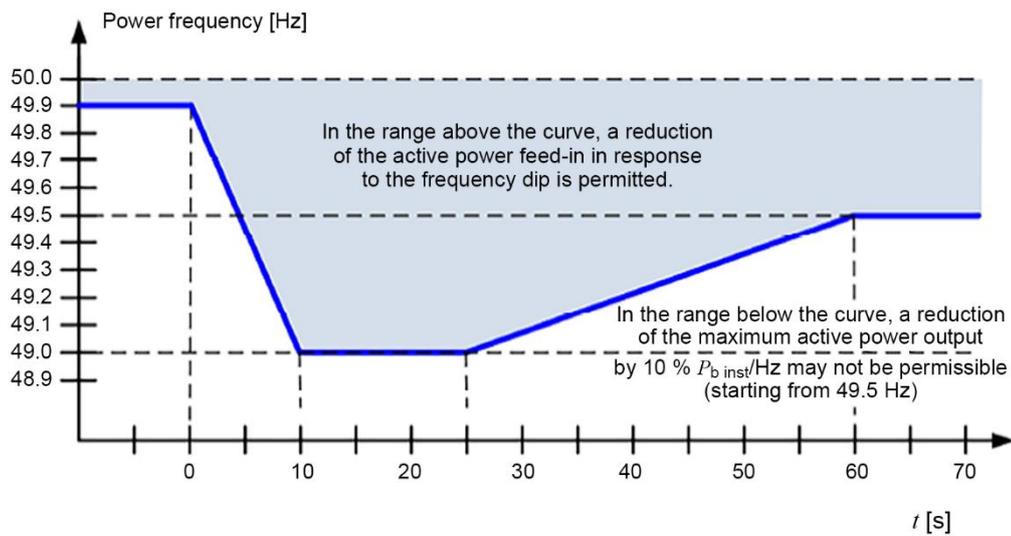


Figure 5 - Requirement for the output power of the PGM in the dynamic short-term range

Figure 5 shows the requirement for the output power of the grid-forming PGU for a possible form of dynamic frequency response to a disturbance of active power balancing. A grid-forming PGU shall not reduce its specified active power output at frequency-response curves between 50 Hz and the blue curve.

4.2.2.5 End of critical network state and return to normal operation

Even if the frequency tends to resume to a value within the range of the market-based primary control of usually $50.0 \text{ Hz} \pm 200 \text{ mHz}$ following a deviation in the range of the PCNB, it shall still be assumed that the network is at risk.

The value of P_{mom} shall be updated only after the network frequency has remained in the tolerance band of $50.0 \text{ Hz} \pm 200 \text{ mHz}$ for an uninterrupted period of at least 30 s.

Adjustment of the active power setpoint to the primary energy supply, which may have increased in the meantime, shall be limited to a gradient not exceeding $10 \% P_{\text{b inst}} / \text{min}$ (except for the provision of operating reserve). Normal network operation is restored only if the network frequency was within the tolerance band of $50.0 \text{ Hz} \pm 100 \text{ mHz}$ for an uninterrupted period of 10 min. Limitation of gradients for the adjustment of the active power setpoint is then no longer required.

The gradient for potential power limitations for the duration of the critical network state shall be specified in accordance with the prioritisation rules specified in Section 4.2.3.

4.2.2.6 Parametrisation of the deadband of the PCNB

If there is a connection to the telecontrol system of a network operator, the grid-forming unit shall have a signal interface to allow the network operator to deactivate (setpoint = 0 mHz) or reactivate the deadband of the PCNB of the grid-forming unit during a critical network state⁷ (e.g. during network restoration or partial network operation).

Transition to the deactivated or activated state shall be conducted as fast as possible and without bumps.

⁷ In addition to this, specifications for market-based primary control are required. It is proposed that the market-based primary control be deactivated when the deadband is reduced. Irrespective of this, the market-based primary control shall generally be operated based on a local frequency measurement or speed measurement at the PGU.

NOTE For the deactivation of the deadband to be implemented, Table C.2 in VDE-AR-N 4110:2023-09, Appendix C.5 shall be updated in accordance with Appendix B.II of this FNN Guideline.

4.2.2.7 Note on determining electrical frequency and RoCoF

The electrical frequency at the terminals of the PGU, the PGSU or storage shall be determined to implement the PCNB for grid-forming units unless the frequency generated internally with inertia is used. The FNN Guideline „Ermittlung und Bewertung der Frequenz in Energieversorgungsnetzen“ (EN: Determination and evaluation of the frequency in energy supply networks) describes adequate measurement procedures typically available. In contrast to the distinctions made in this guideline in the application areas of protection technology and frequency control („Fahren auf der Kennlinie“ [Following the characteristic curve]), a sliding measurement window of 3 to 5 periods with a corresponding evaluation method may be used in conjunction with the frequency determination to implement the PCNB (for an example see the aforementioned FNN Guideline).

A frequency determination over a sliding measurement window of 3 to 5 periods shall be used as basis for the provision of verification with the requirements based on the frequency or RoCoF information (e.g. PCNB), unless a different definition is explicitly specified. The measured values of several consecutive frequency measurements shall be used to determine the RoCoF.

4.2.3 Prioritisation of the requirements

During operation of the grid-forming unit, situations may occur on the network where the requirements of this FNN Guideline or of the Technical Connection Rules may not be fulfilled simultaneously without conflict. In those situations, the requirements of the Technical Connection Rules have priority. They still shall be updated with the requirements for grid-forming behaviour specified in this FNN Guideline. The following requirements deviating from the prioritisation requirements in Clause 8.1 of VDE-AR-N 4130, apply⁸:

- 1 *Avoidance or limitation of damages to the grid-forming unit and electrical equipment.*
- 2 *Compliance with the specifications regarding automation systems specified in Clause 10.2.4.2 (VDE-AR-N 4130)*
- 3 *Voltage source behaviour⁹, including synchronicity, angular stability, damping of power-frequency-oscillations, and damping behaviour for higher frequencies specified in Section 4.2.1*
- 4 *Requirements for the start-up time constant specified in Sections 4.2.1.12 and 4.2.1.13*
- 5 *Compliance with the requirements for the response to overfrequency and underfrequency specified in Section 4.2.2*
- 6 *Frequency control (operating reserve) specified in Clauses 10.5.3 and 10.5.4 (VDE-AR-N 4130) outside the PCNB*
- 7 *Specifications for the network security management of the network operator specified in Clause 10.2.4.2 (VDE-AR-N 4130)*
- 8 *Maximum active power gradients when resuming normal operation specified in Section 4.2.2.5 and other active power gradients*
- 9 *Compliance with the requirements for the reactive power operating mode for steady-state voltage stability specified in Section 4.2.1.3*
- 10 *Specifications of operational setpoints for active power and reactive power*

The following requirements deviating from the prioritisation requirements in Clause 8.1 of VDE-AR-N 4110 and VDE-AR-N 4120, apply:

- 1 *Avoidance or limitation of damages to the grid-forming unit, installations and electrical equipment for which the respective protection equipment specified in Clause 6.3.4 (VDE-AR-N 4110) or Clause 6.3.3 (VDE-AR-N 4120) and Clause 10.3 (VDE-AR-N 4110 and 4120), is the main protection*

⁸ Existing passages in accordance with the Technical Connection Rule are indicated in italics.

⁹ The voltage source behaviour replaces the requirement for dynamic network stability previously specified in the Technical Connection Rules. In addition to that, requirements for robustness are no longer included in the prioritisation list.

- 2 Voltage source behaviour⁹, including synchronicity, angular stability, damping of power-frequency-oscillations, and damping behaviour for higher frequencies specified in Section 4.2.1
- 3 Requirements for the start-up time constant specified in Sections 4.2.1.12 and 4.2.1.13
- 4 *Specifications for the network security management of the network operator specified in Clause 10.2.4.2 and the requirements for $P_{AV,E}$ of the relevant Technical Connection Rule*
- 5 *Compliance with the requirements for the response to overfrequency and underfrequency specified in Section 4.2.2*
- 6 *Compliance with the requirements for the reactive power operating mode for steady-state voltage stability specified in Section 4.2.1.3*
- 7 *Frequency control (operating reserve) outside the PCNB*
- 8 Maximum active power gradients when resuming normal operation specified in Section 4.2.2.5 and other active power gradients
- 9 Specifications of operational setpoints for active power and reactive power

5 Verification of electrical properties for grid-forming units

5.1 Principles of the verification process

The verifications described below for grid-forming units may be applied to:

- Units with existing unit certificates that are upgraded to grid-forming units through a corresponding addition to the unit certificate
- Grid-forming units for which a new unit certificate is created
- Grid-forming units that provide proof of compliance in accordance with this FNN Guideline, in addition to the relevant Technical Connection Rule, using the individual verification procedure (system certificate C or C2)

In the case of an addition to an existing unit certificate, the verifications described below shall be provided by an accredited certification body as a supplement to an existing unit certificate in accordance with VDE-AR-N 4110, VDE-AR-N 4120 and VDE-AR-N 4130. In this case, the verifications required in accordance with Clause 11 of the relevant Technical Connection Rules is partially replaced by corresponding verifications in this FNN Guideline. This information can be found in Section 2 Table 1.

The verifications of the relevant Technical Connection Rule, which are replaced in accordance with Section 2 Table 1, may be omitted for new unit certificates.

A supplement to an existing system certificate in accordance with VDE-AR-N 4110, VDE-AR-N 4120 and VDE-AR-N 4130 shall be provided in accordance with the relevant Technical Connection Rule. The verifications in accordance with Clause 11 of the relevant Technical Connection Rule are partially replaced by the corresponding verifications in Section 2 Table 1 (for grid-forming capabilities). The verifications for the minimum technical requirements, which are replaced in accordance with Section 2 Table 1, may be omitted for new system certificates.

NOTE Table 1 will be updated with the new version of the FNN Guideline regarding the requirements for system certification.

A complete verification according to this FNN Guideline is considered provided by means of a system certificate A or B for grid-forming units that require a system certificate in accordance with NELEV. The statement of compliance may be submitted subsequently within the deadlines specified in the applicable Technical Connection Rule. A system certificate C or C2 alone is not sufficient verification in accordance with this FNN Guideline. The verification is only provided upon submission of the extended statement of compliance.

The verifications in this FNN Guideline contain only points that are not yet included in the FGW TR8, TR4 and TR3 guidelines for verifying the properties from the FNN Guideline "Technical requirements for grid-forming capabilities including the provision of inertia". All other points shall be conducted in accordance with FGW guidelines.

The following principles apply regarding measurement, modelling, model validation and certification:

- Certification of grid-forming units and components as well as the preparation of statements of compliance shall be conducted by an accredited certification body in accordance with DIN EN ISO/IEC 17065.
- Details on the design of the verification procedure and on the scope of evaluation are specified in FGW TR8¹⁰.
- Details on the design of the measurement-based verifications as well as the documentation of the measurement results are described in this FNN Guideline as well as, in addition, in FGW TR3¹⁰. Any additions to the FGW TR3 shall neither undermine nor specify more stringent requirements laid out in this Guideline, which serves as a supplement to the relevant Technical Connection Rule.

¹⁰ Generally, the current version of the FGW TR3, TR4 or TR8 guidelines may apply.

- Details on the design of the modelling, simulation and model validation are described in this FNN Guideline and supplemented with the FGW TR4¹⁰. Any additions to the FGW TR4 guideline shall neither undermine nor specify more stringent requirements laid out in this Guideline, which serves as a supplement to the applicable Technical Connection Rule.

The following requirements apply to a manufacturer's declaration within the meaning of this FNN Guideline:

A manufacturer's declaration shall be signed and justified so that the party providing the verifications is able to perform their own technically comprehensible verification regarding confirming compliance with the requirements. It follows from this:

- Clear reference to the company issuing the certificate
- Stamp and signature of an authorised / responsible person
- Clear reference to the certified product (clear designation as stated in the planned certificate)
- Comprehensible technical justification or verification with the requirement (reference to further technical documents is possible)

5.2 Prototyping requirement for the certification of grid-forming units

5.2.1 General information

For grid-forming units apply the requirements of Section 5.2.2 of this FNN Guideline, which differ from the requirements for prototype requirements laid out in Clause 12 of the relevant Technical Connection Rule. A prototype confirmation shall be issued for grid-forming units in combination with a qualified opinion.

NOTE Due to the new technology of grid-forming units, and particularly the possibility of participating in the inertia market, the requirements for issuing a prototype confirmation for grid-forming units are stricter than the requirements in Clause 12 of the relevant Technical Connection Rule.

Grid-forming Type 1 units for which the electrical properties are verified as part of the individual verification procedure may also be put into operation based on an additional assessment of a qualified opinion in which the requirements laid out in this FNN Guideline are verified.

5.2.2 Prototyping requirement for grid-forming units (transitional rule)

A prototype within the meaning of this FNN Guideline is the first grid-forming unit (Type 1 or Type 2), for which the requirements of this FNN Guideline shall be implemented for the first time, as well as for all further grid-forming units of that specific type (Type 1 or Type 2) that are put into operation within two years of the publication of Version 2.0 of this FNN Guideline from May 2025. The period of validity of the prototype certification for grid-forming units is limited to three years after publication of this FNN Guideline in version 2.0 of May 2025, regardless of the date of their commissioning.

References to this FNN Guideline within this Section refer to Version 2.0 from May 2025.

For the prototype of a grid-forming unit apply the requirements of this FNN Guideline. Within two years of publication of this FNN Guideline, a prototype confirmation of a grid-forming unit in accordance with this FNN Guideline, instead of a unit certificate, may be sufficient if a certification body accredited in accordance with DIN EN ISO/IEC 17065 (for the relevant Technical Connection Rule) confirms compliance with the requirements based on a qualified opinion. The measurements required for the qualified opinion shall be performed by a testing institute accredited in accordance with DIN EN ISO/IEC 17025 (for FGW TR3, Revision 26) in compliance with the verification procedure described in this FNN Guideline. Based on the qualified opinion, the certification body demonstrate in a comprehensible manner clearly state in the prototype confirmation whether the prototype can fulfil the requirements of this FNN Guideline. Furthermore, the certification body shall state in the prototype confirmation whether the requirements for the provision of verification specified in this FNN Guideline were met during the measurements.

In addition, the behaviour of a Type 2 grid-forming unit shall be monitored using a fault recorder for the period of validity of the prototype confirmation by evaluating measured currents and voltages at its terminals. In the

case of several grid-forming units of the same type (Type 1 or Type 2) within an installation, the fault recorder shall be provided for any unit of this type within the installation. Connection of the fault recorder to the network operator's control centre is not required. The party owning the fault recorder shall make the recorded data available to the certification body twice a quarter and then every six months, as well as to the network operator on request. The data recorded by the fault recorder shall be evaluated by the certification body, checked for traceability and verified regarding the requirements of this FNN Guideline.

NOTE If no data is recorded by the fault recorder, this shall be documented and the certification body shall be informed.

The certification body shall also inform the network operator if the recordings of the disturbance recorder are not compliant. The network operator shall then be informed by the plant operator (or by the party performing the certification on request) and, in the case of a connection in a distribution network, the responsible transmission system operator shall be informed by the plant operator (or by the certification body on request). The network operator shall grant a reasonable period of time for rectification in case of non-compliance. Otherwise, the monitoring period within the scope of the prototype approval by the certification body shall end no later than upon issuance of the declaration of compliance. At the discretion of the grid operator, the monitoring period may be terminated earlier after a sufficient number of representative grid events have occurred, each having received a positive compliance assessment by the certification body.

The general requirements of Appendix F of VDE-AR-N 4120 apply to the fault recorder of the Type 2 grid-forming unit. The records shall be made available in the comtrade format in accordance with DIN EN 60255-24 (VDE 0435-3040). In addition to these general requirements, the following extended requirements apply:

- Sampling frequency ≥ 10 kHz.
- Calibration, starting from the secondary side of the transducers, by a calibration or test laboratory accredited to DIN EN ISO/IEC 17025 with corresponding authorisation.

The fault recorder shall continuously detect the following signals:

- Raw values of currents and voltages with sampling frequency.
- Instantaneous values of current, voltage, active and reactive power in the $\alpha\beta$ coordinate system. The instantaneous values of the measured currents and voltages are to be filtered with a moving arithmetic average over 5 ms.
- Fundamental oscillation of the vectors in the positive, negative and zero sequences with 20 ms filter (moving arithmetic averaging over one period).
- Electrical frequency of the voltage with continuous frequency determination over a 100 ms window.

The initiation of a recording of the signals shall be configured so that significant events can be recorded for the grid-forming characteristics. These include in particular:

- Step changes in the voltage value (see definition of a sudden change in voltage in Appendix B.2 in VDE-AR-N 4110 as well as VDE-AR-N 4120, or Appendix B.1 in VDE-AR-N 4130). The threshold value for starting a recording shall be adjustable between 2.5 % and 25 %.
- Step change of the voltage angle. The threshold value for starting a recording shall be adjustable between 2.5 degrees and 25 degrees.
- Fast frequency changes. The threshold value for starting the recording is 50 mHz/s in a sliding 0.5 s time window.

For these events, the instantaneous values shall be recorded with a lead time of up to 10 s and a follow-up time of 30 s. The recordings shall be kept for a period of at least 6 months unless requested by the network operator. Upon request of the network operator, the certification body shall check whether the requirements of this FNN Guideline are fulfilled for the recorded events. If the measured values recorded by the fault recorder prove a critical violation of the requirements in accordance with this FNN Guideline, the procedure

in accordance with Clause 8.8 of the relevant Technical Connection Rules applies while still taking this FNN Guideline into account.

A unit certificate in accordance with this FNN Guideline shall be provided no later than after the deadline mentioned above has expired.

Otherwise, Clause 12 of the relevant Technical Connection Rules from paragraph 8 "NOTE 2 ..." applies (including for the resubmission of the system certificate and the statement of compliance).

5.2.3 Assessment of the requirements of the FNN Guideline as part of the individual verification procedure

This section applies to Type 1 grid-forming units for which the verification of electrotechnical properties is considered provided as part of the individual verification procedure. For these units, the provision of verification for the requirements specified in this FNN Guideline may be performed based on a qualified opinion prepared as part of the individual verification procedure within two years of publication of Version 2.0 of this FNN Guideline in May 2025. The qualified opinion shall be issued by a testing institute accredited in accordance with DIN EN ISO/IEC 17065 (for the relevant Technical Connection Rule) and shall confirm compliance with the requirements described in this FNN Guideline. The measurements required for the qualified opinion shall be performed by a testing institute accredited in accordance with DIN EN ISO/IEC 17025 (for FGW TR3, Revision 26) in compliance with the verification procedure described in this FNN Guideline. Based on the qualified opinion, the certification body shall demonstrate in a comprehensible manner whether the Type 1 grid-forming unit is able to fulfil the requirements of this FNN Guideline. Furthermore, the certification body shall demonstrate whether the requirements for the verification procedure described in this FNN Guideline were met during the measurement.

In addition, the behaviour of the Type 1 grid-forming unit shall be monitored by evaluating measured currents and voltages at its terminals using a fault recorder in accordance with the specifications in Clause 11.6.5 of VDE-AR-N 4120, taking into account the relevant Technical Connection Rule.

A system certificate C in accordance with this FNN Guideline shall be provided for new or retrofitted Type 1 grid-forming units no later than after the deadline mentioned above has expired.

5.3 Transferring measurements to other units

The measurement results obtained for the grid-forming unit may be transferred in full or in part to other grid-forming units provided that:

- 1) the design and the control technology relevant to the electrical properties including the software used in these grid-forming units is technically equivalent; and
- 2) the results for the smallest and largest power variants are available or, alternatively, the rated apparent power of the grid-forming unit to be certified is between $1/\sqrt{10}$ times and $\sqrt{10}$ times (for Type 1 units) or between $1/\sqrt{10}$ times and twice (for Type 2 units) of the rated apparent power of the measured grid-forming unit.
- 3) for the verifications of quasi-steady-state operation and steady-state voltage stability (...), the manufacturer's specifications mentioned under Point 2 may be extended, if the concept of the grid-forming unit as well as the components used are technically equivalent. Under these prerequisites, the transfer of measurements for Type 2 grid-forming units of rated apparent power from 100 kVA to 10 MVA are permitted.

5.4 Type 1 grid-forming units

5.4.1 General information

If the additional flywheel mass can be optionally decoupled from the generator, all verifications described in this FNN Guideline as well as the FRT capability shall be performed in accordance with the relevant Technical Connection Rule with and without the additional flywheel mass. Otherwise, the additional flywheel mass shall be considered in all verifications.

NOTE Results of the measurement of a Type 1 grid-forming unit may be transferred in total or in part to other Type 1 grid-forming units in accordance with Clause 11 of the relevant Technical Connection Rule.

5.4.2 Requirements for simulation models and model accuracy

For Type 2 grid-forming units, FGW TR4, Revision 10, Chapter E.5.2 shall be consulted regarding the requirements for simulation models and model accuracies.

5.4.3 Verification of the response to steep frequency gradients (RoCoF)(Section 4.1.1.1)

The requirement, that PGUs shall be able to ride through fast frequency changes in accordance with Section 4.1.1.1 without disconnection from the network shall be verified in form of a manufacturer declaration in accordance with Clause 11.2.8 of the relevant Technical Connection Rule.

Note for TR8:

A verification is considered provided if the manufacturer's declaration proves that the unit is able to ride through the RoCoF values required in accordance with Section 4.1.1.1 without disconnecting from the network, otherwise the framework conditions for compliance with the requirements shall be indicated in the certificate.

5.4.4 Verifications of the start-up time constant (Section 4.1.1.2)

5.4.4.1 General information

The verification of the mass moments of inertia or start-up time constants of the Type 1 grid-forming unit are required for:

- The generator with an excitation device through a manufacturer's declaration in accordance with Section 5.4.4.2.
- The additional flywheel mass, including the generator-side clutch if applicable, through a manufacturer's declaration in accordance with Section 5.4.4.2.
- The complete shaft train (overall system consisting of generator, turbines, additional flywheel mass, etc.) through measurement-based verification in accordance with Section 5.4.4.3.

5.4.4.2 Verification of the start-up time constants of the generator and of the additional flywheel mass

Aim

The mass moments of inertia or start-up time constants for the alternator as well as the additional flywheel mass shall be determined and stated by the manufacturer in the manufacturer's declaration.

Procedures

The mass inertia of the additional flywheel mass is specified by the manufacturer of the PGU in a calculable and comprehensible manner based on design and material parameters.

The mass inertia of the generator is specified by the manufacturer in a comprehensible manner based on design data. Alternatively, the information in the manufacturer's declaration on the mass inertia of the generator may be determined through a run-down test performed by the manufacturer in accordance with the relevant machine standards (e.g. IEC 60034-4-1). The mass inertia values of the excitation device and other parts of the shaft train that are permanently coupled in phase shifter operation may be included in this verification.

Presentation in the manufacturer's declaration

The manufacturer's declaration shall include a table showing the mass inertia values or start-up time constants according to the manufacturer's specifications, as well as values determined using the appropriate method for:

- The generator with an excitation device.
- The additional flywheel mass, including the generator-side clutch, if applicable.

The mass moments of inertia shall be specified in kgm^2 and the start-up time constants T_A in seconds. The respective rated speeds and the number of pole pairs for the generator shall also be specified. The apparent power of the generator shall be used as the reference value for the start-up time constant.

The manufacturer's declaration shall describe the procedure for determining the mass inertia or start-up time constants of the generator, the $x-t$ diagram associated with the procedure (only available for a run-down test) as well as the determined value of the mass inertia or start-up time constants. It shall be stated which components (e.g. permanently coupled parts of the generator shaft train) were included in the determination of the start-up time constants.

Note for TR8:

The verification of the mass inertia values or start-up time constants is considered provided when the information from the manufacturer and the measured or calculated values are indicated in the manufacturer's declaration and are technically comprehensible for:

- The generator with an excitation device.
- The additional flywheel mass, including the generator-side clutch, if applicable.

If the procedures indicated in the manufacturer's declaration refer to valid standards, the corresponding procedure shall be checked by the certifier for compliance with the standards.

5.4.4.3 Verification of the start-up time constants of the complete shaft train

5.4.4.3.1 Aim of the measurement

The aim of the measurement is to determine the mass inertia or the start-up time constant T_A of the shaft train (of the overall system) and to verify the manufacturer's specifications using the measured values.

5.4.4.3.2 Measurement procedure

The measurement shall be performed in accordance with FGW TR 3, Revision 26, Chapter 7.2.2.3.1.2.

5.4.4.3.3 Evaluation

The evaluation shall be performed in accordance with FGW TR 3, Revision 26, Chapter 7.2.2.3.1.3.

5.4.4.3.4 Presentation in the measurement report

The presentation shall be performed in accordance with FGW TR 3, Revision 26, Chapter 7.2.2.3.1.4.

Note for TR8:

A verification of the start-up time constants of the complete shaft train (complete system consisting of generator, turbines, additional flywheel mass, etc.) is considered provided if the manufacturer's specifications and the measured value are indicated in the manufacturer's declaration. The measured value for the complete shaft train may deviate from the manufacturer's specification by a maximum of 10%.

5.4.5 Verification of the primary control based on network security

5.4.5.1 General information

The verification of primary control based on network security may be provided by means of measurement-based verification (type testing) in accordance with Section 5.4.5.2 part of unit certification or, in the case of PGUs for which unit certification is not possible or too costly, through a simulation-based verification in accordance with Section 5.4.5.3 as part of the individual verification procedure. In the individual verification procedure, test 4 in Section 5.4.5.2.2 shall be performed for verifying the insensitivity of the primary control based on network security.

All tests shall be performed with the standard settings of the structural analysis and documented in the test report.

5.4.5.2 Measurement-based verification (type test) as part of the unit certificate

5.4.5.2.1 Aim of the measurement

It shall be verified that the PGU meets the requirements for the primary control based on network security in accordance with Section 4.1.2 for frequency ranges from 50.2 Hz to 51.5 Hz (or 52.5 Hz, if applicable) or 49.8 Hz to 47.5 Hz. The effective mains primary control based on network security shall be designed with proportional speed control in accordance with the requirements of Section 4.1.2. The design of the primary control based on network security as proportional speed control shall also be confirmed in the manufacturer's declaration.

5.4.5.2.2 Measurement procedure

The test environment described below for measuring a Type 1 grid-forming unit is used to determine the ability of the test object to fulfil PCNB requirements. Four measurement-based tests are used to determine whether the test object demonstrates stability of the steady-state and dynamic control behaviour in the virtual island network operation and in parallel network operation.

Description of the test environment used for measurements

The measurements to verify the time behaviour and the associated compliance with the minimum damping requirements shall be performed on a test bench so that a defined ohmic load (load in the virtual island network) can be supplied in virtual island network operation with an open interconnecting circuit breaker (S_{Network}) to the external network. For this purpose, see also Figure 6. Alternatively, a verification on the network emulator is permissible. The switching state of the interconnecting circuit breaker (S_{Network}) shall not be signalled to the test object.

Before opening the interconnecting circuit breaker (S_{Network}) to the external network, the test object shall be operated at an operating point at $\cos \varphi \approx 1$ or $Q \approx 0$. The voltage regulation of the PGU shall be parametrised so that the load changes to be performed lead to the lowest possible transient voltage deviations and damped behaviour is guaranteed. The voltage-related self-regulation effect shall not exceed 5 % of the rated active power of the PGU in a steady-state and during the dynamic equalisation process, if possible.

NOTE 1 The load power should not change by more than 5 % during the test procedure.

For measurements that simulate the measured frequency or speed, the specified measuring points shall be approached with an accuracy of ± 10 mHz. The specified initial effective power shall maintain a tolerance of $\pm 5\%$ $P_{b \text{ inst}}$. The deviation shall be taken into account in the evaluation.

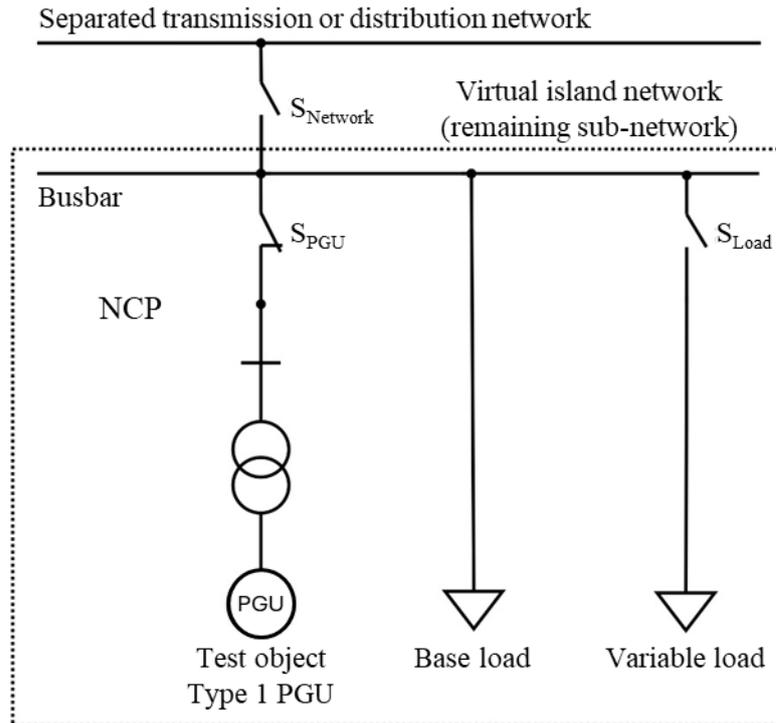


Figure 6 - Virtual island network for verifying the characteristics of a Type 1 PGU

Conducting measurements

Measurements 1 and 2 described below are each performed twice with identical settings for the test object and the test setup while measurements 3 and 4 only need to be performed once.

Measurement 1

Starting from parallel mains operation at $P_{b\ inst}$, open the interconnecting circuit breaker ($S_{Network}$). Set the load of the virtual island network to the lower limit value of the setting range specified in Table 11 to a maximum of 55 % $P_{b\ inst}$ of the test object at nominal voltage. In addition, perform the following repetitions by setting the load of the virtual island network to:

- 65 % $P_{b\ inst}$, 75 % $P_{b\ inst}$ and 85 % $P_{b\ inst}$
- $P_{Emin,E}$ while ensuring that the operating point in parallel operation is set in such a way, that the power is reduced by 45% $P_{b\ inst}$ when the interconnecting circuit breaker ($S_{Network}$) is opened.

NOTE 2 If this test has been passed in the previous repetitions, it is not required to perform it again.

In the case of internal combustion engines with carburetion, set the load of the virtual island network and the power output of the PGU in the previous parallel network operation to achieve a jump of at least 5 % $P_{b\ inst}$ during the transition to virtual island network operation. The transition to virtual island network operation takes place from a previous network parallel operation at $P_{b\ inst}$, as well as from a previous parallel operation at a partial load, which is adjusted in each case so that, during the transition to virtual island network operation, there is a load step to a remaining load in the virtual island of 65 % $P_{b\ inst}$, 75 % $P_{b\ inst}$, 85 % $P_{b\ inst}$ as well as $P_{Emin,E}$.

Measurement 2

Starting from a steady-state with technical minimum power and an open interconnecting circuit breaker (S_{Network}) to the transmission or distribution network, increase the variable load of the virtual island network in steps. Select the steps so that they correspond to the specifications in Table 10 (amplitude in the unlimited control range). Ensure that the steps of the variable load have a tolerance of 2 % $P_{b \text{ inst}}$. Select the last step so that $P_{b \text{ inst}}$ minus the specified step amplitude according to Table 10 is reached in the steady state. Reduce the variable load in the virtual island network in the corresponding steps to one step above the technical minimum power. Ensure the steady-state condition is reached before introducing a new step. The test may start at an operating point in the overfrequency range (e.g. the state that results at the end of test 1).

NOTE 3 During measurement 2, the frequency band of 50 Hz \pm 200 mHz may be traversed.

Measurement 3

Starting from a steady state with technical minimum power and an open interconnecting circuit breaker (S_{Network}) to the transmission or distribution network, simulate the measured frequency as follows:

- actual frequency + 300 mHz; actual frequency - 300 mHz
- actual frequency + 800 mHz; actual frequency - 800 mHz
- actual frequency + 1.3 Hz; actual frequency - 2 Hz.

Perform the measurements with a simulated frequency increase at an initial power of 100 % $P_{b \text{ inst}}$ and start the measurement close to the nominal mains frequency of 50 Hz. Perform the measurements with a simulated frequency reduction at an initial power corresponding to the technical minimum power.

The simulation of the frequency increase and reduction may be based on the nominal frequency of 50 Hz instead of the frequency prevailing during the measurement. In addition, the frequency increase or reduction may be specified on frequency gradients instead of frequency steps, provided that the active power actuating speeds can be verified in accordance with Table 11 .

The measurements are preferably performed in a continuous sequence (50 Hz \rightarrow 50.3 Hz \rightarrow 50.8 Hz \rightarrow 51.3 Hz or 50 Hz \rightarrow 49.7 Hz \rightarrow 49.2 Hz \rightarrow 48.0 Hz), whereby the steady state is required before each frequency change.

NOTE 4 The unit may limit its active power response at its maximum active power output. This behaviour shall be taken into account when evaluating the power response.

Measurement 4

The maximum insensitivity of the frequency-dependent active power adjustment around the measured frequency value may be determined similarly to the procedure described in FGW TR 3 (Chapter 7.2.1.6 in Revision 26) for "Determining the effective deadband", whereby the deadband of 200 mHz shall be set to zero.

5.4.5.2.3 Evaluation

Evaluation of measurement 1 and measurement 2

The time characteristics of the active power and frequency or speed shall be determined. The damping of the transient behaviour shall be determined based on the time profiles of the frequency or speed. Appendix A.I may be used to determine the damping.

Evaluation of measurement 3

The time characteristics of the active power and frequency or speed shall be determined. The gradient of the active power output (active power control speeds) shall be determined based on the time profiles of the active power. Only the limited setting range of the PCNB shall be evaluated. Furthermore, the effective droop of the

PCNB shall be determined based on the respective steady-state step values from the actual and simulated frequency and the respective steady-state values of the active power output.

Evaluation of measurement 4

The evaluation shall be performed in accordance with FGW TR3, Revision 26, Chapter 7.2.1.6.

5.4.5.2.4 Presentation in the measurement report

The measured frequency or speed and the measured active power shall be documented graphically for all tests, starting from the initial steady-state condition before the start of the test up to and including the steady-state condition. Regarding measurement 3, the droop determined in each case and the active power actuating speed determined in each case for the limited setting range of the PCNB shall be indicated.

Regarding measurement 4, the presentation in the measurement report shall be performed similarly to the procedure in FGW TR3, Revision 26, Chapter 7.2.1.6.

Note for TR8:

Measurement 1 is considered passed if the frequency response of the test object meets the specified criteria:

- The frequency value 52.5 Hz is exceeded by a maximum of 0.1 s.
- The frequency value 51.5 Hz is exceeded by a maximum of 10 s.
- The settling response of the measured frequency/speed meets the required damping ratio of $D \geq 0.06$.

Measurement 2 is considered passed if the speed curve of the test object meets the requirement for the damping ratio $D \geq 0.06$ in each case. The damping ratio shall be determined in accordance with the definition in 3.1.14 while taking into account Section A.I.

Measurement 3 is considered passed if the final steady-state values of the active power deviate by a maximum of $\pm 5\%$ of the expected power change or $\pm 0.5\%$ $P_{b\ inst}$ from the values resulting from the set droop and comply at least with the active power actuating speeds according to Table 11 .

Measurement 4 is considered passed if the determined insensitivity complies with the required limit value of ± 10 mHz with a maximum deviation of $\pm 20\%$ relative to the limit value.

By passing the four measurements and a manufacturer's declaration, it can be established that the mains primary control based on network security is designed with a proportional speed control.

5.4.5.3 Simulation-based verification within the framework of the individual verification procedure

5.4.5.3.1 General information

The verification through a simulation of the primary control based on network security on a validated simulation model of the $P(f)$ behaviour of the unit in accordance with Section 5.4.5.3.4 (Verification through a simulation in the individual verification procedure for Type 1 installations) requires the performance of corresponding measurement-based tests in accordance with Section 5.4.5.3.2 on the operational unit. This measurement of the unit is performed in synchronous network operation.

NOTE The verification of the requirements for primary control based on network security is generally related to the individual unit but may also be provided by the installation in the case of inseparably connected generation units (e.g. CCGT systems).

5.4.5.3.2 Measurement-based determination of the $P(f)$ behaviour for model validation as part of the individual verification procedure

5.4.5.3.2.1 Aim of the measurement

The aim of the measurement is to determine the behaviour of the PGU within the limited setting range of the primary control based on network security and to record the $P(f)$ function (regarding unlimited and limited setting ranges) to enable model validation of the simulation model. In the event that the $P(f)$ function within the operating range from minimum technical output $P_{Emin,E}$ to maximum output ($P_{b\ inst}$) is divided into several

sections with different parameters as shown in Table 10 and Table 11, the user may perform the measurements described in the following section for each specified load range of the $P(f)$ function.

Regardless of whether a PGU is operated with adjustable primary energy (e.g. gas turbine), the measurements shall be performed for the overfrequency and underfrequency range. It is recommended that the deadband of the primary control based on network security is maintained at ± 200 mHz when performing the measurements.

NOTE The frequency or speed measurement may be taken into account in the model. However, this is not explicitly validated for Type 1 units.

5.4.5.3.2.2 Measurement procedure

Measurements 1 and 2 described below shall be performed starting from an active power operating point in the range of 70 % to 80 % P_{rE} .

Measurement 1 - Behaviour in the unlimited setting range

Record the positive change in the active power output of the unit caused by a step change in the frequency difference Δf_+ in accordance with the control ranges in Table 10 for the different generation technologies. Select the amplitude of the frequency difference in accordance with the set or effective droop settings and the 200 mHz deadband so that the change in the active power output corresponds to the unlimited setting range of the unit.

After reaching the steady state, cancel the change in the frequency difference. After the steady state is reached again, produce in the same way a step change in the frequency difference in the negative direction with Δf_- and then cancel again after reaching the steady state. If different unlimited setting ranges are specified for a unit in Table 10 for different operating areas, perform the measurement described separately for each of the specified setting ranges.

Measurement 2 - Behaviour in the limited setting range

Extend the measurement described in measurement 1 so that the step change in the frequency difference to be defined initiates a response of the active power output of the unit beyond the unlimited setting range. Select the amplitude of the negative step change in the frequency difference Δf_- so that the active power output, starting from the maximum possible power at the time of the measurement (with at least 75 % P_{rE}), drops to the minimum power $P_{Emin,E}$.

Once the steady state is reached, cancel the change in the frequency difference Δf_- so that the value of the original power output before the start of the test is reached again.

In the same way, starting from the minimum power $P_{Emin,E}$, apply a positive step change in the frequency difference Δf_{++} so that the maximum possible active power output of the unit is reached, with at least 75 % P_{rE} .

Cancel the change in frequency difference again once the steady state is reached. The measurement is complete when the steady state is reached again.

5.4.5.3.2.3 Evaluation

Measurement 1

The time profiles of the active power output of the Type 1 grid-forming units shall be recorded.

Measurement 2

The time profile of the active power shall be determined in each case. The gradient of the active power output of the limited setting range shall be determined based on the time profiles of the active power. Furthermore, the effective steady-state behaviour of the PCNB shall be determined based on the respective

final steady-state values from actual and simulated frequency and the respective steady-state values of active power output.

5.4.5.3.2.4 Presentation in the measurement report

The measured active power shall be documented graphically for all measurements, starting from the initial steady-state condition before the start of the measurement up to and including the final steady-state condition. Regarding measurement 2, the determined droop settings and the active power actuating speed of the limited setting range of the PCNB shall be indicated.

Note for TR8:

The verification of the PGUs behaviour in the limited setting range is considered provided if the final steady-state values of the active power deviate by a maximum of $\pm 5\%$ of the expected power change or $\pm 0.5\%$ $P_{b\ inst}$ from the values resulting from the set droop and comply at least with the active power actuating speeds according to Table 11. There is no assessment of the behaviour of the PGU in the unlimited setting range.

5.4.5.3.3 Model validation

5.4.5.3.3.1 Simulation model

For the simulation-based verification of the PCNB in accordance with Section 4.1.2 for Type 1 PGUs, a simulation model (including the PGM controller, if applicable) for the active power path shall be created for the active power path of a PGU and, if required, for the PGM (e.g. for CCGT plants). The input variables are power and speed deviations. The output variable is the mechanical drive power.

The basic test setup is indicated in Figure 6. This corresponds to the test bench verification, although in contrast to this, the load of the virtual island network shall be assumed to be constant, i.e. independent of frequency and voltage. The level of detail of the simulation model shall be based on the requirements of the primary control based on network security and the required tolerances in the closed control loop of the virtual island network operation. This also applies in particular to the output variable of the power controller. If required for compliance with the model accuracy, additional variables such as a valve position, mass flow, etc. may also be included in the model comparison.

5.4.5.3.3.2 Alignment with the simulation model (model identification)

The static and dynamic active power behaviour of the PGU or PGM shall be determined by evaluating the measurement on the operational installation in accordance with Section 5.4.5.3.2. The agreement between the model and the PGU or PGM shall be assessed.

Requirements on the model accuracy

The model shall comply with the following accuracy requirements:

- 1) The steady-state relationship of the active power output as a function of the effective frequency deviation or the RMS power setpoint shall be recreated by the simulation model with an accuracy of 3 % relative to the nominal value of the active power P_{rE} . If a PI power controller is used, this requirement refers to the output signal of the power controller.
- 2) The evaluation of the deviations of the active power output between measurement and model simulation is based on the specifications according to FGW TR4, Revision 10, Section E.5.2.1.1 or the respective updated specifications in subsequent revisions of TR4.

NOTE Any remaining deviations between the measurement and the simulation model shall be assessed to determine the extent to which they are relevant for compliance with the requirements for the PGU within the specified tolerances.

5.4.5.3.4 Verification of primary control based on network security in the individual verification procedure

5.4.5.3.4.1 General information

If the overfrequency and underfrequency behaviour is verified in accordance with this section using the individual verification procedure, the verification in accordance with Clause 11.2 of the relevant Technical Connection Rule and Section 5.4.5.2 of this FNN Guideline may be omitted.

5.4.5.3.4.2 Aim of the test

It shall be verified by simulation that the PGU meets the requirements for primary control based on network security in the frequency range from 50.2 Hz to 51.5 Hz (52.5 Hz if applicable) or 49.8 Hz to 47.5 Hz in accordance with Section 4.1.2. The effective primary control based on network security shall be designed with proportional speed control in accordance with the requirements of Section 4.1.2.

5.4.5.3.4.3 Conducting tests in the simulation model

The simulation-based verification of the PCNB is performed in the virtual island network based on initial states to be defined at nominal frequency by switching on (generation of a negative frequency deviation) and switching off or reducing a load P_L (generation of a positive frequency deviation) with $P_{L+} = P_L + \Delta P_L$ or $P_{L-} = P_L - \Delta P_L$.

Definition of initial operating states

Select the values of 100 % P_{rE} (IOS_{100}) and 75 % P_{rE} (IOS_{75}) for the initial operating state (IOS) of the active power output for testing the overfrequency behaviour.

Set the initial operating state of the active power output for testing the underfrequency behaviour with values of 75 % P_{rE} (IOS_{75}) and the minimum technical output $P_{Emin,E}$ (IOS_{min}). The value of the load P_{L+} and P_{L-} to be switched on and off corresponds to the magnitude of the unlimited setting range of the PGU as specified in Table 10 .

Test 1 - Damping of the closed control loop

Starting from a steady state with technical minimum power and an open interconnecting circuit breaker ($S_{Network}$) to the transmission or distribution network, increase the variable load of the virtual island network in steps. Select the steps so that they correspond to the specifications in Table 10 (amplitude in the unlimited setting range). Select the last step so that P_{rE} minus the specified step amplitude according to Table 10 is reached in the steady state. Subsequently reduce the load in the virtual island network in the corresponding steps to one step above the technical minimum power. Ensure the steady-state condition is reached before introducing a new step.

Test 2 - Overfrequency behaviour

Starting from the specified PGU or PGM operating states of O_{100} and IOP_{75} , perform a step load disconnection ΔP_L down to the technical minimum power, with a maximum of 45 % $P_{b inst}$. In addition, perform repetitions for step load disconnection ΔP_L by 35 % $P_{b inst}$, 25 % $P_{b inst}$ and 15 % $P_{b inst}$.

NOTE Ensure no instabilities occur if the operating point is below the technical minimum output after the PCNB was applied.

Test 3 - Underfrequency behaviour

Starting from the specified PGU or PGM operating states of IOP_{75} and IOP_{min} , determine the active power response during step load connection ΔP_L . Select the load connection ΔP_L so that the rated PGU drive power (steady-state and dynamic) is not exceeded at the load step ΔP_L . Ensure that the initial state is restored by subsequently cancelling the load connection ΔP_L .

Test 4 - Running through an overfrequency and an underfrequency range

Starting from the specified PGU or PGM operating states of IOP₇₅ at nominal frequency, perform a sudden load connection ΔP_L so that a transient frequency drop to 47.5 Hz - 48.0 Hz occurs. After reaching the steady-state condition, ensure that a load reduction initiates a response of the primary control based on network security within the overfrequency range of 51.0 Hz - 51.5 Hz. Then, after reaching the steady-state condition again, cancel the load changes to return the system to the initial state. Also verify that the PCNB dead band is traversed without bumps relative to the power actuator.

5.4.5.3.4.4 Evaluation and presentation in the test report

For all tests, the active power and frequency or speed curve shall be shown graphically, starting from the initial steady-state condition before the start of the test up to and including the steady-state condition after the test or the respective test step. Amplitude maxima and minima shall be labelled. The respective values shall be indicated. The damping values shall be determined from the labelled or specified amplitude maxima and minima and indicated. Damping values may be determined using Appendix A.I. The droop settings shall be determined from the respective steady-state initial and final states. For Tests 2 to 4, the active power actuating speed for the limited setting range of the PCNB shall also be indicated.

Note for TR8:

The tests are considered passed if:

- *there is compliance with the required frequency limits according to E.9 (VDE-AR-N 4110) or E.7 (VDE-AR-N 4120/4130) with a tolerance of maximum ± 100 mHz,*
- *the speed curve of the test object for the settling process meets the requirement for the required damping ratio of $D \geq 0.06$ with a tolerance of -10 %, i.e. $D \geq 0.054$,*
- *the steady-state final values of the active power deviate by a maximum of $\pm 5\%$ $P_{b\ inst}$ from the values resulting from the set droop settings and at least the active power actuating speeds comply with the values specified in Table 11 ; the primary control based on network security is implemented with proportional speed control (it shall be established that a false control effect is not visible, see also Appendix A.II).*

5.5 Grid-forming units (Type 2, storage and CCUs)

5.5.1 General information

Verification of the grid-forming properties of PGUs, PGSUs, storage and CCUs shall be performed in accordance with one of the following test and measurement setups (see also Table 2):

- 1) Free-field measurements on the real network or on a network emulator
- 2) Test bench tests on the real network or on a network emulator

In some cases, additional verifications based on a validated simulation model may be required.

In the case of wind turbines, the entire grid-forming unit with all associated components (e.g. mechanical components) shall be tested during test bench tests. Any permitted exceptions shall be specified in the corresponding verification procedure.

It is worth noting, that other alternative verification methods for network compliance of grid-forming properties have proven useful. However, these are not addressed in this version of the FNN Guideline. The standard IEC TS 61400-21-4 should be considered for the verification procedure of the grid-forming properties of wind energy units on test stands (M-HIL¹¹ und P-HIL¹²) with missing components such as rotor and generator (these are replaced by simulation). The verification may be also based on the C-HIL¹³ level. As there is currently no established empirical data available on these alternative verification methods, they are not included in the current version of the FNN Guideline. However, the aim is to include these alternative verification procedures in a revision of the FNN Guidance as soon as corresponding empirical values are available. Therefore, all parties involved in the transition period are called upon to investigate such procedures and to share their experience with VDE FNN.

The applicability of the test and measurement setups depends on the type of grid-forming unit. The use of test bench tests instead of free-field measurements may only be used if the behaviour of the grid-forming unit is equivalent to that in the free field in terms of the properties to be tested. The adapted requirements for performing tests on test benches, including the specifications for DC sources for PV PGUs and PGSUs, are listed in Appendix D of FGW TR3. Network emulators shall be used accordingly.

Table 2 provides an overview of the requirements which shall be verified as well as the corresponding verifications. It shows which verifications shall be measured, simulated or provided in the manufacturer's declaration. The verifications are also allocated to the test situation of the virtual island network or synchronous network operation. Measurement-based verifications are also subdivided into field measurements and test bench measurements using a network emulator.

¹¹ M-HIL: Mechanical Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)

¹² P-HIL: Power Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)

¹³ C-HIL: Controller Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)

Table 2 - Overview: Requirements and associated verifications for grid-forming units (Type 2, storage and controllable loads)

Requirement		Verification						
Section	Title	Measurement-based verification				Simulation-based verification		Manufacturer's declaration
		Virtual island network operation		Synchronous network operation		Virtual island network operation	Synchronous network operation	
		Field measurement	Test bench / Network emulator	Field measurement	Test bench / Network emulator			
4.2.1.1	Behaviour of voltage sources	Section 5.5.4 ^{a)} (Evaluation in accordance with Section 5.5.4.4.1)		-		-	-	
4.2.2.2	Response during underfrequency and overfrequency ranges (PCNB) – limited setting range	Section 5.5.4 ^{a)} (Evaluation in accordance with Section 5.5.4.4.2)		-		-	-	
4.2.1.1	Active power response to a phase angle step	-		Section 5.5.5.3 ^{b)}		-	-	
4.2.1.1	Effective impedance	-		Section 5.5.5.4 ^{b)}		-	-	
4.2.1.2	Damping behaviour above 10 Hz	-		-		-	Section 5.5.5.5 ^{b)}	
4.2.1.4	Continuous voltage control – Setpoint response	-		Section 5.5.5.6.1 ^{b)}		Section 5.5.6.3 ^{b)}		
4.2.1.4	Continuous voltage control – Behaviour during disturbances and linearity of the effective impedance	-		Section 5.5.5.6.2 ^{b)}		Section 5.5.6.4 ^{b)}		
4.2.1.5	Robustness through short-term over- and undervoltage events (OVRT/UVRT robustness)	-		Section 5.5.5.6.3 ^{b)}		-	-	
4.2.1.1	Behaviour at the current limits	-		Section 5.5.5.6.4 ^{b)}		-	-	
4.2.1.4.5	Behaviour when resuming a value within the voltage range	-		Section 5.5.5.6.5 ^{b)}		-	-	
4.2.1.6	Fast protection during high during high voltages	-		-		-	Section 5.5.5.6.6 ^{b)}	
4.2.1.9	Response to steep frequency gradients (RoCoF)	-		-		-	Section 5.5.5.7 ^{a)}	
4.2.1.10	Capability of parallel network operation	-		-		-	Section 5.5.6.5 ^{b)}	
4.2.1.11	Damping of power-frequency-oscillations (0.05 Hz – 10 Hz)	-		Section 5.5.5.8 ^{a)}		-	Section 5.5.6.1 ^{c)}	
4.2.1.12 + 4.2.1.13	Provision of inertia (T_A)	-		Section 5.5.5.9 ^{a)}		-	Section 5.5.6.2 ^{c)}	
4.2.2.2	Behaviour in the underfrequency and overfrequency ranges (PCNB) – limited setting range	-		Section 5.5.5.10 ^{a)}		-	-	

a) Measurements shall be performed for $T_A = T_{A,min}$ and $T_A = T_{A,max}$
b) Measurements shall be performed for values of T_A selected by the certification body.
c) If a parametrisation of $T_{A,min} < T_A < T_{A,max}$ is possible, additional simulation-based tests shall be performed.

Existing systems with grid-following technology that are converted to grid-forming technology for providing inertia, shall be measured at the existing NCP. An appropriate test environment shall be provided.

NOTE 2 If the existing installation to be converted to grid-forming technology is based on grid-forming units that were certified in accordance with this FNN Guideline, the procedure described in this FNN Guideline may also be applied to existing installations based on the unit certificate.

The operating points specified in the tests shall be set appropriately via the interfaces provided by the manufacturer of the unit. The use of a parking controller is not required. Unless otherwise specified, the voltage setpoint U_{setpoint} shall be kept constant.

The tests shall always be performed with the default values (PCNB active, with default settings), unless otherwise required. The start-up time constant with which the verifications shall be provided is selected by the certification body as part of the certification from the setting range for which the grid-forming unit is designed. Unless otherwise specified, the start-up time constant verified in accordance with the requirements of this FNN Guideline shall be used and indicated for all verifications. An overview of the values of T_A to be checked in the measurement-based verifications is provided in Table 2 (see footnotes).

NOTE 3 Some verifications shall be performed with $T_{A\text{min}}$ and $T_{A\text{max}}$ and, if required, also for additional values of T_A in the setting range.

Some tests require steady-state operating points in defined ranges regarding active and reactive power. The reactive power operating points "max. ind" and "max. cap" are considered reached if at least 90 % of the reactive power, that the test object can provide in addition to the active power in accordance with the manufacturer's specifications, is provided.

Supplementary simulation-based verifications in accordance with Section 5.5.6 require a manufacturer-specific simulation model, which shall be validated based on the measurements performed on the operational unit for the purpose of certification (see Section 5.5.3.6). Based on the validated simulation model, in addition to the verification of the behaviour of the grid-forming unit on an NCP, supplementary tests in accordance with Section 5.5.6.5 shall be performed in a network environment defined in accordance with Section A.I in the sense of an extended benchmark.

5.5.2 Basic prerequisites

5.5.2.1 Requirements for measurement variables and signals

Signals and measurement variables

In addition to the general requirements for the measurement setup (Section 3.2.1), the measurement technology (Section 3.2.2) in conjunction with Appendix F and the test conditions (Section 3.2.3) specified in FGW TR3 Revision 26, Chapter 3, the following supplementary specifications shall be taken into account if they are required for the selected variants of the provision of verification.

With reference to Chapter 3.2.2 of FGW TR3, Revision 20, the following signals or measurement variables shall also be determined as quantities related to their nominal value (for currents, the nominal apparent current shall be used):

i_a, i_b, i_c	Instantaneous values of the phase currents of the grid-forming unit
u_a, u_b, u_c	Instantaneous values of the phase voltages (phase-to-neutral) of the grid-forming unit
u_α, u_β	$\alpha\beta$ components of the voltage space vector ¹⁴
i_α, i_β	$\alpha\beta$ components of the current space vector ¹⁴
$u_{\alpha\beta}$	Magnitude of the voltage space vector in the $\alpha\beta$ coordinate system ¹⁴
$i_{\alpha\beta}$	Magnitude of the current space vector in the $\alpha\beta$ coordinate system ¹⁴
$i_{P,\alpha\beta}$	Magnitude of the active current vector in the $\alpha\beta$ coordinate system ¹⁴
$P_{\alpha\beta}$	Active power in the $\alpha\beta$ coordinate system
$q_{\alpha\beta}$	Reactive power in the $\alpha\beta$ coordinate system
$u_{\alpha\beta,5ms}$	Magnitude of the voltage space vector in the $\alpha\beta$ coordinate system as a 5 ms average value ¹⁴
$i_{\alpha\beta,5ms}$	Magnitude of the current space vector in the $\alpha\beta$ coordinate system as a 5 ms average value ¹⁴
$i_{P,\alpha\beta,5ms}$	Magnitude of the active current pointer in the $\alpha\beta$ coordinate system as a 5 ms average value ¹⁴
$P_{\alpha\beta,5ms}$	Active power in the $\alpha\beta$ coordinate system as a 5 ms average value ¹⁴
$q_{\alpha\beta,5ms}$	Reactive power in the $\alpha\beta$ coordinate system as a 5 ms average value ¹⁴
$i_{P,1}, i_{P,2}$	Fundamental oscillation of the current vectors (active component) in the positive and negative sequence
$i_{Q,1}, i_{Q,2}$	Fundamental oscillation of the current vectors (reactive component) in the positive and negative sequence
$i_{P,1,100ms}, i_{P,2,100ms}$	Fundamental oscillation of the current vectors (active component) in the positive and negative sequence as 100 ms average value
$i_{Q,1,100ms}, i_{Q,2,100ms}$	Fundamental oscillation of the current vectors (reactive component) in the positive and negative sequence as 100 ms average value

¹⁴ For determining the $\alpha\beta$ components of current and voltage, see Appendix B.V.

u_1, u_2	Fundamental oscillation of the voltage vectors in the positive and negative sequence
p_1, p_2	Fundamental oscillation of the active power in the positive and negative sequence
q_1, q_2	Fundamental oscillation of the reactive power in the positive and negative sequence
$i_{S,1}, i_{S,2}$	Fundamental oscillation of the apparent current vectors in the positive and negative sequence
f_1, f_2	Fundamental oscillation of the frequency in the positive and negative sequence

The measured instantaneous values in the $\alpha\beta$ coordinate system shall be determined from the measured instantaneous values using a moving average over 5 ms.

The fundamental oscillation of the positive sequence vector shall be shown as a 1-period value over an evaluation time adapted according to the determined frequency. The frequency should be determined over a sliding period of maximum 100 ms.

Internal signals of the control of the grid-forming unit

In cases where the start-up time constant T_A can only be determined by analysing internal signals from the control system of the grid-forming unit, all signals from the control system that are used to generate the speed or frequency shall be recorded. This depends largely on the implemented control concept of the grid-forming unit.

Internal signals for evaluating the primary power for wind and PV PGUs

Depending on the manufacturer's technology, additional internal signals may be required to verify the primary power (wind supply, PV irradiation). It shall be demonstrated that the signals defined in this way are used to implement the corresponding control functions (e.g. degree of throttling).

Switching of test signals during tests

When performing tests using test signals, the following requirements apply:

- The required signals shall use digital signals taken directly from the control systems of the grid-forming. The sampling rate should correspond to the cycle rate of the control system.
- The scope of the required signals in accordance with this section is determined in coordination among the accredited certification body, the manufacturer and the accredited measuring institute.
- When performing tests in a simulation environment or in the real system, the switching of the following test signals shall be taken into account if they are required for the selected verification procedure:
 - Voltage setpoint of the controller of the grid-forming unit
 - Signal connection to the internal reference frequency of the grid-forming unit
 - Signal connection to the internal voltage angle of the grid-forming unit
 - Signal connection to the internal power setpoint of the grid-forming unit.

The connection may be performed either via external signal coupling or through a time-controlled activation of internal signal connections via a defined interface.

5.5.2.2 Requirements for test equipment

In addition to the requirements for test bench tests listed in FGW TR 3, Revision, Chapter 3.2.4, the following applies:

If a converter-based load is used, the converter-based load shall mostly behave like a passive load and shall not affect the stability of the grid-forming unit under test. After the transition to virtual island network operation and after the equalisation processes have subsided, the power of the load shall not fluctuate by more than $\pm 5\%$ of the power expected from the final value of the voltage resulting on average in the virtual island and the load characteristic. The equalisation processes shall have subsided before the measurement period relevant for the evaluation begins. The same applies to the use of power sources.

Network emulators, converter-based loads and power sources that are used to evaluate the voltage source behaviour by transitioning into island network operation in accordance with Section 5.5.4 shall not have any grid-forming properties in the operating conditions in which they are used as a load or power source in the virtual island network. This requirement is met if the mains emulators, converter-based loads and power sources can no longer maintain any voltage at their terminals after disconnection from the test object and when this is verified once during the commissioning of the corresponding test setup. If this verification was provided as part of a general qualification of the test device, this explicit test may be omitted.

Requirements for network emulators are specified in IEC 61400-21-4 and should be taken into account in the future. Although this refers to wind turbines, it shall be applied similarly for other technologies within the meaning of this FNN Guideline.

5.5.3 Requirements for simulation models and model accuracy

5.5.3.1 Model categories and general specifications

Simulation models are required as part of the compliance assessment of a grid-forming unit to be certified.

NOTE Appropriate simulation models as part of the certification process shall be provided to the relevant network operator for example, for the assessment of connection requests, for the detailed determination of the dynamic behaviour of installations within a limited network region or for the implementation of extensive ENTSO-E interconnected network studies. The simulation models may only be used within the certification process if they represent the measured properties with sufficient accuracy.

There are three model categories:

EMT models: The EMT model comprises an instantaneous value representation of currents and voltages of the grid-forming unit in the time domain, including the modelling of electrical and control components.

RMS models: The detailed RMS model is based on an RMS value representation of currents and voltages of the grid-forming unit in the positive, negative and zero sequences, including the modelling of electrical, control components and protection functions. Manufacturer-specific components may be modelled in encrypted form in the detailed RMS model.

RMS type models: Standardised generic model with RMS value representation of currents and voltages of the grid-forming unit in the positive, negative and zero sequences, including the modelling of electrical and control components that are effective in a frequency range up to 10 Hz. The model is based on an open (white box), typified basic structure that recreates the behaviour of the manufacturer-specific, detailed RMS model with the required accuracy.

5.5.3.2 General model requirements

The simulation model of a grid-forming unit shall have the following basic properties:

- 1) Depending on the model type, the simulation model shall be provided as an open or partially protected (black box) model. The power section shall not be included in the black box model. If the grid-forming unit includes a unit transformer, filter or other electrical components, these shall be explicitly represented in the simulation model in the respective simulation environment. If the unit transformer is equipped with

an automatic tap changer, the tap changer control shall also be included in the simulation model. The tap-changer control shall be implemented in a separate, switchable part of the model.

- 2) Protection functions (loss of mains protection on the unit such as voltage step-up protection, voltage step-down protection, frequency step-up protection, frequency step-down protection) shall be implemented in a model part which can be disconnected, if they trigger a disconnection of the grid-forming unit when network states occur that lead to the grid-forming unit remaining connected to the network outside of the requirements. It shall at least be possible to deactivate the unit by changing the parameters.
- 3) Modelling of the average houseload supply of less than 3 % $P_{E_{max}}$ (minus intermittent consumers, in accordance with manufacturer's specifications) is not required.
- 4) The model of the grid-forming unit shall have the required input signals for control by an PGM controller.
- 5) It shall be possible to execute any number of instances of the model of the same unit independently of each other in parallel. Unit models shall be able to be instantiated multiple times; this also applies to Dynamic Link Library (DLL) based models.
- 6) The use of the unit's simulation model shall not result in any restrictions in the use of other models, including those from other manufacturers. It shall be possible to use generic RMS models and RMS type models in parallel. This also applies to EMT models, as long as this is supported by the tool environment.
- 7) All simulation models (except for DLL-based models) shall be structured in modules based on sub-models so that sub-functions (protection, PCNB, etc.) can be switched off and parameter changes can be performed easily.

5.5.3.3 Requirements for EMT models

The following requirements apply to the EMT model of a grid-forming unit:

- 1) The EMT model recreates currents and voltages of the grid-forming unit as phase values. The modelling of electrical and control components that are effective in a frequency range up to 1 kHz (if possible, up to 2.5 kHz) shall be represented. Measuring elements shall be taken into account. The level of detail of the simulation model shall always be selected so that model validation can be successfully performed in accordance with Section 5.5.3.6.
- 2) The relevant original controller code shall be used in the form of a DLL, for example. To enable a simplified representation of the power section (power electronic switching elements) for a simplified time-continuous representation of the pulse pattern generation, an output signal of the controller shall be provided in the form of a setpoint for pulse pattern generation. The ability to switch on the pulse pattern generation and the power section is not required.
- 3) The model shall be detailed so that the entire operating range of the system between $P_{E_{min,E}}$ and P_{max} or between Q_{min} and Q_{max} is modelled in the steady initial state as well as during transient balancing processes. The validity range of the model shall include all operating states and operating points in the design of the unit.
- 4) It is recommended that the initialisation of the model is supported so that the currents and voltages resulting from the load flow calculation can be automatically specified as setpoint signals. Provided that the simulation environment allows this, the model shall have a function (model snapshot) that can save steady-states and read or activate them again without re-initialisation.
- 5) The user shall be able to change the parameters of the grid-forming unit defined as adjustable in the requirements (e.g. droop settings of the PCNB). The setting ranges shall be documented in each case.
- 6) The user shall be able to observe all signals and states required for the replication of the tests to verify the requirements for the grid-forming unit and for validation of the simulation model.
- 7) The EMT model may be provided as a black box model.

5.5.3.4 Requirements for the detailed RMS model

The following requirements apply to the detailed RMS models of a grid-forming unit:

- 1) The detailed RMS model is based on an RMS value representation of currents and voltages of the grid-forming unit in the positive, negative and zero sequence system, including the modelling of electrical, control components and protection functions. Aspects of the primary side (e.g. mechanics, chemistry) shall only be modelled if required for model validation. The level of detail of the simulation model shall be chosen to allow the model validation to be performed successfully in accordance with Section 5.5.3.6.
- 2) The controller functions shall be implemented as an equivalent, continuous-time model of the original controller code.

NOTE 1 In contrast to continuous-time models, clocked models cannot be solved efficiently through simulation within a complex and extensive network environment (see note in Section 5.5.3.1), as unacceptable computing times would arise due to the required individual step sizes for each model and adaptive step sizes could not be used.

- 3) The detailed RMS model should provide a simulation step size of ≥ 1 ms. If a smaller step size is required for the calculation of subtransient processes, the model shall be designed to allow step size adaptations of up to at least 15 ms after the subtransient processes subside.
- 4) The model shall be detailed to be able to recreate the entire operating range of the grid-forming unit between $P_{Emin,E}$ and P_{max} or Q_{min} and Q_{max} in the initial steady state, as well as during transient equalisation processes. The validity range of the model shall include all operating states and operating points in the design of the unit.
- 5) The model of the grid-forming unit shall be initialised based on the voltages and currents determined in a load flow calculation at the terminals of the grid-forming unit within the model itself. The derivatives of state variables shall remain below the selected simulation errors ("flat run", i.e. no noticeable settling process is observed). If an operating state was selected for the load flow calculation that is not represented by the simulation model, corresponding messages shall be generated during model initialisation.
- 6) The user shall be able to change the parameters of the grid-forming unit defined as adjustable in the requirements (e.g. droop settings of the PCNB). The setting ranges shall be documented in each case.
- 7) The user shall be able to observe all signals and states required for the simulation of the tests to verify the requirements of the grid-forming unit and for the validation of the simulation model.
- 8) The detailed RMS model may be provided as a black box model.
- 9) The detailed RMS model shall be provided for all common simulation environments used by the German transmission network operators to perform system studies. Specifications for the simulation environments to be supported may be found in the Technical Connection Conditions (TCC) of the German transmission network operators.

NOTE 2 If the network operator providing the connection (distribution network operator) uses a simulation environment that deviates from the specifications of the German transmission network operators (within their TCCs), system studies or network connection studies may be conducted by them based on a tool-independent generic model.

5.5.3.5 Requirements for RMS type models

In addition to the detailed RMS simulation model in accordance with Section 5.5.3.4, a typified simulation model shall be provided.

NOTE 1 The RMS type model aims to categorise different implementations of grid-forming units in a conceptual form so that the behaviour of a grid-forming unit can be reproduced with sufficient accuracy solely by selecting the model type and defining the descriptive parameters, without revealing manufacturer-specific information. An essential prerequisite is that the respective requirements of a Technical Connection Rule are fulfilled by assigning the type category and selecting the parameters without losing the characteristic, manufacturer-specific behaviour. Examples of this type approach may be found in the IEEE model library for PGMs, excitation devices, voltage regulators, PSS, as well as Type 2 grid-following units.

The following requirements apply:

- 1) The model behaviour may be simplified compared to the simulation model described in Section 5.5.3.4 and refer to a generalised representation (e.g. as a VSM or droop model)¹⁵. If the behaviour of a unit cannot be represented with the required accuracy using an existing, publicly available model, the manufacturer may design a corresponding model and include it in the type library.
- 2) The RMS type model shall be implemented as a continuous-time model that can be used in system studies with the shortest possible simulation times.

NOTE 2 In contrast to continuous-time models, clocked models cannot be solved efficiently through simulation within a complex and extensive network environment (see note in Section 5.5.3.1), as unacceptable computing times would arise due to the required individual step sizes for each model and adaptive step sizes could not be used.

- 3) The simplified or typified model shall demonstrably fulfil all requirements for the grid-forming unit (e.g. power response to a phase step, start-up time constant, damping behaviour regarding power-frequency-oscillations, current limitation, FRT behaviour) and thus exhibit comparable behaviour to that of the detailed RMS simulation model in accordance with Section 5.5.3.4 .
- 4) The model shall be detailed to be able to recreate the entire operating range of the grid-forming unit between $P_{Emin,E}$ and P_{max} or Q_{min} and Q_{max} in the initial steady state, as well as during transient equalisation processes. The validity range of the model shall include all operating states and operating points in the design of the unit.
- 5) The typified simulation model shall be validated against the detailed RMS simulation model in accordance with Section 5.5.3.4. The tolerance specifications apply in accordance with Section 5.5.3.6.
- 6) The type RMS model should be designed to work with a simulation step size of ≥ 1 ms. If a smaller step size is required for the calculation of subtransient processes, the model shall be designed to allow step size adaptations of up to at least 15 ms after the subtransient processes subside.
- 7) The RMS type model of the grid-forming unit shall be initialised based on the voltages and currents determined in a load flow calculation at the terminals of the grid-forming unit within the model itself. The derivatives of state variables shall remain below the selected simulation errors ("flat run", i.e. no noticeable transient process is observed). If an operating state is selected for the load flow calculation that is not represented by the simulation model, corresponding messages shall be generated during model initialisation.
- 8) If the selected tool environment supports the calculation of eigenvalues, the model should be designed to allow linearisation using the eigenvalue calculation function.
- 9) The typified model shall be provided as a white box model and be represented based on a block diagram. All state variables, signals, parameters or characteristics shall be accessible to the user. For new technologies for which no suitable publicly available models are yet available in accordance with Point 1), the manufacturer may alternatively provide an RMS type model with encrypted components whose state variables, internal signals, parameters and characteristics do not need to be accessible. Signals that are used for evaluation in the verification process shall be made accessible to the user. The requirement regarding publication under Point 1) does not apply to these models. This applies as long as the relevant Technical Connection Rule does not specify any other requirements in this regard.

5.5.3.6 Validation and documentation of simulation models

5.5.3.6.1 Introduction

The simulation models shall be validated by comparing the behaviour of the grid-forming unit based on the measurement-based tests with a corresponding simulation-based test setup. The following applies to the validation of the model categories:

¹⁵ The following paper provides an overview on VSM und droop control concepts: S. D'Arco and J. A. Suul, "Equivalence of Virtual Synchronous Machines and Frequency-Droops for Converter-Based MicroGrids," in *IEEE Transactions on Smart Grid*, Volume 5, Number 1, Pages 394-395, January 2014

- 1) The EMT model is validated based on the measurement results.
- 2) The detailed RMS model is validated based on the measurement results.
- 3) The RMS type model is validated based on the validated detailed RMS model.

The model validation shall include the following signals if they are required for the respective test:

- 1) All signals that were defined during the tests on the behaviour of the grid-forming unit.
- 2) Magnitude and angle of the internal voltage of the grid-forming unit as well as the internally generated frequency.
- 3) Signalling circuits, insofar as they are required for the tests.

NOTE If T_A is determined using a measurement specification with evaluation of internal signals, the signals required for this shall be included in the model validation. These may involve internal state variables, speed or frequency and internal angle of the voltage source of the grid-forming unit.

5.5.3.6.2 Validation of the simulation models

The validity of the simulation models in accordance with Section 5.5.3.8 (Manufacturer models for certification) and Section 5.5.3.9 (Installation models for network operators) shall be determined by comparing the behaviour of the grid-forming unit during the tests performed in accordance with Sections 5.5.4 and 5.5.5 with the corresponding behaviour of the unit simulation models. The test setup used shall be simulated. The following tests shall be included in the model validation:

- 1) Testing of the voltage source behaviour (Section 5.5.4)
- 2) Testing of the start-up time constant and inertia energy (Section 5.5.5.9)
- 3) Testing of the behaviour of the PCNB (Sections 5.5.4.4.2 and 5.5.5.10)
- 4) Testing of the power response to a phase angle step (Section 5.5.5.3)
- 5) Examination of the effective impedance (Section 5.5.5.4)
- 6) Examination of the behaviour of the continuous voltage control (Section 5.5.5.6)
- 7) Examination of the response to steep frequency gradients (Section 5.5.5.7)
- 8) Examination of the damping of power-frequency-oscillations (Section 5.5.5.8)

The simulation models in accordance with Sections 5.5.3.8 and 5.5.3.9 shall exhibit a behaviour that complies with the requirements. The requirements for the models of the grid-forming unit are fulfilled if compliance can be demonstrated and if the measured behaviour of the grid-forming unit can be reproduced by the simulation models within the specified tolerances.

5.5.3.6.2.1 General specifications for model tolerances

Model tolerances may be exceeded if:

- the tolerances regarding $T_{A,\min}$, $T_{A,\max}$ in accordance with Section 5.5.5.9, as well as the damping of power-frequency-oscillations in accordance with Section 5.5.5.8 are observed,
- the respective simulation models can be used to successfully demonstrate compliance with all requirements, and
- the actual tolerances are indicated.

5.5.3.6.2.2 Validation of the EMT and detailed RMS models

5.5.3.6.2.2.1 Specifications for the signals

For the model validation of the EMT and the detailed RMS model, the signals in accordance with Section 5.5.2.1 shall be used depending on the test, whereby the index "S" indicates the respective simulation values.

The measured and simulated instantaneous values in the $\alpha\beta$ coordinate system shall be determined using a moving average over 5 ms from the measured instantaneous values or the simulated instantaneous values. The values in the negative sequence shall only be used if the simulation environment supports this.

In cases where the comparison between the measured EMT signals and the simulated EMT signals is made based on the fundamental oscillation of the positive sequence vectors ($i_{p,1}, u_1, p_1, q_1$ or $i_{p,1,S}, u_{1,S}, p_{1,S}, q_{1,S}$), the RMS values shall be arithmetically averaged over one period.

5.5.3.6.2.2.2 Specifications for initialising the simulation model

The following specifications apply to the initialisation of the simulation model:

- 1) The steady-state condition of the positive sequence voltage $u_{1,S}$ and the positive sequence current $|i_{p,1,S}|$ before the start of the test shall be determined using an average value over a time window of 1 s. In this time window, the positive sequence voltage shall remain within a tolerance band of $\pm 0.25\%$ relative to the nominal voltage value. The simulation model shall be initialised to the values determined in this way. This also applies to the active and reactive power $p_{1,S}$ and $q_{1,S}$.
- 2) The simulation models shall continue to be initialised so that all transient settling processes have subsided and at least the initial steady state condition specified in Point 1) is reached.

Note for TR8:

The requirement for the initialisation of the simulation models is met if:

- *the simulated positive sequence voltage as well as positive sequence active and reactive power remain for each simulation-based test within a tolerance band of $\pm 0.25\%$ of the nominal value within a time window of 1 s before the start of the test,*
- *the model is initialised to the steady-state starting point (in particular the average value of the positive sequence voltage formed over 1 s) of the respective test, which is determined taking into account line 1, and all temporary transients have subsided before the test begins.*

5.5.3.6.2.2.3 Voltage source behaviour in accordance with the test specified in Section 5.5.4

The test described in Section 5.5.4 shall be simulated in the same way for both the EMT and the detailed RMS model and evaluated in accordance with the specifications in Section 5.5.4.4.1. The initialisation of voltage and current or active and reactive power of the grid-forming unit shall be performed in accordance with Section 5.5.3.6.2.1. Proceed as follows to validate the model:

- 1) The steady-state voltage at the terminals $u_{1,S}$ of the grid-forming unit of the EMT model or detailed RMS simulation model after transitioning into island network operation may deviate from the measured value by a maximum of $\pm 3\%$ relative to its nominal value.
- 2) The profile of the temporary transition to the virtual island network is not examined for neither the EMT nor the detailed RMS model.

Note for TR8:

The model is considered validated regarding the correct representation of the voltage source behaviour of the grid-forming unit if the steady-state voltage at the terminals of the grid-forming unit after transitioning to island network operation deviates from the measured value by a maximum of $\pm 3\%$ relative to its nominal value.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.4 Start-up time constant, inertia power and energy in accordance with the test in Section 5.5.5.9

The test described in Section 5.5.5.9 shall be simulated in the same way for both the EMT and the detailed RMS model. The initialisation of voltage and current or active and reactive power of the grid-forming unit shall be performed in accordance with section 5.5.3.6.2.1. Proceed as follows to validate the model:

- 1) The start-up time constant T_A to be verified shall be set in the respective EMT or detailed RMS simulation model in accordance with the manufacturer's specifications. The tests shall be simulated and evaluated in accordance with Section 5.5.5.9. The tolerance specifications for the verification of the start-up time constant T_A shall be complied with during tests. In the event that active power transient phenomena occur at the respective section transitions, it shall be shown that the frequency of active power transient phenomena $p_{1,S}$ in the simulation model deviates from those in the measurement p_1 by a maximum of $\pm 40\%$ relative to the measured frequencies. In the case of wind energy units, the profile of the active power can be influenced by excitations of the mechanical resonances. The active power superimposed due to the mechanical vibrations may be extracted using Prony analysis in accordance with Appendix A.V. If the mechanical vibrations have been eliminated from the active power curve, both active power curves (without and with the elimination of the influence of mechanical vibrations) shall be shown.
- 2) If no steady states can be determined within the time periods specified in the test specification, the start-up time constant T_A shall be determined by evaluating the internal signals in accordance with Section 5.5.5.9.3.3.

Note for TR8:

The model is considered validated regarding the correct reproduction of the start-up time constant and the inertia power and energy of the grid-forming unit under the following conditions:

- *The simulated power remains within the required tolerance bands within the required times in Section 5.5.5.9.3 after the start of the respective segment.*
- *In the event that settling processes of the active power occur between the respective segments to be traversed as indicated in Figure 4, it also applies that the frequency of the settling processes of the active power of the simulation model deviates by a maximum of $\pm 40\%$ from the measured results.*
- *In the event that no steady-state conditions could be determined within the specified time periods, the start-up time constant may be determined by analysing the internal signals with a maximum deviation of 5% from the agreed value.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.5 Behaviour of the PCNB in accordance with the test in Sections 5.5.4 and 5.5.5.10

The test described in Sections 5.5.4 and 5.5.5.10 shall be simulated in the same way for both the EMT and the detailed RMS model. The initialisation of voltage and current or active and reactive power of the grid-forming unit shall be performed in accordance with Section 5.5.3.6.2.2.2. Proceed as follows to validate the model:

- 1) The droop settings of the PCNB shall be determined based on the initial steady state and the final steady state. In this case, a maximum deviation of $\leq \pm 5\%$ from the value set on the grid-forming unit shall be verified.
- 2) The damping of the settling response of the frequency shall be determined for the simulation-based test in accordance with Section 5.5.4.4.2. Damping may be determined using the method described in Appendix A.I. The damping ratio required for the respective technology in accordance with Table 10 (Appendix B) and the frequency of the transient response of the frequency shall be maintained by the simulation model with an accuracy of $\pm 15\%$ relative to the measured value.
- 3) In the event that the settling process of the frequency of the grid-forming unit is heavily damped and a damping ratio cannot be determined, the transient response of the frequency of the simulation model of

the grid-forming unit shall be compared with the measured frequency on the test object, starting from the initial steady state until the final steady state is reached. When assessing the compliance of the simulation model and the test object, the procedure in accordance with FGW TR4, Revision 10, Chapter E.5.2.1.1 Section (3) applies to the frequency of the grid-forming unit, whereby a value of $\pm 15\%$ relative to the steady-state frequency deviation shall be taken into account for the tolerance band ($\varepsilon_{\text{dyn}}^{16}$) of the frequency.

Note for TR8:

The model is considered validated regarding the correct reproduction of the behaviour in the unlimited and limited setting range of the PCNB of the grid-forming unit under the following conditions:

- *The simulated static value corresponds to the value setting in the grid-forming unit with a maximum deviation of $\pm 5\%$.*
- *Compliance with at least the active power actuating speeds in accordance with Table 11. As long as no minimum requirements are specified for the grid-forming unit in accordance with Table 11, a verification of the actuating speeds is considered provided through their identification.*
- *The simulated damping of the PCNB and the frequency of the settling process of the frequency corresponds to the measured value with a maximum deviation of $\pm 15\%$.*
- *If the procedure in accordance with FGW TR4, Revision 10, Chapter E.5.2.1.1 is applied, the frequency of the simulation model of the grid-forming unit is within the tolerance band of $\pm 15\%$ relative to the steady-state frequency deviation.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.6 Power response to a phase angle step in accordance with the test specified in Section 5.5.5.3

The test described in Section 5.5.5.3 shall be simulated. The short-circuit ratio (SCR) at the terminals of the grid-forming unit in the simulation environment shall be set to the value determined in the test environment. Proceed as follows:

- 1) Starting from the initial steady-state condition and continuing to the final steady-state condition, the active power $p_{\alpha\beta}$ determined from the test shall be compared with the corresponding simulated active power $p_{\alpha\beta,S}$ of the EMT model. The maximum value of the power response to a phase angle step of the simulation model may deviate by a maximum of $-10\% / +25\%$ from the measured maximum value of the power response to a phase angle step in the procured direction and by a maximum of $\pm 25\%$ in the non-procured direction.
- 2) The settling process in terms of damping and frequency shall comply with the response defined in Section 5.5.5.8 and the values shall be indicated.

Note for TR8:

The model is considered validated regarding the correct reproduction of the power response to a phase angle step of the grid-forming unit under the following conditions:

- *The simulated maximum value of the power response to power response to a phase angle step of the EMT model of the grid-forming unit corresponds to the measured maximum value in the procured direction with a maximum deviation of -10% or $+25\%$, and a maximum deviation of $\pm 25\%$ in the non-procured direction.*
- *The values of damping and frequency of the settling process of the active power are indicated.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

¹⁶ See equations E-3 to E-6 and paragraph (3) in FGW TR4, Revision 10, Chapter E.5.2.1.1.

5.5.3.6.2.2.7 Effective impedance in accordance with the test in Section 5.5.5.4

The measurement performed in Section 5.5.5.4.2 from the two alternative measurement procedures 1 or 2 shall be simulated with the EMT model and evaluated in accordance with Section 5.5.5.4.3 for "Measurement 1" or "Measurement 2". The simulated effective impedance shall not deviate by more than $\pm 5\%$ from the measured value. The measured effective impedance shall be specified for the detailed RMS simulation model.

Note for TR8:

The model is considered validated regarding the correct reproduction of the effective impedance of the grid-forming unit if the simulated value of the effective impedance of the grid-forming unit corresponds to the measured value with a maximum deviation of $\pm 5\%$.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.8 Continuous voltage control in accordance with the test in Section 5.5.5.6

The measurements described in Section 5.5.5.6 shall be simulated.

NOTE It is recommended that the short-circuit ratio (SCR) at the terminals of the grid-forming unit in the simulation environment corresponds with sufficient accuracy to the SCR in the test environment.

Setpoint response in accordance with the test in Section 5.5.5.6.1

The measurement described in Section 5.5.5.6.1.2 may be simulated using the EMT model and the detailed RMS model. The simulated rise time of the voltage u_1 or $u_{1,S}$, or alternatively the reactive current $i_{Q,1}$ or $i_{Q,1,S}$ shall be compared with the result of the measurement. The simulated rise time shall not deviate from the measured value by more than $\pm 5\%$ or ± 50 ms. The steady-state currents and voltages simulated using the EMT model or detailed RMS model may only deviate from the measured values by $\pm 5\%$.

Note for TR8:

The model is considered validated regarding the correct representation of the setpoint response of the continuous voltage control of the grid-forming unit if:

- *the simulated rise time of the voltage or reactive current corresponds to the measured rise time with a maximum deviation of $\pm 5\%$,*
- *the simulated steady-state currents and voltages correspond to the measured currents and voltages with a maximum deviation of $\pm 5\%$.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

Interference behaviour and linearity of the effective impedance in accordance with the test in Section 5.5.5.6.2

The measurement described in Section 5.5.5.6.2.2 shall be simulated using the EMT model and detailed RMS model and evaluated in accordance with Section 5.5.5.6.2.3. The settling time of the reactive current $i_{Q,1,S}$ determined with the EMT model and RMS model and the damping of the settling process shall not deviate by more than $\pm 15\%$ from the measured values. The profile of the reactive current shall lie within the curve in accordance with Figure 9 at all times. The steady-state currents and voltages simulated with the EMT model or detailed RMS model may only deviate from the measured values by $\pm 5\%$.

Note for TR8:

The model is considered validated regarding the correct representation of the interference behaviour of the continuous voltage control and the linearity of the effective impedance of the grid-forming unit if:

- *the settling time of the reactive current simulated with the EMT model and the detailed RMS model corresponds to the measured settling time with a maximum deviation of $\pm 5\%$ and the profile of the reactive current is always within the curve in accordance with Figure 9,*

- the simulated damping of the reactive current transient using the EMT model and the detailed RMS model corresponds to the measured damping with a maximum deviation of $\pm 15\%$,
- the simulated steady-state currents and voltages correspond to the respective measured currents and voltages with a maximum deviation of $\pm 5\%$.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

O/UVRT robustness of the continuous voltage control in accordance with the test in Section 5.5.5.6.3

The measurements described in Section 5.5.5.6.3.2 may be simulated using the EMT model and the detailed RMS model. The simulations are evaluated in accordance with Section 5.5.5.6.3.3. The simulated rise time of the instantaneous value of the current shall not deviate by more than $\pm 20\%$ from the measured value. The simulated settling time of the positive sequence reactive current and the damping of the settling process shall not deviate by more than $\pm 20\%$ from the measured value.

Note for TR8:

The model is considered validated regarding the correct representation of the O/UVRT robustness of the grid-forming unit if:

- the simulated rise time of the instantaneous value of the current corresponds to the measured rise time with a maximum deviation of $\pm 20\%$,
- the simulated settling time of the positive sequence reactive current corresponds to the measured settling time with a maximum deviation of $\pm 20\%$,
- the simulated damping of the settling process of the positive sequence reactive current corresponds to the measured value with a maximum deviation of $\pm 20\%$.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

Verification of behaviour when reaching and leaving the current limits in accordance with the tests in Section 5.5.5.6.4

The measurement described in Section 5.5.5.6.4 shall be simulated. The power component may be disregarded in the EMT simulation model, since an evaluation of the THD is not required.

For both the EMT and the detailed RMS model, it shall be verified that:

- the grid-forming unit is stable during voltage dips down to residual voltages ≥ 0.2 p.u,
- the apparent current of the grid-forming unit averaged over the duration of the voltage dip does not fall below 95 % of the rated current or (if the current limit of the grid-forming unit is not reached) of the expected apparent current of the unit resulting from the operating point before the measurement and the average value of the effective impedances determined in Section 5.5.5.4,
- the active current during a voltage dip of approximately 50 % and 25 % with initial conditions at full load is not less than 5 % of the rated current.

Note for TR8:

The model is considered validated regarding the correct representation of the behaviour of the grid-forming unit when reaching and leaving the current limits if:

- the simulation results of the EMT model and the detailed RMS model show that the grid-forming unit is stable during voltage dips ≥ 0.2 p.u,
- the simulation results from the EMT and the RMS models show, that the apparent current of the grid-forming unit averaged over the duration of the voltage dip does not fall below 95 % of the rated current or (if the current limit of the grid-forming unit is not reached) of the expected apparent current of the unit resulting from the operating point before the measurement and the average value of the effective impedances determined in Section 5.5.5.4,

- the simulated active current during the tested voltage dip, starting from an operating point at full load, is not less than 5 % of the rated current.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

Behaviour when resuming a value within the voltage range of $U_c \pm 10 \% U_c$ in accordance with the tests in Section 5.5.5.6.5

The measurement described in Section 5.5.5.6.5 shall be simulated. For the EMT model and detailed RMS model, it shall be demonstrated that the active current recovery after the end of the fault fulfils the conditions for the grid-forming unit. This also applies to the behaviour regarding transient overvoltages.

For both the EMT and the detailed RMS model, it shall be verified that:

- the settling time of the simulated active current to reach the pre-fault active current is ≤ 1 s and the simulated value does not deviate by more than 20 % from the measured value. If this time cannot be achieved due to the effective T_A , the time required to reach the target shall be specified,
- the simulated system overvoltages (overshoot) do not exceed the steady-state end value of the voltage by more than 5 %; notwithstanding, a value of 2.5 % of the steady-state end value of the voltage applies until 31 December 2027,
- the simulated value of the overvoltages does not deviate by more than 20 % from the measured value.

Note for TR8:

The model is considered validated regarding the correct representation of the behaviour of the grid-forming unit when returning to the voltage band of $U_c \pm 10 \% U_c$ if the model meets the following criteria.

- *Regarding the behaviour for the active current recovery, the following applies: the simulated active current reaches the value of the pre-fault active current again after 1 s and the simulated value does not deviate by more than 20 % from the measured value, otherwise, if this target cannot be reached within this time due to the effective T_A , the time required to reach the target shall be specified.*
- *Regarding the behaviour in the event of temporary overvoltages after voltage recovery, the following applies: the simulated system overvoltages (overshoot) do not exceed the steady-state end value of the voltage by more than 5 %; notwithstanding, a value of 2.5 % of the steady-state end value of the voltage applies until 31 December 2027.*
- *The simulated value of the overvoltages does not deviate by more than 20 % from the measured value.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

Fast protection during high voltages in accordance with the tests in Section 5.5.5.6.6

It shall be verified by simulation using the EMT model and the detailed RMS model according to Section 5.5.5.6.6 that the functionality of the fast protection during high voltages (voltage amplitude step to a value greater than 1.35 p.u.) fulfils the following criteria:

- Within 40 ms after the sudden amplitude change, the grid-forming unit transitions permanently to a state in which the half-oscillation RMS value of the current in each conductor is limited to a maximum of 5 % of the rated current. In this case, the half-oscillation RMS values of the currents are indicated for each conductor after the voltage is applied.
- Compliance with the requirements for fast protection at high voltages does not undermine the requirements for OVRT robustness in accordance with Section 4.2.1.6.2.

Note for TR8:

The model is considered validated regarding the correct representation of fast protection during high voltages if:

- the functionality of fast protection during high voltages implemented in the RMS model and EMT model of the grid-forming unit transitions within 40 ms permanently to a state in which the half-oscillation RMS value of the simulated current in each conductor is limited to a maximum of 5 % of the rated current,
- the requirements for OVRT robustness are still met despite the implemented functionality of fast protection during high voltages.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.9 Response to steep frequency gradients in accordance with the test in Section 5.5.5.7

It shall be verified through simulation, that the simulation model can also fulfil the requirements of the relevant Technical Connection Rule in accordance with Clause 10.2.4.3 "Passing through fast frequency changes". If the manufacturer has specified other framework conditions for meeting the requirements in the manufacturer's declaration, these shall be taken into account for the test. In addition, it shall be shown that the frequency profiles indicated in Section 4.2.1.13 in Figure 4 can be run through without disconnecting the unit from the network or without loss of stability of the unit. This validation step is considered successfully completed if the model validation based on the tests for the start-up time constant and inertia energy (Section 5.5.5.9) could be performed without reaching states that would lead to a disconnection of the grid-forming unit by the internal protection or loss of mains protection.

Note for TR8:

The model is considered validated regarding the correct representation of the response of the grid-forming unit to steep frequency gradients:

- the simulation results show that the grid-forming unit can operate through the RoCoF values required in accordance with Clause 10.2.4.3 of the relevant Technical Connection Rules without disconnecting from the grid or losing stability; or if other framework conditions for meeting the requirements were specified by the manufacturer, the stated criteria are fulfilled under these framework conditions,
- simulation results show that the grid-forming unit can operate through the frequency profiles indicated in Figure 4 without disconnecting the unit from the grid or losing stability.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.10 Damping of power-frequency-oscillations according to test in Section 5.5.5.8

The tests described in Section 5.5.5.8 shall be simulated. The short-circuit ratio (SCR) at the terminals of the grid-forming unit in the simulation environment shall be set to the value determined in the test environment or the test environment used shall be included in the model validation.

- 1) Starting from the initial steady-state condition and continuing to the final steady-state condition, the profile of the measured fundamental component of the positive system active power p_1 shall be compared with the corresponding simulated fundamental component of the positive sequence active power $p_{1,S}$ (EMT model or RMS model).
- 2) The damping of the settling response of the positive sequence active power shall be determined for the tests performed. The determination of the attenuation based on a frequency or power response to a phase angle step may be determined according to the procedure contained in the test specification. The required damping ratio corresponds to the requirements for damping power-frequency-oscillations in the frequency range of 0.05 Hz - 10 Hz and shall be used by the simulation model with an accuracy of ± 5 % compared to the measured damping ratio. Similarly, the frequency of the settling process of the measured positive sequence active power p_1 of the grid-forming unit shall be determined and compared with the frequency of the settling process of the positive sequence active power of the simulation model $p_{1,S}$. The frequency of the settling process in the frequency range of the power-frequency-oscillations from 0.05 Hz to 10 Hz of the active power of the simulation model $p_{1,S}$ may deviate by a maximum of ± 5 % from the value p_1 determined from the test.

- 3) In the event that the settling process of the measured power p_1 is heavily damped and a damping ratio cannot be determined, the settling process of the power $p_{1,S}$ of the simulation model shall be compared with the active power p_1 measured on the test object, starting from the initial steady state until the final steady state is reached. The procedure according to FGW TR4, Revision 10, Chapter E.5.2.1.1, Section (3) shall be used to evaluate the agreement between the simulation model and the test object.
- 4) In the case of wind turbines, if the settling process of the active power is superimposed by other system vibrations (e.g. tower vibrations), the active power measurement may be corrected accordingly. The methods used for this shall be agreed with the relevant certification body.

Note for TR8:

The model is considered validated regarding the correct representation of the damping of power-frequency-oscillations of the grid-forming unit:

- *the simulated damping ratio in the frequency range of 0.05 Hz - 10 Hz does not fall below the value of 0.5 by more than 10 % ($D \geq 0.45$) and corresponds to the measured damping ratio with a maximum deviation of ± 5 %,*
- *the frequency of the settling process (in the frequency range of the power-frequency-oscillations) of the simulated active power corresponds to the measured frequency with a maximum deviation of ± 5 %,*
- *Simulation results show that the grid-forming unit can operate through the RoCoF values required in Clause 10.2.4.3 of the relevant Technical Connection Rules without disconnecting from the grid, or otherwise the framework conditions shall be indicated,*
- *if the procedure according to FGW TR4, Revision 10, Chapter E.5.2.1.1 is used, the tolerances specified are verified there.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.3 Validation of RMS type models

Depending on tests, the signals $i_{p,1,S}$, $u_{1,S}$ and $p_{1,S}$ shall be used model validation of the RMS type model.

The model validation of the RMS type model is based on the comparison with the detailed RMS model. The specified model tolerances for the EMT model or detailed RMS model relative to the behaviour of the test object shall be systematically applied to the comparative behaviour between the detailed RMS model and the RMS type model. The following exceptions apply:

- 1) The steady-state voltage at the terminals of the grid-forming unit determined for the RMS type model shall not deviate from the values determined for the detailed simulation model by more than ± 1 % relative to the rated voltage value.
- 2) The maximum value of the power response to a phase angle step determined for the RMS type model shall not deviate from that of the detailed RMS model by more than ± 5 % relative to the nominal value.
- 3) The maximum values of the damping of the power-frequency-oscillations determined for the RMS type model shall not deviate from the values of the detailed RMS model by more than ± 5 %. This also applies to the period of the power-frequency-oscillations.
- 4) The modelled FRT behaviour in the detailed RMS simulation model may be aligned with the simulation in the RMS type model as follows:
 - The curves of the active and reactive currents resulting 100 ms after fault occurrence until fault clearance and 100 ms after fault clearance until the steady state is reached shall be within a tolerance band of ± 15 % around the corresponding values of the detailed RMS simulation model.
 - The tolerance specification of 15 % is to be related to the determined value of the detailed RMS model. The minimum tolerance value is 2 % of the nominal value.

The RMS type model shall fulfil all the requirements of this FNN Guideline.

5.5.3.6.3 Plausibility check of the simulation models

The models provided shall be checked for plausibility in accordance with FGW TR4, Revision 10, Chapter 9.

5.5.3.6.4 Model documentation

The functionality and parametrisation of the simulation model shall be documented. It shall also be shown that the requirements in Section 4.2 have been verified based on simulation in the test environment in accordance with the tests specified in Section 5.5.3.6.2. In detail, the model documentation shall include the following information:

- 1) The simulation model shall be documented in accordance with FGW TR4, Revision 10, Chapter 7.2. Based on the RMS type model, the functionality of the grid-forming unit should be described. Based on the EMT or RMS models, the grid-forming unit as a whole shall then be described in detail. This includes power electronic components, electrical components belonging to the grid-forming unit (e.g. filters), control system, houseload (if relevant), loss of mains protection as well as the internal protection, insofar as it is part of the simulation model.
- 2) The simplifications and assumptions essential for the different simulation models shall be stated.
- 3) In addition, based on a complete project definition, the tests performed on the operational system shall be documented in addition to the corresponding simulations with the validated model types (EMT model, detailed RMS model and RMS type model) for selected measured values or signals of the grid-forming unit such as voltages and currents as well as the intermediate variables identified as required, as a comparison of the signals in standardised graphical representations.
- 4) All parameters for defining types of grid-forming units within a family as well as their parametrisations and operating ranges (e.g. nominal values, PQ - and UQ diagrams) shall be presented in a table. The intended or permissible setting ranges of parameters and any existing dependencies shall be specified.
- 5) The simulation-based verifications required in accordance with Section 5.5.6 for non-measured values of the start-up time constant T_A shall be included in the model documentation, including any additional parametrisations that may be required.

5.5.3.7 Requirements for the simulation environment and tool independence

The requirements of FGW TR4, Revision 10, Chapter 4 for the modelling software and tool environment apply. If users (manufacturers, certification bodies and network operators) develop additional features that simplify the process and have not yet been incorporated into new revisions of FGW TR4, these shall be taken into account.

Such developments include:

- 1) Availability of controller code in the form of a universally usable DLL with input and output signals (C interface) for use in EMT models and/or detailed RMS models in the agreed simulation environments or for flexible connection to other simulation tools used.
- 2) Use of new de facto standards for the integration of controller code (e.g. FMI for CS, FMI for ME, IEEE/Cigre/IEC, etc.).

Deviations from the requirements of FGW TR4, Revision 10 may be permitted as long as modelling requirements and their validation are not affected. This always requires the coordination among the certification body, network operator and manufacturer.

The simulation models shall be made available for the agreed simulation environment for the software versions supported by the manufacturer of the simulation software. The manufacturer is responsible to ensure that the simulation models are executable in the currently supported software versions and that older model versions remain usable. Commercially available programmes that are predominantly used by network operators and certification bodies are considered as agreed simulation environments.

5.5.3.8 Manufacturer models for the purpose of certification

The manufacturer may determine the level of detail of the simulation model of the grid-forming unit. However, the level of detail shall be selected to fulfil the requirements for model accuracy for all simulation-based verifications based on a uniform model parametrised for a defined T_A . If required, the parameter used for different T_A s shall be documented. The signals listed in Section 5.5.2.1 and the intended parametrisations shall be made available if they are required for the corresponding verifications.

5.5.3.9 Models for use by the network operator

The simulation models of the system to be provided in accordance with the relevant Technical Connection Rules or individual Technical Connection Conditions of the network operator shall be created based on suitable, verified unit models. If the relevant Technical Connection Rules or Technical Connection Conditions do not result in more stringent requirements, unit models that fulfil the requirements of Section 5.5.3 shall be used.

The disclosure of open, executable models with model type assignments, corresponding descriptions and applicable parameters published by the manufacturer in a publicly accessible type library is permitted at any time.

The disclosure of EMT models and RMS models with included controller code or otherwise encrypted components requires the consent of the respective manufacturer. The disclosure to third parties for the purpose of using the models in the context of network studies always requires the agreement of a standardised non-disclosure agreement (NDA) between the third party and the network operator.

5.5.4 Verifications for virtual island network operation

5.5.4.1 Aim of the measurements

The following properties shall be verified by the measurements on the virtual island network:

- 1) Behaviour of voltage sources in accordance with Section 4.2.1.1
- 2) Compliance with the requirements for the response to overfrequency and underfrequency (PCNB) in accordance with Section 4.2.2.

The design of the primary control based on network security as proportional speed control shall also be confirmed in the manufacturer's declaration.

5.5.4.2 Test environment for measurement in virtual island network operation

The grid-forming unit is operated in synchronism with the network or on a network emulator for measurement in virtual island network operation in a test environment as shown in Figure 7. The short-circuit power ratio should be $SCR \geq 3^{17}$.

The test environment includes adjustable loads (switchable load banks P and/or converter-based loads with adjustable P -range with constant power or resistance characteristics) that correspond to the grid-forming unit adjusting its loading condition from the technical minimum power $P_{Emin,E}$ to the maximum active power P_{Emax} .

The internal protection of the unit and the PCNB shall be active.

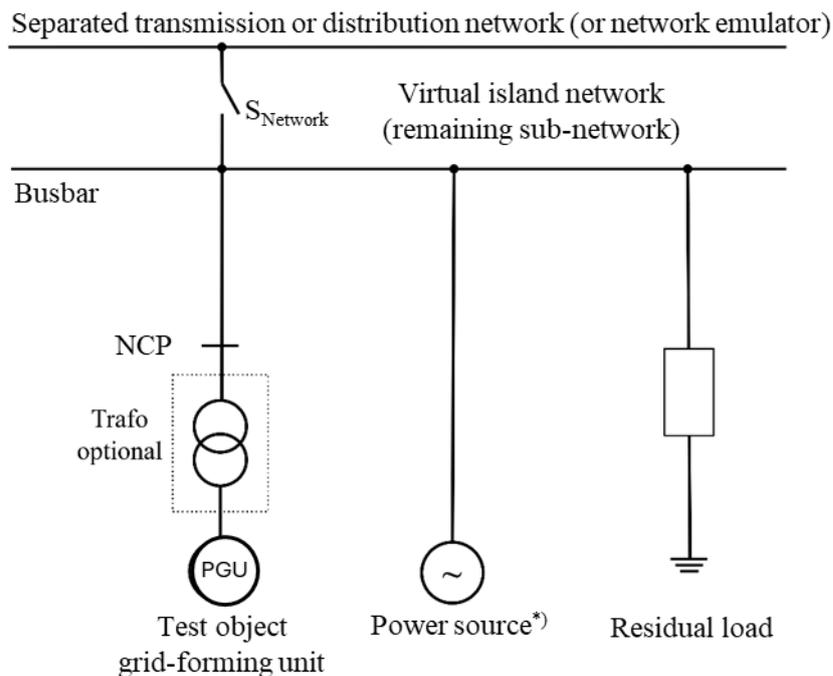


Figure 7 - Example test environment for measurements in the virtual island network

*) only required for test 1.4)

¹⁷ The test results obtained with a low SCR value may be used.

5.5.4.3 Measurement procedure

Introduction

The test environment for measuring a grid-forming unit described in Section 5.5.4.2 is used to measure the ability of the device to fulfil the requirements for voltage source behaviour in accordance with Section 4.2.1.1 and to fulfil the PCNB requirements in accordance with Section 4.2.2. For both properties, it shall be determined based on the measurement-based tests in Table 3 whether the test object in the virtual island network meets the requirements for stability of the small and large signal behaviour. Both properties shall be evaluated individually based on the measurement procedures described in this section in Section 5.5.4.4 and documented individually in Section 5.5.4.5.

Table 3 - Measurements in the virtual island network for the verification of inherent stability, voltage source behaviour and PCNB for units which provide negative inertia

Measurement		Initial power of the grid-forming unit		Residual load	
		P_{mom} (% P_{Emax})	Q / P_{Emax} (-)	P_{residual} (-)	$\frac{Q_{\text{rest}}}{P_{\text{Emax}}}$ (-)
Behaviour as a voltage source (large signal) and PCNB in the procured direction of inertia power	1.1	$\geq (P_{\text{residual}} + 23 \% P_{\text{Emax}}^{\text{e}})$	0.0	45 % P_{Emax} to 65 % P_{Emax} alternatively - 45 % P_{Emax} to - 65 % P_{Emax} when measuring 1.4	0.0
	1.2		max. ind.		
	1.3		max. cap.		
	1.4 ^{a)}	$P_{\text{Emax}} + P_{\text{residual}}$	0.0		
Small-signal behaviour in the non-procured direction of inertia	2.1 ^{b)-d)}	85 % – 95 % P_{residual}	0.0		

a) Check load step with active power reversal only for units that operate both as load and generation (e.g. storage).
b) Suitable throttled operation and sufficient primary energy supply are required for this test.
c) If lower values are permitted in accordance with Table 10 Appendix B.I. regarding the power amplitude, these may be applied.
d) Not applicable if the inertia is procured in both positive and negative directions.
e) This corresponds to at least half of the power response to a phase angle step of 45% P_{Emax} in the (negative) procured direction in accordance with the requirements. This is a compromise to enable the tests to be performed in practice with reasonable effort.

Conducting measurements

Starting from a steady-state operating point of the output power of the grid-forming unit in parallel network operation (Columns 3 and 4 in Table 3), generate the operating condition of virtual island network according to Figure 7 for all measurements specified in Table 3 by opening the network interconnecting circuit breakers (S_{Network}), in which the grid-forming unit to be measured exclusively supplies the adjustable residual load (P_{residual}) (Columns 5 and 6 in Table 3). Set the values for the residual load according to Table 3 for the respective measurements before the start the operation of the virtual island network.

Ensure that the operating condition of the virtual island network is maintained until a stable operating point is reached, for at least 50 seconds.

Inductive or capacitive components (such as cables and transformers) required in the test setup may be disregarded in the following measurements and their influence neglected.

5.5.4.4 Evaluation

5.5.4.4.1 Evaluation of the voltage source behaviour

The maximum/minimum and steady-state values of the recorded positive sequence variables of active power p_1 , reactive power q_1 , frequency f_1 and voltage u_1 shall be determined for all measurements according to Table 3.

Furthermore, the respective deviations from the steady-state starting points shall be determined. The achievement of a steady-state, stable final value shall be determined in each case.

5.5.4.4.2 Evaluation of the behaviour during overfrequency and underfrequency (PCNB) in the unlimited setting range

The maximum/minimum and steady-state values of the recorded positive sequence variables of active power p_1 and frequency f_1 shall be determined for all measurements according to Table 3.

In the case of wind energy units, the frequency profile can be influenced by excitations of the mechanical resonances. The frequency superimposed due to mechanical vibrations may be extracted using Prony analysis in accordance with Appendix A.V .

Furthermore, the respective deviations from the initial steady-state points shall be determined. The achievement of a steady-state, stable final value shall be determined in each case.

Measurement 2.1 performed in accordance with Table 3 shall also be evaluated as follows: the damping shall be determined for the settling process of the frequency to the final steady-state value. This may be done by evaluating two successive frequency minima or frequency maxima, whereby the first frequency maximum or frequency minimum should not be included in the evaluation (see also Appendix A.I).

If a settling process is observed with no consecutive detectable amplitude maxima or minima, the damping may be determined by approximation using a 2nd order vibration equation by parameter adaptation. If no clear value for the damping can be determined in this way either, the damping may be assumed to be aperiodic with a damping ratio $D > 0.5$.

5.5.4.5 Presentation in the measurement report

5.5.4.5.1 Presentation in the measurement report: Behaviour of voltage sources

The measured or calculated positive sequence variables of active power p_1 , reactive power q_1 , frequency f_1 and the positive and negative sequence components of the voltage u_1, u_2 shall be documented graphically, starting from the steady-state condition before the start of the test until the steady-state condition is reached in the virtual island network. Maximum, minimum and steady-state values shall be labelled. If the mechanical vibrations have been eliminated from the active power curve, both active power curves (without and with the elimination of the influence of mechanical vibrations) shall be shown.

The instantaneous values of the phase currents i_a, i_b, i_c and phase voltages u_a, u_b, u_c at the terminals of the grid-forming unit shall be shown from two network periods before the time at which the operating condition of the virtual island network is established over a total of 15 - 30 network periods.

Note for TR8:

The verification shall be considered successful, provided the following conditions are fulfilled:

Starting from an operating state at rated frequency, a steady-state of the frequency and active power output of the grid-forming unit corresponding to the preset residual load is achieved after the interconnecting circuit breaker ($S_{Network}$) is opened, without triggering the internal protection within the FRT limit curves specified in the relevant Technical Connection Rule, which would lead to a complete disconnection of the grid-forming unit.

5.5.4.5.2 Presentation in the measurement report: Response to overfrequency and underfrequency (PCNB) in the unlimited setting range

The measured positive sequence components of the active power p_1 and frequency f_1 shall be documented graphically for all measurements, starting from the initial steady-state condition before the start of the measurement up to and including the steady-state condition achieved in the virtual island network. Maximum, minimum and steady-state values shall be labelled.

The amplitude minima and maxima used to determine the damping values shall be labelled in a graphic. The corresponding amplitude values shall be indicated. The damping ratio determined shall be stated. If the damping is determined by approximation using a 2nd order vibration equation, the measured frequency shall

be compared with the frequency adapted by calculation. If no clear damping value could be determined and a damping ratio $D > 0.5$ was assumed, this shall be documented in a comprehensible manner.

If the mechanical vibrations are eliminated from the frequency profile, both frequency profiles (without and with the elimination of the influence of mechanical vibrations) shall be shown.

Note for TR8:

The verification is considered provided if operation in the virtual island network can be maintained in a stable manner and the following criteria are fulfilled for measurements 1.1 to 1.4:

- *the frequency value 52.5 Hz is exceeded by a maximum of 0.1 s,*
- *the frequency value 51.5 Hz is exceeded for a maximum of 10 s,*
- *the settling behaviour of the measured frequency meets the required damping ratio according to Table 10 .*

Also, the verification is provided when the measured frequency profile as part of measurement 2.1 meets the requirement for the damping ratio in accordance with Table 10 . In addition, successfully performed measurements 1.1 to 1.4 and 2.1 together with a manufacturer's declaration shall establish that the primary control based on network security is implemented with proportional frequency control.

5.5.5 Verifications in synchronous operation

5.5.5.1 Aim of the tests

The following properties shall be verified by testing the grid-forming unit in synchronous operation:

- 1) The requirements for the power response to a phase angle step and the effective impedance in accordance with Section 4.2.1.1
- 2) Damping behaviour above 10 Hz in accordance with Section 4.2.1.2
- 3) The required behaviour of the voltage regulation including robustness against short-term overvoltage and undervoltage events (O/UVRT robustness) as well as fast protection during high voltages in accordance with Sections 4.2.1.4 to 4.2.1.6
- 4) The robustness against steep frequency gradients (ROCOF) in accordance with Section 4.2.1.9
- 5) The basic network parallel operation capability in accordance with Section 4.2.1.10
- 6) Damping of power-frequency-oscillations in accordance with Section 4.2.1.11
- 7) The inertia power and energy in accordance with Section 4.2.1.13 corresponding to the start-up time constant T_A in accordance with Section 4.2.1.12
- 8) The characteristics of the behaviour in the event of overfrequency and underfrequency (PCNB) in the limited setting range in accordance with Section 4.2.2.2

The tests mentioned under points 1) to 8) are explained further in the following sections.

5.5.5.2 Test environment for measurements in synchronous operation

The grid-forming unit is operated in synchronism with the network or on a network emulator for measurements in virtual island network operation in a test environment as shown in Figure 8. Part of the test environment is an FRT test device, which consists, for example, of a switchable series and cross reactor.

As an alternative to the test setup with an FRT test device, the grid-forming unit may be operated directly at an NCP. However, this test arrangement is only possible if a test in accordance with Section 5.5.5.1, points 1) to 8), can be performed through the activation of appropriate signals on the grid-forming unit.

Unless otherwise specified, the test environment according to this section applies to all tests specified in Section 5.5.5.1, points 1) to 8).

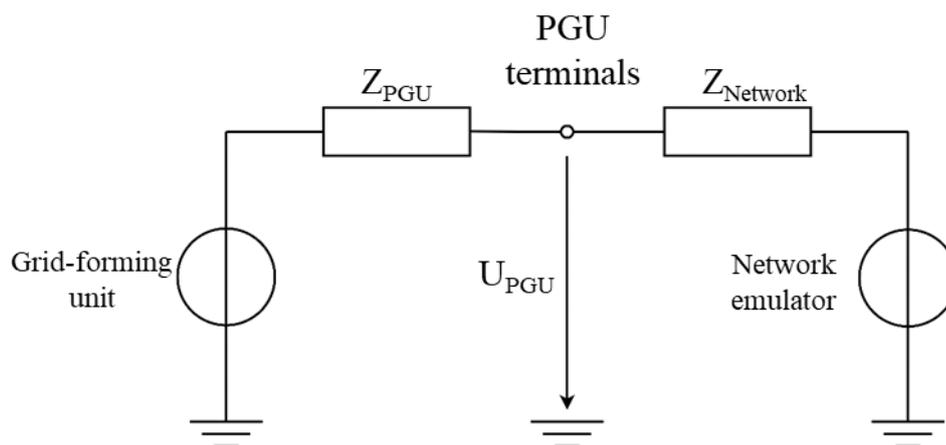


Figure 8 - Example test environment for measurements in synchronous operation

5.5.5.3 Verification of the power response to a phase angle step (Section 4.2.1.1)

5.5.5.3.1 Aim of the measurement

The aim of the measurement is to determine the power response to a phase angle step provided by the grid-forming unit. This involves checking compliance with the requirements in Section 4.2.1.1.

5.5.5.3.2 Measurement procedure

Based on an operating point of $50\% P_{E_{\max}} \pm 5\% P_{E_{\max}}$, one of the following two measurement procedures shall be performed, whereby the reactive power feed-in at the start of the test shall be within a range of $\pm 5\%$ (relative to $P_{E_{\max}}$).

Measurement procedure 1 - Activation of an angular jump

Apply an angular step change $\Delta\theta_{\text{setpoint}}$ to the internal voltage angle θ_{intern} to the grid-forming unit so that a corresponding change in the active power output ΔP_{PGU} of at least $45\% P_{E_{\max}}$ can be measured at the terminals of the grid-forming unit in the procured direction. Repeat this measurement starting from the same operating point $\pm 5\% P_{E_{\max}}$ with the identical phase angle step with a negative sign $-\Delta\theta_{\text{setpoint}}$.

Measurement procedure 2 - Application of a change in angle

Apply an angular change on the voltage at the terminals of the grid-forming unit, for example through a network emulator or FRT test device, so that a corresponding change in the active power P_{PGU} output of at least $45\% P_{E_{\max}}$ can be measured at the terminals of the grid-forming unit in the procured direction. Repeat this measurement starting from the same operating point $\pm 5\% P_{E_{\max}}$ with the identical phase angle step with a negative sign $-\Delta\theta_{\text{setpoint}} \pm 10\%$. It is no longer required to take into account the voltage changes at the terminals of the grid-forming unit associated with the phase angle step.

Determine the voltage angle of the voltage at the terminals of the grid-forming unit as the angle of the voltage space vector in a coordinate system rotating at nominal frequency.

5.5.5.3.3 Evaluation

Measurement procedure 1

A maximum angle change is determined from the transient curve of the voltage angle at the terminals of the grid-forming unit based on the initial steady state. The difference between the applied angle change of the internal voltage angle and the determined maximum angle change of the voltage at the terminals of the grid-forming unit shall be determined ($\Delta\delta_1$). The transient change in active power (i.e. power response to a phase angle step) and change in active current $\Delta i_{\text{P,PGU}}$ shall be determined as an instantaneous value based on the initial steady state.

Equation (6) is used to determine the required maximum value $\Delta i_{\text{P1,PGU,max}}$. In this equation, the linearity of the sine shape may be assumed:

$$(\sin(\delta_{n1}) - \sin(\delta_{v1})) \approx \sin(\Delta\delta_1) \quad (7)$$

This means that the maximum value $\Delta i_{\text{P1,PGU,max}}$ of the active current response $\Delta i_{\text{P,PGU}}$ triggered by a jump of the voltage phase angle shall be determined and indicated as follows based on the previously determined $\Delta\delta_1$:

$$\Delta i_{\text{P1,PGU,max}} = -\frac{1}{z_{\text{w,max}}} \sin(\Delta\delta_1) \quad (8)$$

where the values for $z_{\text{w,max}}$ can be found in Section 4.2.1.1.

Measurement procedure 2

The transient change in measurement 2 in active power $p_{\alpha\beta}$ (i.e. power response to a phase angle step) and change in active current $\Delta i_{\text{P,PGU}}$ shall be determined as space vector $i_{\text{P,\alpha\beta}}$ values based on the initial steady-state. At the time when the maximum change in active power occurs, the angle difference of the voltage at the terminals of the grid-forming unit to its initial value shall be determined ($\Delta\delta_1$) (see Appendix B.VI). Equation

(6) is used to determine the required maximum value $\Delta i_{P1,PGU,max}$. The assumption described for Equation (7) is permissible.

This means that the maximum value $\Delta i_{P1,PGU,max}$ of the active current response $\Delta i_{P,PGU}$ triggered by the jump of the voltage phase angle shall be determined and indicated based on the value of $\Delta\delta_1$ which had been previously determined using equation (8).

5.5.5.3.4 Presentation in the measurement report

The measured active power $p_{\alpha\beta}$ and the measured active current $i_{P,\alpha\beta}$ shall be documented graphically from the initial steady-state condition before the start of the measurement up to and including the final steady-state condition after the measurement. The maximum values of the active power and the active current shall be labelled and their values shall be indicated.

Note for TR8:

The test is considered passed if the maximum change in active current $\Delta i_{P,PGU}$ in the procured direction is at least 50 % and in the non-procured direction at least 5 % of the determined maximum value $\Delta i_{P1,PGU,max}$. A tolerance of 1 % of the nominal active current may be assumed. Alternatively, the test is considered passed in the non-procured direction, if the maximum change in active power is at least 5 % P_{Emax} .

5.5.5.4 Verification of the effective impedance (Section 4.2.1.1)

5.5.5.4.1 Aim of the measurement

The aim of the measurement is to determine the effective impedance and compliance with the maximum values ($z_{w,max}$) in accordance with Section 4.2.1.1 when the voltage amplitude at the terminals of the grid-forming unit changes.

5.5.5.4.2 Measurement procedure

The effective impedance is determined using one of the measurement procedures described below. In both measurement procedures, two different changes in the voltage at the terminals occur, starting with an operating state with:

- an active power feed $> 55 \% P_{Emax}$,
- at the two reactive power operating points of 10 % ($\pm 5 \%$) and - 10 % ($\pm 5 \%$) relative to P_{Emax} and
- a short-circuit power ratio of $SCR \geq 3^{18}$.

Active power throttled operation is permitted and the active power shall be kept as constant as possible during the measurements ($\pm 10 \% P_n$).

Measurement procedure 1 - Excitation by activating a jump in the setpoint

Energize the grid-forming unit by connecting a setpoint step, which leads to a change in $\Delta u_{setpoint}$ to the voltage at the terminals setpoint $u_{setpoint}$ of the grid-forming unit (see also Figure 2). The setpoint step $\Delta u_{setpoint}$ should be $\pm 0.03 - 0.05$ p.u. Wait until the steady state is reached before a new change in the voltage setpoint ($\Delta u_{setpoint} = +0.03 - 0.05$ p.u. \rightarrow 0 p.u. \rightarrow -0.03 - 0.05 p.u. \rightarrow 0 p.u.).

NOTE 1 *The $\Delta u_{setpoint}$ specifications at the terminals of the grid-forming unit will not be reached due to the P-characteristic of the continuous voltage control.*

¹⁸ The test results obtained with a low SCR value may be used.

NOTE 2 The short-circuit power ratio at the terminals of the grid-forming unit may depend on the test device. If the short-circuit power ratio of the test device does not permit values of $SCR \geq 3$, the measurement may also be performed with a value of $SCR \geq 1$.

Measurement procedure 2 - Change in voltage at the terminals

The terminal voltage of the grid-forming unit is changed (e.g. by a network emulator or bridging or by cancelling a bridging of the series reactor or correspondingly small steps of the transverse reactor of the FRT test device). The measurement consists of two steps that lead to a change in the terminal voltage Δu_{PGU} of the grid-forming unit. Taking into account the influence of the voltage regulation, adjust the values of the positive sequence terminal voltage (resulting from the two steps) Δu_I and Δu_{II} of the grid-forming unit so that they differ in magnitude by at least 2 % both from the original operating point and from each other (e.g. $\Delta u_I = 0.03 - 0.05$ p.u. and $\Delta u_{II} = 0.07 - 0.1$ p.u.). To avoid external influences, these two steps should be performed in quick succession. Angle steps associated with the connection of the voltage step are already taken into account in the evaluation.

Repeat the measurements of both measurement procedures based on an active power output in the range of 15 % - 45 % $P_{E_{max}}$ and a reactive power feed-in in the range ± 10 % (relative to $P_{E_{max}}$), whereby the voltage setpoint jump $\Delta u_{setpoint}$ (according to measurement procedure 1) shall now only occur in the negative direction. At this operating point the unit may operate with throttled active power.

NOTE 3 No current limitation should apply during measurements.

5.5.5.4.3 Evaluation

Measurement procedure 1

Based on the terminal voltage $\underline{u}_{1,v}$ of the grid-forming unit before (v) the start of the measurement and the associated apparent current $\underline{i}_{S1,v}$, the steady-state terminal voltage $\underline{u}_{1,n}$ of the grid-forming unit and the associated apparent current $\underline{i}_{S1,n}$ after (n) the measurement was performed and the specified setpoint change $\Delta u_{setpoint}$, the effective impedance $\underline{z}_{w,1}$ shall be determined as follows:

$$\underline{z}_{w,1} = \frac{\underline{u}_{1,n} - \underline{u}_{1,v} \pm \Delta u_{setpoint}}{\underline{i}_{S1,n} - \underline{i}_{S1,v}} \quad (9)$$

The angle of the internal voltage is relevant for the evaluation. If the effective impedance is determined using this method, the angle of the internal voltage source shall be evaluated in order to determine the internal voltage change according to magnitude and phase.

Measurement procedure 2

Based on the terminal voltage $\underline{u}_{1,v}$ of the grid-forming unit before (v) the start of the measurement and the associated apparent current $\underline{i}_{S1,v}$, the steady-state terminal voltage $\underline{u}_{1,n}$ of the grid-forming unit and the associated apparent current $\underline{i}_{S1,n}$ after (n) the measurement was performed, the effective impedance $\underline{z}_{w,1}$ shall be determined as follows:

$$\underline{z}_{w,1} = \frac{\underline{u}_{1,n} - \underline{u}_{1,v}}{\underline{i}_{S1,n} - \underline{i}_{S1,v}} \quad (10)$$

The values are considered to be in a steady state if all positive sequence values averaged over 100 ms have not changed by more than ± 2 % of the respective nominal value over 2 s. The values to be used in Equation (10) correspond to the positive sequence values averaged over 2 s for the evaluation window under consideration.

5.5.5.4.4 Presentation in the measurement report

The progression over time of the measured positive sequence terminal voltages u_1 of the grid-forming unit and the active and reactive components $i_{P,1}$, $i_{Q,1}$ of the positive sequence apparent current $i_{S,1}$ shall be

documented graphically, starting from the initial steady state before the start of the measurement up to and including the steady state after the measurement was performed. The steady-state values of the voltages $\underline{u}_{1,v}$, $\underline{u}_{1,n}$ and currents $\underline{i}_{S1,v}$, $\underline{i}_{S1,n}$ shall be labelled and their values shall be indicated.

The values of the impedance $\underline{z}_{w,1}$ resulting from the steady-state values of the voltages and currents shall be indicated in magnitude and phase angle.

Note for TR8:

The verification is considered provided if the values of the determined impedance $|\underline{z}_{w,l}|$ correspond to the specifications for the maximum value $z_{w,max}$ in Section 4.2.1.1.

5.5.5.5 Verification of the damping behaviour above 5 Hz (Section 4.2.1.2)

Verification of damping behaviour in the frequency range from 5 Hz to 1 kHz is determined through the manufacturer's declaration. The manufacturer's declaration shall state the impedance of the grid-forming unit in the frequency range from 5 Hz to 1 kHz. The specifications given here regarding procedures and evaluation shall be taken into account.

Procedures

The impedance curve in the specified frequency range may be determined using the following procedures, e.g. taking into account the procedure in Appendix A.IV:

- Measurement of the unit in the field or on the test bench (e.g. P-HIL, M-HIL)
- Measurement of individual components (e.g. converter with filter)
- C-HIL simulation, provided that the semiconductor components are simulated
- Off-line simulation, provided that the semiconductor components and the real control algorithms are simulated based on manufacturer models

If a test bench procedure (e.g. P-HIL) is used, the components that are not relevant (e.g. mechanical components) may be neglected or replaced by simulation, in deviation from the basic requirements for test bench tests for wind turbines (see Section 5.5.1).

Regardless of the method chosen, all control systems shall be activated in their standard parametrisation in accordance with the requirements of this FNN Guideline (in particular for PCNB).

The manufacturer may decide whether the specified impedance includes the unit transformer or not. If the impedance of the unit transformer was taken into account in the impedance of the grid-forming unit, this shall be indicated separately.

In the selected method, the evaluation described below shall be performed for the operating points specified in Table 4, in the case of storage devices for both charging and discharging operation.

Table 4 - Operating points for the examination of the impedance behaviour in the range of 5 Hz to 1 kHz

Operating point	$P_{\text{mom}}^{\text{a})}$ [% P_{Emax}]	Q / P_{Emax} [-]
1	0 - 25	0.0
2	25 - 50	0.0
3	50 - 75	0.0 / max. ind./ max cap.
4	75 - 100	0.0

a) PGUs with fluctuating power output may limit its active power by throttling in order to remain within the operating range.

Evaluation and presentation in the manufacturer's declaration

In the frequency range from 5 Hz to 1 kHz, the impedance curve in terms of magnitude and phase shall be determined and indicated for the positive and negative sequences. The step size shall not exceed 5 Hz (the range $45 \text{ Hz} < f < 55 \text{ Hz}$ may be excluded).

NOTE 1 Since the criterion of a 'positive real part' is not meaningful in the range $45 \text{ Hz} < f < 55 \text{ Hz}$, the impedance in this range may be omitted in the manufacturer's declaration.

The impedance curve shall take into account both the physical impedance and the proportion of control impedance and, where applicable, other influences of the converter control that are effective in the frequency range under investigation.

NOTE 2 The required impedance is not the pure ratio of voltage to current at the terminals of the grid-forming unit, as this ratio may be influenced by equivalent sources (such as Norton equivalent circuits). Therefore, the impedance shall be determined differentially, i.e. from the differences in voltage and current at two different operating points (see procedure in Appendix A.IV).

Note for TR8:

The manufacturer's declaration is comprehensible technically if the impedance of the grid-forming unit has a positive real part in the frequency range from 5 Hz to 1 kHz and the method used by the manufacturer to determine the impedance values is comprehensible and justified. No evaluation is made below 100 Hz.

5.5.5.6 Verification of continuous voltage control and FRT behaviour (Sections 4.2.1.4 to 4.2.1.5)

5.5.5.6.1 Verification of setpoint response

5.5.5.6.1.1 Aim of the measurement

The aim of the measurement is to determine the behaviour of the continuous voltage control when the setpoint changes.

5.5.5.6.1.2 Measurement procedure

The behaviour of the grid-forming unit when the setpoint changes is verified similarly as in measurement 1 in Section 5.5.5.4 by applying a setpoint jump under the initial operating conditions and excitation conditions specified there are reached.

NOTE The short-circuit power ratio at the terminals of the grid-forming unit may depend on the test device. If the short-circuit power ratio of the test equipment does not allow values of $SCR \geq 3$, a value of $SCR \geq 1$ may be used for the verification.

5.5.5.6.1.3 Evaluation

The rise time of u_1 relative to the final value shall be determined from the time profile of the positive sequence voltage u_1 . The time $t = 0$ at which the setpoint is changed shall be determined appropriately depending on the test environment. If the RMS voltage change (e.g. due to a high short-circuit power ratio) is not suitable for evaluation, the reactive current $i_{Q,1}$ of the PGU may be then used to evaluate the rise time.

5.5.5.6.1.4 Presentation in the measurement report

The profile of the setpoint and the evaluated variable (u_1 or $i_{Q,1}$) shall be documented graphically. The determined rise time shall be indicated.

Note for TR8:

The verification is considered provided if the determined rise time of the voltage u_1 (or alternatively of the current $i_{Q,1}$) is $< 1 \text{ s}$.

5.5.5.6.2 Verification of the disturbance response and the linearity of the effective impedance

5.5.5.6.2.1 Aim of the measurement

The aim of the measurement is to determine the rise time of the apparent current, the settling time and damping of the reactive current, and the linearity of the effective impedance in the small-signal or operating range without current limitation as a result of a sudden change in the mains voltage. The behaviour of the grid-forming unit is also determined in direct parallel operation with other grid-forming units.

5.5.5.6.2.2 Measurement procedure

The measurement to determine the behaviour of the grid-forming unit in the event of a sudden change in its terminal voltage at a constant setpoint is performed in accordance with the specifications of measurement procedure 2 in Section 5.5.5.4.2.

NOTE Measurement 1 in Section 5.5.5.4.2 may only be used if the setpoint is processed sufficiently quickly in the grid-forming unit.

The behaviour of the grid-forming unit in combination with several grid-forming units operated directly in parallel is determined by repeating the measurement in parallel operation analogous to the configuration mentioned above of at least two grid-forming units. This additional measurement is not required if the grid-forming unit is connected via a transformer assigned to the grid-forming unit (or its own transformer windings).

5.5.5.6.2.3 Evaluation

The sudden change in the amplitude of the terminal voltage of the grid-forming unit is determined by evaluating the voltage $u_{\alpha\beta,5ms}$ in $\alpha\beta$ coordinates (see Appendix B.V). The start of a sudden change in the amplitude of the terminal voltage, and thus time $t = 0$, is defined as the moment at which the change exceeds $u_{\alpha\beta,5ms}$ 10 % of the final value of the voltage change Δu compared to the arithmetic average of the last 25 ± 5 network periods before the voltage change. In the case of small voltage changes ($\Delta u \leq 0.1$ p.u.), this threshold may be increased to up to 25% of the final value of the voltage change Δu , provided that a clear threshold value cannot be determined due to excessive ripple of $u_{\alpha\beta,5ms}$.

The rise time of the current is evaluated using $i_{\alpha\beta,5ms}$ (see Appendix B.V).

The value of $\Delta i_{Q,End}$, as the final steady-state value of the reactive current change, is determined in the same way as the steady-state apparent currents $i_{S1,v}$ and $i_{S1,n}$ for use in equation (10) in Section 5.5.5.4.3.

The settling time of the reactive current is evaluated using the time profile of the positive sequence reactive current $i_{Q,1}$. The settling tolerances are +20 % I_r and -10 % I_r for $\Delta i_{Q,End} > 0$ or -20 % I_r and +10 % I_r for $\Delta i_{Q,End} < 0$.

The envelope curve in Figure 9 may be used to determine compliance with the damping requirements. This is based on a PT2 element with a damping factor of $D = 0.3$ and the final steady-state value $\Delta i_{Q,End}$ of the reactive current component $i_{Q,1}$ determined from $i_{S1,v}$ or $i_{S1,n}$ in a similar way as described in Section 5.5.5.4.3.

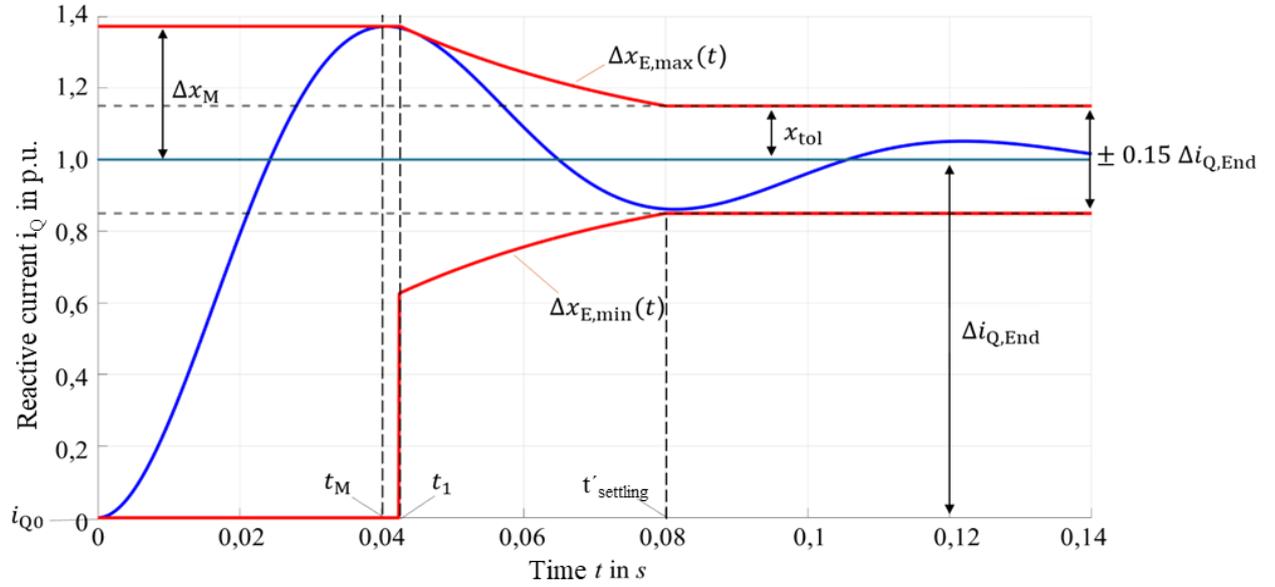


Figure 9 - Envelope curve for determining the damping of the continuous voltage control (i_Q is related to $\Delta i_{Q,End}$)

Equations (11) to (16) apply for the corner points of the envelope elements in Figure 9.

$$\Delta x_M = e^{-\frac{D}{\sqrt{1-D^2} \cdot \pi}} \cdot \Delta i_{Q,End} = 0.03723 \cdot \Delta i_{Q,End} \quad (11) \quad \Delta x_{E,max}(t) = \left(1 + \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} t}}{\sqrt{1-D^2}} \right) \cdot \Delta i_{Q,End} \quad (12)$$

$$\Delta x_{E,min}(t) = \left(1 - \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} t}}{\sqrt{1-D^2}} \right) \cdot \Delta i_{Q,End} \quad (13) \quad t'_{settling} = t_{settling} + 20 \text{ ms} = 80 \text{ ms} \quad (14)$$

$$t_1 = 42.6 \text{ ms} \quad (15) \quad t_M = 40.65 \text{ ms} \quad (16)$$

NOTE 1 The tolerance band for the settling time differs in its reference value from the steady-state band for evaluating the damping. Figure 9 shows only the band for evaluating the damping.

The linearity L_Z of the reactive current change or impedance is determined by evaluating the ratio of the voltage amplitude and reactive current changes according to equation (17).

$$L_Z = \frac{\Delta u_I \cdot \Delta i_{Q,II}}{\Delta u_{II} \cdot \Delta i_{Q,I}} \quad (17)$$

Where Δu_I and Δu_{II} are the measured differences in the positive sequence terminal voltages u_1 relative to the original operating point and $\Delta i_{Q,I}$ and $\Delta i_{Q,II}$ are the two resulting changes in the positive sequence reactive current components from $i_{S,1}$ analogous to measurement procedure 2 in Section 5.5.5.4.3, where the following applies:

$$\Delta i_{Q,I} = i_{Q1,n} - i_{Q1,v} \text{ as a response to the voltage step } \Delta u_I \quad (18)$$

$$\Delta i_{Q,II} = i_{Q1,n} - i_{Q1,v} \text{ as a response to the voltage step } \Delta u_{II} \quad (19)$$

5.5.5.6.2.4 Presentation in the measurement report

For each of the initial operating states listed in Section 5.5.5.4 and each unit measured (possibly in parallel operation with another unit), the following applies:

The instantaneous values of the phase currents i_a , i_b , i_c and phase voltages u_a , u_b , u_c at the terminals of the grid-forming unit shall be shown from two network periods before the sudden voltage change over a total of 15 - 30 network periods.

The time profiles of the variables $u_{\alpha\beta,5\text{ms}}$, $i_{\alpha\beta,5\text{ms}}$ and $i_{Q,1}$ shall be documented graphically.

The respective rise time of the instantaneous value of the current shall be indicated.

The progression over time of the measured positive sequence terminal voltages u_1 of the grid forming unit and the active and reactive components $i_{P,1}$, $i_{Q,1}$ of the positive sequence apparent current $i_{S,1}$ shall be documented graphically, starting from the initial steady state before the start of the measurement up to and including the steady state after the measurement was performed. The respective steady-state values shall be labelled and their values shall be indicated.

The respective steady-state time t'_{settling} of the positive sequence reactive current $i_{Q,1}$ shall be indicated.

The envelope curve used for verifying compliance with the damping requirements and steady-state tolerances shall be indicated together with the time history of the reactive current.

The respective linearity L_Z of the effective impedance per operating point shall be indicated.

Note for TR8:

The requirement for the rise time of the apparent current is met if the moving average instantaneous value of the current $i_{\alpha\beta,5\text{ms}}$ averaged over 5 ms, reaches 90 % of the final value for the first time no later than 15 ms after the sudden change in voltage.

The requirement for the settling time of the reactive current is met if the reactive current $i_{Q,1}$ remains within the tolerance band for reactive current in the period between 80 ms and 150 ms after the sudden change in voltage.

The damping requirement of the reactive current is met if the curve of the reactive current component as a result of the sudden voltage change (according to the specifications of measurement procedure 2 in Section 5.5.5.4.3) lies within the envelope curve according to Figure 9.

The requirement for the linearity of the effective impedance is met if $L_Z = 0.85 \dots 1.15$.

5.5.5.6.3 Verification of robustness and voltage control during short-term overvoltage and undervoltage events (O/UVRT robustness) in Section 4.2.1.5

5.5.5.6.3.1 Aim of the measurement

The aim of the measurement is to determine the behaviour of the grid-forming unit during overvoltage and undervoltage events regarding the transient and steady-state behaviour and the damping of the current.

5.5.5.6.3.2 Measurement procedure

The grid-forming unit shall be capable of compensating for symmetrical and asymmetrical voltage dips of the mains voltage by Δu to a value between 0.7 p.u. and 0.8 p.u., 0.45 p.u. and 0.6 p.u., 0.2 p.u. and 0.3 p.u. and for < 0.05 p.u. (VDE AR-N 4120 and VDE-AR-N 4130) for a minimum period after the boundary line shown in Figure 14 (VDE-AR-N 4110) or Figure 12 (VDE-AR-N 4120 or VDE-AR-N 4130).

The measurement shall be performed at steady-state operating points at full load ($> 0.9 P_n$ for free-field tests and $> 0.98 P_n$ for test bench tests) and additionally at partial load (0.1 to 0.5 P_n).

NOTE 1 For symmetrical voltage dips in the range of $\leq 30 \% U_c$, the results of the tests indicated in Table 14 (VDE-AR-N 4110), Table 11 (VDE-AR-N 4120) or Table 8 (VDE-AR-N 4130) are applicable.

The behaviour of the voltage regulation of the grid-forming unit during overvoltages shall be verified by a voltage step of at least 0.1 p.u. to a value > 1.1 p.u. for symmetrical overvoltages and to ≥ 1.1 p.u. as the maximum outer conductor voltage for asymmetrical voltage increases with a duration of ≥ 5 s.

NOTE 2 The voltage of the test equipment when the test object is connected in short-circuit is relevant for assessing the level of residual voltage.

5.5.5.6.3.3 Evaluation

The sudden change in the amplitude of the terminal voltage is determined by evaluating the voltage $u_{\alpha\beta,5ms}$ in $\alpha\beta$ coordinates (see Appendix B.V).

The rise time of the current is evaluated using $i_{\alpha\beta,5ms}$ (see Appendix B.V). The moment at which the change from $u_{\alpha\beta,5ms}$ exceeds 10% of the final value of the voltage change Δu is defined as the start of a sudden change in the amplitude of the terminal voltage and thus as time $t = 0$.

The evaluation of the rise time of the instantaneous value of the apparent current is based on the evaluation of the filtered instantaneous value of the current $i_{\alpha\beta,5ms}$ (see Appendix B.V).

The value of $\Delta i_{Q,End}$ is determined from the difference between the average value of the reactive current in the period between 150 ms and 300 ms after the sudden voltage change and the pre-fault reactive current. For shorter fault durations (residual voltage < 0.05 p.u.), the last 60 ms before voltage recovery may be used to calculate the average value.

In the event that any existing overcurrent capacity exceeding the nominal continuous current is used for more than 150 ms, this behaviour shall be documented by the manufacturer.

The settling time of the reactive current is evaluated using the time profile of the reactive components in the positive and negative sequences $i_{Q,1}$, $i_{Q,2}$. The settling tolerances are $+20 \% I_r$ and $-10 \% I_r$ for $\Delta i_{Q,End} > 0$ or $-20 \% I_r$ and $+10 \% I_r$ for $\Delta i_{Q,End} < 0$.

The maximum difference between the reactive current and $\Delta i_{Q,End}$ occurring between 80 ms and 130 ms and between 130 ms and 300 ms after the sudden change in voltage shall be indicated in each case.

NOTE These values may be used to determine damping.

Above $120 \% U_n$, continuous voltage control is required according to the capability of the unit. The capacity shall be set out in the unit certificate.

5.5.5.6.3.4 Presentation in the measurement report

The instantaneous values (abc) of the phase currents i_a , i_b , i_c and phase voltages u_a , u_b , u_c at the terminals of the grid-forming unit shall be shown from two network periods before the sudden voltage change over a total of 15 - 30 network periods.

The time profiles of the variables $u_{\alpha\beta,5ms}$, $i_{\alpha\beta,5ms}$, $i_{Q,1}$ and $i_{Q,2}$ over this specified time period shall be documented graphically.

The respective rise time of the instantaneous value of the current shall be indicated.

The progression over time of the measured positive sequence terminal voltages u_1 of the grid-forming unit and the active and reactive components $i_{P,1}$, $i_{Q,1}$ of the positive sequence apparent current $i_{S,1}$ shall be documented graphically, from the initial steady state before the start of the measurement until voltage recovery is achieved. The final values $\Delta i_{Q1,End}$ and $\Delta i_{Q2,End}$ used for the evaluation shall be labelled and their values shall be indicated.

The settling time of the positive sequence reactive current $i_{Q,1}$ shall be indicated.

The maximum difference between the reactive current in the positive or negative sequence and the final value shall be indicated relative to the final value for the sections 80 ms to 130 ms after the sudden voltage change and 130 ms after the sudden voltage change until recovery is achieved.

The assumptions made regarding the relevant influencing variables and any restrictions shall be indicated to show whether it is possible or not possible to control a symmetrical voltage step of at least 0.15 p.u. to a value > 1.15 p.u. for ≥ 5 s or ≥ 1.15 p.u. for ≥ 60 s.

Note for TR8:

The verification for compliance with the requirement for robustness against overvoltage and undervoltage events is considered provided if the unit remains connected to the mains during all voltage dips and rises.

The requirement for the rise time of the apparent current is met if the moving average instantaneous value of the current $i_{\alpha\beta,5ms}$, averaged over 5 ms, reaches 90 % of the final value no later than 15 ms after the sudden change in voltage.

The requirement for the settling time of the reactive current is met if the reactive current in the positive and negative sequences ($i_{Q,1}$ and $i_{Q,2}$) remains within the tolerance band for the reactive current no later than 80 ms after the sudden voltage change ($+20\% I_r$ and $-10\% I_r$ for $\Delta i_Q > 0$ or $-20\% I_r$ and $+10\% I_r$ for $\Delta i_Q < 0$).

The damping requirement for the reactive current is met if, 80 ms after the sudden voltage change, the positive and negative components of the terminal voltage of the grid-forming unit (u_1 , u_2) can be proved to have a damping of least 0.3 (see Appendix B.IV).

Alternatively, the damping requirement for the reactive current is fulfilled if the reactive current components in the positive and negative sequence ($i_{Q,1}$ and $i_{Q,2}$) remain, 80 ms after the sudden voltage change, within a band of $\pm 15\%$ of $\Delta i_{Q,End,1,2}$ and, in the period from 130 ms to 300 ms after the sudden voltage change, within a band of $\pm 5\%$ of $\Delta i_{Q,1,2,End}$.

Only quantities whose value $\Delta i_{Q,1,2,End} > 0.1$ p.u. (relative to I_r) shall be used for an evaluation of the damping.

The additional requirement presented in Figure 10 (VDE-AR-N 4110, VDE-AR-N 4120, VDE-AR-N 4130) is fulfilled if the manufacturer declaration contains at least the assumptions for relevant influencing variables and the restrictions, if any, under which compliance is possible. Where the indicated requirements are verified by a suitable test, they are considered fulfilled and a corresponding manufacturer declaration is not required.

The verification that a symmetrical voltage step of at least 0.15 p.u. to a value > 1.15 p.u. or ≥ 1.15 p.u. can be managed for ≥ 60 s is considered provided if indicated in a corresponding manufacturer's declaration.

5.5.5.6.4 Verification of behaviour when reaching and leaving current limits (Section 4.2.1.4.4)

5.5.5.6.4.1 Aim of the measurement

The aim of the measurement is to determine the behaviour and verify compliance with the requirements of the grid-forming unit at the current limits regarding:

- current clipping in accordance with Section 4.2.1.1,
- the magnitude of current limitation and
- the transition into the operating state without current limitation.

5.5.5.6.4.2 Measurement procedure

The measurement shall be performed in accordance with Section 5.5.5.6.3. The currents from the grid-forming unit resulting from the measurement performed in accordance with Section 5.5.5.6.3 shall be recorded. The requirements for metrology for measuring harmonics in accordance with Chapter 3.2.2 of FGW TR 3 apply.

5.5.5.6.4.3 Evaluation

The voltage dips relating to the requirements when reaching and leaving the current limits in accordance with Section 4.2.1.4.4 shall be evaluated as follows:

For each symmetrical voltage dip, determine the THD (up to 2.5 kHz with a resolution of 25 Hz) of the currents i_a , i_b , i_c of the grid-forming unit using a sliding evaluation with a step size of 1 ms over a 40 ms wide measurement window. The THD is determined based on IEC 61000-4-7. The value to be used for evaluation at a point in time t_1 THDI(t_1) corresponds to the result of the measurement window from $t_1 - 40$ ms until t_1 .

If the THD criterion is not met when evaluating the current i_a , i_b , i_c of the grid-forming units, or if the evaluation is not possible for other reasons, the THD may be determined based on a signal from the grid-forming unit that indicates the use of current clipping under the same time conditions.

NOTE For details on the evaluation, see Appendix B.VIII.

In addition, evaluate the time profile of the apparent current $i_{S,1}$, $i_{S,2}$ as well as the active and reactive components $i_{P,1}$, $i_{P,2}$, $i_{Q,1}$, $i_{Q,2}$ of the positive and negative sequence components of the current of the grid-forming unit. Determine the average value of the apparent current $i_{S,1}$, $i_{S,2}$ exchanged with the network over the duration of the voltage dip or overvoltage.

Determine the average value of the active and reactive current $i_{P,1}$, $i_{Q,1}$ measured between 150 ms and 300 ms after the sudden voltage change for each required initial operating point and the residual voltage.

For shorter fault durations (residual voltage < 0.05 p.u.), the last 60 ms before voltage recovery may be used to calculate the average value.

5.5.5.6.4.4 Presentation in the measurement report

The instantaneous values of the phase currents i_a , i_b , i_c and phase voltages u_a , u_b , u_c at the terminals of the grid-forming unit shall be shown graphically from two network periods before the sudden voltage change over a total of 15 - 30 network periods.

For all measurements relating to symmetrical overvoltage and undervoltage tests, the instantaneous values of the phase voltages u_a , u_b , u_c and phase currents i_a , i_b , i_c as well as the time profile of the THD of the current shall be shown graphically.

If the THD was determined based on a signal output by the grid-forming unit which indicates the use of current clipping, the time profile of this signal shall be shown graphically.

For all measurements, the profile of the active and reactive components $i_{P,1}$, $i_{Q,1}$ and $i_{P,2}$, $i_{Q,2}$ of the current of the grid-forming unit in the positive and negative sequences shall be shown graphically.

The average values $i_{P1,End}$, $i_{P2,End}$, $i_{Q1,End}$, $i_{Q2,End}$ of the active and reactive current $i_{P,1}$, $i_{P,2}$, $i_{Q,1}$, $i_{Q,2}$ measured between 150 ms and 300 ms after the sudden voltage change shall be shown graphically for each required initial operating point above the respective residual voltage in the positive and negative sequences.

The values of the active current $i_{P1,End,25}$, $i_{P1,End,50}$ and $i_{P1,End,75}$ in the current limitation shall be indicated. Index '75' stands for the value set during the test of a voltage dip to approximately 0.7 p.u. to 0.8 p.u., index '50' stands for the value during the test with a voltage dip 0.45 p.u. to 0.6 p.u., and index '25' stands for the value set during a voltage dip 0.2 p.u. to 0.3 p.u.

The average value of the apparent current $i_{S,1}$, $i_{S,2}$ exchanged with the network over the duration of the voltage dip or overvoltage shall be indicated.

Note for TR8:

The proof of compliance with the requirements for the maximum time for current clipping when the current limits specified in Section 4.2.1.1 are reached is considered provided if the determined THD of the current is not significant no later than 100 ms after the start of a sudden change in the amplitude of the terminal voltage.

NOTE 1 This applies provided that there is no mains-side cause for the continuous injection of harmonic current components (e.g. arcing, harmonic loads, inrush situations, resonance points, harmonics of the mains voltage) or saturation effects of the test equipment.

If the THD criterion is not met when evaluating the current of the grid-forming units, or if the evaluation is not possible for other reasons, a signal from the grid-forming unit that indicates the use of current clipping may be used instead for the evaluation. If this indicates operation without current clipping for the failed or non-passed THD evaluation 40 ms after the sudden change in voltage amplitude, the verification is provided.

Proof of compliance with the requirements for current limitation in terms of magnitude (or when no direct reactive current prioritisation takes place) is considered provided if:

- the grid-forming unit is stable during voltage dips down to residual voltages ≥ 0.2 p.u.,*
- the apparent current of the grid-forming unit averaged over the duration of the voltage dip does not fall below 95 % of the rated current or (if the current limit of the grid-forming unit is not reached) of the expected apparent current of the unit resulting from the operating point before the measurement and the average value of the effective impedances determined in Section 5.5.5.4,*
- the active current during a voltage dip of approximately 50 % and 25 % with initial conditions at full load is not less than 5 % of the rated current.*

NOTE 2 The magnitude of the current limitation would be expected to result in higher effective currents at residual voltages higher than 0.2 p.u. This criterion is intended to prevent pure reactive current prioritisation without imposing prescriptive requirements on the effective current behaviour until further notice.

The verification that the unit immediately switches to the operating state without current limitation (when current limitation is no longer required) is considered provided if, the reactive current does not exceed a steady-state tolerance of $\pm 10\%$ I_T close to the final steady-state value of the reactive current during voltage recovery 150 ms after the positive sequence voltage enters the voltage band of $U_n \pm 10\%$ U_n .

NOTE 3 If inrush effects occur on the transformers in the test setup during the measurement, these may be taken into account when determining the times, so that longer settling times can be accepted if required. Comparative simulations may also be used.

5.5.5.6.5 Verification of behaviour upon return to the voltage band of $U_c \pm 10 \% U_c$ (Section 4.2.1.4.5)

5.5.5.6.5.1 Aim of the measurement

The aim of the measurement is to determine and verify compliance with the requirements for the behaviour of the grid-forming unit after a network fault, as well as to verify that the active current returns to the required level after such a fault, in addition to limiting temporary overvoltages.

5.5.5.6.5.2 Measurement procedure

The measurement shall be performed in accordance with Section 5.5.5.6.3.

5.5.5.6.5.3 Evaluation

The evaluation is based on the positive and negative sequence components of the terminal voltage u_1, u_2 as well as the active and reactive current $i_{P,1}, i_{P,2}, i_{Q,1}, i_{Q,2}$ of the grid-forming unit.

The reference time for voltage recovery is the time at which the positive sequence voltage u_1 at the terminals of the grid-forming unit reaches the voltage band of ± 0.1 p.u. close to the pre-fault value.

The pre-fault values for active current and active power use the average values of the positive sequence variables $i_{P,1}$ or p_1 over the last seconds before the sudden voltage change.

To determine the rise time of the active current $i_{P,1}$ after the end of the fault, a tolerance band of ± 0.1 p.u. of the (related) rated current of the unit is applied close to the pre-fault active current to be regulated. The rise time of the active current $i_{P,1}$ after the end of the fault is the time interval between voltage recovery and the point in time at which the active current first enters the tolerance band of the active current. If the active current is already within the tolerance band at the end of the fault, the rise time is specified as zero seconds.

To determine the system transients at the terminals of the unit, the positive sequence voltage u_1 after voltage recovery shall be evaluated. The maximum value relative to the final steady-state value shall be determined. The voltage after voltage recovery is considered steady if its average positive sequence value over 100 ms has not changed by more than ± 0.02 p.u. over 2 s. The average positive sequence value of the evaluation window under consideration over these 2 s is the final steady-state value of the voltage.

5.5.5.6.5.4 Presentation in the measurement report

The instantaneous values of the phase currents i_a, i_b, i_c and phase voltages u_a, u_b, u_c at the terminals of the grid-forming unit shall be shown graphically from two network periods before voltage recovery over a total of 15 - 30 network periods.

The progression over time of the measured positive sequence terminal voltages u_1 of the grid-forming unit as well as the active and reactive components $i_{P,1}, i_{Q,1}$ of the positive sequence apparent current $i_{S,1}$ shall be documented graphically, starting from the initial steady state before the start of the measurement until the final steady state value of the voltage u_1 is reached after voltage recovery.

The time of voltage recovery and the time at which the active current $i_{P,1}$ reaches the tolerance band of the previous fault active current shall be labelled, and the rise time of the active current after voltage recovery shall be indicated.

The final value $u_{1,End}$ to be used for the evaluation and the maximum value of the positive sequence voltage u_1 after voltage recovery shall be labelled and their values shall be indicated.

Note for TR8:

The verification of correct behaviour for active current recovery after the end of a fault is considered provided if the pre-fault active current is reached again after 1 s. If the active current cannot reach this time due to technical restrictions, this shall be justified.

The proof of compliance with the requirements for behaviour regarding temporary overvoltages after voltage recovery is considered provided if the determined system overvoltages u_1 do not exceed 5% (or 2.5% if the unit is put into service after 31 December 2027) of the final steady-state value $u_{1,End}$ of the voltage.

5.5.5.6.6 Verification of fast protection during high voltages (Section 4.2.1.6)

The proof of compliance with the requirements for fast protection at high voltages shall be provided in the form of a manufacturer's declaration. The manufacturer's declaration shall clearly demonstrate and confirm that, when a sinusoidal voltage is applied to the terminals of the grid-forming unit and the amplitude of this voltage jumps to a value greater than 1.35 p.u., the criteria of the requirements in Section 4.2.1.6.2 are fulfilled.

Note for TR8:

The verification is considered provided if the manufacturer's declaration clearly documents that, when a sinusoidal voltage is applied to the terminals of the grid-forming unit and there is a sudden change in the amplitude of this voltage to a value greater than 1.35 p.u., the following criteria are fulfilled:

- Within 40 ms after the sudden amplitude change, the grid-forming unit transitions permanently to a state in which the half-oscillation RMS value of the current in each conductor is limited to a maximum of 5 % of the nominal current. In this case, the half-oscillation RMS values of the currents shall be indicated for each conductor after the voltage is applied.*
- It shall be demonstrated that compliance with the requirements for fast protection during high voltages does not undermine the requirements for OVRT robustness in accordance with Section 4.2.1.6.2.*
- The criteria used for shutdown shall be specified.*

5.5.5.7 Response to steep frequency gradients (RoCoF)(Section 4.2.1.9)

The requirement, that PGUs shall be able to ride through fast frequency changes in accordance with Section 4.2.1.9 without disconnection from the network shall be verified by means of a manufacturer's declaration in accordance with Clause 11.2.8 of the relevant Technical Connection Rule.

Note for TR8:

A verification is considered to be provided if the manufacturer's declaration proves that the unit is able to ride through the RoCoF values required in accordance with Section 4.2.1.9 without disconnecting from the network, otherwise the framework conditions for compliance with the requirements shall be indicated in the certificate.

5.5.5.8 Verification of damping of power-frequency-oscillations (Section 4.2.1.11)

5.5.5.8.1 Aim of the measurement

The aim of the measurement is to determine the damping of power-frequency-oscillations of the grid-forming unit during synchronous operation.

5.5.5.8.2 Measurement procedure

The measurement may be performed based on the equivalent and therefore freely selectable measurement procedures described in this section, whereby the individual tests presented in Table 5 shall be performed in each case.

In connection with the damping of power-frequency-oscillations, additional simulations in accordance with Section 5.5.6.5 shall be performed.

Regardless of the test and measurement setup selected, the test object shall be operated with an SCR greater than 3 at the terminals of the grid-forming unit. The test results obtained with a low SCR value may be used. If the test is not passed in this case, or if the SCR value of the test equipment is unknown, a simulation-based verification (in accordance with Section 5.5.6.1) may be performed using a validated simulation model with an SCR of 3. As a prerequisite, the required model validation shall include the test environment.

The active power output shall be in the range of 50 % - 75 % $P_{E_{max}}$. The power factor $\cos \varphi$ shall be set to 1.0. If several settings are provided for the start-up time constant, the test shall be carried out for $T_{A,min}$ and $T_{A,max}$. For values in between, the verification may be simulated in accordance with Section 5.5.6.1.

NOTE 1 In test bench tests, the short-circuit power ratio (SCR_{PGU}) is used to define the maximum network impedance (fundamental frequency, positive sequence, emulated or physical). The specifications regarding the short-circuit power ratio do not constitute a requirement for the maximum currents of the network emulator.

General information on performing measurements on wind and PV installations

- The active power curve may be influenced by a time-varying primary energy supply. To avoid this influence, the operating points defined in Table 5 should be reached in a throttled state.
- In the case of wind energy units, the profile of the active power can be influenced by excitations of the mechanical resonances. The active power superimposed by the mechanical vibrations may be extracted using Prony analysis in accordance with Appendix A.V.

Measurement procedure 1 - Excitation by means of a frequency step

Power-frequency-oscillations are excited by a frequency step change of approximately 250 mHz to 500 mHz (see Table 5, column: Disturbance after measurement procedure 1). Select the amplitude of the frequency change so that the change in active power in response to the frequency step does not lead to a limitation of the current of the grid-forming unit. This may be achieved by changing the frequency at the terminals, e.g. through a network emulator or by superimposing a frequency change on the internal frequency of the grid-forming unit. When superimposing a signal, ensure that the frequency change also has an effect on the PCNB.

Table 5 - Tests to verify the damping of power-frequency-oscillations

Test	Active power	PCNB	Disturbance after measurement procedure 1	Disturbance after measurement procedure 2
1	50 - 75 % $P_{E_{max}}$ a)	deactivated	$+\Delta f_{ref}$	$\Delta\theta_{pd}^{c)}$
2	50 - 75 % $P_{E_{max}}$ a)	deactivated	$-\Delta f_{ref}$	$\Delta\theta_{npd}^{c)}$
3	50 - 75 % $P_{E_{max}}$ a)	activated ^{b)}	$+\Delta f_{ref}$	$\Delta\theta_{pd}^{c)}$
4	50 - 75 % $P_{E_{max}}$ a)	activated ^{b)}	$-\Delta f_{ref}$	$\Delta\theta_{npd}^{c)}$
a) For bidirectional units, the tests shall be performed for both power directions. b) The frequency dead band of the PCNB (typically ± 200 mHz) shall be deactivated. c) pd: procured direction / npd: non-procured direction				

Measurement procedure 2 - Excitation by means of a phase angle step

Apply a phase angle step to the grid-forming unit and evaluate the active power response of the unit (see Table 5, column: Disturbance after measurement procedure 2). The excitation by a phase angle step may be generated by various methods:

- Application through a network emulator,
- Connection of a phase angle step to the internal phase angle, or
- in network synchronous operation by a load step nearby or the jump of the network impedance, for example by switching the longitudinal impedance of an FRT test device.

Select the magnitude of the phase angle step so that it results in a change in active power of 15 % to 30 % $P_{E_{max}}$ in the procured direction or 2 % to 4 % $P_{E_{max}}$ in the non-procured direction.

Ensure that the change in active power in response to the phase angle step does not lead to a limitation of the current of the grid-forming unit.

5.5.5.8.3 Evaluation

The first maximum and minimum values (up to four) are determined from the signal path of the positive sequence active power p_1 of the grid-forming unit (moving time window over one fundamental period). The amplitude ratio of the successive minimum and maximum values shall be determined from these values. This is shown in the examples in Figure 10 for amplitude ratios AR_{21} , AR_{32} and AR_{43} .

NOTE The signal path of the active power change in Figure 10 is based on a second-order system with a damping ratio of 0.45.

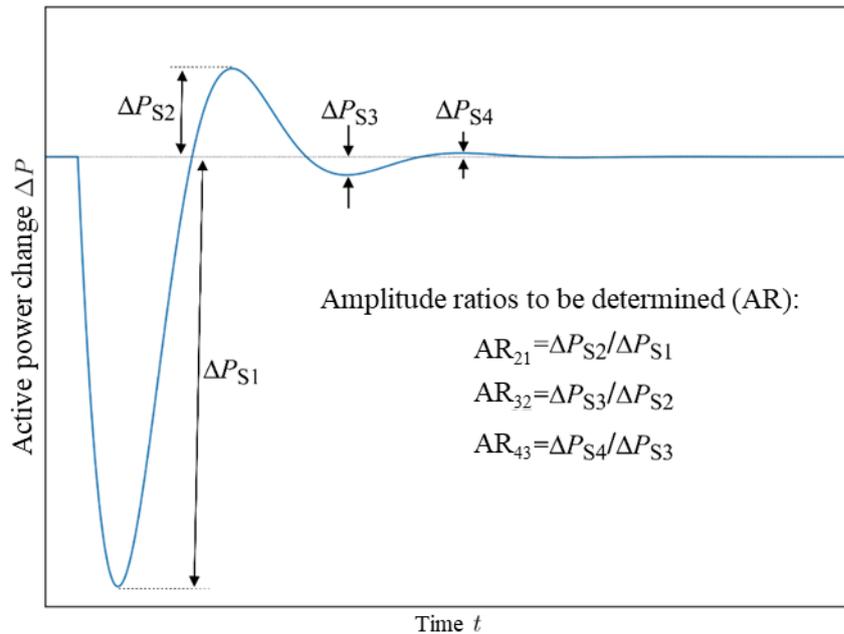


Figure 10 - Examples for determining damping of power-frequency-oscillations

5.5.5.8.4 Presentation in the measurement report

The signal used to excite the power-frequency-oscillations and the profile of the active power p_1 of the grid-forming unit shall be shown graphically. Amplitude maxima and minima shall be labelled. The respective values shall be indicated. If the mechanical vibrations have been eliminated from the active power curve, both active power curves (before and after the elimination of the influence of mechanical vibrations) shall be shown.

Note for TR8:

The damping requirement is fulfilled if the determined damping factor does not fall below the value specified in Section 4.2.1.11 by more than 10% (i.e. $D \geq 0.45$). If a total of four maxima and minima can be identified from the profile of the positive sequence active power, the three determined amplitude ratios of the successive minima and maxima (AR_{21} , AR_{32} and AR_{43}) shall be less than 0.2. If fewer than four maxima and minima can be identified from the profile of the positive sequence active power, the condition is also considered to be fulfilled, provided that the first amplitude ratio (AR_{21}) is less than 0.25.

5.5.5.9 Verification of the start-up time constants T_A and the inertia power and energy (Sections 4.2.1.12 and 4.2.1.13)

5.5.5.9.1 Aim of the measurement

The aim of the measurement is to verify the start-up time constant set in the grid-forming unit and to verify the provision of the inertia power and energy resulting from the requirements.

5.5.5.9.2 Measurement procedure

If a verification of a setting range for T_A is provided, the following measurements shall be performed at least with the minimum and maximum setting values $T_{A,\min}$ and $T_{A,\max}$. For the range between these values, a simulation-based verification in accordance with Section 5.5.6.2 may be provided using the simulation model validated with the measurements.

Regardless of whether negative, positive or symmetric inertia is procured, measurement procedures 1 and 2 shall be performed. These are evaluated differently depending on the direction of procurement.

Measurement procedure 1 – Behaviour during positive frequency deviations

Starting from an active power output in accordance with Table 6 and a reactive power of $0 \pm 5\%$ relative to $P_{E\max}$, perform the measurement shall be performed in accordance with one of the following variants:

- 1) The grid-forming unit is connected to a network emulator. For measurements 1.1 to 1.6 (Table 6), the frequency of the network emulator is replaced by the frequency profile as shown in Figure 4 (a).
- 2) The grid-forming unit is connected to a real network. For measurements 1.1 to 1.6, the frequency difference to the nominal frequency as shown in Figure 4 (a) is applied to the internal frequency of the grid-forming unit with a negative sign. During measurements 1.5 and 1.6, the PCNB shall be active, and the frequency profile as shown in Figure 4 (a) shall be effective.

If only positive inertia is procured through the market, measurements 1.1 to 1.4 are not required.

The grid-forming unit shall be in normal operating condition in both variants. A constant primary energy supply is assumed for measurements 1.1 and 1.2 for grid-forming PGUs. A constant primary energy supply shall be used when performing this test on a test bench. For free-field measurements, the available primary power continuously determined on the PGU side or a representative substitute variable for grid-forming PGUs shall be recorded continuously. The measurement shall be repeated if the available primary power or the power derived from it changes by more than $\pm 5\%$ $P_{E\max}$ during the measurement. Alternatively, measurements 1.1 and 1.2 may be performed in a throttled state.

The minimum value $P_{\text{limitneg,min}}$ and maximum value $P_{\text{limitneg,max}}$ for the full provision of inertia as well as the value $P_{\text{min,dyn}}$ shall be determined by the manufacturer and indicated in the unit certificate.

Measurements 1.3 and 1.4 shall be performed only if T_A in segment (3) in Figure 4 (a) could not be verified through measurements 1.1 and 1.2.

Table 6 - Test cases: Measurement procedure 1 for verifying the response of the unit to positive frequency deviations in Figure 4 (a)

Measurement	Active power operating point of the PGU/PGSU	PCNB	Implementation of the active power operating point	Aim of the measurement
1.1	$P_{\text{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\%$ P_{Emax})	deactivated	Throttled state permitted for PGUs	Testing of T_A in segments (1) and (2) and, if required, (3)
1.2	$P_{\text{limitneg,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\%$ P_{Emax})	deactivated		
1.3	$P_{\text{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\%$ P_{Emax})	deactivated	Throttled state permitted for PGUs ^{a)}	Testing of T_A in segment (3)
1.4	$P_{\text{limitneg,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\%$ ^{b)} P_{Emax})	deactivated		
1.5	$P_{\text{limitneg,min}}$ or $P_{\text{limitpos,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\%$ P_{Emax})	activated	Throttled state permitted for PGUs	Testing of 1.5 times the energy amount If applicable, testing of T_A in segment (3) with disclosure of internal signals
1.6	$P_{\text{limitneg,max}}$ or $P_{\text{limitpos,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\%$ P_{Emax})	activated		
<p>a) The throttling should enable sufficient power reserve for the provision of positive inertia in segment (3) in Figure 4 (a). However, the power reserve shall not exceed the expected inertia contribution of $+5\% P_{\text{Emax}}$.</p> <p>b) The output active power operating point may be reduced if, based on the maximum value for the full provision of inertia for this measurement due to the unit reaching its power limit (e.g. P_{Emax}), there is insufficient reserve for the positive inertia to be provided in segment (3) in Figure 4 (a).</p>				

Table 7 - Test cases: Measurement procedure 2 for verifying the response of the unit to negative frequency deviations in Figure 4 (b)

Measurement	Active power operating point of the PGU/PGSU	PCNB	Aim of the measurement
2.1	$P_{\text{limitpos,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\% P_{\text{Emax}}$)	deactivated	Testing of T_A in segments (1) and (2) and, if required, (3)
2.2	$P_{\text{limitpos,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\% P_{\text{Emax}}$)	deactivated	
2.3	$P_{\text{limitpos,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\% {}^a)_{\text{Emax}}$)	deactivated	Testing of T_A in segment (3)
2.4	$P_{\text{limitpos,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\% {}^a)_{\text{Emax}}$)	deactivated	
2.5	$P_{\text{limitpos,min}}$ or $P_{\text{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance $\pm 5\% P_{\text{Emax}}$)	activated	Testing of 1.5 times the energy amount
2.6	$P_{\text{limitpos,max}}$ or $P_{\text{limitneg,max}}$: Maximum value for the full provision of inertia (tolerance $\pm 5\% P_{\text{Emax}}$)	activated	If applicable, testing of T_A in segment (3) with disclosure of internal signals
c) The output active power operating point may be increased if, based on the minimum or maximum value for the full provision of inertia for this test due to the unit reaching its power limit (minimum power) (e.g. $P_{\text{Emax,B}}$ during charging of storage), there is insufficient reserve for the negative inertia to be provided in segment (3) in Figure 4 (b).			

Measurement procedure 2 – Response to negative frequency deviations

Starting from an active power output in accordance with Table 7 and a reactive power of $0 \pm 5\%$ relative to P_{Emax} , the measurement shall be performed in accordance with one of the following variants:

- 1) The grid-forming unit is connected to a network emulator. For measurements 2.1 to 2.6, the frequency of the network emulator is replaced by the frequency profile according to Figure 4 (b).
- 2) The grid-forming unit is connected to a real network. For measurements 2.1 to 2.6, the frequency difference to the nominal frequency according to Figure 4 (b) is applied to the internal frequency of the grid-forming unit with a negative sign. During measurements 2.5 and 2.6, the PCNB shall be active and the frequency profile according to Figure 4 (b) shall be effective.

If only negative inertia is procured, measurements 2.1 to 2.4 are not required.

The grid-forming unit shall be in normal operating condition in both variants. A constant primary energy supply is assumed for measurements 2.1 and 2.2. The measurements shall not be performed at an active power operating point with power reduction. A constant primary energy supply shall be used when performing this test on a test bench. For free-field measurements, the available primary power continuously determined on the PGU side or a representative substitute variable for grid-forming PGUs shall be recorded continuously. The measurement shall be repeated if the available primary power or the power derived from it changes by more than $\pm 5\% P_{\text{Emax}}$ during the measurement.

The minimum value $P_{\text{limitpos,min}}$ and maximum value $P_{\text{limitpos,max}}$ for the full provision of inertia as well as the value $P_{\text{max,dyn}}$ shall be indicated by the manufacturer in the unit certificate.

Measurements 2.3 and 2.4 shall be performed only if T_A in segment (3) (Figure 4 (b)) could not be verified through measurements 2.1 and 2.2.

For grid-forming units with a $T_A > 10$ s the following applies: If, during a measurement, the maximum inertia power in segment 1 is consistently more than 5% below the expected value, the respective test of segment 1 shall be repeated with an adjusted active power operating point until the tolerance limit of -5% below the inertia power expected for the original active power operating point (see Table 7) in segment 1 is exceeded.

5.5.5.9.3 Evaluation

5.5.5.9.3.1 General information

The evaluation of the measurement procedures described in Section 5.5.5.9.2 is laid out in Section 5.5.5.9.3.2. If the criteria specified there for the verification of the start-up time constants cannot be fulfilled, the T_A shall also be determined in accordance with Section 5.5.5.9.3.3 based on the evaluation of internal signals.

5.5.5.9.3.2 Evaluation: Measurement procedures 1 and 2

Evaluation of measurement procedure 1 for the market-based procurement of negative or symmetric inertia

- 1) It shall be determined whether the grid-forming unit remains connected to the network during all measurements.
- 2) The specified T_A shall be checked using the output active power p_1 for segments (1) and (2) (Figure 4 (a)) when performing measurements 1.1 and 1.2, and for segment (3) when performing measurements 1.3 and 1.4. If the verification of T_A in segment (3) in Section 5.5.5.9.2 were agreed to be performed through measurements 1.1 and 1.2 instead of 1.3 and 1.4, T_A shall be checked for all segments ((1) to (3)) based on measurements 1.1 and 1.2. The expected inertia power is determined using the equation (20) for each segment or time period in Figure 4 (a).

$$\Delta P = -T_A \cdot P_{E\max} \cdot \left(\frac{\Delta f / f_n}{\Delta t} \right) \quad (20)$$

This results in the expected inertia powers for segments (1), (2) and (3) in Figure 4 (a) (ΔP_1 , ΔP_2 and ΔP_3) according to equations (21) to (23).

$$\Delta P_1 = -T_A \cdot P_{E\max} \cdot \left(\frac{2 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (21)$$

$$\Delta P_2 = -T_A \cdot P_{E\max} \cdot \left(\frac{1/3 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (22)$$

$$\Delta P_3 = -T_A \cdot P_{E\max} \cdot \left(\frac{-1 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (23)$$

This results in the following expected active power changes from the start of segment (1) in Figure 4 (a) and the respective transitions to segments (2) and (3) (see illustration in Figure 11):

$$\Delta P_{01} = \Delta P_1 \quad (24)$$

$$\Delta P_{12} = \Delta P_2 - \Delta P_1 \quad (25)$$

$$\Delta P_{23} = \Delta P_3 - \Delta P_2 \quad (26)$$

To check that the expected values were achieved, a tolerance band of $\pm 5\%$ of the expected change in inertia power (ΔP_{01} , ΔP_{12} and ΔP_{23}) according to equations (24) to (26) is used, provided that the T_A to be verified is < 10 s. It shall be determined whether the measured power p_1 remains within this tolerance

band no later than 800 ms after the start of the respective segment. In the case of $T_A > 10$ s, the following applies:

- Segment (1): a tolerance band of ± 15 % after no later than 1 s after the start of the segment,
- Segments (2) and (3): a tolerance band of ± 5 % after no later than 1.3 s after the start of each segment,

If, during a measurement, the maximum inertia power in segment (1) is consistently more than 5% below the expected value, the evaluation of segment (1) shall be repeated with an adjusted active power operating point until in the time period of segment (1) the tolerance limit of -5% below the inertia power expected for the original active power operating point (see Table 7) in segment (1) is exceeded.

If it cannot be determined that the specified tolerance bands are maintained within the specified times, T_A may be determined based on internal signals in accordance with Section 5.5.5.9.3.3.

- 3) No further evaluation is required if the active power p_1 in measurements 1.5 and 1.6 remains continuously below the initial active power (active power operating point of the grid-forming unit according to Table 6) from the end of segment (3) Figure 4 t (a). If the active power p_1 exceeds its initial value from the end of segment (3) Figure 4 (a), ΔE_{neg} and ΔE_{pos} shall be determined according to:

$$\Delta E_{\text{neg}} = \int_{t_{n1}}^{t_{n2}} (P(t) - P_0) dt \quad (27)$$

$$\Delta E_{\text{pos}} = \int_{t_{p1}}^{t_{p2}} (P(t) - P_0) dt \quad (28)$$

where the parameters in between are defined as follows:

$P(t)$	time profile of active power
P_0	initial value of active power
t_{n1}	time of the start of the segment (1)
t_{n2}	time of the end of the segment (2)
t_{p1}	time at which the active power output value is exceeded
t_{p2}	time at which the active power returns to below the initial value

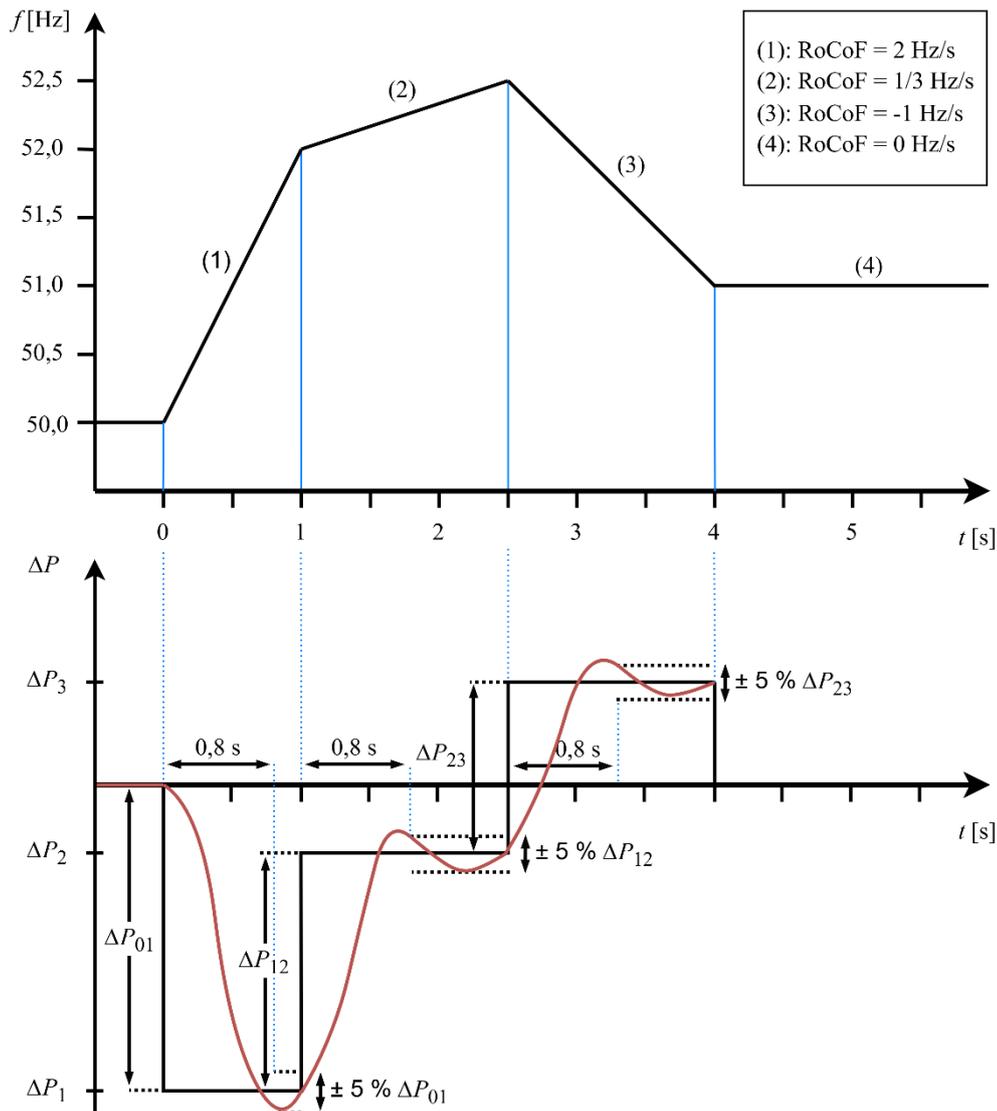


Figure 11 - Example of an evaluation of the start-up time constants and the inertia power during the market-based procurement of negative inertia for $T_A < 10$ s

Evaluation of measurement procedure 1 for the market-based procurement of positive inertia

- 1) It shall be determined whether the grid-forming unit remains connected to the network during measurements 1.5 and 1.6.
- 2) The evaluation window $T_{\text{Evaluation}}$ covers from the start of segment (1) of the reference frequency profile in Figure 4 (a) up to the time in which the steady state is reached after segment (3) with a tolerance band of $\pm 5\% P_{\text{Emax}}$.
- 3) In segments (1) and (2) (Figure 4 (a)), for the periods in which the active power p_1 is above or below the initial active power (active power operating point of the grid-forming unit according to Table 6), an integral value ($\Delta E_{\text{pos},12}$ or $\Delta E_{\text{neg},12}$ according to equation (28) or (27)) shall be determined for the deviation of the active power p_1 from the initial value.
- 4) In segment (3) (Figure 4 (a)), for the time periods in which the active power p_1 is above or below the initial active power, an integral value ($\Delta E_{\text{pos},3}$ or $\Delta E_{\text{neg},3}$ according to equation (28) or (27)) shall be determined based on the deviation of the active power p_1 from the initial value.

- 5) From the end of segment (3) in Figure 4 (a), for the periods in which the active power p_1 is above or below the initial active power, an integral value ($\Delta E_{\text{pos},4}$ or $\Delta E_{\text{neg},4}$ according to equation (28) or (27)) shall be determined based on the deviation of the active power p_1 from the initial value.

Evaluation of measurement procedure 2 for the market-based procurement of positive or symmetric inertia

- 1) It shall be determined whether the grid-forming unit remains connected to the network during all measurements.
- 2) The specified T_A shall be checked in sections for time periods (1) and (2) (Figure 4 (b)) for measurements 2.1 and 2.2, and for measurements 2.3 and 2.4 for time period (3) using the output active power p_1 If the verification of T_A in segment (3) in Section 5.5.5.9.2 was agreed to be performed through measurements 2.1 and 2.2 instead of 2.3 and 2.4, T_A shall be checked for all segments ((1) to (3)) based on measurements 1.1 and 1.2. The expected inertia power is determined using the equation (29) for each segment or time period in Figure 4 (b).

$$\Delta P = -\frac{T_A}{P_{r,E}} \cdot \left(\frac{\Delta f / f_n}{\Delta t} \right) \quad (29)$$

This results in the expected inertia powers for segments (1), (2) and (3) in Figure 4 (b) (ΔP_1 , ΔP_2 and ΔP_3) according to equations (30) to (32).

$$\Delta P_1 = -\frac{T_A}{P_{r,E}} \cdot \left(\frac{-2 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (30)$$

$$\Delta P_2 = -\frac{T_A}{P_{r,E}} \cdot \left(\frac{-1/3 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (31)$$

$$\Delta P_3 = -\frac{T_A}{P_{r,E}} \cdot \left(\frac{+1 \text{ Hz/s}}{50 \text{ Hz}} \right) \quad (32)$$

This results in the active power changes from the start of segment (1) in (Figure 4 (b)) and the respective transitions to segments (2) and (3) in according to equations (24) and (26).

To check that the expected values were achieved, a tolerance band of $\pm 5\%$ of the expected change in inertia power (ΔP_{01} , ΔP_{12} and ΔP_{23}) according to equations (24) to (26) is used, provided that the T_A to be verified is < 10 s. It shall be determined whether the measured power p_1 remains within this tolerance band no later than 800 ms after the start of the respective segment. In the case of $T_A > 10$ s, the following applies:

- Segment (1): a tolerance band of $\pm 15\%$ after no later than 1 s after the start of the segment,
- Segments (2) and (3): a tolerance band of $\pm 5\%$ after no later than 1.3 s after the start of each segment,

If, during a measurement, the maximum inertia power in segment (1) is consistently more than 5% below the expected value, the evaluation of segment (1) shall be repeated with an adjusted active power operating point until in the time period of segment (1) the tolerance limit of -5% below the inertia power expected for the original active power operating point (see Table 7) in segment (1) is exceeded.

If it cannot be determined that the specified tolerance bands are maintained within the specified times, T_A may be determined based on internal signals in accordance with Section 5.5.5.9.3.3.

- 3) No further evaluation is required if the active power p_1 in measurements 2.5 and 2.6 remains continuously above the initial active power (active power operating point of the grid-forming unit according to Table 7) from the end of segment (3) in Figure 4 (b). If the active power p_1 exceeds its initial value from the end

of segment (3), ΔE_{pos} and ΔE_{neg} shall be determined using equation (28) or (27) taking Figure 4 (b) into account.

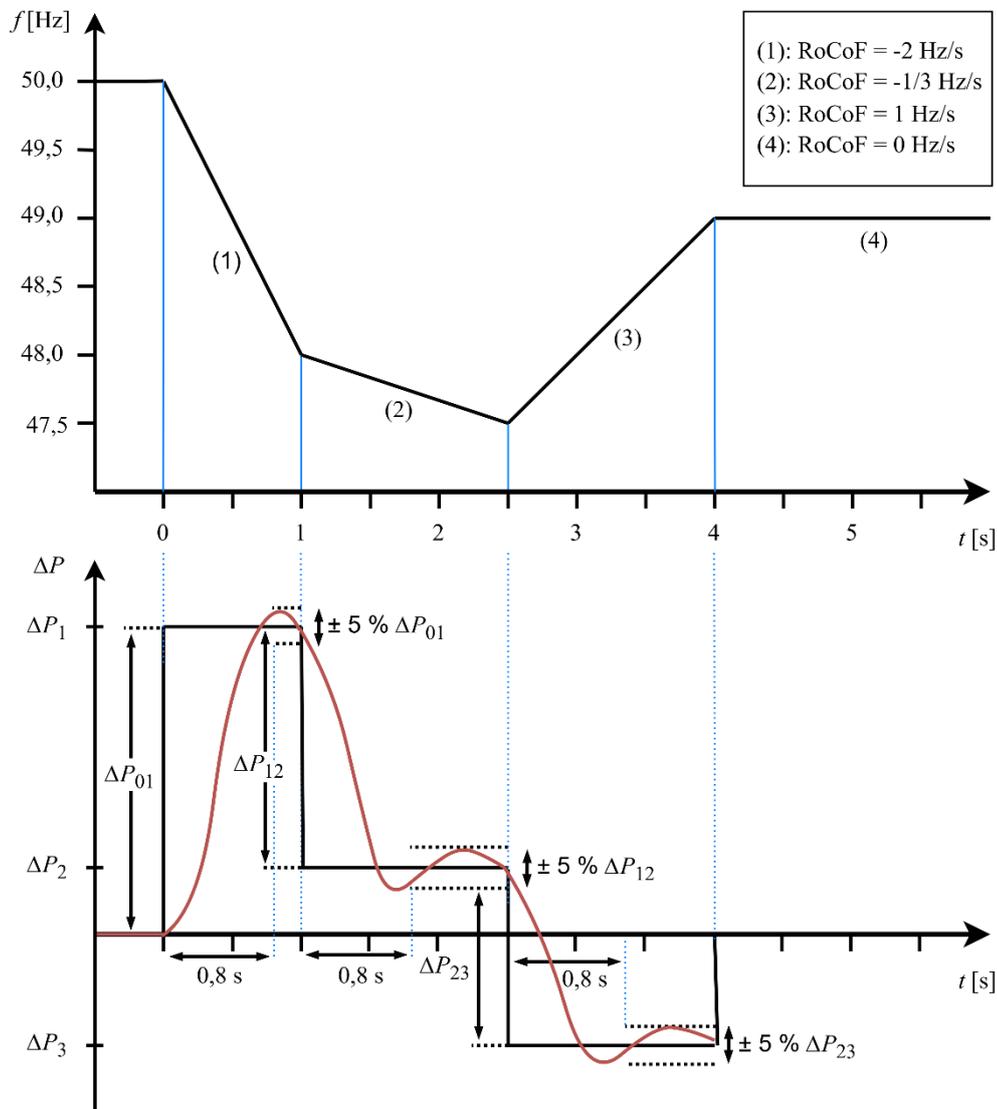


Figure 12 - Example of an evaluation of the start-up time constants and the inertia power during the market-based procurement of positive inertia for $T_A < 10$ s

Evaluation of measurement procedure 2 for the market-based procurement of negative inertia

- 1) It shall be determined whether the grid-forming unit remains connected to the network during measurements 2.5 and 2.6.
- 2) The evaluation window $T_{\text{Evaluation}}$ covers from the start of segment (1) of the reference frequency profile in Figure 4 (b) up to the time in which the steady state is reached after segment (3) with a tolerance band of $\pm 5\% P_{\text{Emax}}$.
- 3) In segments (1) and (2) (Figure 4 (b)), for the time periods in which the active power p_1 is above or below the initial active power, an integral value ($\Delta E_{\text{pos},12}$ or $\Delta E_{\text{neg},12}$ according to equation (28) or (27)) shall be determined for the deviation of the active power p_1 from the initial value.

- 4) In segment (3) (Figure 4 (b)), for the time periods in which the active power p_1 is above or below the initial active power, an integral value ($\Delta E_{\text{pos},3}$ or $\Delta E_{\text{neg},3}$ according to equation (28) or (27)) shall be determined for the deviation of the active power p_1 from the initial value.
- 5) From the end of segment (3) in Figure 4 (b) until the end of the evaluation time window $T_{\text{Evaluation}}$ and again for the time periods in which the active power p_1 is above or below the initial active power, an integral value ($\Delta E_{\text{pos},4}$ or $\Delta E_{\text{neg},4}$ according to equation (28) or (27)) shall be determined based on the deviation of the active power p_1 from the initial value.

5.5.5.9.3.3 Evaluation: alternative method to determine and verify the start-up time constant T_A

If the start-up time constant T_A cannot be determined according to the (evaluation) criteria in Section 5.5.5.9.3.2, the value of T_A shall be determined in accordance with the specifications in that section, in addition to the verification procedure described in Section 5.5.5.9.3.2. In this case, the start-up time constant T_A shall be determined from the gradients of the speed or frequency and the input variables of the variables forming the frequency (often state variables) based on a recalculation from the profile of the recorded variables in accordance with the individual implementation for implementation of the start-up time constants. When evaluating the tests, it shall be ensured that the effective start-up time constant T_A is not distorted by limit signals.

The established procedure for frequency generation shall be disclosed to the certification body in order to determine the variables to be recorded which allow a recalculation of the effective start-up time constant T_A . The certification body shall confirm that the procedure is systematically correct. However, documentation of the determination of the start-up time constant in the test report is not required.

The procedure that is possible is explained using the example of the virtual synchronous machine (VSM) concept:

In the VSM algorithm, the power relationship of a rotating mass is simulated based on the resulting torques (or power, neglecting speed deviation). If the equation for the torque characteristic is solved for the start-up time constant, the following calculation rule applies: $T_A = (p_{\text{gen}} - p_{\text{actual}} - p_D) / (d\omega/dt)$, where p_{gen} is the primary side generating power, p_{actual} is the output electrical power and p_D is the damping power. From this, the start-up time constant can be determined continuously and output as a signal. All signals that can be considered as damping contributions may be combined in the signal P_D . A clear explanation of the synthesis of this signal is not required.

5.5.5.9.4 Presentation in the measurement report

The time profile of the positive sequence voltage u_1 , the positive sequence active current $i_{p,1}$ and the positive sequence active and reactive power p_1, q_1 at the terminals of the grid-forming unit shall be shown. In addition, the tolerance band required in Section 5.5.5.9.3.2 shall be shown.

In Point 1) of measurement procedures 1 and 2, the time profile of the measured frequency f_1 shall be shown. In Point 2) of measurement procedures 1 and 2, the time profile of the connected frequency difference shall be shown.

If the start-up time constant was determined in accordance with Section 5.5.5.9.3.3, the determined start-up time constant T_A shall be indicated in the measurement report.

Note for TR8:

Measurement procedure 1 is considered passed for the market-based procurement of negative or symmetric inertia if:

- the grid-forming unit remains connected to the network,

- the measured power remains within the required tolerance bands within the required times in Section 5.5.5.9.3.2 after the start of the respective segment,
- the measured power at $T_A > 10$ s in segment (1) (if applicable, with an adjusted active power operating point) reached 95% of the expected inertia power,
- provided that the start-up time constant was determined in accordance with Section 5.5.5.9.3.3, this is considered verified if the determined value does not deviate by more than 5% from the agreed value,
- the evaluation of Point 3) of measurement procedure 1 shows that $\Delta E_{\text{pos}} \leq 1.5 \Delta E_{\text{neg}}$.

Measurement procedure 1 is considered passed for the **market-based procurement of positive inertia** if:

- the grid-forming unit remains connected to the network,
- the evaluation of the measurement shows that $(|\Delta E_{\text{pos},12}| + |\Delta E_{\text{neg},3}| + |\Delta E_{\text{pos},4}| + |\Delta E_{\text{neg},4}|) \leq 1.5 \cdot (|\Delta E_{\text{neg},12}| + |\Delta E_{\text{pos},3}|)$.

Measurement procedure 2 is considered passed for the **market-based procurement of positive or symmetric inertia** if:

- the grid-forming unit remains connected to the network,
- the measured power remains within the required tolerance bands within the required times in Section 5.5.5.9.3.2 after the start of the respective segment,
- the measured power at $T_A > 10$ s in segment (1) (if applicable, with an adjusted active power operating point) reached 95% of the expected inertia power,
- provided that the start-up time constant was determined in accordance with Section 5.5.5.9.3.3, this is considered verified if the determined value does not deviate by more than 5% from the agreed value,
- the evaluation of Point 3) of measurement procedure 2 shows that $\Delta E_{\text{neg}} \leq 1.5 \Delta E_{\text{pos}}$.

Measurement procedure 2 is considered passed for the **market-based procurement of negative inertia** if:

- the grid-forming unit remains connected to the network,
- the evaluation of the measurement shows that $(|\Delta E_{\text{neg},12}| + |\Delta E_{\text{pos},3}| + |\Delta E_{\text{neg},4}| + |\Delta E_{\text{pos},4}|) \leq 1.5 \cdot (|\Delta E_{\text{pos},12}| + |\Delta E_{\text{neg},3}|)$.

5.5.5.10 Verifications of the behaviour in the event of overfrequency and underfrequency (PCNB) in the limited setting range (Section 4.2.2)

5.5.5.10.1 Aim of the measurement

The aim of the measurement is to determine the behaviour of the grid-forming unit during overfrequency and underfrequency in the limited setting range of the primary control based on network security. This involves determining the control speeds and droop settings of the primary control based on network security.

5.5.5.10.2 Measurement procedure

The control speeds and droop of the PCNB in the limited setting range are determined by simulating the mains frequency (see also FGW TR3, Revision 26, Chapter 7.2.1.1.3.2). A distinction shall be made between positive and negative frequency deviations. The frequency deviation may be simulated, for example, by adding a corresponding offset signal to the setpoint of the PCNB controller or by completely simulating the mains frequency (e.g. using a network emulator or by overwriting the measured mains frequency). The market-based primary control shall be deactivated during the measurement.

Measurement procedure 1

Perform the measurement with positive frequency deviations based on an effective power output of 100 %, at least in the range of 75 % to 100 %. Provide the following frequency steps for the offset to be applied to the frequency setpoint:

- Step 1: set - actual frequency + 300 mHz
- Step 2: set - actual frequency + 800 mHz

- Step 3: set - actual frequency + 1.3 Hz
- Step 4: set - actual frequency + 0.0 Hz

Ensure that the steady-state value of the active power output is reached before activating a frequency step.

Measurement procedure 2

- Ensure that the measurement with negative frequency deviations is based on active power output corresponding to the minimum power. Proceed with the intended frequency steps as follows:
 - Step 1: set - actual frequency - 300 mHz
 - Step 2: set - actual frequency - 800 mHz
 - Step 3: set - actual frequency - 2.0 Hz
 - Step 4: set - actual frequency + 0.0 Hz
- Ensure that the steady-state value of the active power output is reached before activating a frequency step.

5.5.5.10.3 Evaluation

For measurement procedures 1 and 2, the gradient of the output active power (active power actuating speed) shall be determined for each measurement (step) from the entire profile of the active power p_1 of the grid-forming unit. The rise time, which is relative to the first time that 90% of the final steady-state value of the active power change is reached, shall be taken into account to form the gradient. Furthermore, the effective droop of the PCNB shall be determined based on the respective steady-state step values from the actual and simulated frequency and the respective steady-state values of the active power output.

5.5.5.10.4 Presentation in the measurement report

The measured positive sequence active power p_1 of the grid-forming unit and the simulated frequencies shall be documented graphically for all steps from the initial steady-state condition before the start of the measurement up to and including the final steady-state condition after the measurement (step). The steady-state values shall be labelled and their values shall be indicated. In addition, the T_A used to parametrise the grid-forming unit during the measurements shall be specified.

Note for TR8:

The measurement is considered passed if the final steady-state values of the active power p_1 deviate by a maximum of $\pm 5\%$ of the expected power change or $\pm 0.5\% P_{Emax}$ from the values resulting from the set droop and comply at least with the active power actuating speeds according to Table 11. If no minimum requirements are specified for the grid-forming unit in accordance with Table 11, the verification of the actuating speeds is considered provided through their identification.

5.5.6 Supplementary verifications based on simulations

5.5.6.1 Simulation-based verification of damping of power-frequency-oscillations (Section 4.2.1.11)

5.5.6.1.1 General information

The tests described below shall only be performed if the manufacturer of the grid-forming unit has specified more than two parametrisations of the start-up time constant T_A , meaning $T_{A,min}$ and $T_{A,max}$, in the grid-forming unit to be tested. The tests may also be performed if the measurement verification in accordance with Section 5.5.5.8.2 has not been passed due to low short-circuit power ratios or if the SCR value of the test equipment is unknown. As a prerequisite, the required model validation shall include the test environment. If the requirements were verified for the values to be indicated between $T_{A,min}$ and $T_{A,max}$ through a measurement-based verification in accordance with Section 5.5.5.8, it is not required to perform the simulation-based tests described below.

5.5.6.1.2 Aim of the test

The aim of the simulation-based test is to determine the damping of power-frequency-oscillations of the grid-forming unit in synchronous operation for values of T_A between $T_{A,\min}$ and $T_{A,\max}$. If, instead of a measurement-based verification of the damping of power-frequency-oscillations for $T_{A,\min}$ and $T_{A,\max}$ in accordance with Section 5.5.5.8.2, a simulation-based verification is used, the damping of power-frequency-oscillation for values of $T_{A,\min}$ and $T_{A,\max}$ shall be determined.

5.5.6.1.3 Test procedure

Test environment

The simulation-based test is performed based on the detailed RMS model validated in accordance with Section 5.5.3.6.2 in a simulation-based test environment that corresponds to the test environment in Figure 8. The network emulator shown in Figure 8 shall be replaced by a network equivalent in the simulation environment. The elements of the test environment shall be parametrised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. The test environment shall be parametrised so that the simulation-based tests of the grid-forming unit are carried out at an SCR of 3.

Performance of the test

In the detailed RMS model, set the start-up time constant T_A and, if required, additional parameters in accordance with the manufacturer's specifications which require a verification of the damping of power-frequency-oscillations for the grid-forming unit. Simulate the measurements in Section 5.5.5.8.2, but perform only one of the freely selectable 'measurement procedure 1' and 'measurement procedure 2'. In both cases, perform the individual tests contained in Table 5 (Section 5.5.5.8.2).

Set the active and reactive power operating points of the grid-forming unit in accordance with the specifications in Section 5.5.5.8.2 before performing the test.

The 'General notes on performing measurements for wind and PV installations' in Section 5.5.5.8.2 also apply to the simulation-based verification.

5.5.6.1.4 Evaluation and presentation in the test report

The simulation-based test shall be evaluated in accordance with the requirements of Section 5.5.5.8.3, taking into account the simulated active power $p_{1,S}$. Alternatively, the damping of frequency-power-oscillations may also be determined taking into account Appendix A.I based on the simulated active power $p_{1,S}$. Intrinsic value determination may be used, provided that the intrinsic values determined for $T_{A,\min}$ and $T_{A,\max}$ do not deviate from the measurement results by more than $\pm 10\%$.

The signal used to excite the power-frequency-oscillations and the profile of the active power $p_{1,S}$ of the grid-forming unit shall be shown graphically in the test report. Amplitude maxima and minima shall be labelled. The respective values shall be indicated. If the mechanical vibrations are eliminated from the active power curve, both active power curves (before and after the elimination of the influence of mechanical vibrations) shall be shown.

Note for TR8:

The damping requirement is fulfilled if the determined damping factor does not fall below the value specified in Section 4.2.1.11 by more than 10% (i.e. $D \geq 0.45$).

If the damping was determined through the evaluation of the amplitude ratios, the following additional requirement applies: if a total of four maxima and minima can be identified from the profile of the positive sequence active power, the three determined amplitude ratios of the successive minima and maxima (AR_{21} , AR_{32} and AR_{43}) shall be less than 0.2. If fewer than four maxima and minima can be identified from the

profile of the positive sequence active power, the condition is also considered to be fulfilled, provided that the first amplitude ratio (AR_{21}) is less than 0.25.

5.5.6.2 Simulation-based verification of the start-up time constants as well as the inertia power and energy (Sections 4.2.1.12 and 4.2.1.13)

5.5.6.2.1 General information

The tests described below shall only be performed if the manufacturer of the grid-forming unit has specified more than two parametrisations of the start-up time constant T_A , meaning $T_{A,\min}$ and $T_{A,\max}$, in the grid-forming unit to be tested. It is not required to perform the simulation-based tests described below if the requirements are verified for the values between $T_{A,\min}$ and $T_{A,\max}$ through a measurement-based verification in accordance with Section 5.5.5.9.

5.5.6.2.2 Aim of the test

The aim of the simulation-based test is to determine the start-up time constant set or parametrised in the grid-forming unit as well as the inertia power and energy resulting from this. The value for T_A resulting from the simulation-based test shall be checked for compliance with the manufacturer's specifications. The unit shall comply with the requirements in Sections 4.2.1.12 and 4.2.1.13.

5.5.6.2.3 Test procedure

Test environment

The simulation-based test is performed based on the detailed RMS model validated in accordance with Section 5.5.3.6.2 in a simulation-based test environment that corresponds to the test environment in Figure 8. The network emulator shown in Figure 8 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parametrised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions.

Performance of the test

Set the start-up time constant T_A to be verified in the detailed RMS model in accordance with the manufacturer's specifications. Simulate measurements 1 and 2 described in Section 5.5.5.9.2. Ensure that the tolerance specifications for the verification of the start-up time constant T_A comply with the requirements in Section 5.5.5.9.

5.5.6.2.4 Evaluation and presentation in the test report

The simulation-based test shall be evaluated in accordance with the requirements of Section 5.5.5.9.3, taking into account the simulated active power $p_{1,S}$.

The test report shall show the time sequence of the simulated positive sequence voltage $u_{1,S}$, positive sequence current $i_{P,1,S}$ and positive sequence active power and reactive power $p_{1,S}$, $q_{1,S}$ determined at the terminals of the grid-forming unit. In addition, the tolerance bands required in Section 5.5.5.9.3.2 shall be shown.

In Point 1) of the simulated measurement procedures 1 and 2, the time profile of the simulated frequency $f_{1,S}$ shall be shown. In Point 2) of the simulated measurement procedures 1 and 2, the time profile of the connected frequency difference shall be shown.

Note for TR8:

*The simulated measurement procedure 1 is considered passed for the **market-based procurement of negative or symmetric inertia** if:*

- *the grid-forming unit remains synchronous to the network,*
- *the simulated power remains within the required tolerance bands within the required times in Section 5.5.5.9.3.2 after the start of the respective segment,*

- the simulated power at $T_A > 10$ s in segment (1) (if applicable, with an adjusted active power operating point) reached 95% of the expected inertia power,
- provided that the start-up time constant was determined in accordance with Section 5.5.5.9.3.3, this is considered verified if the determined value does not deviate by more than 5% from the agreed value,
- the evaluation of Point 3) of simulated measurement procedure 1 shows that $\Delta E_{\text{pos}} \leq 1.5 \Delta E_{\text{neg}}$.

The simulated measurement procedure 1 is considered passed for the **market-based procurement of positive inertia** if:

- the grid-forming unit remains synchronous to the network,
- the evaluation of the simulated measurement shows that $(|\Delta E_{\text{pos},12}| + |\Delta E_{\text{neg},3}| + |\Delta E_{\text{pos},4}| + |\Delta E_{\text{neg},4}|) \leq 1.5 \cdot (|\Delta E_{\text{neg},12}| + |\Delta E_{\text{pos},3}|)$.

The simulated measurement procedure 2 is considered passed for the **market-based procurement of positive or symmetric inertia** if:

- the grid-forming unit remains synchronous to the network,
- the simulated power remains within the required tolerance bands within the required times in Section 5.5.5.9.3.2 after the start of the respective segment,
- the simulated power at $T_A > 10$ s in segment (1) (if applicable, with an adjusted active power operating point) reached 95% of the expected inertia power,
- provided that the start-up time constant was determined in accordance with Section 5.5.5.9.3.3, this is considered verified if the determined value does not deviate by more than 5% from the agreed value,
- the evaluation of Point 3) of simulated measurement procedure 2 shows that $\Delta E_{\text{neg}} \leq 1.5 \Delta E_{\text{pos}}$.

The simulated measurement procedure 2 is considered passed for the **market-based procurement of negative inertia** if:

- the grid-forming unit remains synchronous to the network,
- the evaluation of the simulated measurement shows that $(|\Delta E_{\text{neg},12}| + |\Delta E_{\text{pos},3}| + |\Delta E_{\text{neg},4}| + |\Delta E_{\text{pos},4}|) \leq 1.5 \cdot (|\Delta E_{\text{pos},12}| + |\Delta E_{\text{neg},3}|)$.

5.5.6.3 Simulation-based test of the setpoint response of the continuous voltage control (Section 4.2.1.4)

5.5.6.3.1 General information

The simulation-based tests described below shall be performed in addition to the measurement-based tests in accordance with Section 5.5.5.6.1.

5.5.6.3.2 Aim of the test

The aim of the simulation-based test is to determine the setpoint response of the continuous voltage control of the grid-forming unit at SCR ratios different from those specified in the measurement-based tests in accordance with Section 5.5.5.6.1, in order to test the entire range of the required short-circuit power.

5.5.6.3.3 Test procedure

Test environment

The simulation-based test is performed based on the detailed RMS model validated in accordance with Section 5.5.3.6.2 in a simulation-based test environment that corresponds to the test environment in Section 5.5.5.2. The network emulator shown in Figure 8 shall be replaced by a network equivalent in the simulation environment. The elements of the test environment shall be parametrised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions.

Performance of the test

Ensure that the setpoint for the voltage regulator of the detailed RMS model changes for network impedances of $Z_{\text{Network}} = 0.05$ p.u. and 0.3 p.u. relative to S_{Emax} of the grid-forming unit (corresponds to SCR = 20 or 3

at the grid-forming unit). Select the setpoint change to achieve a reactive power change of at least 50% of the reactive power setting range of the grid-forming unit. A reactive power change of more than 30% relative to $P_{E_{\max}}$ is not required.

5.5.6.3.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications in Section 5.5.5.6.1.3, taking into account the simulated positive sequence voltage $u_{1,S}$ and the simulated reactive and active current $i_{Q,1,S}$, $i_{P,1,S}$.

The test report shall show the time profile of the setpoint and the evaluated variable ($u_{1,S}$ or $i_{Q,1,S}$). The determined rise time shall be indicated.

Note for TR8:

The verification is considered provided if the determined rise time of the simulated voltage (or alternatively of the simulated current) is < 1 s.

5.5.6.4 Simulation-based verification of the disturbance behaviour of the continuous voltage control (Section 4.2.1.4)

5.5.6.4.1 General information

The simulation-based tests described below shall be performed in addition to the measurement-based tests in accordance with Section 5.5.5.6.2.

5.5.6.4.2 Aim of the test

The aim of the simulation-based test is to determine the disturbance behaviour of the continuous voltage control of the grid-forming unit as well as to check compliance with the dynamic requirements for voltage regulation at the different SCR ratios specified in the measurement-based tests in accordance with Section 5.5.5.6.2, in order to test the entire range of the required short-circuit power. In addition, the disturbance behaviour of the continuous voltage control of the grid-forming unit in parallel operation with another grid-forming unit shall be determined if required.

5.5.6.4.3 Test procedure

Test environment

The simulation-based test is performed based on the detailed RMS model validated in accordance with Section 5.5.3.6.2 in a simulation-based test environment that corresponds to the test environment in Section 5.5.5.2. The network emulator shown in Figure 8 shall be replaced by a network equivalent in the simulation environment. The elements of the test environment shall be parametrised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. If the grid-forming unit under test is not connected via a transformer assigned to it (or transformer windings assigned specifically to it), the simulation-based test environment shall be expanded in a second test step so that a second grid-forming unit of the same type is operated in parallel with the first unit. The test setup in Figure 8 shall be wired as a standard setup specified by the manufacturer.

Performance of the test

Apply an amplitude step on the mains voltage source without additional parallel units. Select the amplitude step to achieve a reactive power change of at least 50% of the reactive power setting range of the grid-forming unit. This verification is required for network impedances of $Z_{\text{Network}} = 0.05$ p.u. and 0.3 p.u. relative to $S_{E_{\max}}$ of the grid-forming unit (corresponds to SCR = 20 or 3 at the PGU). A reactive power change of more than 30% relative to $P_{E_{\max}}$ is not required. If required, repeat the test in parallel operation with a grid-forming unit of the same type.

5.5.6.4.4 Evaluation and presentation in the test report

The simulation-based tests shall be evaluated in accordance with the requirements of Section 5.5.5.6.2.3, taking into account the simulated voltages $u_{\alpha\beta,5ms,S}$, $u_{1,S}$ and the simulated currents $i_{\alpha\beta,5ms,S}$, $i_{Q,1,S}$.

For each of the initial operating states listed in Section 5.5.5.4 and for each unit measured (possibly in parallel operation with another unit), the tests shall be documented in accordance with the specifications in the Section 5.5.5.6.2.4, taking into account the simulated variables determined in each case.

Note for TR8:

The requirement for the rise time of the apparent current is fulfilled if the moving average instantaneous value of the simulated current $i_{\alpha\beta,5ms,S}$, averaged over 5 ms, reaches 90 % of the final value for the first time no later than 15 ms after the sudden change in voltage.

The requirement for the settling time of the simulated reactive current is fulfilled if the reactive current $i_{Q,1,S}$ remains within the tolerance band for reactive current no later than 80 ms after the sudden change in voltage.

The requirement for damping of the reactive current is fulfilled if the profile of the simulated component of the reactive current remains within the envelope curve as shown in Figure 9 after the sudden voltage change (according to the requirements for measurement procedure 2 in Section 5.5.5.4.3).

The requirement for the linearity of the effective impedance is fulfilled if $L_{Z,S} = 0.85 \dots 1.15$.

5.5.6.5 Verifications for parallel operation (Section 4.2.1.10)

5.5.6.5.1 General information

The simulation-based tests described below shall be performed.

5.5.6.5.2 Aim of the test

The tests for network parallel operation capability serve to demonstrate that a PGU that meets the requirements relative to a simplified test and verification configuration (PGU or PGM at the NCP) can be operated stably in a network environment that deviates from this. The verifications shall be simulated. The detailed RMS models or EMT models shall be used according to Section 5.5.3. The verifications are based on a standardised benchmark model network described in Appendix B.VI.

5.5.6.5.3 Test procedure

Description of the test environment and its initialisation

The test environment for the verification of parallel operation capability (benchmark-network) consists of the following network and PGU/PGM components:

- 1) Two PGMs, each consisting of three identical grid-forming PGUs to be tested. The internal interconnection of the PGU in the PGM of the benchmark-network is shown in Appendix B.VI. Any required deviations from the basic specifications of the benchmark-network shall be justified.
- 2) The extra-high-voltage network is assumed to be frequency-rigid and is modelled using a voltage source.
- 3) The operating equipment data for the model network shall be specified based on the specifications in Appendix B.VI so that the network connection configuration of the PGU is taken into account sufficiently.

The simulation models of the PGUs shall be initialised based on the results of a load flow calculation performed prior to the simulation. This shall be configured so that the voltage setpoints of the PGUs are defined so that the reactive power feed-in corresponds to the specifications of the calculation cases. Dynamic modelling of the PGM controllers should not be taken into account in the simulation model. PGM controllers shall be recreated to an appropriate extent for the load flow calculation of the initialisation.

The tests are intended to achieve the following objectives:

- 1) Verification that several identical PGUs connected together to an NCP can be operated stably at all times.
- 2) Verification of stable operation of several identical grid-forming PGMs connected to a frequency-rigid EHV network. Considered are voltage control, FRT behaviour, PCNB behaviour and the verification of sufficient damping of power-frequency-oscillations.
- 3) Verification that the PGU does not have a damping effect on power-frequency-oscillations with periods of 0.05 Hz - 2 Hz occurring in the upstream network.

Performance of the test

Test 1

Based on voltage setpoint changes at a single PGU, verify that the voltage and active power control always remain stable and that the voltage control requirements are fulfilled. If no corresponding interface is considered provided in the models of the grid-forming units, the excitation may also be provided, for example, by the tap setting of the unit transformer or by switching an impedance. Ensure that the excitation is applied once to the first PGU of PGM-1 and once to the first PGU of PGM-2.

Use the EMT model for this test (with a simplified representation of the power section according to Point 2), Section 5.5.3.3).

Test 2

Test 2a (fault far from the PGM)

Simulate a three-phase short circuit without residual fault voltage with a fault duration of 150 ms as a fault far from the PGM at the network node 'EHV-1'.

Test 2b (fault far from the PGM)

Simulate a three-phase short circuit at the network node 'HV-1' with linear, inductive fault impedance with a residual fault voltage of 25% (no-load at node 'HV-1') with a fault duration of 500 ms, whereby no additional shutting down of equipment is required to clear the fault.

Test 2c (fault in neighbouring MV feeders to the PGM)

Simulate a three-phase (3K) and a two-phase (2K) short circuit without fault impedance at node 'MV-1' with a fault duration of 450 ms in each case. Ensure that the short circuit is applied at the network node 'MV-1-EOL'. Ensure that the fault is cleared by switching off the feeder circuit breaker. Repeat the test for a fault at the network node 'MV-2-EOL' under identical conditions and with the residual voltage at node 'MV-2'.

Select the simulation duration so that the dynamic compensation processes have clearly reached their steady state.

Use the EMT model for these tests (with a simplified representation of the power section according to Point 2), Section 5.5.3.3).

Test 3

Verify the stable control of the PCNB, even within an extended test environment, by connecting the reference curves in accordance with Section 4.2.1.13, Figure 4 to the frequency of the EHV voltage source 'ext EHV Network' at the network node 'EHV-1'. Select the simulation duration so that the dynamic compensation processes have clearly reached their steady state.

Use the detailed RMS model for these tests.

Test 4

In order to show that the PGU under assessment has damping characteristics that do not adversely affect generator or network oscillations present in the network, determine the frequency responses for various test configurations in this simulation-based test. Modulate the supply frequency of the voltage source at the

network node 'EHV-1' sinusoidally in the range from 0.05 Hz to 2 Hz. Determine the Bode plot (frequency and phase response) of the transfer function $G_p(s) = P_{EZE}(s) / f_{SP}(s)$.

Perform the following calculations:

Determination of the frequency response relative to the electrical power of an PGU of PGM-1 with operation of PGM-1 and PGM-2.

To create the Bode plot, the supply frequency of the voltage source at node 'EHV-1' may be modulated sinusoidally with an amplitude Δf of 0.1 Hz and a frequency f_{excite} in the range 0.05 Hz to 2 Hz in steps from ≤ 0.05 Hz (in the rotating coordinate system with $f = 50 \text{ Hz} + \Delta f \cdot \sin(2\pi f_{excite} \cdot t)$).

In wind turbines, this excitation can lead to mechanical interactions. The wind turbine manufacturer may specify up to three frequencies for the unit to be certified regarding mechanical resonances. These three frequencies (f_{res}), including a tolerance band of ± 0.1 Hz or ± 20 % of f_{res} , are not taken into account when creating the Bode diagram.

Deactivate the PCNB for the tests. This may be achieved by increasing the frequency dead band or by adjusting the droop settings.

Use the detailed RMS model for this test.

5.5.6.5.4 Evaluation

Test 1

It shall be shown, that compliance with the requirements for continuous voltage control of the grid-forming unit in accordance with Section 4.2.1.4 and the corresponding measurement-based verification in accordance with Section 5.5.5.6 also lead to stable operation of the grid-forming PGUs in an installation within the defined network environments.

Test 2

It shall be shown, that compliance with the requirements for FRT capability of the grid-forming unit in accordance with Section 4.2.1.5 and the corresponding measurement-based verification in accordance with Section 5.5.5.6.3 also lead to stable operation of the grid-forming PGUs in an installation within the defined network environments. Furthermore it shall be shown, that the introduction and removal of power limitations of the grid-forming units proceed in a stable manner and that no unstable interactions between the PGUs of a PGM or between the PGMs are observed.

Test 3

It shall be shown, that the frequency profiles in accordance with Section 4.2.1.13, Figure 4 are stable for all PGUs of PGM-1 and PGM-2 and that no unstable interactions between the PGUs or PGMs occur.

Test 4

It shall be shown, that, in the frequency range from 0.05 Hz to 2 Hz, the phase angle of the PGU active power in the generator sign convention remains within the range of $-180^\circ \pm 90^\circ$ with respect to the phase angle of the voltage source. The respective phase reserve at the $\pm 90^\circ$ limits shall be indicated.

5.5.6.5.5 Presentation in the measurement report

The verification of parallel network capability shall be provided in a test report, which shall contain the following:

- 1) A description of the network model and the selected parameters, as well as any necessary deviations from the basic specifications of the benchmark network. Required deviations shall be justified.
- 2) A list of the specific network operating cases of the benchmark network with reference to the specific values of the PGU whose properties shall be verified.

- 3) A representation of the essential variables within $x-t$ -diagrams with labelling or marking of relevant states. This includes at least the following variables:
 - 3.1) Test 1: PGU setpoint and actual voltages, active and reactive power, as well as active, reactive and apparent currents for all PGUs.
 - 3.2) Test 2: PGU active and reactive power, positive and negative sequence current, frequency, positive sequence voltage and internal variables, if available for all PGUs, voltage at the fault location and at the NCPs.
 - 3.3) Test 3: PGU active and reactive power, apparent current, frequency, voltage and internal variables, if available for all PGUs, as well as frequency of the voltage sources.
 - 3.4) Test 4: A representation of the determined Bode diagrams indicating the resonance point and phase reserve at frequencies of 0.05 Hz and 2 Hz. If mechanical resonances were taken into account in the case of wind turbines, these shall be shown in the Bode diagram with the corresponding tolerance band.
- 4) A written summary of the results with regards to the properties of the grid-forming PGUs shall be shown.

NOTE Any response deviating from the requirements and detected during the specified tests in the form of instabilities or unsystematic behaviour shall be indicated accordingly.

Note for TR8:

The test is considered passed if the results are clearly documented in the test report.

5.6 Procedure for system certification

5.6.1 General information

For customer installations with grid-forming units, a system certificate shall be submitted to the network operator by the connection owner in accordance with the requirements of the relevant Technical Connection Rules. In this respect, Clause 11.4 shall be taken into account. Deviations from the requirements for the system certification in accordance with Clause 11.4 of the relevant Technical Connection Rules are described below.

NOTE The requirements for system certification will be further specified in a revision of the FNN Guideline.

5.6.2 Deviations from TCR requirements within the scope of system certification

5.6.2.1 Deviations from requirements in Clause 11.4.1 (General information)

Clause 11.4.1 of the relevant Technical Connection Rule applies. In addition to Clause 11.4.1, the conversion of existing grid-following Type 2 units (existing installations) to grid-forming Type 2 units is always considered a significant change. Therefore, a new system certificate shall be issued for these. In addition to Clause 11.4.1 of the relevant Technical Connection Rule, the following applies to these installations:

"A new system certificate shall be issued for existing systems that are converted to grid-forming Type 2 units. The following requirements apply for issuing this certificate:

- A unit certificate in accordance with this FNN Guideline (or a prototype confirmation for grid-forming units in accordance with Section 5.2 of this FNN Guideline) shall be submitted for the unit to be converted.
- The implementation of necessary software updates shall be verified for all converted units through a relevant extract from the event log.
- The replacement of necessary hardware components shall be verified by a manufacturer's declaration.
- A parameter extract for the converted unit shall be submitted.
- Based on internally switchable signals on a unit in the field freely selectable by the certifier, the following measurements shall be performed in accordance with Sections 5.5.5.3, 5.5.5.8 and 5.5.5.9 (evaluation in accordance with Section 5.5.5.9.3.3) and compliance with the requirements described shall be verified. Alternatively, the converted unit may be monitored using a fault recorder in accordance with the criteria in Section 5.2.2.
- *NOTE In this case, the specifications in Section 5.2.2 on monitoring in an installation with several identical grid-forming units apply.*
- This may be omitted if the conversion was performed solely based on a software update.
- The certifier has checked on site that all units in the installation correspond to the status of the tested or monitored unit."

5.6.2.2 Deviations from the requirements in Clause 11.4.2 (Documents to be provided by the connection owner for the preparation of system certificates)

The following data sheets from Appendix C of this FNN Guideline shall be submitted to the certification body instead of the data sheets specified in table row number 1 of Clause 11.4.2 of the relevant Technical Connection Rule:

VDE-AR-N 4110

- E.1 in VDE-AR-N 4110: Data sheet E.1 (Appendix C.I.1)
- E.7 in VDE-AR-N 4110: Data sheet E.7 (Appendix C.I.2)
- E.8 in VDE-AR-N 4110: Data sheet E.8 (Appendix C.I.3)
- E.9 in VDE-AR-N 4110: Data sheet E.9 (Appendix C.I.4)
- E.10 in VDE-AR-N 4110: Data sheet E.10 (Appendix C.I.5)
- E.11 in VDE-AR-N 4110: Data sheet E.11 (Appendix C.I.6)
- E.12 in VDE-AR-N 4110: Data sheet E.12 (Appendix C.I.7)

VDE-AR-N 4120

- E.1 in VDE-AR-N 4120: Data sheet E.1 (Appendix C.II.1)
- E.5 in VDE-AR-N 4120: Data sheet E.5 (Appendix C.II.2)
- E.6 in VDE-AR-N 4120: Data sheet E.6 (Appendix C.II.3)
- E.7 in VDE-AR-N 4120: Data sheet E.7 (Appendix C.II.4)
- E.8 in VDE-AR-N 4120: Data sheet E.8 (Appendix C.II.5)
- E.9 in VDE-AR-N 4120: Data sheet E.9 (Appendix C.II.6)
- E.10 in VDE-AR-N 4120: Data sheet E.10 (Appendix C.II.7)

VDE-AR-N 4130

- E.6 in VDE-AR-N 4130: Data sheet E.6 (Appendix C.III.1)

A. Appendix (informative)

A.I. Qualitative considerations for the determination of the damping ratio

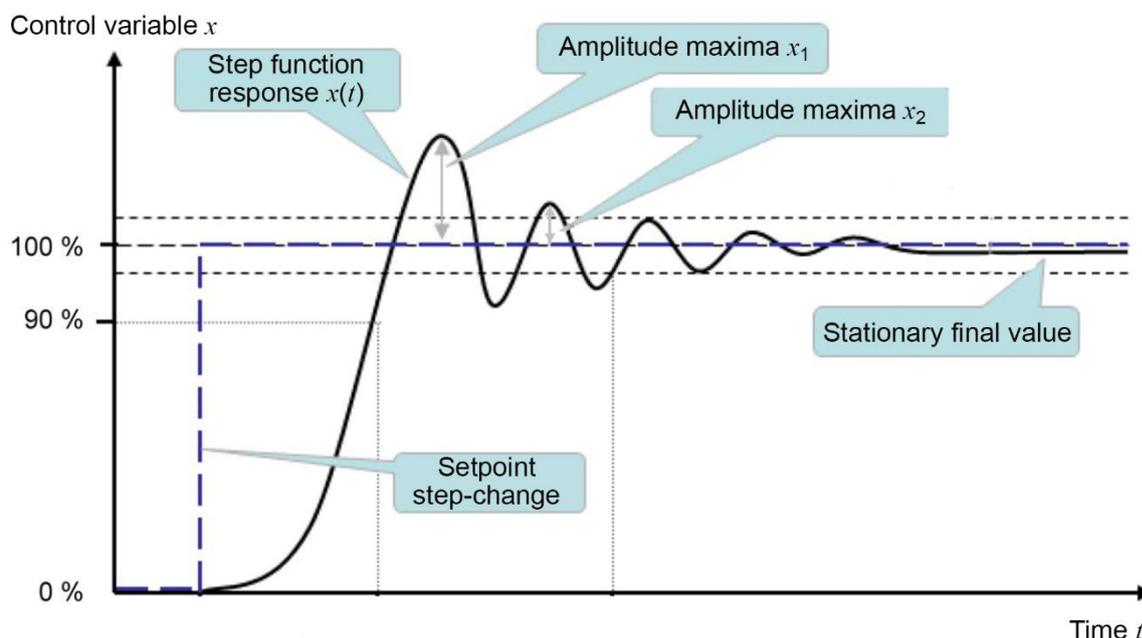


Figure 13 - Step response of a closed-loop control system for the quantitative determination of the damping factor

Based on the amplitude maxima x_1 and the amplitude maxima x_2 as shown in Figure 13, the amplitude ratio yields the following logarithmic decrement:

$$\Lambda = \ln\left(\frac{x_n}{x_{n+1}}\right) \quad (33)$$

The damping ratio D can be derived from the logarithmic decrement Λ :

$$D = \frac{\Lambda}{\sqrt{(2\pi)^2 + \Lambda^2}} \quad (34)$$

NOTE Based on practical experience, the second and third amplitude maxima or amplitude minima should be evaluated.

A.II. Considerations for small-signal stability of the primary control in the unlimited setting range and recommendations for the controller stability of Type 1 installations

Small-signal stability of the primary control

Small-signal stability describes, in general, the damping of the small-signal behaviour of a dynamic system in a specific operating point. The small-signal behaviour may be defined as follows.

Small-signal behaviour describes a behaviour of the system when controlled or modulated with “small” signals, where the word “small” is to be understood not as a small distance to the zero point but to a specific operating point. In the case of non-linear relationships between input and output signals, “small” signals are those which have an approximately **linear transfer behaviour** within a **limited** range that is nonetheless **essential** for the task.

In an interconnected system that includes rotating masses (e.g. synchronous machines and loads), an imbalance between the primary-side generation power and the power consumed in the electrical network acts as an acceleration torque on the rotating flywheel masses and hence results in a frequency change.

Therefore, the frequency (speed), which is identical to the network frequency apart from short-term dynamic oscillations, is an integrating control variable for the power balance available throughout the network.

The primary control (market-based or based on network security) in the network is therefore an elementary task that shall be constantly performed to maintain frequency stability. The primary control may be structured into the following sub-tasks requiring different actions:

- 1) Maintaining small-signal stability¹⁹
- 2) Handling a normative power imbalance with a frequency above the lower frequency limit (49.2 Hz) without impairing the function of the system (e.g. without unplanned disconnection of a consumer load)
- 3) Handling an abnormal power imbalance with a resulting frequency gradient (RoCoF) of up to ± 1 Hz/s and in compliance with extended frequency limits (47.5 Hz to 51.5 Hz, transient up to 52.5 Hz) with a foreseeable impairment of the function of the system (e.g. frequency-dependent disconnection of a consumer load)

The focus is to maintain small-signal stability. Maintaining small-signal stability means that the frequency remains constant in undisturbed operation in the virtual island network and, most importantly, that no oscillations occur. Small-signal stability is therefore a basic prerequisite for any practical operation. As all variables with an influence on frequency, it results from the accumulated effect of all installations in a synchronous zone with frequency or speed control. This also applies to the small-signal stability of large interconnected systems.

An installation without the capability to maintain a stable operating point with constant speed or frequency in standalone operation (or in island operation, partial network operation) relies on the stabilising support of the network in parallel operation. This is always the case when the control system active during network operation does not allow standalone operation while maintaining small-signal stability.

Unlimited and limited setting range

Small-signal stability may be evaluated based on the dynamic behaviour of specific process variables after minor disturbances at a specific operating point. In this context, the damping of the primary control of a load step change in standalone operation is defined and tested. The chosen load change should be large enough to ensure that e.g., the response thresholds of the control are significantly exceeded. On the other hand, the load change shall not lead to process-related limitations becoming effective and having a significant impact during the control process. This refers solely to non-linear limitations and not to time constants which are inherent to the inertia of certain processes. Thus, the behaviour of the installation in the respective operating points may generally be represented approximately using linear models. This describes the unlimited setting range²⁰.

Standalone operation of an installation with undefined load conditions is not normally considered a typical operating condition as it occurs mostly after a disturbance. However, the requirements for small-signal stability are defined for this situation, which is therefore designated as virtual island network operation. Testing shall therefore be performed frequently through simulation using suitable dynamic models.

This FNN Guideline states that a setting range shall be specified for the unlimited setting range as required for the PCNB (i.e. outside the range of 49.8 Hz to 50.2 Hz) for Type 1 installations in standalone operation after a load step change by up to 10 % from $P_{b \text{ inst}}$. For the market-based primary control (i.e. within the range of 49.8 Hz to 50.2 Hz), the value for the step load change is at most equal to the balancing power

¹⁹ The terms controller stability and small-signal stability are used interchangeably.

²⁰ The definition of small-signal behaviour uses the term "limited range" for small deviations from a specific operating point. This corresponds to the "unlimited setting range."

procured through the market. The primary control shall maintain a specified damping ratio in the unlimited setting range. All possible operating points (from $P_{Emin,E}$ to $P_{b\ inst}$ as well as f_{min} to f_{max}) shall be considered as starting points for the unlimited setting range in which the load change is performed.

The limited setting range applies to all control processes that go beyond the unlimited setting range and are influenced mainly by non-linear limitations typical of the installation under consideration.

Recommendations for the controller structure

Speed control is not only required for island operation of an installation (e.g. during start-up until synchronisation with the network or during operation of the houseload network), but it is also of utmost importance for the primary control in the interconnected system. The power control, however, is not capable of ensuring stable primary control, rather, it is subject to limitations on network dynamics which apply even if the frequency influence has no effect on the control. The following notes on power control may be derived only in part from aspects of network dynamics which are beyond the scope of this document. However, they should still be considered for the development of controller structures and the specification of parameters:

- 1) False control effect: after a spontaneous load connection, the electrical power output of the generator (P_{actual}) increases and the active power output is greater than the active power setpoint ($P_{setpoint}$). This results in a negative control deviation at the input of the power controller, which causes the power control to issue a setting command to reduce the power. That causes the original power imbalance to be unnecessarily increased as a function of the inertia of the power control. Only when the frequency decreases may the setting signal of the power controller be increased above the frequency-dependent power setpoint in order to adjust the power of the installation to the increased load. Particularly in the case of a power control that is much faster than frequency dynamics, this false control effect significantly increases the dynamic frequency deviation (f_{nadir}, f_{zenith}).
- 2) Negative contribution to the damping of the primary control: when operating in parallel with other PGUs, mutual accelerations are required between individual installations with different dynamics during a dynamic control process of the primary control in order to maintain the synchronism. These mutual accelerations lead to dynamic power changes which affect a fast power control adversely. The result is an opposing control response which reduces the damping of the primary control.
- 3) Negative damping of phase swinging and inter-area oscillations: network dynamics studies show that the damping of both local phase swinging and widespread inter-area oscillations are adversely affected by a fast power control.

Two basic structures for power controllers in PGMs are described as follows in order to comply with the requirements for small-signal stability of the frequency control by applying a suitable parametrisation and taking into account the aspects mentioned above.

The controller structure indicated in Figure 14 contains three different paths:

- a power controller with P-I capabilities which ensures that the specified power setpoint ($P_{setpoint}$) is maintained in a steady state,
- a proportional part which changes the power setpoint ($P_{setpoint}$) as a function of frequency or speed,
- a proportional frequency or speed controller, whose output signal generates the setting command when added to the output signal of the power controller. This controller may contain dynamic correction devices to fulfil the damping requirements.

The characteristic of the influence of the frequency regarding the deadband is defined in the f deadband block.

(such as synchronous machines or grid-forming converters), grid-following converters reduce the ESCR at the NCP under consideration. Correspondingly, the short-circuit power available at the Type 2 unit may be significantly lower.

The ESCR is the ratio of the short-circuit power $S''_{k,GForming,NCP}$ present at an NCP and originating solely from grid-forming (GForming) PGUs, to the generation capacity $P_{inst,NCP}$ which is installed at the NCP and originating from grid-forming units and the sum of the nominal power of all installations $P_{inst,GFollowing,l}$ of the Type 2 PGUs with grid-following converters (GFollowing) which are connected to the NCP so as to be electrically effective:

$$ESCR_{NCP} = \frac{S''_{k,GForming,NCP}}{P_{inst,NCP} + \sum_l^m (IF_{NCP,l} \cdot P_{inst,GFollowing,l})} \quad (35)$$

The interaction factor (*Wirkfaktor*) $IF_{NCP,l} = \frac{\Delta U_{NCP}}{\Delta U_l}$ takes into account the virtual island voltage change ΔU_{NCP} at the NCP which in turn would be caused by the voltage change ΔU_l at node l.

Grid-following Type 2 units are deemed to be electrically effective if their $IF_{NCP,l}$ terms, when weighted for their nominal power, contribute significantly to the total sum. The short-circuit power $S''_{k,GForming,NCP}$ determined for grid-forming installations shall be determined in such a way, that it may be assigned exclusively to Type 2 PGUs connected to the NCP while not being used by Type 2 PGUs beyond the NCP.

For Type 2 PGUs in close electrical proximity to the NCP, the active factor $IF_{NCP,l}$ converges to unity. For Type 2 PGUs electrically disconnected from the NCP the active factor approaches zero. The ESCR effective at the unit is calculated as follows:

$$ESCR_E = \frac{S''_{k,GForming,E}}{P_{inst,E} + \sum_l^m (IF_{E,l} \cdot P_{inst,GFollowing,l})} \quad (36)$$

A.IV. Example of a verification procedure for determining the internal impedance and voltage sources above 5 Hz

A.IV.1. Aim of the measurement

The aim of the measurement is to determine the frequency-dependent internal impedance of the grid-forming unit during synchronous operation. In addition, this measurement may be used to determine the harmonic sources of the unit. This measurement therefore enables the frequency-dependent Thévenin equivalent of the grid-forming unit (voltage source with internal impedance) or its frequency-dependent Norton equivalent (current source with parallel impedance) to be determined for any desired frequency.

NOTE Thévenin equivalent and Norton equivalent are convertible into each another. For simplicity, only the Thévenin equivalent is used here.

A.IV.2. Measurement procedure

Description of the test environment for measurements

Differential impedance spectroscopy is used to determine the internal impedance and internal harmonic sources of the grid-forming unit. For this purpose, the test object is subjected to an additional small-signal harmonic excitation during operation (see Figure 15).

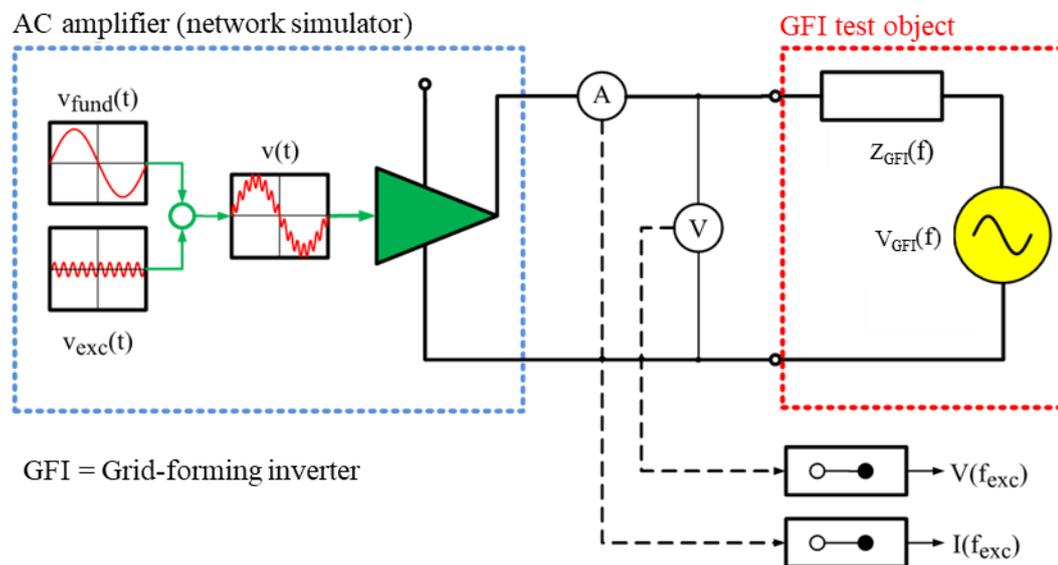


Figure 15 - Principle of differential impedance spectroscopy for determining the internal impedances and harmonics sources of a unit

The measurement may be performed based on the following four test setups.

Test setup 1 – Operation on a network emulator

The grid-forming unit is operated on a network emulator which can absorb or supply at least the maximum apparent power and the maximum current of the test object and, in addition to the fundamental frequency, can regulate the angles and amplitudes of additional excitation voltages in the required frequency range (5 Hz to 1 kHz).

Test setup 2 – Operation on the mains with a parallel harmonic source

The grid-forming unit is operated at an NCP which allows the unit to be operated across the entire operating range. In addition (in parallel or in series), a harmonic source is operated which is capable of regulating corresponding voltage harmonics at the test object terminals. Optionally, an additional impedance may be introduced between the NCP and the harmonic source (e.g. by means of the longitudinal impedance of an FRT test device).

Test setup 3 - Simulated measurement using controller hardware-in-the-loop (C-HiL) setup

The real controller unit of the grid-forming unit is operated on a real-time simulator that is capable of replicating the real power hardware, including all relevant components, as well as a corresponding test source at clock frequency. The real-time model shall replicate the relevant effects that influence the impedance curve and the harmonic sources. The manufacturer shall demonstrate this through a suitable manufacturer's declaration.

Test setup 4 - Simulated offline measurement using software-in-the-loop environment

The real controller code of the grid-forming unit is simulated in a suitable software environment that is capable of replicating the real power hardware, including all relevant hardware and software components, as well as a corresponding test source at clock frequency. The simulation model shall replicate the relevant effects that influence the impedance curve and the harmonic sources. The manufacturer shall demonstrate this through a suitable manufacturer's declaration.

Performing the measurements

The basic procedure for performing the measurements does not differ between the test setups.

Maintain the small-signal harmonic excitation for a sufficient duration for each selected frequency and record the current response of the test object. Change the amplitude or phase of the harmonic excitation and perform a second measurement. Repeat this procedure in steps for each required frequency^{21,22}.

Perform an impedance spectroscopy for each of the operating points in Table 8. Ensure that the test object is operated at its rated voltage ($\pm 5\%$). The frequency range to be investigated is between 5 Hz and 1 kHz with a maximum step size of 5 Hz.

Table 8 - Measurements to verify the higher frequency damping behaviour (and harmonic sources)

Measurement	Active power [% P_n]	Reactive power [% P_n]
1	0 - 25	0
2	25 - 50	0
3	50 - 75	0
4	75 - 100	0
5	175 - 100	max. ind.
6	75 - 100	max cap.

Excitation voltage amplitude:

Ensure that the amplitude of the harmonic used to excite the system is clearly distinguishable from the general measurement noise and that it does not exceed 3 % of the fundamental vibration amplitude.

NOTE 2 An amplitude in the range of 0.5 % to 1.5 % has proven to be ideal. At significantly higher amplitudes, the small-signal behaviour is violated and the necessary correlation between excitation and response is no longer ensured.

Phase angle of the excitation voltage:

Perform at least two measurements with different excitation voltages per frequency point. Either the amplitude or the phase angle of the excitation may be changed. Due to the limited amplitude range (see Note 2), the different phase positions for each frequency should be used.

NOTE 3 To determine the impedance and the internal voltage source, a system of equations with two unknowns shall be solved (see Appendix A.IV.3). This requires at least two independent measurements. This is made possible by

²¹ S. Rogalla, S. Kaiser, B. Burger und B. Engel, „Measured Impedance Characteristics of Solar Inverters up to 1 MW“, 19th Wind Integration Workshop, 2020

²² S. Rogalla, S. Kaiser, B. Burger und B. Engel, „Determination of the Frequency Dependent Thévenin Equivalent of Inverters Using Differential Impedance Spectroscopy“, IEEE International Symposium on Power Electronics for Distributed Generation Systems; PEDG, 11th, 2020

excitation with three different phase positions. Selecting more than two independent excitations results in overdetermination, which eliminates possible measurement errors caused by transient processes, for example.

NOTE 4 It is relevant to ensure that the phase position or amplitude differs between measurements in order to obtain independent measurements. The phase position relative to the fundamental frequency is not relevant.

Frequency steps:

For each of the *operating points specified in Table 8*, follow two independent excitation signals (e.g. with different amplitude or phase angle of the excitation voltage) with frequencies from 5 Hz to 1 kHz in steps of maximum 5 Hz in the positive and negative sequences. The frequency range between 47 Hz < f < 53 Hz does not apply.

Table 9 - Steps for tests to verify higher frequency damping behaviour (and harmonic sources)

Frequency range	Step size Δf	Symmetrical component	Window size t _a
5 Hz to 1 kHz	5 Hz	Positive and negative sequence	200 ms

Window size

Determine the window size t_a, in which each frequency step shall be excited and evaluated, by the necessary resolution of the Fourier transform and depends on the step size Δf. In general, the following applies:

$$t_a = \frac{1}{\Delta f} \tag{37}$$

For the maximum step size of 5 Hz required in this document, this results in a window size of 200 ms.

NOTE 5 The excitation shall be kept constant over an integer multiple of the excitation frequency.

Recording duration:

In order to detect settling processes and other transient effects, record at least three windows of duration t_a for each excitation. The minimum recording duration is therefore t_b = 3 · t_a.

Excitation duration:

The excitation duration per frequency step is also at least three windows of duration t_a therefore t_b = 3 · t_a.

NOTE 6 If a relevant change occurs between the second and third windows, this may indicate that the transient processes and transient effects have not subsided and that the excitation duration may need to be extended.

A.IV.3. Evaluation

For each excitation (at least two per frequency step and symmetrical components), the recorded windows with the duration t_a shall be evaluated. For each window, a Fourier transformation of the voltages and currents shall be first performed (the requirements for the Fourier transformation are based on the specifications in EN 61000-4-7), followed by the calculation of the symmetrical components.

For each frequency and each window, two voltages $U_{a1,2}(f)$, $U_{b1,2}(f)$ and currents $I_{ax}(f)$, $I_{bx}(f)$ per symmetrical component differing in phase or amplitude of the excitation may then be obtained from the spectrum. The formulas (38) to (41) may be used to determine the impedance and voltage sources in the positive and negative sequences. Only the frequency and symmetrical components that were excited are evaluated.

$$\underline{Z}_1(f) = \frac{U_{a1}(f) - U_{b1}(f)}{I_{a1}(f) - I_{b1}(f)} \quad (38)$$

$$\underline{Z}_2(f) = \frac{U_{a2}(f) - U_{b2}(f)}{I_{a2}(f) - I_{b2}(f)} \quad (39)$$

$$\underline{U}_1(f) = \frac{U_{a1}(f) \cdot I_{b1}(f) - U_{b1}(f) \cdot I_{a1}(f)}{I_{b1}(f) - I_{a1}(f)} \quad (40)$$

$$\underline{U}_2(f) = \frac{U_{a2}(f) \cdot I_{b2}(f) - U_{b2}(f) \cdot I_{a2}(f)}{I_{b2}(f) - I_{a2}(f)} \quad (41)$$

The last window is generally considered in the evaluation.

NOTE 7 If more than two independent measurements (difference in excitation in magnitude or phase) were performed, several values for the voltage source and impedance per frequency value can be determined by combining the results. For example, with three measurements a, b, c, which can be combined with each other, three results are obtained. If there are significant differences between these values, this indicates a measurement error, for example due to transients, a non-steady state of excitation or response, or non-synchronised excitation and evaluation in at least one measurement.

A.IV.4. Presentation in the measurement report

The measurement report shall contain detailed information on the following points:

- Operating modes of the AC and DC sources (if available)
- Table of all measured operating points
- Table of the measured impedance and voltage sources in magnitude and phase

The determined impedances are each displayed in a diagram separated by magnitude and phase over the frequency. For direct comparison, several curves with different operating points may also be shown together. If required, the magnitude of the impedance may be plotted in a logarithmic scale.

The internal voltage sources are shown as a bar chart separated by magnitude and phase over the frequency. For direct comparison, several curves with different operating points may also be shown together. If required, the magnitude of the voltages may be plotted in a logarithmic scale.

In general, all measured operating points shall be shown graphically at least once.

A.V. Applying Prony analysis to eliminate the influence of mechanical vibrations from the active power curve

In wind turbines, mechanical interactions can influence the active power or frequency curve. The wind turbine manufacturer may specify up to three frequencies for the unit to be certified regarding mechanical resonances. These three frequencies (f_{res}), including a tolerance band of ± 0.1 Hz or ± 20 % of f_{res} , are eliminated when evaluating the damping.

This appendix describes the procedure for correcting an active power or frequency response curve for vibrations caused by mechanical resonances with known frequencies using Prony analysis²³. Prony analysis is a method for analysing signals that allows to model a signal using several vibrations with different frequencies and damping.

The active power or frequency profile of vibrations caused by mechanical resonances is corrected using the following steps, which are explained for any signal $g(t)$ (use $p_1(t)$ for correcting the active power curve and $f_1(t)$ for the frequency curve):

1) Removal of the signal path before the event

The section before the start of the event shall be removed from the signal path so that the time $t = 0$ corresponds to the start of the event.

2) Division of the signal path into several components (Prony analysis)

The signal path $g(t)$ resulting from Step 1 is divided into several vibration components with different frequencies using Prony analysis. The i -th amplitudes A_i , frequencies f_i , phase angles φ_i and damping parameters d_i of the n identified vibration components shall be determined. The signal $g_{\text{prony}}(t)$ modelled by the Prony analysis (i.e. the sum of all vibration components) represents an approximation of the signal path $g(t)$:

$$g_{\text{prony}}(t) = \sum_{i=1}^n A_i e^{d_i t} \cos(2\pi f_i t + \varphi_i) \quad (42)$$

3) Comparison of identified frequencies with frequencies of mechanical resonances

Frequencies f_i of the vibration components identified by the Prony analysis shall be compared with the manufacturer's specifications regarding the frequencies of the mechanical resonances.

4) Cleaning up the signal path

If the identified frequency of one or more components lies within the frequency band of the mechanical resonances, these components may be subtracted from the signal path. The result of the subtraction represents the clean signal path.

²³ Further information on Prony analysis can be found in: J. Machowski, Z. Lubosny, J. W. Bialek, and J. R. Bumby, *Power System Dynamics: Stability and Control*, 3. Hoboken Publisher House, NJ, USA: John Wiley & Sons, 2020.

B. Appendix (normative)

B.I. Parameters for the primary control based on network security

Table 10 - Dynamic requirements on the primary control based on network security for the active power setting ranges of Type 1 and Type 2 PGMs, PGSU and storage in the unlimited setting range

PGM technology	Type	Unlimited (ub) setting range ⁽¹⁾			
		Setting range		Frequency reduction & increase	
		$P_{ub,min}$	$P_{ub,max}$	Amplitude	Damping ratio
Gas turbine ≤ 2 MW ⁽²⁾	1	$10 \% P_{b inst}$	$100 \% P_{b inst}$	$\pm 10 \% P_{b inst}$	≥ 0.06
Gas turbine > 2 MW ⁽²⁾		$55 \% P_{b inst}^{(9)}$	$100 \% P_{b inst}^{(9)}$	$\pm 10 \% P_{b inst}^{(8)}$	≥ 0.06
Steam turbine ⁽⁶⁾		$20 \% P_{b inst}$	$100 \% P_{b inst}$	$\pm 10 \% P_{b inst}^{(8)}$	≥ 0.06
Combined-cycle power plant		$55 \% P_{b inst}^{(9)}$	$100 \% P_{b inst}^{(9)}$	$\pm 10 \% P_{b inst}^{(8)}$	≥ 0.06
Internal combustion engines (for power generation) ≤ 2 MW ⁽³⁾		$50 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 10 \% P_{E_{max}}$	≥ 0.06
Internal combustion engines (for power generation) > 2 MW ⁽³⁾		$50 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 10 \% P_{E_{max}}$	≥ 0.06
Gas engine ≤ 2 MW ⁽⁴⁾		$50 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 5 \% P_{E_{max}}$	≥ 0.06
Gas engine > 2 MW ⁽⁴⁾		$50 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 7 \% P_{E_{max}}$	≥ 0.06
Hydroelectric power plants in turbine and, where applicable, pump operation		(7)	(7)	(7)	
Geothermal energy		$10 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 10 \% P_{E_{max}}$	≥ 0.06
Battery storage	$-100 \% P_{mn}^{(5)}$	$100 \% P_{mn}^{(5)}$	$\pm 100 \% P_{mn}^{(5)}$	≥ 0.2	
Fuel cell	No requirements				
PV plant	2	$10 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$\pm 90 \% P_{E_{max}}$	≥ 0.2
Wind power plant		$45 \% P_{E_{max}}$	$100 \% P_{E_{max}}$	$- 10 \% / + 1 \% P_{E_{max}}$	≥ 0.1
		$15 \% P_{E_{max}}$	$45 \% P_{E_{max}}$	$- 10 \% P_{E_{max}}$	

1) Unlimited setting range: Range of the small-signal stability of the primary control (see definition in Section 3.1.24.2) for $\cos \varphi = 1$.

2) This applies to natural gas. Other values may be agreed between the network operator and the plant operator for alternative fuels (diesel, digester gas, heating oil, kerosene, syngas and hydrogen with at least a 10 Vol% mix by volume or fuel switching).

3) All liquid fuels.

4) This applies to natural gas. Other values may be agreed between the network operator and the plant operator for alternative fuels (biogas, digester gas, syngas and hydrogen with at least a 10 Vol% mix by volume or fuel switching).

5) Maximum usable (mn) operating range of power output/power consumption (according to manufacturer's specifications) which depends on the design of the unit.

6) All fuels, including: lignite, hard coal, biomass, "waste incineration".

7) Both the total working range and the unlimited setting range of the PCNB shall be agreed with the network operator on a project-by-project basis and determined through the hydraulic characteristics of the installation. For installations with a $P_{A_{max}} > 45$ MW, additional coordination with the transmission network operator is required. Designs with ineffective working and associated setting ranges are not permissible.

8) For Type 1 units or plants with $P_{b inst} > 350$ MW, the maximum amplitude is: $\pm \frac{35 \text{ MW}}{P_{b inst}} \cdot 100 \%$.

9) If, for technological reasons, the entire setting range cannot be covered with the required amplitude, this shall be justified on technical grounds and the restrictions shall be agreed between the plant operator and the network operator in accordance with Appendix B.II.

Table 11 - Dynamic requirements on the primary control based on network security for the active power setting ranges of Type 1 and Type 2 PGMs in the limited setting range

PGM technology	Type	Limited setting range ⁽¹⁾							
		Frequency reduction in the range between 49.8 Hz and 47.5 Hz		Frequency reduction in the range between 51.5 Hz and 50.2 Hz		Frequency rise in the range between 50.2 Hz and 51.5 Hz		Frequency rise in the range between 47.5 Hz and 49.8 Hz	
		Setting range	Minimum actuating speed	Setting range	Minimum actuating speed	Setting range	Minimum actuating speed	Setting range	Minimum actuating speed
Gas turbine ≤ 2 MW ⁽³⁾	1	10 % - 100 %	66 % P_b inst /min	10 % - 100 %	66 % P_b inst /min	10 % - 100 %	66 % P_b inst /min	10 % - 100 %	66 % P_b inst /min
Gas turbine > 2 MW ⁽³⁾⁽⁶⁾		55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min
Steam turbine ⁽⁴⁾		20 % - 100 %	20 % P_b inst /5 min	20 % - 100 %	20 % P_b inst /5 min	20 % - 100 %	45 % P_b inst /8s	20 % - 100 %	45 % P_b inst /8s
Combined-cycle power plant ⁽⁶⁾		55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min	55 % - 100 %	20 % P_b inst /min
Internal combustion engines (for power generation) ≤ 2 MW ⁽³⁾		50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min
Internal combustion engines (for power generation) > 2 MW ⁽³⁾		50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min
Geothermal energy		10 % - 100 %	20 % P_b inst /5 min	10 % - 100 %	20 % P_b inst /5 min	10 % - 100 %	45 % P_b inst /8 s	10 % - 100 %	45 % P_b inst /8s
Hydropower		(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)
Fuel cell ≤ 2 MW	2	50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min	50 % - 100 %	66 % P_b inst /min
Fuel cell > 2 MW		50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min	50 % - 100 %	20 % P_b inst /min
Wind power plant		65 % - 100 % 45 % - 65 % 15 % - 45 %	6 % P_b inst /s 4 % P_b inst /s 2 % P_b inst /s	65 % - 100 % 45 % - 65 % 15 % - 45 %	6 % P_b inst /s 4 % P_b inst /s 2 % P_b inst /s	15 % - 100 %	25 % P_b inst /s	15 % - 100 %	25 % P_b inst /s

- 1) Limited setting range: (large-signal behaviour); consideration of the open control loop 'as it is today'
- 2) The setting range is relative to $P_{E_{max}}$, but for Type 1 units of gas turbine, steam turbine and gas and steam plant technologies it is relative to $P_{b \text{ inst}}$.
- 3) All fuels, including: diesel, natural gas, digester gas, fuel oil, kerosene, syngas. Other values may be agreed between the network operator and the plant operator for alternative fuels (with at least a 10 % of hydrogen by volume or fuel switching).
- 4) All fuels, including: lignite, hard coal, biomass, waste.
- 5) The total active power setting range available for the PCNB as well as the unlimited setting range of the PCNB shall be specified on a project-by-project basis and determined through the hydraulic characteristics of the installation. For installations with a $P_{A_{max}} > 45$ MW additional coordination with the transmission network operator is required. Designs with ineffective working and associated setting ranges are not permissible.
- 6) If, for technological reasons, the entire range cannot be covered with the required amplitude, this shall be justified on technical grounds and the restrictions shall be agreed between the plant operator and the network operator in accordance with Appendix B.II.

B.II. Technology-specific limitations of actuating speeds of Type 1 units within the framework of primary control based on network security

Due to technological limitations in the boundary areas of the compressor guide vane adjustment range, gas turbines are often unable to cover load connections or disconnections with an amplitude of $10\% P_{b\ inst}$.

For example, a $10\% P_{b\ inst}$ load connection (requirements for fast output power) starting from a power point of $90\% P_{b\ inst}$ is associated with a temperature overshoot of the turbine inlet temperature, which can lead to combustion instability and damage to the burner or combustion chamber in many gas turbine types. Continued operation of the PGU would not be possible after such an event.

To protect the gas turbine, the amplitude in the unlimited setting range shall be limited as shown in Figure 16. The power range from approx. 95% to $100\% P_{b\ inst}$ can only be approached with a low gradient.

In addition, in CCGT plants, the slow subsequent steam process limits the possibility of fast power increase of the steam turbine during load additions in the unlimited and limited setting range $>$ approx. $80\% P_{b\ inst}$ (CCGT).

In the transient setting range $>$ approx. $80\% P_{b\ inst}$ (CCGT), the gas turbine is no longer able to overcompensate for the lack of power increase from the steam process and to respond to load switching with unlimited power supply. In many cases, the maximum gas turbine output is reached too early.

During load disconnection (requirements for fast power reduction), limitations may also occur due to the technological process in the gas turbine and in the CCGT plant, which can lead to an adjustment according to Figure 16 in the lower setting range $<$ approx. $70\% P_{b\ inst}$ (CCGT).

This behaviour requires an adjustment of the requirements (actuating speed or amplitude) in the boundary zones of the limited and unlimited setting range according to Figure 16.

Both scenarios (load disconnection in the lower control range or load connection in the upper control range) should be treated separately when evaluating the adjustment of the setting ranges (unlimited or limited).

The same applies to the requirements for pure gas or steam turbines (single cycle) and CCGT plants (combined cycle). The technological possibilities shall be adapted to the specific machine and project. Figure 16 should only be seen as an example.

NOTE For Type 1 units or installations with $P_{b\ inst} > 35\text{ MW}$, the maximum amplitude is: $\pm \frac{35\text{ MW}}{P_{b\ inst}} \cdot 100\%$.

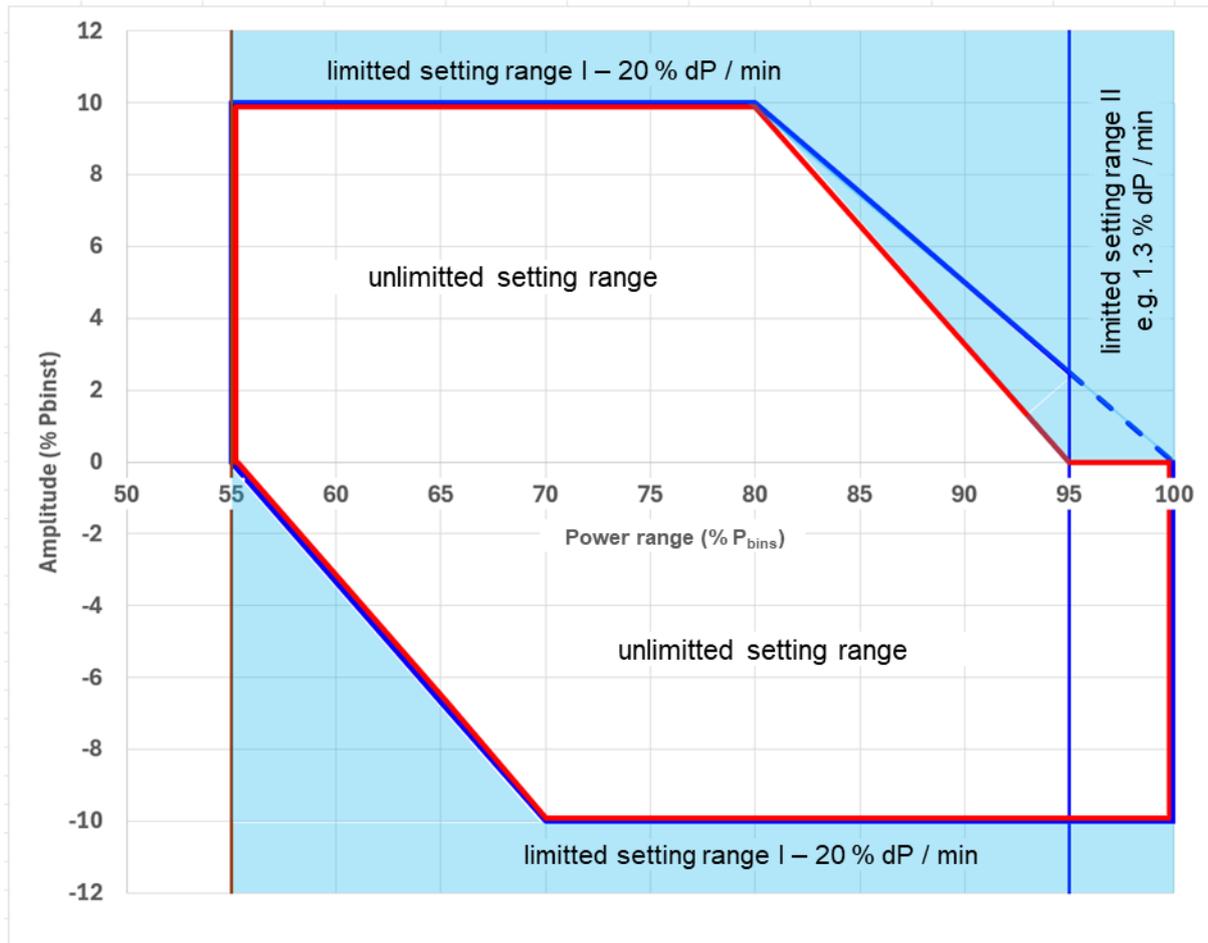


Figure 16 - Technological limitations of the setting ranges (example CCGT)

Key:

- Blue: amplitude capability (static control reserve)
- Red: boundaries of the unlimited or limited setting range (dynamics)
- Blue dashed line: limited amplitude and further limited gradients in the limited setting range

As shown in Figure 16, the blue and red characteristic curves diverge at approx. 80 % $P_{b \text{ inst}}$ (CCGT) in the positive unlimited setting range. This is due to the behaviour of a gas turbine or a CCGT plant.

The blue characteristic curve can still be followed, but no longer with unlimited gradients.

For example, at a power of 95% $P_{b \text{ inst}}$ (CCGT), a control reserve of 2.5% $P_{b \text{ inst}}$ (CCGT) is still available, but this can only be provided with limited gradients.

B.III. Supplementary specifications regarding the scope of process data (VDE-AR-N 4110, Appendix C.5)

Regarding the deactivation of the deadband of the PCNB in accordance with Section 4.2.2.6, Table C.2 of VDE-AR-N 4110:2023-09, Appendix C.5 shall be updated in accordance with Table 12.

Table 12 - Supplement to Table C.2 (VDE-AR-N 4110:2023-09) "Example of additional process data for power-generating modules (1 of 2)"

Control commands	Function	Requirement O... Optional M... Minimum	Range values/resolution	of	Unit
[...]	[...]	[...]	[...]		[...]
Deactivation of the deadband of the primary control based on network security (4.2.2.6)	Setting command	M	2 x binary		
Activation of the deadband of the primary control based on network security (4.2.2.6)	Setting command	M	2 x binary		
[...]	[...]	[...]	[...]		[...]
Feedback messages (for checking the transmitted values)	Function	Requirement O... Optional M... Minimum	Range values/resolution	of	Unit
[...]	[...]	[...]	[...]		[...]
Activation of the deadband of the primary control based on network security (4.2.2.6)	Setting command	M	2 x binary		
Activation of the deadband of the primary control based on network security (4.2.2.6)	Setting command	M	2 x binary		
[...]	[...]	[...]	[...]		[...]

B.IV. Construction of the envelope curve for determining the damping of continuous voltage control

The basis for evaluating the damping requirements for the fault behaviour of the voltage regulation or the effective impedance in accordance with Section 5.5.5.6.2 is the steady-state behaviour of a PT2 element with a damping factor of $D = 0.3$ and the start and continuation of the reactive current in a tolerance band of $\pm 15\%$ relative to the final value ($\Delta x_{tol} = 15\% \cdot \Delta i_{Q,End}$) no later than 80 ms after a sudden change in the terminal voltage of the unit (see Figure 9). Figure 9 is shown again below for illustrative purposes.

NOTE The key points of the requirement were selected based on the +20 / -30 % I_T tolerance band for the settling time of 60 ms (plus 20 ms for the formation of the positive sequence value) in the large signal evaluation of dynamic reactive current support in the Technical Connection Rules.

To construct the envelope curve, the final value of the reactive current change $\Delta i_{Q,End}$ is first determined relative to the pre-fault reactive current in accordance with Section 5.5.5.6.2.3 or 5.5.5.4.3.

The overshoot Δx_M for the required damping ratio of $D = 0.3$ is generally a maximum of

$$\Delta x_M = e^{-\frac{D}{\sqrt{1-D^2} \cdot \pi}} \cdot \Delta i_{Q,End} = 0.3723 \cdot \Delta i_{Q,End} \quad (43)$$

and limits the envelope curve in the first section upwards until time t_1 .

The time t_M of the first maximum is around

$$t_M = \frac{-1}{\ln(\Delta x_{\text{tol}} \cdot \sqrt{1-D^2})} \cdot \frac{D \cdot \pi}{\sqrt{1-D^2}} \cdot t'_{\text{settling}} = 40.65 \text{ ms} \quad (44)$$

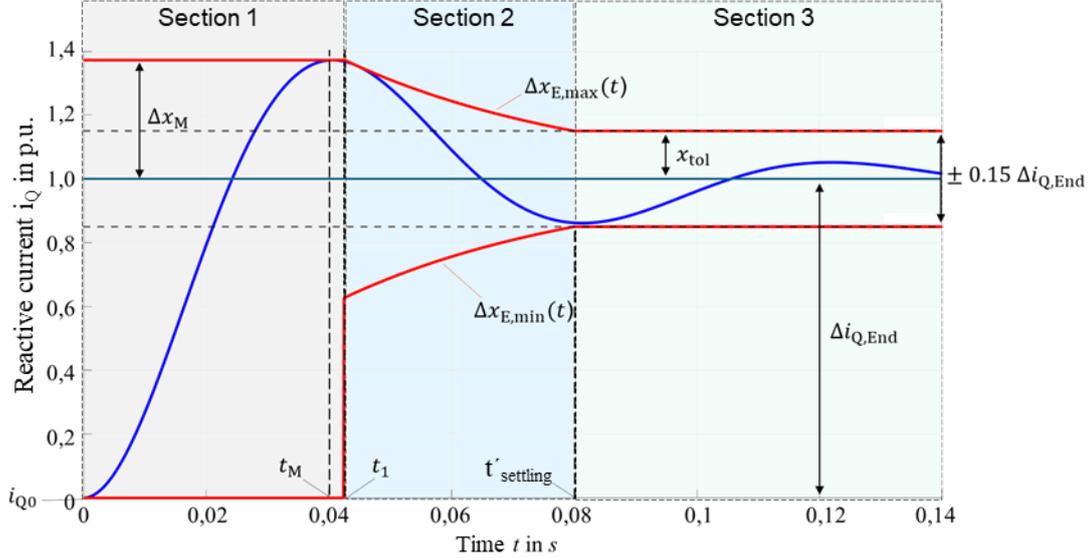


Figure 9 - (Repetition) Envelope curve for determining the damping of continuous voltage control

To construct the second section of the envelope curve, the point in time is determined at which the e-function of the envelope can start from the maximum in order to affect the transient response of the PT2 element:

$$t_1 = \left(1 - \frac{\sqrt{1-D^2}}{\pi \cdot D} \cdot \ln(\sqrt{1-D^2}) \right) \cdot t_M = 42.6 \text{ ms} \quad (45)$$

Based on this, the upper and lower envelopes $\Delta x_{E,\text{max}}(t)$ or $\Delta x_{E,\text{min}}(t)$ in the form of e-functions in the second section of the envelope curve are:

$$\text{(upper envelope)} \quad \Delta x_{E,\text{max}}(t) = \left(1 + \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} t}}{\sqrt{1-D^2}} \right) \cdot \Delta i_{Q,\text{End}} \quad (46)$$

$$\text{(lower envelope)} \quad \Delta x_{E,\text{min}}(t) = \left(1 - \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} t}}{\sqrt{1-D^2}} \right) \cdot \Delta i_{Q,\text{End}} \quad (47)$$

In the third section, a tolerance band of Δx_{tol} of $\pm 15\% \cdot \Delta i_{Q,\text{End}}$ limits the envelope curve upwards and downwards.

This approach also forms the basis for the evaluation of the large-signal behaviour in accordance with Section 5.5.5.6.3. In contrast to the small-signal evaluation, the damping is only evaluated from 80 ms after the sudden voltage change. In order to prevent residual oscillations of excessive amplitude, the tolerance band is narrowed to $\pm 5\% \cdot \Delta i_{Q,\text{End}}$ 130 ms after the sudden voltage change occurs. This is done in line

with the further development of the second section of the envelope curve beyond $t'_{\text{settling}} = 80 \text{ ms}$ (see Figure 17).

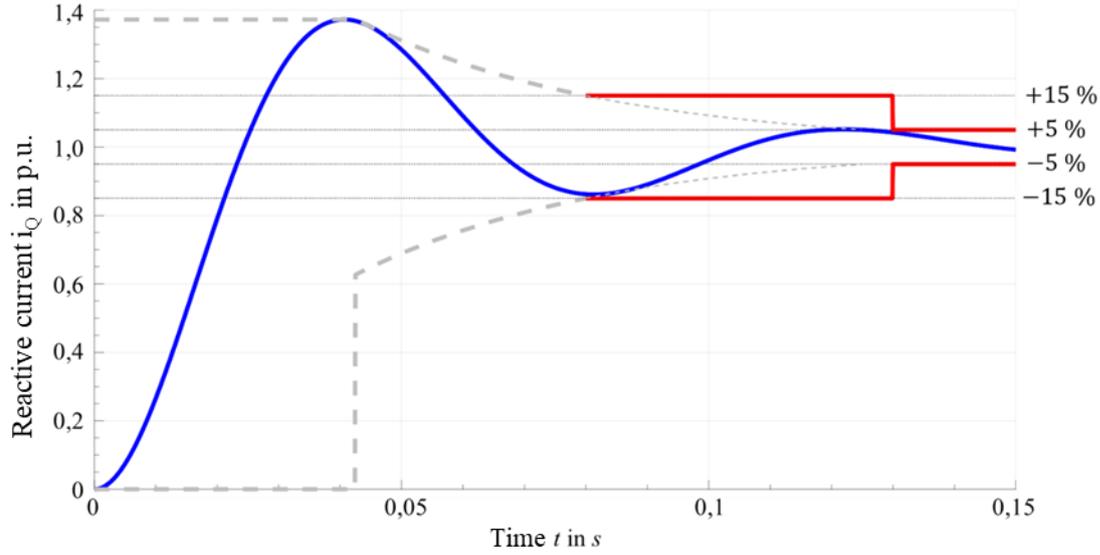


Figure 17 - Envelope curve for evaluating the damping behaviour during large signal changes in the voltage amplitude at the terminals of the grid-forming unit

B.V. Determination of instantaneous values

Instantaneous values are determined using $\alpha\beta$ coordinates with the aid of the Clarke transformation. The $\alpha\beta$ coordinates of the voltages are determined as follows:

$$u_{\alpha} = \frac{\sqrt{2}}{3} \cdot (u_a - 0.5 \cdot u_b - 0.5 \cdot u_c) \quad (48)$$

$$u_{\beta} = \frac{\sqrt{2}}{3} \cdot \left(\frac{\sqrt{3}}{2} \cdot u_b - \frac{\sqrt{3}}{2} \cdot u_c \right) \quad (49)$$

$$u_0 = \frac{\sqrt{2}}{3} \cdot \left(\frac{1}{\sqrt{2}} \cdot u_a + \frac{1}{\sqrt{2}} \cdot u_b + \frac{1}{\sqrt{2}} \cdot u_c \right) \quad (50)$$

The $\alpha\beta$ coordinates of the currents are determined as follows:

$$i_{\alpha} = \frac{\sqrt{2}}{3} \cdot (i_a - 0.5 \cdot i_b - 0.5 \cdot i_c) \quad (51)$$

$$i_{\beta} = \frac{\sqrt{2}}{3} \cdot \left(\frac{\sqrt{3}}{2} \cdot i_b - \frac{\sqrt{3}}{2} \cdot i_c \right) \quad (52)$$

$$i_0 = \frac{\sqrt{2}}{3} \cdot \left(\frac{1}{\sqrt{2}} \cdot i_a + \frac{1}{\sqrt{2}} \cdot i_b + \frac{1}{\sqrt{2}} \cdot i_c \right) \quad (53)$$

Provided that no zero sequence components occur in the system under consideration (symmetrical three-wire system), the magnitude of the voltage and current space vector in the $\alpha\beta$ coordinate system is calculated as the RMS value using:

$$|u_{\alpha\beta}| = \sqrt{(u_{\alpha}^2 + u_{\beta}^2)} \quad (54)$$

$$|i_{\alpha\beta}| = \sqrt{(i_{\alpha}^2 + i_{\beta}^2)} \quad (55)$$

The modulus bars of $|u_{\alpha\beta}|$ and $|i_{\alpha\beta}|$ have been omitted from this document for the sake of simplicity.

The instantaneous active power in the three-phase system is defined as:

$$p = u_a \cdot i_a + u_b \cdot i_b + u_c \cdot i_c \quad (56)$$

The active power determined using equation (56) corresponds to the active power in the $\alpha\beta$ coordinate system, i.e.:

$$p_{\alpha\beta} = p \quad (57)$$

The magnitude of the active current vector in the $\alpha\beta$ coordinate system may be determined as the RMS value as follows:

$$|i_{p,\alpha\beta}| = \frac{p}{3 \cdot u_{\alpha\beta}} \quad (58)$$

The modulus bars of $|i_{\alpha\beta}|$ have been omitted from this document for the sake of simplicity.

The instantaneous reactive power in the $\alpha\beta$ coordinate system is defined as:

$$q_{\alpha\beta} = 3 \cdot (-u_{\alpha} \cdot i_{\beta} + u_{\beta} \cdot i_{\alpha}) \quad (59)$$

To suppress measurement noise, a moving average over 5 ms is formed for the evaluation of these variables in this FNN Guideline according to:

$$u_{\alpha\beta,5ms} = \frac{1}{5 \text{ ms}} \cdot \int_{t-5 \text{ ms}}^t u_{\alpha\beta} \cdot dt \quad (60)$$

$$i_{\alpha\beta,5ms} = \frac{1}{5 \text{ ms}} \cdot \int_{t-5 \text{ ms}}^t i_{\alpha\beta} \cdot dt \quad (61)$$

$$i_{p,\alpha\beta,5ms} = \frac{1}{5 \text{ ms}} \cdot \int_{t-5 \text{ ms}}^t i_{p,\alpha\beta} \cdot dt \quad (62)$$

$$p_{\alpha\beta,5ms} = \frac{1}{5 \text{ ms}} \cdot \int_{t-5 \text{ ms}}^t p_{\alpha\beta} \cdot dt \quad (63)$$

$$q_{\alpha\beta,5ms} = \frac{1}{5 \text{ ms}} \cdot \int_{t-5 \text{ ms}}^t q_{\alpha\beta} \cdot dt \quad (64)$$

B.VI. Determination of the angular change over time

The angular change over time may be determined by the following steps:

- 1) Determination of the $\alpha\beta$ components u_α u_β from the three-phase voltages using $\alpha\beta$ transformation (see equations (48) and (49)).
- 2) Calculation of the phase angle:

$$\varphi_{u,\alpha\beta} = \begin{cases} \operatorname{atan}\left(\frac{u_\beta}{u_\alpha}\right) + \left(\frac{3\pi}{2}\right) & , \text{ if } u_\alpha < 0 \\ \operatorname{atan}\left(\frac{u_\beta}{u_\alpha}\right) + \left(\frac{\pi}{2}\right) & , \text{ if } u_\alpha \geq 0 \end{cases} \quad (65)$$

- 3) Determination of the raw phase angle change, including changes due to the sawtooth waveform:

$$\Delta\varphi_{u,\alpha\beta} = \varphi_{u,\alpha\beta}^{(2\dots n)} - \varphi_{u,\alpha\beta}^{(1\dots(n-1))} \quad (66)$$

where n corresponds to the number of data points.

- 4) Removing the influence of the sawtooth waveform in the phase angle change:

$$\Delta\varphi_{u,\alpha\beta,\text{korrr0}} = \begin{cases} \Delta\varphi_{u,\alpha\beta}^{(-2\pi)} & , \text{ if } \Delta\varphi_{u,\alpha\beta} > \pi \\ \Delta\varphi_{u,\alpha\beta} & , \text{ if } \Delta\varphi_{u,\alpha\beta} \leq \pi \end{cases} \quad (67)$$

$$\Delta\varphi_{u,\alpha\beta,\text{korrr}} = \begin{cases} \Delta\varphi_{u,\alpha\beta,\text{korrr0}}^{(+2\pi)} & , \text{ if } \Delta\varphi_{u,\alpha\beta,\text{korrr0}} < -\pi \\ \Delta\varphi_{u,\alpha\beta,\text{korrr0}} & , \text{ if } \Delta\varphi_{u,\alpha\beta,\text{korrr0}} \geq -\pi \end{cases} \quad (68)$$

- 5) Determination of the instantaneous (noise-affected) frequency:

$$f = \frac{\Delta\varphi_{u,\alpha\beta,\text{korrr}}}{2\pi \cdot \Delta t} \quad (69)$$

where Δt corresponds to the time resolution of the data points.

- 6) Calculation of frequency averages with two moving time windows of 5 ms and 1 s:

$$f_{5\text{ms}} = \frac{1}{5\text{ms}} \cdot \int_{t-5\text{ms}}^t f \cdot dt \quad (70)$$

$$f_{1\text{s}} = \frac{1}{1\text{s}} \cdot \int_{t-1\text{s}}^t f \cdot dt \quad (71)$$

- 7) Determination of the difference between the two aforementioned frequency averages (in steady state, this difference is zero):

$$\Delta f = f_{5\text{ms}} - f_{1\text{s}} \quad (72)$$

- 8) Calculation of the integral of the frequency difference over time and conversion from rad to degrees:

$$\varphi_{\text{rad}} = 2\pi \cdot \int_{t-1\text{s}}^t \Delta f \cdot dt \quad (73)$$

$$\varphi_{\text{grad}} = \frac{\varphi_{\text{rad}}}{\pi \cdot 180^\circ} \quad (74)$$

B.VII. Benchmark system for the verification of network parallel operation capability

The benchmark network model (BN) to be used to verify network parallel operation capability is shown in Figure 18 and consists of two PGMs (PGM-1 and PGM-2). The PGUs of these two PGMs correspond to the grid-forming unit to be certified. The two PGMs are integrated into a network in accordance with Figure 18.

PGM-1 corresponds to an installation with a network connection at network level (NL) 5 with low SCR while PGM-2 corresponds to a network connection at network level 4 with high SCR. All PGUs of PGM-1 and PGM-2 are in operation.

Specification of voltage levels

The rated voltage of the nodes can be found in Table 13.

Table 13 - Rated voltages of the nodes in the benchmark system (verification of network parallel operation capability)

Nodes	Nominal voltage
EHV-1	380 kV
E.1, HV-0, HV-1, HV-2	110 kV
E.1, MV-1, MV-2, NCP-1-NCP2 MV 1.x, MV 2.x, (x = 1,2,3) MV-1-EOL, MV-2-EOL	20 kV
NV 1.x, NV 2.x (x = 1,2,3)	accordingly for PGUs

Specification of the parameters of the boundary network

The extra-high-voltage network is modelled as an impedance-loaded, frequency-rigid voltage source with controllable amplitude, angle and frequency of the voltage.

The associated equivalent voltage source 'ext EHV Network' shall be defined so that a maximum initial short-circuit AC current I''_{kss} of 45 kA occurs at node 'EHV-1' (VDE 0102). The R/X ratio should be 0.1.

Specification of the parameters of the network transformers

1) General information

- a) All transformers are parametrised with realistic design data just as in real networks. The data is adjusted depending on the selected network connection point (network level).
- b) The design data of the transformers shall also be taken into account in full for asymmetrical calculations (e.g. transformer connection group, internal delta balancing winding). The zero sequence may be ignored.
- c) Transformer tap changers in typical dimensions and controllers shall be taken into account when determining the operating point using the initial load flow in order to set the operating points (see below) of the PGM.
- d) The magnetic circuit of the transformers may be modelled linearly without saturation effects and hysteresis.

2) The transformers are designed as standard mains transformers in accordance with Table 14.

Table 14 - (network) transformer data in the benchmark system (verification of network parallel operation capability)

Transformer	Switching group	Power [MVA]	u_k [%]	u_{kr} [%]
TRF EHV 1	YNyn0d5 (optional as internal balancing winding)	350	21	0.25
TRF HV 1 / 2	YN(d5)yn0 (internal balancing winding)	40	15	0.45

- 3) If the sum of the rated outputs of the PGUs in an installation is greater than half the rated apparent power S_T of transformers TRF HV 1 or 2, or if the SCR ratio at 'NCP-2' is less than 20, the rated output of both transformers shall be increased identically until the condition is met.

Specifications for the parameters of other network equipment

- 1) The connection between nodes 'HV-0' and 'HV-1' may be either a line or a concentrated impedance. The parameter of the connection shall be defined so that an initial short-circuit AC current I''_{kss} of 5 kA occurs at node 'EV-1'. The R/X ratio of the connection should be 0.35.
- 2) The 110kV line 'L 110' from node 'HV-1' to 'HV-2' is designed as an overhead line with the following parameters: $R' = 0.15$ Ohm/km, $X' = 0.4$ Ohm/km, $C_1' = 9$ nF/km, line length: 30km.
- 3) The connection between nodes 'MV-1' and 'NCP-1' may be either a line or a concentrated impedance. The parameter of the connection shall be defined so that an SCR of 3 occurs at node 'NCP-1'. The R/X ratio of the connection should be 0.05.
- 4) The connection between nodes 'MV-2' and 'NCP-2' is designed as an impedance-free connection.
- 5) The sheathing (R', X') of the cables between nodes 'MV-1' and 'MV-1-EOL' as well as 'MV-2' and 'MV-2-EOL' should have an R/X ratio of 2. The length or impedance of the feeders shall be selected so that, in the event of an impedance-free three-phase-to-earth fault at the node 'MV-1-EOL' or 'MV-2-EOL', a positive sequence residual voltage at the network node 'MV-1' or 'MV-2' is achieved in accordance with test 2c shown in Section 5.5.6.5.3. The model of the feeder circuit breaker of lines MV-Out-1 and 2 shall represent the interruption of the current at the natural zero crossing per phase when clearing a fault.

Specifications for the structure and parameters of the equipment of the PGU / PGM

- 1) The arrangement of the PGUs in PGM 1 or 2 relative to the NCP corresponds to the typical interconnection of the PGUs, either as:
 - a series connection via medium-voltage cables and the respective PGU transformer in accordance with Figure 18,
 - a parallel connection of the PGU on the low-voltage side of a common PGU transformer in accordance with Figure 19, or
 - it shall be examined in both of the variants above, whether both implementation variants are possible.
- 2) The medium-voltage cables within the two PGMs shall be designed for the series connection variant based on standard design criteria for corresponding PGMs or, alternatively, the following criteria:
 - a) Minimum possible cross-sectional dimensioning per section individually or identical across all sections.
 - b) Compliance with the nominal line load capacity I_T across all sections.
 - c) R/X value of the partial section according to the following formula: R/X [p.u.] = $(0.3 \cdot I_T$ [kA])^{-1.5}.

- d) Maximum voltage drop along the entire bundle conductor $< 1\%$ at rated active power or compliance with an impedance of the bundle conductor < 0.01 p.u. relative to the base impedance $Z_B = U_{n,LL} / I_n$ of one unit:
- 3) In the parallel connection variant of the PGUs, PGU 2 and 3 shall be connected in parallel within each PGM using the concentrated impedances Z-DUT-X.Y or, optionally, cables that are designed according to the usual planning criteria for the corresponding PGM or, alternatively, according to the following criteria:
- Minimum possible cross-sectional dimensioning per section individually or identical across all sections.
 - Compliance with the nominal line load capacity I_T across all sections.
 - R/X value of the partial section according to the following formula: R/X [p.u.] = $(0.28 \cdot I_T$ [kA])^{-1.67}.
 - Voltage drop along the impedance Z-DUT-X.2(3) for PGM 2(3) of 0.5(1.0) % at rated active power or 0.005(0.01) p.u. relative to the base impedance $Z_B = U_{n,LL} / I_n$ of the unit.
- 4) The rated voltage of the PGU terminals corresponds to the nominal voltage of the units.
- 5) The data for the PGU transformers shall be taken from the data sheets or plausible typical values shall be used:
- The rated power is scaled to match the rated power of the PGU (e.g. 1 p.u.) or the sum of the PGUs for the parallel connection variant. The relative short-circuit voltages and losses are scaled to match the typical values for the rated power.
 - A Dyn5 or Dyn11 connection group is typical. The connection group usually contains at least one D winding, which effectively decouples the neutral system from the mains. Mains-side neutral points are not usually treated as neutral points (remain open).
 - Tap changers may be reproduced as required. Any available controller for the tap changer shall be taken into account when determining the operating point using the initial load flow in order to set the operating points (see below) of the PGM.
 - The magnetic circuit of the transformers may be modelled linearly without saturation effects and hysteresis.
- 6) The primary loss of mains protection of the PGM or the loss of mains protection of the PGU may be disregarded.

Operating states and parameters of PGM-1 and PGM-2

The tests distinguish between two cases:

- The 'market (M)' case simplifies the necessary framework conditions for the plant design and operation of the units for participation in the market ('availability').
 - The 'interaction (I)' case corresponds to situations that could arise during periods of 'unavailability' for the market and that could be critical for stability and network operation. It also serves to test the controller design.
- Table 15 applies for the active and reactive power operating points of the PGU in the initial state. For PGUs (storage), the specified active power operating points shall also be checked in the event of a negative sign (consumption).
 - The reactive power operating points or voltage setpoints of the PGU are determined individually in the initial state in the 'market' case by the power flow initialisation. Plant controllers of the PGM and step changers of the PGU or PGM transformers shall be taken into account.
 - The active and reactive power operating points for each PGU shall be set after initialisation, equally for the transformer and PGM controllers that are effective during initialisation.

- 4) The tests shall be performed with the smallest and largest start-up time constant T_A specified for the unit.

Table 15 - Active and reactive power operating points in the benchmark system (verification of network parallel operation capability)

Test	Configuration	Case	PGM 1 (SCR = 3)						PGM 2 (SCR >> 10)						Initialisation
			PGU 1.1		PGU 1.2		PGU 1.3		PGU 2.1		PGU 2.2		PGU 2.3		
			P [%]	cos(φ)	P [%]	cos(φ)	P [%]	cos(φ)	P [%]	cos(φ)	P [%]	cos(φ)	P [%]	cos(φ)	
1	B	M	80	a)	80	a)	80	a)	80	a)	80	a)	80	a)	a
1	B	I	75	0.9	50	-0.9	75	0.9	75	0.9	50	-0.9	75	0.9	b
2a-c	B	M	80	a)	80	a)	80	a)	80	a)	80	a)	80	a)	a
2a-c	B	I	90	1	75	-0.9	50	0.9	90	1	75	-0.9	50	0.9	c
3	B	M	80	a)	80	a)	80	a)	80	a)	80	a)	80	a)	a
3	B	I	75	0.9	50	-0.9	75	0.9	75	0.9	50	-0.9	75	0.9	b
4	B	M	75	1	75	1	75	1	75	1	75	1	75	1	d

a) Reactive power as per the initialisation of the plant controller (see Point 2 under operating states and parameters of the PGM-1 and PGM-2)

b) *Consumption of active power: rated apparent power

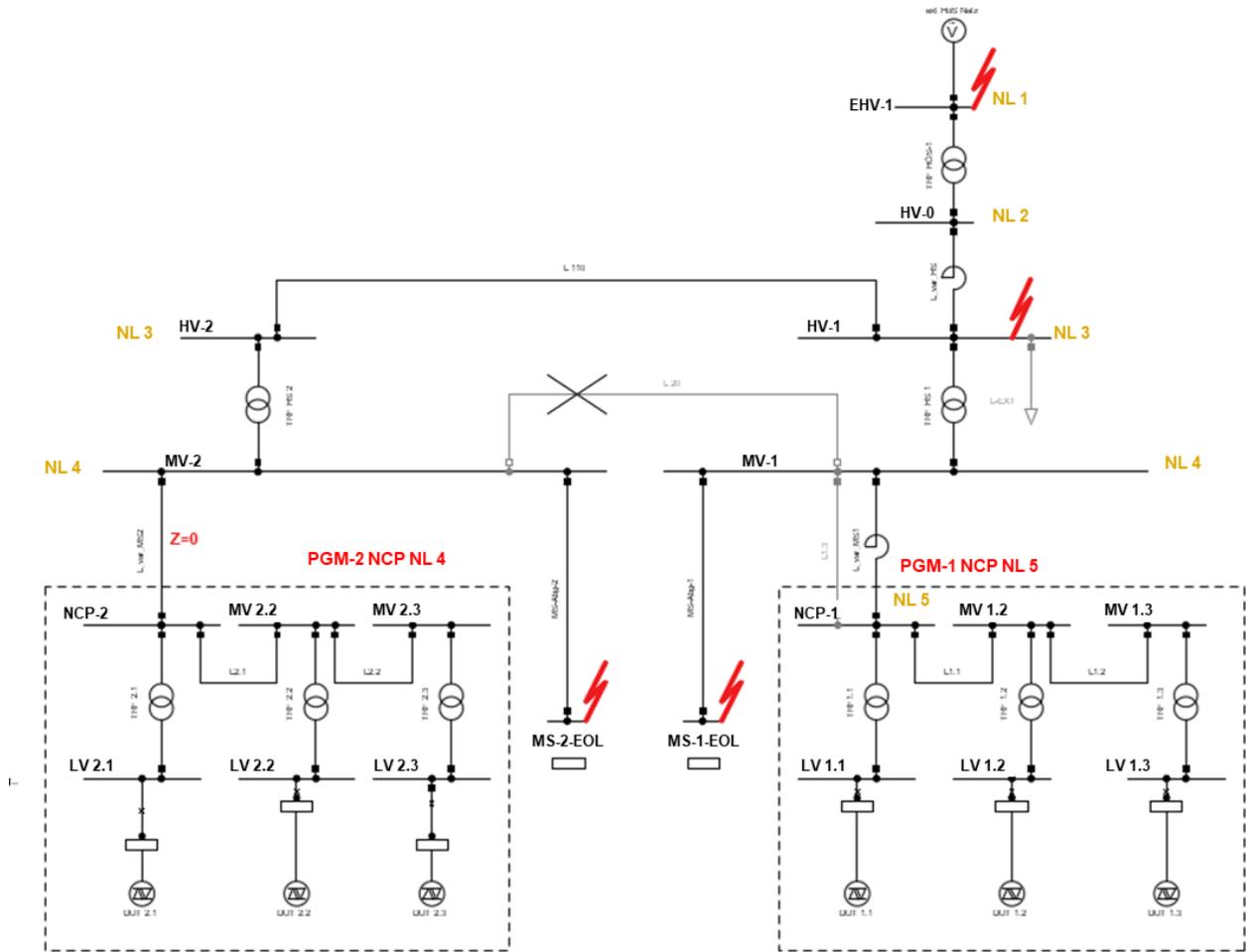


Figure 18 – Benchmark system for the verification of network parallel operation capability

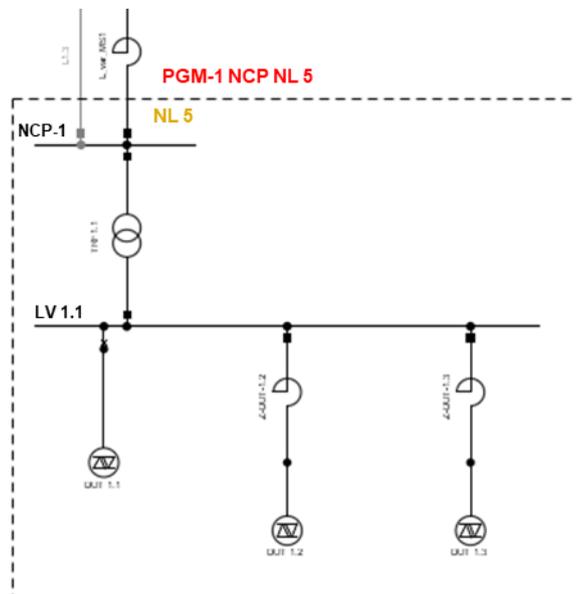


Figure 19 - Alternative configuration of the PGM 1 (same for PGM 2)

B.VIII.Evaluation of harmonic currents during current limitation to identify current clipping

The current distortion is determined based on the harmonic evaluation in accordance with FGW TR 3 or IEC 61000-4-7. Since the period to be evaluated only covers a few network periods, adjustments are necessary. A continuous determination of the THD with a step size of 1 ms is used for evaluation. No grouping is performed. Instead, the frequency components above 50 Hz are evaluated with a resolution of 25 Hz (corresponding to the window width of 40 ms) up to a frequency of 2.5 kHz. The value to be used for evaluation at a point in time t_1 THDI(t_1) corresponds to the result of the measurement window from $t_1 - 40$ ms until t_1 .

The input variable is the instantaneous value of the respective phase current. A Fourier analysis of the signal is performed for this purpose.

These framework conditions result in the following specifications for the calculation:

$$f(t) = c_0 + \sum_{k=1}^{\infty} c_k \sin\left(\frac{k}{N} \omega_1 t + \varphi_k\right) \quad (75)$$

$$c_k(t_1) = |b_k(t_1) + ja_k(t_1)| = \sqrt{b_k(t_1)^2 + a_k(t_1)^2} \quad (76)$$

$$Y_{C,k}(t_1) = \frac{c_k(t_1)}{\sqrt{2}} \quad (77)$$

$$b_k(t_1) = \frac{2}{T_N} \int_{t_1-T_N}^{t_1} f(t) \times \sin\left(\frac{k}{N} \omega_1 t\right) dt \quad (78)$$

$$a_k(t_1) = \frac{2}{T_N} \int_{t_1-T_N}^{t_1} f(t) \times \cos\left(\frac{k}{N} \omega_1 t\right) dt \quad (79)$$

$$c_0(t_1) = \frac{1}{T_N} \int_{t_1-T_N}^{t_1} f(t) dt \quad (80)$$

The time profile of THD is then determined from:

$$THD(t_1) = \sqrt{\sum_{k=N+1}^{h_{\max} \times N} \left(\frac{Y_{C,k}(t_1)}{Y_{H,1}(t_1)}\right)^2} = \sqrt{\sum_{k=N+1}^{h_{\max} \times N} \left(\frac{Y_{C,k}(t_1)}{Y_{C,N}(t_1)}\right)^2} \quad (81)$$

When using

ω_1

Angular frequency of the fundamental oscillation, $\omega_1 = 2 \cdot \pi \cdot f_{H,1}$

$T_N = 40$ ms

Width (or duration) of the time window; the time window is the time span of a temporal function over which the Fourier transform is performed.

c_0

Constant component

c_k

Amplitude of the component with frequency $f_{C,k} = \frac{k}{N} \cdot f_{H,1}$

$Y_{C,k}$

RMS value of the component c_k

$Y_{H,1}(t_1) = Y_{C,k}(t)$

RMS value of the fundamental oscillation

$f_{H,1} = 50$ Hz

Frequency of the fundamental oscillation of the energy supply system

k	Ordinal number (order of the spectral line), relative to the frequency resolution $f_{c,1} = \frac{1}{T_N} = 25 \text{ Hz}$
$N = 2$	Number of fundamental oscillation periods within a window width
Φ_k	Phase angle of the spectral line k
$h_{\max} = 50$	Maximum harmonic order as a multiple of the frequency resolution
$f_{H,h}$	Frequency that is an integer multiple of the (fundamental) frequency of the energy supply system $f_{H,h} = h \cdot f_{H,1}$
THD(t_1)	Moving THD with a time step of 1 ms

C. Appendix (normative)

The forms in this Appendix C are intended to be duplicated by the user of this FNN Guideline. The forms in this appendix replace the forms specified in Appendix E of the relevant Technical Connection Rule in the operating licence procedure for grid-forming units and grid-forming installations.

C.I. Forms for operating licence procedures – Medium-voltage

C.I.1. (E.1) Application – Medium-voltage

This form replaces Appendix E.1 of VDE-AR-N 4110.

(This form is intended to be replicated by the user of this VDE application guide.)

Application for network connection (medium-voltage) (to be completed by the connection owner)		1 (4)
Description of the construction project	_____	
Location of the installation	Postcode, town, district _____ Street, number or floor _____ Number / district number _____	
Connection owner	Company _____ First name, surname _____ Street, number _____ Postcode, town, district _____ Phone, email _____	
Property owner	<input type="checkbox"/> Connection owner is the property owner <input type="checkbox"/> Authority the property owner is supplied with the application	
Plant installer (if known)	Company, postcode, town _____ Phone, email _____	
Installation type	<input type="checkbox"/> Demand installation <input type="checkbox"/> Power-generating module <input type="checkbox"/> Mixed installation <input type="checkbox"/> Charging system for electric vehicles <input type="checkbox"/> Storage <input type="checkbox"/> Temporary connection (e.g. power for a construction site) <input type="checkbox"/> Emergency power generator	
Allocation of network connection	<input type="checkbox"/> New installation	<input type="checkbox"/> Extension or modification <input type="checkbox"/> Dismantling
Position of the customer installation with suggestions marked for possible locations of the transfer station. Plans to a suitable scale (e.g. layout plan to a scale of 1 : 25 000 or 1 : 10 000, detailed plan to a scale of at least 1 : 500) attached? In the case of power-generating modules or mixed installations, the location of the generation units shall be clearly indicated.		<input type="checkbox"/> yes <input type="checkbox"/> no
Anticipated active connection power $P_{AV, B}$ and $P_{AV, E}$ [kW]		
	previously	total value required hereafter (in final stage after measure)
Consumption active power $P_{AV, B}$		
Feed-in active power $P_{AV, E}^*$		
For power-generating modules, mixed installations or storage, pages 2 (4) and 3 (4) of E.1 form shall also be completed. For charging devices for electric vehicles, page 4 (4) shall also be completed.		
Provision of the measuring equipment and metering point operation to be performed by: <input type="checkbox"/> basic MPO <input type="checkbox"/> other MPO _____		
Power expected to be consumed on site	<input type="checkbox"/> no if yes: power _____ kW	Starting date _____
Is a data sheet for assessing system perturbations (Form E.2) for the connection of a demand installation attached?	<input type="checkbox"/> yes <input type="checkbox"/> no	
Time schedule for the construction works attached?	<input type="checkbox"/> yes <input type="checkbox"/> no	
Planned commissioning date / planned completion of the measure		_____
Place, date	Signature of the connection owner	

NOTE* Maximum active power of the customer installation fed into the medium-voltage network connected upstream.

Application for network connection (medium-voltage) (to be completed by the connection owner of power-generating modules / mixed installations / storage)			2 (4)
Type of the power-generating module (multiple choice possible for energy mix)	<input type="checkbox"/> Wind energy	<input type="checkbox"/> Hydropower	<input type="checkbox"/>
	<input type="checkbox"/> Photovoltaics	<input type="checkbox"/> Ground area	<input type="checkbox"/> Roof area
	<input type="checkbox"/> CHP plant	Fuel type used (e.g. natural gas, biogas, biomass)	
	<input type="checkbox"/> Thermal power plant	..... ...
	<input type="checkbox"/> Storage	<u>Operating mode:</u> <input type="checkbox"/> <u>Peak load coverage / Optimisation of household consumption</u> <input type="checkbox"/> <u>Balancing energy market / Ancillary services</u> <input type="checkbox"/> <u>Island operation</u> <input type="checkbox"/> <u>Other:</u> _____	
Operating mode	<input type="checkbox"/> <u>Peak load coverage / optimisation of household consumption</u> <input type="checkbox"/> <u>Balancing energy market / ancillary services</u> <input type="checkbox"/> <u>Island operation</u> <input type="checkbox"/> <u>Inertia</u> <input type="checkbox"/> <u>Other:</u> _____		
	<input type="checkbox"/> Stand-by generator with > 100 ms parallel network operation <input type="checkbox"/> Stand-by generator with ≤ 100 ms parallel network operation	<u>Operating mode:</u> <input type="checkbox"/> Trial operation in accordance with DIN 6280-13 or VDE 0100-560 (VDE 0100 560) <input type="checkbox"/> Peak consumption coverage <input type="checkbox"/> Balancing energy market <input type="checkbox"/> _____	
<u>Measure for a power-generating module</u>	<input type="checkbox"/> <u>New installation</u>	<input type="checkbox"/> <u>Extension or modification</u>	<input type="checkbox"/> <u>Dismantling</u>
Power data	Existing (inventory)	New installation / extension / dismantling	in final configuration (new planned total value)
Maximum generation active power, cumulated $\sum P_{Amax}^*$	.....kW	.....kW	.....kW
Maximum generation apparent power, cumulated $\sum S_{Amax}^*$	.....kVA	.....kVA	.....kVA
For PV: module power [kWp]			
Houseload of the power-generating module .....kW			
All energy fed into the network of the network operator?			<input type="checkbox"/> yes <input type="checkbox"/> no
Is feed-in monitoring (PAV, E – monitoring) planned at the network connection point?			<input type="checkbox"/> yes <input type="checkbox"/> no
Comments on the power-generating module:			

* Calculated from the sum of the maximum 10-minute average values of all installed power-generating units and storage in accordance with the information in the unit certificates at the network connection point. Any permanent active power reduction on the power-generating units shall be taken into account. For power-generating units and storage without a unit certificate, the rated active power P_{TE} and S_{TE} may be used as an alternative.

** Module power: maximum output power (P_{max}) under standard test conditions (STC conditions) in accordance with DIN EN 50380 (0126-390).

Application for network connection (medium-voltage) (to be completed by the connection owner; use one data sheet for every structurally different power-generating unit or unit)		3 (4)
Number of identically constructed power-generating units/ storage: units		
Unit certificate available <input type="checkbox"/> yes <input type="checkbox"/> no. When no: <input type="checkbox"/> Prototype <input type="checkbox"/> Verification through the individual verification procedure		
ZEREZ ID (additional information on storage is still required):		
If no ZEREZ ID is available, the following information is required:		
Unit type	<input type="checkbox"/> double-fed asynchronous machine	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Synchronous machine (coupled directly)	<input type="checkbox"/> Phase shifter operation
	<input type="checkbox"/> Network connection with full converter (no storage)*	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Storage	<input type="checkbox"/> Inertia
	Other	
Unit manufacturer:	.....	Type:
Power data of the PGU / storage	Rated apparent power S_{rE} *	..... kVA
	Maximum active power (10-minute average) $P_{E_{max}}$ **	..... kW
	$P_{min,dyn}$: minimum dynamic active power available for the provision of negative inertia	..... kW
	$P_{max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia	..... kW
	$P_{limitneg,max}$: maximum dynamic active power for the provision of negative inertia	..... kW
	$P_{limitpos,min}$: minimum dynamic active power for the provision of positive inertia	..... kW
	Transient minimum power	..... kW
	T_A : start up time constant	..... s
	Effective impedance z_w :	
	without a unit transformer (or on the low-voltage side of the unit):	.....p.u.
including a unit transformer (or on the medium-voltage side of the unit):	.....p.u.	
if applicable, at high-voltage level: 0.50 p.u.	.....p.u.	
Contribution to the initial short-circuit AC current I_K'' kA ***	at V	
<input type="checkbox"/> Cover sheet of the unit certificate in accordance with VDE-AR-N 4110 and extract from the test report Network compatibility of FGW TR 3 attached		
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance %		
<input type="checkbox"/> Manufacturer data sheet attached		
Additional data for storage		
Connection of storage	<input type="checkbox"/> via its own inverter <input type="checkbox"/> via the inverter of another Power-generating unit (in a PGSU) <input type="checkbox"/> direct connection to the AC-network or three-phase network	
Operation of storage	<input type="checkbox"/> Consumption and feed-in from/into the network of the network operator	Feed-in from the storage into the network of the network operator planned simultaneously with power-generating units <input type="checkbox"/> yes <input type="checkbox"/> no
	<input type="checkbox"/> No consumption, but feed-in into the network of the network operator	
	<input type="checkbox"/> No consumption and no feed-in from/into the network of the network operator	
	<input type="checkbox"/> Consumption, but no feed-in into the network of the network operator	

* In the case of full converters, the network-side data of the full converters shall be provided in data sheet E.1.3 (4).

** If the value is not explicitly known, the rated electrical active power P_{rE} of the power-generating unit may be used. In the case of PV plants and storage, these quantities shall be indicated for the inverters.

*** For estimation purposes, the contribution from the power-generating units without inverter (I_K'') may be added to the RMS value of the source current from power-generating units with inverter (I_{skPF}) (see Clause 11.2.11).

Application for network connection (medium-voltage) (to be completed by the connection owner for charging equipment for electric vehicles)		4 (4)	
General information of the charging device		<input type="checkbox"/> public <input type="checkbox"/> not public (private)	
Power data of the charging device		Maximum simultaneous active power consumption of the charging devices	..... kW
		A charging management system for controlling charging devices is planned*	<input type="checkbox"/> yes <input type="checkbox"/> no
Information of each identically constructed charging device	Number of charging devices	Maximum charging capacity of the charging device	Charging technology
		.... kW	<input type="checkbox"/> AC <input type="checkbox"/> DC** <input type="checkbox"/> Bidirectional*** ZEREZ ID:
			<input type="checkbox"/> AC <input type="checkbox"/> DC**
			<input type="checkbox"/> AC <input type="checkbox"/> DC**
Metering	Is a separate counting of the charging devices by the responsible party or a third-party metering point operator desired?		<input type="checkbox"/> yes*** <input type="checkbox"/> no

* The network operator may require a device to control the active power.

** The reactive power specifications of the network operator for DC charging devices > 12 kVA shall be observed.

*** Commissioning or start-up order is required.

C.I.2. (E.7) Commissioning report for transfer stations – Medium-voltage

This form replaces Appendix E.7 of VDE-AR-N 4110.
(This form is intended to be replicated by the user of this VDE application guide.)

Commissioning report (medium-voltage) (to be completed by the operator of the transfer station)		1 (1)		
Postal address of the installation	Station name or field number Street, number Postcode, town			
Plant operator	First name, surname Phone, email			
Plant installer	Company, place Phone, email			
Metering point operation	The measuring equipment is considered provided by the basic metering point operator (MPO) or by another MPO (in that case indicate the MPO ID as given in the MPO framework contract):			
Station data	<input type="checkbox"/> Stub <input type="checkbox"/> Double stub <input type="checkbox"/> Looping-in <input type="checkbox"/> Reference customer <input type="checkbox"/> Feeder <input type="checkbox"/> Mixed installation/storage			
TF blocks (blocker for audio-frequency ripple control)	Required in the connection acceptance: <input type="checkbox"/> yes <input type="checkbox"/> no			
	Installed: <input type="checkbox"/> yes <input type="checkbox"/> no	Test protocol available: <input type="checkbox"/> yes <input type="checkbox"/> no		
Documentation: Updated project documents handed over to the network operator at least 2 weeks prior to commissioning of the transfer station <input type="checkbox"/> yes <input type="checkbox"/> no				
<table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: none; vertical-align: top;"> <input type="checkbox"/> Commissioning order (E.5) is available <input type="checkbox"/> Network sales prerequisites are satisfied <input type="checkbox"/> Network control agreement is available <input type="checkbox"/> Schematic circuit diagram, wiring diagrams for secondary technical equipment, if any <input type="checkbox"/> Test protocol of the transfer protection and for PGMs of the primary loss of mains protection <input type="checkbox"/> Carryover arrangement (together with the network operator) <input type="checkbox"/> Protection checked by switch tripping <input type="checkbox"/> Calibration certificates for the transducers <input type="checkbox"/> Protocol of the earth connection measurement </td> <td style="width: 50%; border: none; vertical-align: top;"> <input type="checkbox"/> Confirmation in accordance with DGUV Regulation 3 <input type="checkbox"/> For power-generating modules: Equipment for network security management checked Optional for telecontrol systems: <input type="checkbox"/> Measurement value transmission checked <input type="checkbox"/> Reports checked <input type="checkbox"/> Remote control checked (including emergency-stop circuit breaker) <input type="checkbox"/> For power-generating modules: Measurement value transmission <i>P, Q</i> checked </td> </tr> </table>			<input type="checkbox"/> Commissioning order (E.5) is available <input type="checkbox"/> Network sales prerequisites are satisfied <input type="checkbox"/> Network control agreement is available <input type="checkbox"/> Schematic circuit diagram, wiring diagrams for secondary technical equipment, if any <input type="checkbox"/> Test protocol of the transfer protection and for PGMs of the primary loss of mains protection <input type="checkbox"/> Carryover arrangement (together with the network operator) <input type="checkbox"/> Protection checked by switch tripping <input type="checkbox"/> Calibration certificates for the transducers <input type="checkbox"/> Protocol of the earth connection measurement	<input type="checkbox"/> Confirmation in accordance with DGUV Regulation 3 <input type="checkbox"/> For power-generating modules: Equipment for network security management checked Optional for telecontrol systems: <input type="checkbox"/> Measurement value transmission checked <input type="checkbox"/> Reports checked <input type="checkbox"/> Remote control checked (including emergency-stop circuit breaker) <input type="checkbox"/> For power-generating modules: Measurement value transmission <i>P, Q</i> checked
<input type="checkbox"/> Commissioning order (E.5) is available <input type="checkbox"/> Network sales prerequisites are satisfied <input type="checkbox"/> Network control agreement is available <input type="checkbox"/> Schematic circuit diagram, wiring diagrams for secondary technical equipment, if any <input type="checkbox"/> Test protocol of the transfer protection and for PGMs of the primary loss of mains protection <input type="checkbox"/> Carryover arrangement (together with the network operator) <input type="checkbox"/> Protection checked by switch tripping <input type="checkbox"/> Calibration certificates for the transducers <input type="checkbox"/> Protocol of the earth connection measurement	<input type="checkbox"/> Confirmation in accordance with DGUV Regulation 3 <input type="checkbox"/> For power-generating modules: Equipment for network security management checked Optional for telecontrol systems: <input type="checkbox"/> Measurement value transmission checked <input type="checkbox"/> Reports checked <input type="checkbox"/> Remote control checked (including emergency-stop circuit breaker) <input type="checkbox"/> For power-generating modules: Measurement value transmission <i>P, Q</i> checked			
Comments:				
I/We hereby confirm to have installed, tested, and completed the installation of the transfer station duly taking into consideration the relevant legislation and official decrees as well as the acknowledged rules of technology, in particular following the DIN VDE standards, VDE-AR-N 4110, and the Technical Connection Conditions of the network operator. The results of the tests were documented. During handover, the installer of the electrical installation has instructed the plant operator and has declared the transfer station operational in accordance with DGUV Regulation 3 § 3 and § 5. The transfer station is considered a closed electrical service location as defined by the currently valid DIN VDE regulations and the accident prevention regulation DGUV Regulation 3. Those locations shall only be entered by electrically skilled or electrically instructed persons. Laymen shall enter this closed electrical service location only in the company of electrically skilled or electrically instructed persons.				
..... Place, date Plant operator Installer of the electrical installation (electric company)		
The transfer station was connected to the medium-voltage network on: Date:..... Time:.....				
..... Place, date Network operator			

C.I.3. (E.8) Data sheet for a power-generating unit or storage – Medium-voltage

This form replaces Appendix E.8 of VDE-AR-N 4110.
 (This form is intended to be replicated by the user of this VDE application guide.)

Data sheet for a power-generating module – Medium-voltage (to be completed by the connection owner, also applies to mixed installations and storage)		1 (4)
Feeder number of the connection owner _____		
Location of the installation	Postcode, town, district _____ Street, number or floor number / district number _____	
Connection owner	Company _____ First name, surname _____ Street, number _____ Postcode, town _____ Phone, email _____	
Is the information on the power-generating module in data sheet E.1, page 2(4) and page 3(4) currently valid? If the information in data sheet E.1, page 2(4) and page 3(4) is no longer valid, it shall be updated and submitted with the form E.8. In the event of changes that affect the network of the network operator, a new network compatibility assessment by the network operator may be required.		<input type="checkbox"/> yes, Date E.1 _____ <input type="checkbox"/> no
Are existing power-generating modules or storage connected to the network connection point? <input type="checkbox"/> yes <input type="checkbox"/> no Final system certificate number: _____ Date: _____ NOTE If no system certificate is available for existing power-generating modules or storage, page 3 (4) in form E.8 shall be completed.		
Minimum technical performance of the power-generating module?		<input type="checkbox"/> yes, .....kW <input type="checkbox"/> no
Island operation intended?		<input type="checkbox"/> yes <input type="checkbox"/> no
Black start capability provided?		<input type="checkbox"/> yes <input type="checkbox"/> no

Data sheet for a power-generating module – Medium-voltage (the following information shall be shown in the overview diagram of the power-generating module)		2 (4)
Information on the mains transformer owned by the connection owner (if applicable)	<ul style="list-style-type: none"> • Upper rated voltage U_{ROV} in kV • Lower rated voltage U_{rUV} in kV • Rated apparent power S_r in MVA • Operating voltage (controller setpoint voltage of the tap changer) U_{bUS} in kV • Short-circuit voltage u_k in % • Switching group • Control range of the tap changer \pm in % • Number of steps 	
Generator transformer	<ul style="list-style-type: none"> • Rated apparent power S_r in kVA • Short-circuit voltage u_k in % • Switching group • Control range of the tap changer \pm in % • Planned stepping in kV/kV • Rated voltage OV in kV • Rated voltage UV in kV 	
Details of the connection owner's own MV network	<ul style="list-style-type: none"> • Neutral-point treatment (to be completed only if connection owner's own network is galvanically separated from the DSO network): • schematic overview plan of the network attached with details on the types, lengths, and cross-sections of all cables used 	
Reactive power compensation system (if available)	<ul style="list-style-type: none"> • Rated reactive power • Number of steps • Degree of choking in % / Resonant frequency in Hz 	
Audio frequency lock (if available)	Values in Hz	

Data sheet for a power-generating module – Medium-voltage (to be completed by the connection owner; use one data sheet for every structurally different existing power-generating unit or storage without a system certificate)		3 (4)
Number of identically constructed power-generating units or storage: units		
Unit type	<input type="checkbox"/> Double-fed asynchronous machine	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Synchronous machine (coupled directly)	<input type="checkbox"/> Phase shifter operation
	<input type="checkbox"/> Network connection with full converter *(no storage)	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Storage	<input type="checkbox"/> Inertia
	Others	
Operating mode	<input type="checkbox"/> <u>Peak load coverage / Optimisation of houseload consumption</u> <input type="checkbox"/> <u>Balancing energy market / Ancillary services</u> <input type="checkbox"/> <u>Island operation</u> <input type="checkbox"/> Inertia <input type="checkbox"/> Other	
Unit manufacturer:	.....	Type:
Power data	Rated apparent power S_{rE}^*	..... kVA
	maximum active power (10-minute average) $P_{E_{max}}^{**}$	..... kW
	$P_{min,dyn}$: minimum dynamic active power available for the provision of negative inertia	..... kW
	$P_{max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia	..... kW
	$P_{limitneg,max}$: maximum dynamic active power for the provision of negative inertia	..... kW
	$P_{limitpos,min}$: minimum dynamic active power for the provision of positive inertia	..... kW
	Transient minimum power	..... kW
	T_A : start up time constant	..... s
	effective impedance z_w :	
	without a unit transformer (or on the low-voltage side of the unit):	
including a unit transformer (or on the medium-voltage side of the unit):	.....p.u.	
if applicable, at high-voltage level: 0.50 p.u.	.....p.u.	
	.....p.u.	
Contribution to the initial symmetrical short-circuit current I_K'' kA ***	at V	
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance %		
<input type="checkbox"/> Manufacturer data sheet attached		

* In the case of full converters, the network-side data of the full converters are to be entered.

** In the case of PV plants and storage, these quantities shall be indicated for the inverters.

*** For estimation purposes, the contribution from the power-generating units without inverters (I_K'') may be added to the RMS value of the source current from power-generating units with inverters (I_{skPF}) (see Clause 11.2.9).

Data sheet for a power-generating module – Medium-voltage		4 (4)
(Check list for the information to be submitted to the network operator by the connection owner; to be completed by the connection owner)		
Single-phase overview circuit diagram of the customer's system (minimum requirements): <input type="checkbox"/>		
<ul style="list-style-type: none"> • Transfer station (medium-voltage switchgear with specification of technical parameters) • Measurement, protection and control devices (if protection devices are present, it indicates where the measurement variables for short-circuit protection and, in the case of power-generating modules, additionally for loss of mains protection devices are recorded and on which switchgear the protection device acts, data of the auxiliary power source); • Mains transformers/machine transformers (see page 2(4)) • Illustration of the customer's own medium-voltage cable connections (see page 2(4)) <ul style="list-style-type: none"> ○ Specification of cable types, lengths and cross-sections 		
Current planned date of commissioning		
This data sheet and the application data sheet (E.1) together with the questionnaire E.9 to be completed by the network operator serve as the basis for issuing the system certificate. Changes of any kind shall be immediately indicated in writing to the relevant network operator. These data sheets will only be processed if fully completed.		
..... Place, date	..... Signature of the connection owner	

C.I.4. (E.9) Questionnaire for the network operator – Medium-voltage

This form replaces Appendix E.9 of VDE-AR-N 4110.

(This form is intended to be replicated by the user of this VDE application guide.)

Network operator questionnaire for new installations							1 (7)			
Connection/modification of a power-generating module or storage										
Designation of the power-generating module										
Maximum generation active power, cumulated $\sum P_{Amax}$ Agreed active connection power $P_{AV,E}$ Agreed apparent connection power $S_{AV,E}$		Existing unit				New installation		Complete (existing + new installation)		
	$\sum P_{Amax}$		kW				kW			kW
		Current (actual)				Total (new)				
	$P_{AV,E}$		kW				kW			
	$S_{AV,E}$		kVA				kVA			
$P_{AV,E}$ - Monitoring		<input type="checkbox"/> Yes				<input type="checkbox"/> No				
Information from the network operator	Date of the TCC MV			Contact details (e.g. email or telephone)						
Registration number of the network operator										
Designation of the transfer station										
Designation of the network connection point ²⁴										
Demand facility at the same network connection point (except for houseload of the power-generating module)	Demand installation provided <input type="checkbox"/> yes (mixed installation in accordance with VDE-AR-N 4110) <input type="checkbox"/> no					Agreed active connection power $P_{AV, B}$				
						$P_{AV, B}$			kW	
Other comments:										

²⁴ Line designation when connected to a line or designation of the adjacent station(s) or designation of the feeder switch panel of the substation when directly connected to the busbar of a network operator's own substation.

1. Set values for the protection equipment at the network connection point

1.1 Short-circuit protection equipment (check where appropriate)

Take-away circuit

Distance protection:

Settings	Default settings network operator		<input type="checkbox"/> separate settings sheet attached Comments:
	Old (actual)	New (setpoint)	
Overcurrent excitation $I >> [A]$			.....
Undercurrent excitation	$I > [A]$		.....
	$I >> [A]$		.....
	$U < [kV]$		.....
Under-impedance excitation	For this type of excitation, a separate settings sheet is always to be attached		.....
Zero sequence starter	$I_E > [A]$		.....
	$U_{NE} > [kV]$		.....

Overcurrent protection HH-fuse with maximum.....A

Settings	Default settings network operator		<input type="checkbox"/> separate settings sheet attached Comments:
	Old (actual)	New (setpoint)	
$I >> [A]$		
$t_I >> [ms]$		
$I > [A]$		
$t_I > [ms]$		

Ground fault protection no customer-owned MV network

Settings	Default settings network operator		<input type="checkbox"/> integrated in the distance or overcurrent protection <input type="checkbox"/> separate settings sheet attached Comments:
	Old (actual)	New (setpoint)	
$I_E >> [A]$		
$t_{IE} >> [ms]$		
$I_E > [A]$		
$t_{IE} > [ms]$		
$U_E > [kV]$		
$t_{UE} > [ms]$		

Network operator questionnaire for new installations			3 (7)
Connection/change of a power-generating module			
1.2 Primary loss of mains protection			
Function	Settings	Recommendation in accordance with VDE-AR-N 4110	Default settings from the network operator
Overvoltage protection	$U \gg$	1.20 U_c	<input type="checkbox"/> U_c <input type="checkbox"/> kV
	$t_U \gg$	300 ms	ms
Overvoltage protection	$U >$	1.10 U_c	<input type="checkbox"/> U_c <input type="checkbox"/> kV
	$t_U >$	180 s	s
Undervoltage protection	$U <$	0.8 U_c and at least 0.1 I_N	<input type="checkbox"/> U_c <input type="checkbox"/> kV
	$t_U <$	2.7 s	s
$P_{AV,E}$ – Protection device	$P \gg$	See FNN Guideline $P_{AV,E}$ – Monitoring [Table 5]	kW
	$t \gg$		s
	$P >$		kW
	$t >$		s
	$P <$		kW
	$t <$		s
1.3 Mixed installations (if demand installation available)			
Primary loss of mains protection	Medium-voltage measurement location	Trigger location	
	<input type="checkbox"/> Transfer station <input type="checkbox"/> Power-generating module	Power-generating module	
Other comments			

NOTE For existing systems, Q - U -protection may be deactivated during the repeated test in accordance with Clause 11.5.5.

Network operator questionnaire for new installations				4 (7)	
Connection/change of a power-generating module					
2. Default settings for power-generating units (e.g. power-generating unit or temporarily stored loss of mains protection)					
2.1 Loss of mains protection					
Function	Settings	Recommendation in accordance with VDE-VDE-AR-N 4110 MV-SS	Recommendation in accordance with VDE-VDE-AR-N 4110 MV network	Default settings ²⁵ network operator	
Overvoltage protection	$U >>$	$1.25 U_{LV}^{26}$	$1.25 U_{LV}^7$		U_{LV}
	$t_U >>$	100 ms	100 ms		ms
Undervoltage protection	$U <$	$0.8 U_{LV}^7$	$0.8 U_{LV}^7$		U_{LV}
	$t_U <$	stepped (see below)	300 ms ... 1.0 s		ms
	$U <<$	$0.30 U_{LV}^7$	$0.45 U_{LV}^7$		U_{LV}
	$t_U <<$	800 ms	0 ms to 300 ms		ms
Overfrequency protection	$f >>$	52.5 Hz	52.5 Hz		Hz
	$t_f >>$	≤ 100 ms	≤ 100 ms		ms
	$f >$	51.5 Hz	51.5 Hz		Hz
	$t_f >$	10 s	10 s		s
Underfrequency protection	$f <$	47.5 Hz	47.5 Hz		Hz
	$t_f <$	≤ 100 ms	≤ 100 ms		ms
If stepping shall be performed within a power-generating module, specify the following stepping values:	Settings for stepping			Default settings	
	$t_U < 1$	1.5 s			
	$t_U < 2$	1.8 s			
	$t_U < 3$	2.1 s			
	$t_U < 4$	2.4 s			
2.2 Continuous voltage control (for Type 2 installations only)					
Function	Default settings from the network operator				
Limited continuous voltage control: Suspend power supply below $0.7 U_C$	<input type="checkbox"/> enable				
Droop k of the continuous voltage control	<input type="checkbox"/> $k = 2$ <input type="checkbox"/> $k = \dots\dots$ <input type="checkbox"/> no specification (grid-forming)				

25 The defaults are to be set unless they impair the internal protection of the PGU. For default settings incompatible with the internal protection of the PGU, re-coordination with the DSO is required.

26 U_{LV} is the voltage on the low-voltage side of the generator transformer. It results from $U_{LV} = U_c/\bar{u}$.

3. Steady-state voltage stability

Reactive power adjustment range	<input type="checkbox"/> 0.33 $Q/P_{b \text{ inst}}$ under-excited to 0.33 $Q/P_{b \text{ inst}}$ over-excited in accordance with VDE-AR-N 4110 <input type="checkbox"/> under-excited to over-excited (separate closed-loop control)																																							
<input type="checkbox"/> Reactive power/voltage Characteristic $Q(U)^{27}$	<input type="checkbox"/> Standard characteristic in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110 <input type="checkbox"/> individual values Gradient of the characteristic: Upper voltage limit $U_{MAX}/U_C = \dots\dots\dots$ (e.g. 1.04) Lower voltage limit $U_{MIN}/U_C = \dots\dots\dots$ (e.g. 0.96) Maximum reactive power $Q_{MAX\text{-under-excited}}/P_{b \text{ inst}} = \dots\dots\dots$ (e.g. 0.33) Voltage deadband = $\pm \dots\dots\dots \% U_C$ (e.g. $\pm 1.0 \% U_C$) Reference voltage: <input type="checkbox"/> $U_{Q0,ref}/U_n = \dots\dots\dots$ (e.g. 1.00) <input type="checkbox"/> Reference voltage variable through a telecontrol system ²⁸																																							
<input type="checkbox"/> Characteristic $Q(P)^{29}$	<input type="checkbox"/> Standard pairs of values in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110 <input type="checkbox"/> Individual values <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <tr> <td style="width: 15%;">$P/P_{b \text{ inst}} [\%]$</td> <td style="width: 5%;"></td> </tr> <tr> <td>$Q/P_{b \text{ inst}} [\%]$</td> <td></td> </tr> </table>	$P/P_{b \text{ inst}} [\%]$																			$Q/P_{b \text{ inst}} [\%]$																			
$P/P_{b \text{ inst}} [\%]$																																								
$Q/P_{b \text{ inst}} [\%]$																																								
<input type="checkbox"/> Reactive power Q with voltage limitation function	<input type="checkbox"/> Standard pairs of values in the MV-network in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110 <input type="checkbox"/> Standard pairs of values UW-Direkt/SS in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110 <input type="checkbox"/> Individual values characteristic with $P1 (U_{P1}/U_C; Q_{ref}/P_{b \text{ inst}}) = \dots\dots\dots$ (e.g. 0.94; -0.33) $P2 (U_{P2}/U_C; Q_{ref}/P_{b \text{ inst}}) = \dots\dots\dots$ (z. B. 0.96; 0) $P3 (U_{P3}/U_C; Q_{ref}/P_{b \text{ inst}}) = \dots\dots\dots$ (z. B. 1.04; 0) $P4 (U_{P4}/U_C; Q_{ref}/P_{b \text{ inst}}) = \dots\dots\dots$ (e.g. 1.06(1.08); +0.33) <input type="checkbox"/> variable by means of a telecontrol system ¹⁰ <input type="checkbox"/> Schedule ³⁰																																							
<input type="checkbox"/> Displacement factor $\cos \varphi$	<input type="checkbox"/> $\cos \varphi = \dots\dots\dots$ <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited <input type="checkbox"/> variable via a telecontrol system ¹⁰ <input type="checkbox"/> Schedule ¹²																																							
Control behaviour at setpoint steps	For $Q(U), Q(P), Q, \cos(\varphi)$ Time constant 3 Tau = s (setting range 10 s to 60 s (for Type 1), 6 s to 60 s (for Type 2))																																							
Response in the event of a telecontrol system failure ¹¹	<input type="checkbox"/> continue operation with the last received value <input type="checkbox"/> $U_{Q0}/U_C = \dots\dots; Q = \dots\dots \text{ kvar}; \cos \varphi = \dots$ (depending on the chosen method) <input type="checkbox"/> switch-over to <input type="checkbox"/> $Q(U),$ <input type="checkbox"/> $Q(P),$ <input type="checkbox"/> $Q,$ <input type="checkbox"/> $\cos \varphi$ ¹³																																							
Response in the event of a failure of either the PGM controller or the associated measurement or the connection between PGM controller and PGU	<input type="checkbox"/> Continue operation of all PGUs with the value received last <input type="checkbox"/> Continue operation of all PGUs with $P = \dots\dots\dots$ (aggregate value for the PGM) <input type="checkbox"/> Continue operation of all PGUs with $Q = \dots\dots\dots$ (aggregate value for the PGM) <input type="checkbox"/> Continue operation of all PGUs with $\cos \varphi = \dots\dots\dots$																																							
Requirements for the reactive power behaviour of	<input type="checkbox"/> Integration into the reactive power control of the new installation <input type="checkbox"/> $\cos \varphi = \dots\dots\dots$ at the NCP <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited																																							

²⁷ Recommendations can be found in Clause 10.2.2.4, Section a).
²⁸ If setpoints are provided by a telecontrol system. Specifications of the telecontrol system shall be provided by the network operator or can be found in the TCC of the network operator.
²⁹ Up to 10 pairs of values may be predefined.
³⁰ If schedules are required, they shall be provided as a separate sheet or under other comments.
¹³ Specifications are handed over by the network operator or can be found in the network operator's. In the case of several existing power-generating modules with differing reactive power behaviours or agreements with the network operator, please attach detailed information for each of the existing power-generating modules on a separate page (e.g. in the form of this page 5 (7)).

the existing units in mixed parks of different PGMs ^{31,32}	<input type="checkbox"/> $\cos \varphi = \dots\dots\dots$ at the PGU <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited <input type="checkbox"/>under-excited to over-excited <input type="checkbox"/> maintain existing operation (unless otherwise specified , a $\cos(\varphi)$ value of 1 may be assumed in the verification process)
	MV measurement of the reference variable U : <input type="checkbox"/> at the transfer station <input type="checkbox"/> at the PGM
Other comments	

³¹ In addition to the mode of operation agreed for the existing power-generating modules, their actual behaviour shall be considered. The calculation method is described in FGW TR 8.

Network operator questionnaire for new installations		6 (7)
Connection/change of a power-generating module		
4. Network data		
Agreed supply voltage of the network, U_c		kV
Voltage band set at the voltage controller of the supplying transformer station	to	kV
Rated short-time current I_k (for $T_k = 1$ s) ³³	≥	kA
Minimum network short-circuit power at the point of common coupling ³⁴ S_{kV}^*		MVA
Network impedance angle at the point of common coupling ψ_k^*		°
Minimum short-circuit power at the normal disconnection point (only to be specified for connections in the MV network)		MVA
Power-generating module factor ¹⁹ k_E		
Demand facilities factor ³⁵ k_B		
Storage factor ¹⁹ k_S		
Resonance factor for the harmonics ¹⁹ k_V		applies for _____ Hz
Resonance factor for the interharmonics k_μ ¹⁹		applies for _____ Hz
Resonance factor for the supraharmonics k_b ¹⁹		applies for _____ Hz
Centralized ripple-control frequency		Hz
Effective network capacity	.....	µF
Apparent power of the distribution transformer connected upstream, $S_{Network}$		MVA
R of the distribution transformer connected upstream		Ohm
X of the distribution transformer connected upstream		Ohm
5. Neutral-point treatment of the network operator's MV network connected upstream		
Type of neutral-point treatment	<input type="checkbox"/> Resonant neutral earthing (earth fault compensation) <input type="checkbox"/> Neutral earthing with low impedance <input type="checkbox"/> Solid neutral earthing <input type="checkbox"/> No neutral-point treatment (free, isolated neutral point)	

* For the normal network switching state.

³³ For dimensioning of the transfer station regarding the short-circuit current capability.

³⁴ In order to allow for the system certificate to be prepared, the network operator should provide the network data including the network short-circuit power S_{kV} and the network impedance angle ψ_k for the network connection point determined initially. These data are used as basis for the proof of compliance of the behaviour of the power-generating module according to the relevant rules.

³⁵ k_E , k_B , k_S , k_V , k_μ and k_b are factors for determining the proportional harmonics emissions of the power-generating module. Where no information is given, the simplified assumptions of Section 5.4.4 apply.

Network operator questionnaire for new installations		7 (7)
Connection/change of a power-generating module		
6. Neutral-point treatment of the network operator's HV network connected upstream		
Type of neutral-point treatment	<input type="checkbox"/> Resonant neutral earthing (earth fault compensation) <input type="checkbox"/> Neutral earthing with short-time low impedance Ω <input type="checkbox"/> Neutral earthing with low impedance Ω <input type="checkbox"/> Solid neutral earthing <input type="checkbox"/> No neutral-point treatment (free, isolated neutral point)	
7. PGM model		
<input type="checkbox"/> The network operator has a model of the power-generating module at its disposal for performing network calculations:		
<input type="checkbox"/> Set of parameters in accordance with Appendix C.5 <input type="checkbox"/> with optional additional information <input type="checkbox"/> Set of parameters in accordance with the specifications of the network operator <input type="checkbox"/> Set of parameters in accordance with the specifications of the network operator <input type="checkbox"/> Computable dynamic model in accordance with network operator specifications		
Other comments		
_____	_____	
Place, date	Signature of the network operator The questionnaire for the network operator (E.9) is valid until:	

C.I.5. (E.10) Commissioning report for power-generating units and storage - Medium-voltage

This form replaces Appendix E.10 of VDE-AR-N 4110.

(This form is intended to be replicated by the user of this VDE application guide.)

Commissioning report for power-generating units – MV (to be completed by the plant operator; also applies to storage)		1 (2)
Plant designation	.....
Number of PGUs:	..... Manufacturer of PGUs:	..... Type of PGUs:
Registration number of the DSO	.....
Postal address of the power-generating unit	Postcode: Town: Street, number:	
Location of the power-generating unit (when no address available)	Local sub-district: Cadastral section: Plot:	
	<input type="checkbox"/> Gauss-Krüger coordinates Reference ellipsoid: <input type="checkbox"/> UTM coordinates Zone: Easting: Northing:	
Point of connection to the network of the network operator	Designation: Metering point for billing purposes:	..... .....
Official approval	Type: <input type="checkbox"/> Construction permit <input type="checkbox"/> Approval as required by the BImSchV <input type="checkbox"/> Authorization under the water law <input type="checkbox"/> File number: Date:	
Compliance with legal provisions (EEG/KWK-G)	<input type="checkbox"/> The requirements of § 9(1) or (2) EEG are fulfilled (network protection and network management in compliance with statutory power limits) <input type="checkbox"/> The requirements of § 9(5) No. 1 EEG are fulfilled (hydraulic retention time, applicable for biogas plants only) <input type="checkbox"/> The requirements of § 9(5) No. 2 EEG are fulfilled (including gas consumption devices for preventing biogas release, applies only to biogas plants) <input type="checkbox"/> The prerequisites for a compensation installation summary in accordance with § 24 Abs. 2 EEG are not met (applicable to ground PV plants only)	
	Index number for the Market Master Data Register Award number as per § 35 EEG:	
	<input type="checkbox"/> Application for approval as CHP plant as per § 10 KWK-G (Law on CHP) (attach Federal Office of Economics and Export Control [BAFA] acknowledgement of receipt) <input type="checkbox"/> Notification of the CHP plant as per § 10 Abs. 6 KWK-G (attach the notification filed with BAFA) <input type="checkbox"/> Approval as a CHP plant as per § 10 KWK-G (attach the BAFA approval)	
Certification body for the power-generating unit	Name:	.....
	Postal address: Unit certificate number:	..... ..... Date of issue:
Certification body for power-generating modules	Name:	.....
	Postal address: System certificate number:	..... ..... Date of issue:
Power data	Maximum active power: kW (instantaneous power installed as per § 3 No. 31 EEG; for PV plants use the DC module rating) Maximum apparent power: kVA (for PV plants use the inverter output power on the network side) Storage capacity kWh (in storage)	

Commissioning report for power-generating units – MV		2 (2)	
(to be completed by the plant operator; also applies to storage)			
Documentation	<input type="checkbox"/> Loss of mains protection successfully tested (attach protection test reports) <input type="checkbox"/> Continuous voltage control of the power-generating unit is in accordance with the system certificate <input type="checkbox"/> limited continuous voltage control <input type="checkbox"/> continuous voltage control, k -factor set k -Faktor to $k = \dots\dots\dots$ (The k -factor is not applicable to directly coupled synchronous machines) <input type="checkbox"/> all other parameters influencing the electrical properties are set in accordance with the system certificate <input type="checkbox"/> Power-generating unit integrated into the network security management <input type="checkbox"/> Proportion of nominal effective power for inertia market $m = \dots\dots\dots$ <input type="checkbox"/> Start-up time constant $T_A = \dots\dots\dots$		
Commissioning	The power-generating unit was commissioned on:	Date:	Time:
	The power-generating unit has started feeding energy into the network of the network operator (in the case of mixed installations has started generating energy):	Date:	Time:
<p>The electrical installation of the power-generating unit is regarded as a closed electrical service location as defined by the currently valid DIN VDE regulations and the accident prevention regulation DGUV Regulation 3. Those locations shall only be entered by qualified electricians or persons trained in electrical engineering. Laymen shall enter this service location only in the company of qualified electricians or persons trained in electrical engineering.</p> <p>The power-generating unit was installed in accordance with the conditions specified in VDE-AR-N 4110 and the Technical Connection Conditions of the network operator. During handover, the installer of the electrical installation has instructed the plant operator and has declared the power-generating unit operational in accordance with DGUV Regulation 3, § 3 and § 5.</p>			
I/We hereby declare all of the information given above to be truthful and I/we undertake to immediately communicate in writing any changes made to the installation to the network operator to whose network the power-generating unit is connected. The details are based on the relevant legal regulations and statutory orders.			
Installer or commissioner of the electrical installation Company: Name of the editor: Street, number: Postcode, town: Date, stamp and signature		Plant operator Company: Name of the editor: Street, number: Postcode, town: Date, stamp and signature	

C.I.6. (E.11) Commissioning statement for power-generating modules or storage – Medium-voltage

This form replaces Appendix E.11 of VDE-AR-N 4110.
(This form is intended to be replicated by the user of this VDE Application rule.)

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)				1 (7)
Designation of the power-generating module				
Power-related data of the power-generating module		Agreed active connection power for feed-in $P_{AV,E}$		kW
		Agreed apparent connection power for feed-in $S_{AV,E}$		kVA
		Agreed active connection power for consumption $P_{AV,B}$		kW
		Installed active power P_{inst}		kW
		$P_{min,dyn}$: minimum dynamic active power available for the provision of negative inertia		kW
		$P_{max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia		kW
		$P_{limitneg,max}$: maximum dynamic active power for the provision of negative inertia		kW
		$P_{limitpos,min}$: minimum dynamic active power for the provision of positive inertia		kW
Transient minimum power		kW		
Registration number of the network operator				
Designation of network connection point				
Creator of the commissioning statement		Company		
		Street, number		
		Postcode, town		
		Phone, email		
Connection owner		Company		
		Street, number		
		Postcode, town		
		Phone, email		
Issuer of the System certificate		Certification body		
		Street, number		
		Postcode, town		
		System certificate number:		
		Date of issue		
Information from the commissioning report for transfer stations (E.7)				
Designation of the transfer station				
Commissioning report as of:				
Commissioning of the PGM controller				
Manufacturer	Type	Firmware version	Serial number	Commissioning date

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		3 (7)
The following protocols and verifications can be found in the attachment	Type of document	attached
Functional test of the entire chain of action of the active and, if applicable, reactive power control by the control centre of the network operator (protocol to be provided by the network operator);	Verification of the network operator	<input type="checkbox"/>
Alternative 1: Test of the entire chain of action by simulating the interface to the telecontrol system of the network operator (if agreed with the network operator)	Verification	<input type="checkbox"/>
Alternative 2: Test of the entire chain of action with the network operator to be agreed at a later date. Including confirmation from the network operator (not part of the commissioning declaration)	Confirmation from the network operator	<input type="checkbox"/>
Functional test of the telecontrol system up to the transfer station (if required by the network operator), to be performed by the network operator (request test, process data scope)	Verification of the network operator	<input type="checkbox"/>
Verification of the response to telecontrol system failure, unless proven in the component certificate of the PGM controller and documented in the settings records of the PGM controller (requirement: see E.9)	Verification	<input type="checkbox"/>
Verification of the response to failure of the PGM controller or the associated measurement or the connection between the PGM controller and the PGU, unless proven in the unit certificate and documented in the settings records of the PGU (requirement: see E.9)	Verification	<input type="checkbox"/>
Function test of the reactive power characteristic curve or the reactive power fixed values in accordance with specifications from the network operator (see E.9) based on recorded operating measurements of the PGM controller or other recording devices at the network connection point (recording period: at least 7 days and at least 20 % P_{inst} , for $Q(P)$ - or $\cos\phi(P)$ characteristic curve at least 60 % P_{inst}). Or alternatively, the reactive power characteristic curve function was tested with a test characteristic curve (by means of simulated reference variable U or P). After the test, the original characteristic has again been set.	Test report	<input type="checkbox"/>
Protection test report for the protection equipment at the network connection point	Protection test report(s)	<input type="checkbox"/>
Protection test reports for protection equipment on the individual power-generating units or, if applicable, the intermediate storage protection devices	Protection test report(s)	<input type="checkbox"/>

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		4 (7)
<p>Adjustment protocol for the power-generating units (in particular for implementing O/UVRT robustness) including designation, the parameters used in VDE-AR-N 4110; minimum information:</p> <ul style="list-style-type: none"> - Manufacturer, type, serial numbers and, if applicable, firmware of the PGU for which the following parameters were set - Protection setting values - Switch-on parameters in undisturbed network operation - Reset parameters after protection tripping - FRT mode, k-factor set if applicable and FRT entry thresholds - Active power gradient - Active power limitation (set maximum active power) - Active power adjustment at over- and under-frequency ($P(f)$ characteristic curve) - Response to a PGM controller failure <p>If applicable, for plant control exclusively via the PGU:</p> <ul style="list-style-type: none"> - See the PGM controller setting records for details. 	Settings record(s)	<input type="checkbox"/>
<p>Setting records of the PGM controller including designation, parameters used in VDE-AR-N 4110; minimum information:</p> <ul style="list-style-type: none"> - Manufacturer, type, serial numbers and, if applicable, firmware version - Verifiable setting of the characteristic curve type required in accordance with E.9 - Description of all reference points of the characteristic curve - Specification of the (maximum) active power, if applicable, setting of an active power limit - Settling time (3 Tau) in accordance with E.9 - Response to a connection failure between the remote control system and the PGM controller in accordance with E.9 - Integration and control of any existing system components - If not set on the PGU: Active power gradient and active power adjustment in case of overfrequency and underfrequency ($P(f)$ characteristic curve), switch-on parameters in undisturbed network operation 	Settings record	<input type="checkbox"/>
Arc fault qualification certificate for the switchgear or risk assessment for existing systems	Verification	<input type="checkbox"/>
Photographic documentation (the assignment to operating equipment shall be recognisable). The certification body may accept alternative verifications. Minimum information:	Photos	
- Type plates (with serial number) and front view of all installed protection devices and the associated test terminal strips (documentation as part of the protection test may be accepted)		<input type="checkbox"/>
- Type plates of the MV switchgear		<input type="checkbox"/>
- Type plates of the transformers (if used for protection/PGM controllers; type plates on the measuring cell or documentation as part of the protection test may be accepted)		<input type="checkbox"/>

Commissioning statement for power-generating modules or storage		5 (7)
(to be completed by the plant operator; also applies to storage)		
- Type plates of transformers with tap changers		<input type="checkbox"/>
- Type plates of switchgear (e.g. circuit breakers) assigned to the protection devices		<input type="checkbox"/>
- Protection settings that are set directly on the switchgear (e.g. rotary switches/dip switches)		<input type="checkbox"/>
- Type plates of network analysis devices (if used for protection/PGM controllers)		<input type="checkbox"/>
- Type plates of PGM controller (with serial number)		<input type="checkbox"/>
- Type plates of mains-independent auxiliary power supplies/UPS (with recognisable capacity of the connected battery) of the transfer station and, if applicable, the temporarily stored protection devices		<input type="checkbox"/>
- Fuse outlets with type and size		<input type="checkbox"/>
- Nameplates for all stations		<input type="checkbox"/>
Comments:		
Notice: The scope of the declaration of commissioning in the individual verification procedure shall be agreed with the certification body on a project-by-project basis.		
Confirmation		
<p>The actual built-in power-generating units (indicating their designation and serial number), including the main components listed in the unit certificate (including firmware versions) are listed in the section 'Commissioning of all power-generating units'</p> <p>The built-in components/PGM controllers installed (by name and serial number) are listed in the sections 'Commissioning of the PGM controller' and 'Commissioning of additional components'.</p> <p>The operating equipment of the PGM (characteristic values and step settings of the operating equipment transformers, cable lengths and types) are listed as an appendix or enclosed as photographic documentation.</p> <p>The signatory confirms the accuracy of the information provided in the commissioning declaration, including the required attachments.</p>		
..... Date	..... ..	Signature of the person who prepared the declaration of commissioning

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)	6 (7)
Minimum information of the protection test reports at the network connection point and on the individual power-generating units or the intermediate storage protection devices	
<p>Protection test reports for the protection equipment at the network connection point</p> <p>Minimum information, see Appendix *1:</p> <ul style="list-style-type: none"> – System designation, installation location in the plant and date of testing – Manufacturer, type and serial number of the protection device – transformers used with transmission ratio, accuracy class and installation location in the plant – Indication of the switchgear on which the protection device acts – For all voltage values, indicate whether the value refers to the line-line voltage or line-earth voltage – Indication that the tripping of the voltage rise protection and voltage dip protection are linked for all phases – Identification of all setting thresholds and times (in accordance with E.9) – Measurement values of all tripping thresholds (in MV: Line-to-line voltages) and tripping for all phases – Indication of whether the tripping times take into account the inherent time of the switchgear (switchgear tripped) – Measured value of the inherent time of the switchgear – Indication that the tripping time is not less than the setting time required by the network operator (not applicable if the network operator specifies a time range without a lower time value, e.g. ≤ 300 ms or 0 .. 300 ms) – Specification of the setting and measured values of the reset ratios of all voltage increase and voltage decrease protection thresholds – Specification of whether automatic reconnection was deactivated in the protection device or, if applicable, by external wiring – Checking the tripping of the switchgear in the event of: <ul style="list-style-type: none"> • Failure of the auxiliary power supply • If applicable, when connecting the life contact: failure of the life contact or its connection • Failure of the measurement voltage of the protection device • Failure of the control voltage of the switchgear • if the protection device and switchgear are spatially separated: connection failure between the protection device and switchgear <p>The network operator may specify different requirements and request further tests.</p>	

Commissioning statement for power-generating modules or storage

7 (7)

(to be completed by the plant operator; also applies to storage)

Protection test reports for protection equipment on the individual power-generating units or, if applicable, the intermediate storage protection devices

Minimum information:

- System designation, installation location in the plant and date of testing
- Manufacturer, type and serial number of the protection device
- for temporarily stored protection devices: firmware version of the protection device (in accordance with the component certificate)
- transformers used with transmission ratio, accuracy class and installation location in the plant or, in the case of direct measurements: measurement location in the plant
- Specification of the transmission ratio of the transformer and the agreed supply voltage U_c (to determine whether U_{NV} was calculated correctly)
- Specification of the switchgear on which the protection device acts
- For all voltage values, specify whether the value refers to the conductor-conductor voltage or the conductor-earth voltage
- Identification of all setting thresholds and times (in accordance with E.9)
- Measured values of all tripping thresholds and times for all phases
- Indication of whether the tripping times take into account the inherent time of the switchgear (switchgear tripped)
- Measured value of the inherent time of the switchgear
- Indication that the tripping time is not less than the setting time required by the network operator (not applicable if the network operator specifies a time range without a lower time value, e.g. ≤ 300 ms or $0 \dots 300$ ms)
- Specification of the setting and measured values of the reset ratios of all voltage increase and voltage decrease protection thresholds
- Setting values of all connection parameters in undisturbed network operation or indication that this was deactivated in the protection device
- Setting values of all switch-on parameters after protection tripping
- Checking the tripping of the switchgear in the event of:
 - Failure of the auxiliary power supply
 - If the protection device and switchgear are spatially separated: connection failure between the protection device and switchgear

The network operator may specify different requirements and request further tests.

C.I.7. (E.12) Statement of compliance for power-generating modules or storage – High-voltage

This form replaces Appendix E.12 of VDE-AR-N 4110.

(This form is intended to be replicated by the user of this VDE application guide.)

<p style="text-align: center;">Name of the certification body.....</p> <p style="text-align: center;">Accredited in accordance with DIN EN ISO/IEC 17065 for VDE-VDE-AR-N 4110</p>	<p style="font-size: 2em; font-weight: bold; text-align: center;">LOGO</p> <p style="text-align: right;">1 (2)</p>	
<p style="font-size: 1.5em; font-weight: bold;">Statement of compliance</p> <p style="font-weight: bold;">for power-generating modules or storage</p>		
Project description		
Connection owner		
Power data of the power-generating module or storage	Agreed active connection power $P_{AV, E}$	_____ kW
	Agreed apparent connection power $S_{AV, E}$	_____ kVA
	Agreed active connection power $P_{AV, B}$	_____ kW
	Agreed apparent connection power $S_{AV, B}$	_____ kVA
	Installed active power P_{inst}	_____ kW
Issuer of the system certificate	First name, surname Street, number Number of verifications for the installation Date of issue	_____ _____ _____ _____
Creator of the commissioning statement	First name, surname Street, number Date of issue	_____ _____ _____
<p>The power-generating module or storage (components, units, and equipment, etc.) was installed in accordance with the system certificate and the provisions of the network operator.</p> <p><input type="checkbox"/> Passed</p> <p>NOTE</p> <p>_____</p> <p>_____</p>		
<p>The component parts and settings of the power-generating module or storage installed set out in the commissioning statement are in accordance with the system certificate.</p> <p><input type="checkbox"/> Passed</p> <p>NOTE</p> <p>_____</p> <p>_____</p>		
<p>The concept for static reactive power supply, the concept for active power control, the implementation of O-/UVRT robustness and the protection concept were implemented taking into consideration the provisions of the network operator.</p> <p><input type="checkbox"/> Passed</p> <p>NOTE</p> <p>_____</p> <p>_____</p>		

The power-generating module or storage described above

- meets the requirements of VDE-AR-N 4110 "TCR Medium-voltage"
- meets the requirements of the FNN Guideline "Technical requirements for grid-forming capabilities including the provision of inertia"
- meets the requirements of the network operator's TCC and was installed in compliance with the system certificate indicated above.

NOTE _____

In case the harmonic oscillations are exceeded, the following aspects shall be considered.

- Installation and start of the measurement were performed on: _____
- _____

The required functional tests of active and reactive power behaviour

- Were performed in the context of the commissioning statement.
- Could not be performed for the following reasons and will be performed in coordination with the network operator at a later point in time
- _____

The statement of compliance includes the following attachments:

- Commissioning statement
 - Additional documents reviewed in order to complete the statement of compliance: _____
- _____

Confirmation in cases of subsequent verification measurements:

- Measurement in the time period of _____ to _____ could not provide evidence of compliance with the required harmonic levels (deadline 6 months after commissioning of the PGM).
- Measurement in the time period of _____ to _____ could not provide the evidence required. Reworks are required.

Place, date (DD.MM.YYYY)

Confirmation by the certification body, postal address, email

- Reworks were conducted. The measurement completed within the period from _____ to _____ could provide proof of compliance with the required harmonics levels (a deadline of 12 months following the failed evidence measurement).

Place, date (DD.MM.YYYY)

Confirmation by the certification body, postal address, email

Place, date (DD.MM.YYYY)

Certification body, postal address, email

This certificate shall not be used in parts.

C.II. Application for network connection - High-voltage

C.II.1. (E.1) Application - High-voltage

This form replaces Appendix E.1 of VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

Application for network connection (high-voltage) (to be completed by the connection owner)		1 (4)
Designation of the construction project	_____	
Location of the installation	Postcode, town, district Street, number or floor number / district number	_____ _____
Connection owner	Company First name, surname Street, number Postcode, town, district Phone, email	_____ _____ _____ _____
Property owner	<input type="checkbox"/> Connection owner is the property owner <input type="checkbox"/> Authority the property owner is supplied with the application	
Plant installer (if known)	Company, postcode, town Phone, email	_____ _____
Installation type	<input type="checkbox"/> Demand installation <input type="checkbox"/> Power-generating module <input type="checkbox"/> Mixed installation	<input type="checkbox"/> Charging system for electric vehicles <input type="checkbox"/> Storage <input type="checkbox"/> Temporary connection (e.g. power for a construction site) <input type="checkbox"/> Emergency power generator
Allocation of network connection	<input type="checkbox"/> New installation <input type="checkbox"/> Extension or modification	<input type="checkbox"/> Dismantling
Position of the customer installation with suggestions marked for possible locations of the transfer station. Plans to a suitable scale (e.g. layout plan to a scale of 1 : 25 000 or 1 : 10 000, detailed plan to a scale of at least 1 : 500) attached? In the case of power-generating modules or mixed installations the location of the power-generation units shall be clearly indicated.		<input type="checkbox"/> yes <input type="checkbox"/> no
Anticipated active connection power $P_{AV, B}$ and $P_{AV, E}$ [kW]		
	previously	total value required hereafter (in final stage after measure)
Consumption active power $P_{AV, B}$		
Feed-in active power $P_{AV, E}^*$		
For power-generating modules, mixed installations or storage, pages 2 (4) and 3 (4) of E.1 form shall also be completed. For charging devices for electric vehicles, page 4 (4) shall also be completed.		
Provision of the measuring equipment and metering point operation to be performed by: <input type="checkbox"/> basic MPOs <input type="checkbox"/> other MPOs _____		
Power expected to be consumed on site	<input type="checkbox"/> no	If yes: Power _____ kW
Starting date	_____	
Is a data sheet for assessing system perturbations (Form E.2) for the connection of a demand installation attached?	<input type="checkbox"/> yes <input type="checkbox"/> no	
Time schedule for the construction works attached?	<input type="checkbox"/> yes <input type="checkbox"/> no	
Planned commissioning / completion date of the measure	_____	
Place, date	Signature of the connection owner	

NOTE* Maximum active power of the customer installation fed into the medium-voltage network connected upstream.

Application for network connection (high-voltage) (to be completed by the connection owner of power-generating modules, mixed installations or storage)			2 (4)	
Type of the power-generating module (multiple choice possible for energy mix)	<input type="checkbox"/> Wind energy	<input type="checkbox"/> Hydropower	<input type="checkbox"/>	
	<input type="checkbox"/> Photovoltaics	<input type="checkbox"/> Ground area	<input type="checkbox"/> Roof area	<input type="checkbox"/> Other
	<input type="checkbox"/> CHP plant	Fuel type used (e.g. natural gas, biogas, biomass)		
	<input type="checkbox"/> Thermal power plant	.....	
	<input type="checkbox"/> Storage			
Operating mode	<input type="checkbox"/> <u>Peak load coverage / Optimisation of houseload consumption</u> <input type="checkbox"/> <u>Balancing energy market / Ancillary services</u> <input type="checkbox"/> <u>Island operation</u> <input type="checkbox"/> <u>Inertia</u> <input type="checkbox"/> <u>Other:</u>			
	<input type="checkbox"/> Stand-by generator with > 100 ms parallel network operation <input type="checkbox"/> Stand-by generator with ≤ 100 ms parallel network operation	Operating mode: <input type="checkbox"/> exclusively in trial operation in accordance with DIN 6280-13 or VDE 0100-560 (VDE 0100 560) <input type="checkbox"/> Peak consumption coverage <input type="checkbox"/> Balancing energy market <input type="checkbox"/>		
Measure for a power-generating module	<input type="checkbox"/> New installation	<input type="checkbox"/> Extension or modification	<input type="checkbox"/> Dismantling	
Power data	Available (existing)	New installation / extension / dismantling	in final configuration (new planned total value)	
Maximum generation active power, cumulated $\sum P_{Amax}^*$	.....kW	.....kW	.....kW	
Maximum generation apparent power, cumulated $\sum P_{Amax}^*$	.....kVA	... ..kVA	... ..kVA	
For PV: module power [kWp]				
Houseload of the power-generating module.....kW				
All energy fed into the network of the network operator?			<input type="checkbox"/> yes	<input type="checkbox"/> no
Is feed-in monitoring ($P_{AV, E}$ – monitoring) planned at the network connection point?			<input type="checkbox"/> yes	<input type="checkbox"/> no
Notes on the power-generating module:				

* Calculated from the sum of the maximum 10-minute average values of all installed power-generating units and storage in accordance with the information in the unit certificates at the network connection point. Any permanent active power reduction on the power-generating units shall be taken into account. For power-generating units and storage without a unit certificate, the rated active power P_{rE} and S_{rE} may be used as an alternative.

** Module power (maximum initial power (P_{max}) at Standard Test Conditions (STC)) in accordance with DIN EN 50380 (VDE 0126-390).

Application for network connection (high-voltage) (to be completed by the connection owner; use one data sheet for every structurally different power-generating unit or storage)		3 (4)
Number of identically constructed power-generating units or storage: units		
Unit certificate available <input type="checkbox"/> yes <input type="checkbox"/> no. When no: <input type="checkbox"/> Prototype <input type="checkbox"/> Verification through the individual verification procedure		
ZEREZ ID (additional information on storage is still required):		
If no ZEREZ ID is available, the following information is required:		
Unit type	<input type="checkbox"/> Double-fed asynchronous machine	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Synchronous machine (coupled directly)	<input type="checkbox"/> Phase shifter operation
	<input type="checkbox"/> Network connection with full converter (no storage)*	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Storage	<input type="checkbox"/> Inertia
	Other	
Unit manufacturer:	..... Type:	
Power data of the power-generating unit or storage	Rated apparent power S_{rE} *	..... kVA
	maximum active power (10 minute average) $P_{E_{max}}$ **	..... kW
	$P_{min,dyn}$: minimum dynamic active power available for the provision of negative inertia	..... MW
	$P_{max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia	..... MW
	$P_{limitneg,max}$: maximum dynamic active power for the provision of negative inertia	..... MW
	$P_{limitpos,min}$: minimum dynamic active power for the provision of positive inertia	..... MW
	transient minimum power	..... MW
	T_A : start up time constant	..... s
	Effective impedance z_w :	
	without a unit transformer (or on the low-voltage side of the unit):	..... p.u.
	including a unit transformer (or on the medium-voltage side of the unit):	..... p.u.
if applicable, at high-voltage level: 0.50 p.u.	..... p.u.	
Contribution to the initial short-circuit AC current S_k'' kA ***	at V	
<input type="checkbox"/> Cover sheet of the unit certificate prepared in accordance with VDE-AR-N 4120 and extract from the test report		
Network compatibility of FGW TR 3 attached		
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance %		
<input type="checkbox"/> Manufacturer data sheet attached		
Additional data for storage		
Connection of storage	<input type="checkbox"/> via its own inverter <input type="checkbox"/> via the inverter of another PGU (in a PGSU) <input type="checkbox"/> direct connection to the AC-network or three-phase network	
Operation of storage	<input type="checkbox"/> Consumption and feed-in from and into the network of the network operator	Feed-in from the storage into the network of the network operator planned simultaneously with PGUs <input type="checkbox"/> yes <input type="checkbox"/> no
	<input type="checkbox"/> No consumption, but feed-in into the network of the network operator	
	<input type="checkbox"/> No consumption and no feed-in from/into the network of the network operator	
	<input type="checkbox"/> Consumption, but no feed-in into the network of the network operator	

* In the case of full converters, the network-side data of the full converters shall be provided in data sheet E.1.3 (4)

** If the value is not explicitly known, the rated electrical active power P_{rE} of the PGU may be used. In the case of PV plants and storage, these quantities shall be indicated for the inverters.

*** For estimation purposes, the contribution of power-generating units without inverters (I''_k) may be added to the RMS value of the source current from power-generating units with inverters (I_{skPF}) (see Section 11.2.11).

Application for network connection (high-voltage) (to be completed by the connection owner for charging equipment for electric vehicles)		4 (4)	
General information of the charging device		<input type="checkbox"/> public <input type="checkbox"/> not public (private)	
Power data of the charging device		Maximum simultaneous active power consumption of the charging devices	..... kW
		A charging management system for controlling charging devices is planned*	<input type="checkbox"/> yes <input type="checkbox"/> no
Information of each identically constructed charging device	Number of charging devices	Maximum charging capacity of the charging device	Charging technology
		.... kW	<input type="checkbox"/> AC <input type="checkbox"/> DC** <input type="checkbox"/> Bidirectional*** ZEREZ ID:
			<input type="checkbox"/> AC <input type="checkbox"/> DC**
			<input type="checkbox"/> AC <input type="checkbox"/> DC**
Metering	Is a separate counting of the charging devices by the responsible party or a third-party metering point operator desired?		<input type="checkbox"/> yes*** <input type="checkbox"/> no

* The network operator may require a device to control the active power.

** The reactive power specifications of the network operator for DC charging devices > 12 kVA apply.

*** Commissioning or start-up order is required.

C.II.2. (E.5) Commissioning report for transfer stations - High-voltage

This form replaces Appendix E.5 of VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

Commissioning report (high-voltage) (to be completed by the plant operator of the transfer station)		1 (1)
Postal address of the installation	Station name or field number Street, number Postcode, town	
Plant operator	Company, place First name, surname Phone, email	
Installer of the electrical installation	Company, place First name, surname Phone, email	
Metering point operation	The measuring equipment is considered provided by the basic metering point operator or by another metering point operator (MPO; in that case indicate the MPO ID as given in the MPO framework contract):	
Station data	<input type="checkbox"/> Stub <input type="checkbox"/> Double stub <input type="checkbox"/> Looping-in <input type="checkbox"/> Demand installation <input type="checkbox"/> Feeder <input type="checkbox"/> Mixed installation/storage	
TF blocks (blocker for audio-frequency ripple control)	Required in the connection acceptance: <input type="checkbox"/> yes <input type="checkbox"/> no Installed: <input type="checkbox"/> yes <input type="checkbox"/> no Test protocol available: <input type="checkbox"/> yes <input type="checkbox"/> no	
Documentation: Updated project documents handed over to the network operator at least 2 weeks prior to commissioning of the transfer station: <input type="checkbox"/> yes <input type="checkbox"/> no		
<input type="checkbox"/> Network control agreement available <input type="checkbox"/> Calibration certificates for the transducers <input type="checkbox"/> Network operation prerequisites fulfilled <input type="checkbox"/> Protocol of the earth connection measurement <input type="checkbox"/> Schematic circuit diagram, wiring diagrams for secondary equipment, if any <input type="checkbox"/> Confirmation in accordance with DGUV Regulation 3 <input type="checkbox"/> Test protocol of the transfer protection and for power-generating modules of the primary loss of mains protection <input type="checkbox"/> Measurement value transmission checked <input type="checkbox"/> Joint commissioning (with the network operator) <input type="checkbox"/> Reports checked <input type="checkbox"/> Protection checked by switch tripping <input type="checkbox"/> Remote control checked (including emergency-stop circuit breaker)		
Comments:		
<p>I/We hereby confirm to have installed, tested, and completed the installation of the transfer station duly taking into consideration the relevant legislation and official decrees as well as the acknowledged rules of technology, in particular following the DIN VDE standards, VDE-AR-N 4120, and the Technical Connection Conditions of the network operator. The results of the tests were documented. During handover of the installation, the installer of the electrical installation instructed the plant operator and declared the transfer station operational in accordance with DGUV Regulation 3 § 3 and § 5.</p> <p>The transfer station is considered a closed electrical service location as defined by the currently valid DIN VDE regulations and the accident prevention regulation DGUV Regulation 3 [16]. Those locations shall only be entered by electrically skilled or electrically instructed persons. Laymen shall enter this closed electrical service location only in the company of electrically skilled or electrically instructed persons.</p>		
..... Place, date	..... Plant operator	..... Installer of the electrical installation
The customer installation was connected to the high-voltage network on: Date: Time:		
..... Place, date	..... network operator	

C.II.3. (E.6) Data sheet for power-generating modules or storage - High-voltage

This form replaces appendix E.6 of the VDE-AR-N 4120.
 (This form is intended to be replicated by the user of this VDE application guide.)

Data sheet for power-generating modules – High-voltage (to be completed by the connection owner, also applies to mixed installations and storage)		1 (4)
Feeder number of the connection owner _____		
Location of the installation	Postcode, town, district _____ Street, number or floor number / district number _____	
Connection owner	Company _____ First name, surname _____ Street, number _____ Postcode, town _____ Phone, email _____	
Is the information on the power-generating module in data sheet E.1, page 2(4) and page 3(4) currently valid? If the information in data sheet E.1, page 2(4) and page 3(4) is no longer valid, it shall be updated and submitted with the form E.8. In the event of changes that affect the network of the network operator, a new network compatibility assessment by the network operator may be required.		<input type="checkbox"/> yes, Date E.1 _____ <input type="checkbox"/> no
Are existing power-generating modules or storage connected to the network connection point? <input type="checkbox"/> yes <input type="checkbox"/> no Final system certificate number: _____ Date: _____ NOTE If no system certificate is available for existing power-generating modules or storage, page 3 (4) in form E.8 shall be completed.		
Minimum technical performance of the power-generating module?		<input type="checkbox"/> yes, .....kW <input type="checkbox"/> no
Island operation intended?		<input type="checkbox"/> yes <input type="checkbox"/> no
Black start capability provided?		<input type="checkbox"/> yes <input type="checkbox"/> no

Data sheet for power-generating modules – High-voltage (the following information shall be shown in the overview diagram of the power-generating module)		2 (4)
Details on the HV/MLV transformer	<ul style="list-style-type: none"> • Upper rated voltage U_{rOV} in kV • Lower rated voltage U_{rUV} in kV • Rated apparent power S_r in MVA • Operating voltage (controller setpoint voltage of the tap changer) U_{bUS} in kV • Short-circuit voltage u_k in % • Switching group • Control range of the tap changer \pm in % • Number of steps 	
Generator transformer	<ul style="list-style-type: none"> • Rated apparent power S_r in kVA • Short-circuit voltage u_k in % • Switching group • Control range of the tap changer \pm in % • Planned steps in kV/kV • Rated voltage OV in kV • Rated voltage UV in kV 	
Details of the connection owner's own MV network	<ul style="list-style-type: none"> • Neutral-point treatment (to be provided only if connection owner's own network is galvanically separated from the DSO's network): • schematic overview plan of the network with details on the types, lengths, and cross-sections of all cables used 	
Reactive power compensation system (if available)	<ul style="list-style-type: none"> • Rated reactive power • Number of steps • Degree of choking in % / Resonant frequency in Hz 	
Audio frequency lock (if available)	Values in Hz	

Data sheet for power-generating modules – High-voltage (to be completed by the connection owner; use one data sheet for every structurally different existing power-generating unit or storage without a system certificate)		3 (4)
Number of identically constructed power-generating units or storage: units		
Unit type	<input type="checkbox"/> Double-fed asynchronous machine	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Synchronous machine (coupled directly)	<input type="checkbox"/> Phase shifter operation
	<input type="checkbox"/> Network coupling with full converter*	<input type="checkbox"/> Inertia
	<input type="checkbox"/> Storage	<input type="checkbox"/> Inertia
	Other	
Operating mode	<input type="checkbox"/> <u>Peak load coverage / Optimisation of houseload consumption</u> <input type="checkbox"/> <u>Balancing energy market / Ancillary services</u> <input type="checkbox"/> <u>Island operation</u> <input type="checkbox"/> <u>Inertia</u> <input type="checkbox"/> <u>Other</u>	
Unit manufacturer:	.....	Type:
Power data	Rated apparent power S_{rE}^*	..... kVA
	Maximum active power (10 minute average) $P_{E\max}^{**}$	..... kW
	$P_{\min,dyn}$: minimum dynamic active power available for the provision of negative inertia	.....MW
	$P_{\max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia	.....MW
	$P_{\text{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia	.....MW
	$P_{\text{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia	.....MW
	Transient minimum power	.....MW
	T_A : start up time constant	..... s
	Effective impedance z_w :	
	without a unit transformer (or on the low-voltage side of the unit):	.....p.u.
including a unit transformer (or on the medium-voltage side of the unit):	.....p.u.	
if applicable, at high-voltage level: 0.50 p.u.	.....p.u.	
Contribution to the initial short-circuit AC current I_k'' kA ***	at V	
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance %		
<input type="checkbox"/> Manufacturer data sheet attached		

* In the case of full converters, the network-side data of the full converters are to be entered.

** In the case of PV plants and storage, these quantities shall be indicated for the inverters.

*** For estimation purposes, the contribution from the power-generating units without inverters (I_k'') may be added to the RMS value of the source current from power-generating units with inverters (I_{skPF}) (Clause 11.2.9).

Data sheet for power-generating modules – High-voltage (check list for the information to be submitted to the network operator by the connection owner; to be completed by the connection owner)		4 (4)
Single-phase overview circuit diagram of the customer's system (minimum requirements): <input type="checkbox"/>		
<ul style="list-style-type: none"> • Transfer station (high-voltage switchgear with specification of technical parameters) • Measurement, protection and control devices (if protection devices are present, it indicates where the measurement variables for short-circuit protection and, in the case of power-generating modules, additionally for loss of mains protection devices are recorded and on which switchgear the protection device acts, data of the auxiliary power source) • Mains transformers/machine transformers (see page 2(4)) • Illustration of the customer's own medium-voltage cable connections (see page 2(4)) <ul style="list-style-type: none"> ○ Specification of cable types, lengths and cross-sections 		
Current planned date of commissioning		
This data sheet and the application data sheet (E.1) together with the questionnaire E.9 7 to be completed by the network operator serve as the basis for issuing the system certificate. Changes of any kind shall be immediately indicated in writing to the relevant network operator. These data sheets will only be processed if fully completed.		
..... Place, date	..... Signature of the connection owner	

C.II.4. (E.7) Questionnaire for network operators – High-voltage

This form replaces appendix E.7 of the VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

Network operator questionnaire for new installations							1 (6)				
Connection/modification of a power-generating module or storage											
Designation of power-generating module											
Maximum generation active power, cumulated $\sum P_{Amax}$ Agreed active connection power $P_{AV,E}$ Agreed apparent connection power $S_{AV,E}$			Existing unit				New installation		Complete (existing + new installation)		
	$\sum P_{Amax}$			MW				MW		MW	
			Current (actual)			Total (new)					
	$P_{AV,E}$				MW				MW		
	$S_{AV,E}$				MVA				MVA		
$P_{AV,E}$ monitoring			<input type="checkbox"/> yes				<input type="checkbox"/> no				
Information from the network operator			Date of the TCC HV			Contact details (e.g. email or telephone)					
Registration number of the network operator											
Designation of the transfer station											
Designation of the network connection point ³⁶											
Demand facility at the same network connection point (except for houseload of the power-generating module)			Demand installation provided				Agreed active connection power $P_{AV, B}$				
			<input type="checkbox"/> yes (mixed installation in accordance with VDE-AR-N 4120) <input type="checkbox"/> no				$P_{AV, B}$				MW
Other comments:											

³⁶ Line designation for connection to a line or designation of neighbouring station(s) or designation of the feeder switch panel of the substation for direct connection to the busbar of a transformer station owned by the network operator.

Network operator questionnaire for new installations Connection/modification of a power-generating module or storage	3 (6)
--	-------

1.2 Loss of mains protection					
Function	Settings	Recommendation in accordance with VDE-AR-N 4120	Default settings from the network operator		
High-voltage side					
Over-voltage protection	$U >$	$1.25 U_n$			
	$t_U >$	500 ms			
Undervoltage protection	$U <$	$0.8 U_n$			
	$t_U <$	5.0 s			
Overfrequency protection	$f >$	51.5 Hz			
	$t_f >$	5.4 s			
Underfrequency protection	f	47.5 Hz			
	$t_f <$	≤ 400 ms			
Low-voltage side (ge: Unterspannungsseite)					
Overvoltage protection	$U >>$	$1.20 U_{MV}$			valid for $U_{MV} = \dots \text{ kV}^{37}$
	$t_U >>$	300 ms			
	$U >$	$1.10 U_{MV}$			
	$t_U >$	180 s			
$P_{AV,E}$ protection device	$P >>$	See FNN Guideline $P_{AV,E}$ monitoring (Table 5)			
	$t >>$				
	$P >$				
	$t >$				
1.3 Mixed installations (if demand installation available)					
	Point of measurement		Trigger location		
Primary loss of mains protection	<input type="checkbox"/> Transfer station <input type="checkbox"/> Power-generating module		<input type="checkbox"/> Transfer station <input type="checkbox"/> Power-generating module		

NOTE For existing systems, Q - U -protection may be deactivated during the repeated test in accordance with Clause 11.5.5.

³⁷ U_{MV} is the controller setpoint voltage of the tap changer located at the HV/MV transformer. If the controller setpoint voltage set differs from the specified value, then the set values of the rise-in-voltage protection shall be converted correspondingly. The controller setpoint voltage set shall be given in the statement of compliance.

Network operator questionnaire for new installations			4 (6)	
Connection/modification of a power-generating module or storage				
2. Default settings for power-generating units (e.g. PGU or temporarily stored loss of mains protection)				
2.1 Loss of mains protection				
Function	Settings	Recommendation in accordance with VDE-AR-N 4120 HV network	Default settings ³⁸ network operator	
Overvoltage protection	$U >>$	$1.25 U_{LV}^7$		U_{LV}
	$t_U >>$	100 ms		ms
Undervoltage protection	$U <$	$0.8 U_{LV}^7$		U_{LV}
	$t_U <$	300 ms ... 1.0 s		ms
	$U <<$	$0.45 U_{LV}^7$		U_{LV}
	$t_U <<$	0 ms to 300 ms		ms
Overfrequency protection	$f >>$	52.5 Hz		Hz
	$t_f >>$	≤ 100 ms		ms
	$f >$	51.5 Hz		Hz
	$t_f >$	10 s		s
Underfrequency protection	$f <$	47.5 Hz		Hz
	$t_f <$	≤ 100 ms		ms
If stepping shall be performed within a power-generating module, please, specify the following stepping values:	Settings for stepping		Default settings	
	$t_U < 1$	1.5 s		
	$t_U < 2$	1.8 s		
	$t_U < 3$	2.1 s		
	$t_U < 4$	2.4 s		
2.2 Continuous voltage control (for Type 2 installations only)				
Function	Default settings from the network operator			
Drop k of the continuous voltage control	<input type="checkbox"/> $k = 2$ <input type="checkbox"/> $k = \dots\dots$ <input type="checkbox"/> no specification (grid-forming)			

³⁸ The default values shall be used in the settings, as long as they do not impair the internal protection of the PGU. For default settings incompatible with the internal protection of the PGU, re-coordination with the DSO is required.

Network operator questionnaire for new installations		5 (6)
Connection/modification of a power-generating module or storage		
3. Steady-state voltage stability		
Reactive power adjustment range	<input type="checkbox"/> Option 1 in accordance with Clause 10.2.2 <input type="checkbox"/> Option 2 in accordance with Clause 10.2.2 <input type="checkbox"/> Option 3 in accordance with Clause 10.2.2 <input type="checkbox"/> under-excited to over-excited (separate closed-loop control)	
Desired reactive power value and method	<input type="checkbox"/> to be found in the TCC Date:	
	<input type="checkbox"/> Reactive power/voltage characteristic $Q(U)^{39}$	Gradient of the characteristic curve: Upper voltage limit $U_{MAX}/U_n = \dots\dots$ (e.g. 1.04) Maximum reactive power $Q_{MAX-under-excited}/P_{b inst} = \dots\dots$ (e.g. 0.33) Voltage deadband = $\pm \dots\dots\%$ U_n (e.g. $\pm 1.0\%$ U_n) Reference voltage: $U_{Q0,ref}/U_n = \dots\dots$ (e.g. 1.00) <input type="checkbox"/> U_{Q0}/U_n variable by means of a telecontrol system ⁴⁰ Step response time $T_{step_response_90\%} = \dots\dots$ s (default: $T_{step_response_90\%} = 5$ s)
	<input type="checkbox"/> Reactive power Q	Characteristic with P1 (U_1/U_{MV} ; $Q_A/P_{b inst}$) =;..... (e.g. 0.94; -0.33) P2 (U_2/U_{MV} ; $Q_{ref}/P_{b inst}$) =;..... (e.g. 0.94; 0) P3 (U_3/U_{MV} ; $Q_{ref}/P_{b inst}$) =;..... (e.g. 1.06; 0) P4 (U_4/U_{MV} ; $Q_B/P_{b inst}$) =;..... (e.g. 1.06; +0.33) <input type="checkbox"/> $Q = \dots\dots$ Mvar <input type="checkbox"/> variable by means of a telecontrol system ⁴¹ <input type="checkbox"/> Schedule ⁴²
	<input type="checkbox"/> Displacement factor $\cos \varphi$	<input type="checkbox"/> $\cos \varphi = \dots\dots$ <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited <input type="checkbox"/> variable by means of a telecontrol system ¹² <input type="checkbox"/> Schedule ¹³
Control behaviour for setpoint step changes	For $Q(U)$ and Q ; time constant 3 Tau = s (setting range 5 s to 60 s)	
Response to telecontrol system failure ⁴³	<input type="checkbox"/> continue operation with the value received last <input type="checkbox"/> $U_0 = \dots\dots$ kV; $Q_{ref} = \dots\dots$ Mvar; $\cos \varphi = \dots\dots$ (depending on the chosen method) <input type="checkbox"/> switch-over to ⁴⁴ <input type="checkbox"/> $Q(U)$ <input type="checkbox"/> Q <input type="checkbox"/> $\cos \varphi$	
Response to a failure of either the PGM controller or the associated measurement or the connection between PGM controller and PGU	<input type="checkbox"/> Continue operation of all PGUs with the value received last <input type="checkbox"/> Continue operation of all PGUs with $P = \dots\dots$ (aggregate value for the PGM) <input type="checkbox"/> Continue operation of all PGUs with $Q = \dots\dots$ (aggregate value for the PGM) <input type="checkbox"/> Continue operation of all PGUs with $\cos \varphi = \dots\dots$	
Requirements for the reactive power behaviour of the existing units for mixed installations ^{45, 46}	<input type="checkbox"/> Integration into the reactive power control system of the new installation <input type="checkbox"/> $\cos \varphi = \dots\dots$ at the NCP <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited <input type="checkbox"/> $\cos \varphi = \dots\dots$ at the PGU <input type="checkbox"/> over-excited <input type="checkbox"/> under-excited <input type="checkbox"/>under-excited to over-excited <input type="checkbox"/> maintain existing operation behaviour (unless otherwise specified, a $\cos(\varphi)$ value of 1 may be assumed for verification purposes)	

* For the normal network switching state.

³⁹ Recommendations can be found in Section 10.2.2.4.

⁴⁰ If setpoints are provided by means of a telecontrol system. The telecontrol system specifications shall be enclosed by the network operator or they can be found in the network operator's TCC.

⁴¹ The telecontrol system specifications shall be enclosed by the network operator or they can be found in the network operator's TCC.

⁴² If schedules are required, they shall be provided as a separate sheet or under other comments.

⁴³ If setpoints are provided by means of a telecontrol system.

⁴⁴ Specifications are provided by the network operator or to be found in the network operator's TCC.

⁴⁵ If several old installations with different reactive power responses or different reactive power agreements with the network operator exist, provide detailed information on a separate sheet.

⁴⁶ In addition to the mode of operation agreed for the existing installations, their actual behaviour shall be considered. The calculation method is described in FGW TR 8 [10].

Network operator questionnaire for new installations		6 (6)
Connection/modification of a power-generating module or storage		
4. Network data		
Nominal voltage of the high-voltage network U_n	.....	kV
Rated short-time current I_k (for $T_k = 1$ s) ⁴⁷	.....	kA
Minimum network short-circuit power at the point of common coupling ⁴⁸ S_{kV}^*	.....	MVA
Network impedance angle at the network connection point ψ_k^*	.....	°
Cabling proportion of the network	.....	% of the system length
Reference power ⁴⁹ S_0	.....	MVA
Centralized ripple-control frequency	.....	Hz
Effective network capacity	.....	µF
5. Neutral-point treatment		
Type of neutral-point treatment	<input type="checkbox"/> Resonant neutral earthing (earth fault compensation) <input type="checkbox"/> Neutral earthing with low impedance <input type="checkbox"/> Solid neutral earthing <input type="checkbox"/> No neutral-point treatment (free, isolated neutral point)	
6. PGM model		
<input type="checkbox"/> The network operator has a model of the power-generating module at its disposal for performing network calculations: <input type="checkbox"/> Set of parameters in accordance with Appendix C.4 <input type="checkbox"/> with optional additional information <input type="checkbox"/> Set of parameters in accordance with the specifications of the network operator <input type="checkbox"/> Set of parameters in accordance with the specifications of the network operator <input type="checkbox"/> Computable dynamic model in accordance with network operator specifications		
Other comments		
.....		
.....		
.....	
Place, date	Signature of the network operator The questionnaire for the network operator (E.7) is valid until:	

⁴⁷ For dimensioning of the high-voltage transfer station regarding the short-circuit current capability.

⁴⁸ In order to allow for the system certificate/ qualified opinion to be prepared, the network operator should provide the network data, including network short-circuit power S_{kV} and network impedance angle ψ_k , for the network connection point determined initially. These data are used as basis for the proof of compliance of the behaviour of the power-generating module according to the relevant rules.

⁴⁹ If the power-generating module is connected to a line section between two transformer stations, then the thermal limit power of this line section is taken as the reference power. If the power-generating module is connected to a transformer substation, either directly or via a customer-owned line, then the maximum generation power that can be connected to that transformer substation is to be used as S_0 .

C.II.5. (E.8) Commissioning report for power-generating modules and storage - High-voltage

This form replaces Appendix E.8 of the VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

Commissioning report for power-generating units – HV (to be completed by the plant operator; also applies to storage)		1 (2)
Plant designation	.....
Number of PGUs:	.....	Manufacturer of PGUs: Type of PGUs:
Registration number of the DSO	.....
Postal address of the power-generating unit	Postcode: Town: Street, number:	
Location of the power-generating unit (when no address available)	Local sub-district: Cadastral section: Plot:	
	<input type="checkbox"/> Gauss-Krüger coordinates Reference ellipsoid: <input type="checkbox"/> UTM coordinates Zone: Easting: Northing:	
Point of connection to the network of the network operator	Designation:	.....
	Metering point for billing purposes:	.....
Official approval	Type: <input type="checkbox"/> Construction permit <input type="checkbox"/> Approval as required by the BImSchV <input type="checkbox"/> Authorization under the water law <input type="checkbox"/> File number: Date:	
Compliance with legal provisions (EEG/KWK-G)	<input type="checkbox"/> The requirements of § 9(1) or (2) EEG are complied with (network protection and network management in compliance with statutory power limits) <input type="checkbox"/> The requirements of § 9(5) No. 1 EEG are complied with (hydraulic retention time, applicable for biogas plants only) <input type="checkbox"/> The requirements of § 9(5) No. 2 EEG are fulfilled (including gas consumption devices for power limits) <input type="checkbox"/> The prerequisites for a compensation side plant summary in accordance with § 24 Abs. 2 EEG are not satisfied (applicable to ground PV plants only)	
	Index number for the Market Master Data Register Award number in accordance with § 35 EEG:	
	<input type="checkbox"/> Application for approval as CHP plant as per § 10 KWK-G (Law on CHP) (please attach Federal Office of Economics and Export Control [BAFA] acknowledgement of receipt) <input type="checkbox"/> Notification of the CHP plant as per § 10 Abs. 6 KWK-G (please attach the notification filed with BAFA) <input type="checkbox"/> Approval as a CHP plant as per § 10 KWK-G (please attach the BAFA approval)	
Certification body for the power-generating unit	Name:	.....
	Postal address:	.....
	Unit certificate number:	..... Date of issue:
Certification body for power-generating modules	Name:	.....
	Postal address:	.....
	System certificate number:	..... Date of issue:
Power data	Maximum active power: kW (instantaneous power as per § 3 No. 31 EEG; for PV plants use the DC module rating)	
	Maximum apparent power: kVA (for PV plants use the inverter output power on the network side)	
	Storage capacity kWh (in storage)	

Commissioning report for power-generating units – HV		2 (2)	
(to be completed by the plant operator; also applies to storage)			
Documentation	<input type="checkbox"/> Loss of mains protection successfully tested (please attach the protection test reports) <input type="checkbox"/> Continuous voltage control of the power-generating unit is in accordance with the system certificate <input type="checkbox"/> continuous voltage control, k -factor set to $k = \dots\dots\dots$ (the k -factor is not applicable to directly coupled synchronous machines) <input type="checkbox"/> all other parameters influencing the electrical properties are set in accordance with the system certificate <input type="checkbox"/> The power-generating unit is integrated into the network security management <input type="checkbox"/> Proportion of nominal effective power for inertia market $m = \dots\dots\dots$ <input type="checkbox"/> Start-up time constant $T_A = \dots\dots\dots$		
Commissioning	The power-generating unit was commissioned on:	Date:	Time:
	The power-generating unit has started feeding energy into the network of the network operator (in the case of mixed installations has started generating energy):	Date:	Time:
<p>The electrical installation of the power-generating unit is regarded as a closed electrical service location as defined by the currently valid DIN VDE regulations and the accident prevention regulation DGUV Regulation 3 [16]. Those locations shall only be entered by electrically skilled or electrically instructed persons. Laymen shall enter this service location only in the company of qualified electricians or persons trained in electrical engineering.</p> <p>The power-generating unit was erected in accordance with the conditions specified in VDE-AR-N 4120 and the Technical Connection Conditions of the network operator. During handover of the installation, the installer of the electrical installation has instructed the plant operator and has declared the power-generating unit operational in accordance with DGUV Regulation 3 [16] § 3 and § 5.</p>			
I/We hereby declare all the information given above to be truthful and I/we undertake to immediately communicate in writing any changes made to the installation to the network operator to whose network the power-generating unit is connected. The details are based on the relevant legal regulations and statutory orders.			
Installer or commissioner of the electrical installation		Plant operator	
Company:		Company:	
Name of the editor:		Name of the editor:	
Street, number:		Street, number:	
.....		
Postcode, town:		Postcode, town:	
.....		
Date, stamp and signature		Date, stamp and signature	

C.II.6. (E.9) Commissioning statement for power-generating modules or storage - High-voltage

This form replaces appendix E.9 of the VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)				1 (7)
Designation of the power-generating module				
Power-related data of the power-generating module	Agreed active connection power for feed-in $P_{AV,E}$			MW
	Agreed apparent connection power for feed-in $S_{AV,E}$			MVA
	Agreed active connection power for consumption $P_{AV,B}$			MW
	Installed active power P_{inst}			MW
	$P_{min,dyn}$: minimum dynamic active power available for the provision of negative inertia			MW
	$P_{max,dyn}$: maximum dynamic active power available for the provision of the maximum inertia			MW
	$P_{limitneg,max}$: maximum dynamic active power for the provision of negative inertia			MW
	$P_{limitpos,min}$: minimum dynamic active power for the provision of positive inertia			MW
	Transient minimum power			MW
Registration number of the network operator				
Designation of network connection point				
Creator of the commissioning statement	Company			
	Street, number			
	Postcode, town			
	Phone, email			
Connection owner	Company			
	Street, number			
	Postcode, town			
	Phone, email			
Issuer of the system certificate	Certification body			
	Street, number			
	Postcode, town			
	System certificate number:			
	Date of issue			
Information from the commissioning report for transfer stations (E.7)				
Designation of the transfer station				
Commissioning report as of:				
Commissioning of the PGM controller				
Manufacturer	Type	Firmware version	Serial number	Commissioning date

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		3 (7)
The following test protocols and verifications can be found in the attachment	Type of document	attached
Functional test of the entire chain of action of the active and, if applicable, reactive power control by the control centre of the network operator (protocol to be provided by the network operator);	Verification of the network operator	<input type="checkbox"/>
Alternative 1: Test of the entire chain of action by simulating the interface to the telecontrol system of the network operator (if agreed with the network operator)	Verification	<input type="checkbox"/>
Alternative 2: Test of the entire chain of action with the network operator to be agreed at a later date. Including confirmation from the network operator (not part of the commissioning declaration)	Confirmation from the network operator	<input type="checkbox"/>
Functional test of the telecontrol system up to the transfer station (if required by the network operator), to be performed by the network operator (request test, process data scope)	Verification of the network operator	<input type="checkbox"/>
Verification of the response to telecontrol system failure, unless proven in the component certificate of the PGM controller and documented in the setting records of the PGM controller (requirement: see E.97)	Verification	<input type="checkbox"/>
Verification of the response to telecontrol system failure, unless proven in the component certificate of the PGM controller and documented in the settings records of the PGM controller (requirement: see E.97)	Verification	<input type="checkbox"/>
Function test of the reactive power characteristic curve or the reactive power fixed values in accordance with specifications from the network operator (see E.97) based on recorded operating measurements of the PGM controller or other recording devices at the network connection point (recording period: at least 7 days and at least 20 % P_{inst} , for $Q(P)$ - or $\cos\phi(P)$ characteristic curve at least 60 % P_{inst}). Or alternatively, the reactive power characteristic curve function was tested with a test characteristic curve (using simulated reference variable U or P). After the test, the original characteristic has again been set.	Test protocol	<input type="checkbox"/>
Protection test report for the protection equipment at the network connection point Minimum information, see Appendix on page 6 of 7	Protection test report(s)	<input type="checkbox"/>
Protection test reports for protection equipment on the individual power-generating units or, if applicable, the intermediate storage protection devices Minimum information, see Appendix on page 6 of 7	Protection test report(s)	<input type="checkbox"/>

<p>Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)</p>	4 (7)
<p>Adjustment protocol for the power-generating units (in particular for implementing O/UVRT robustness) including designation, the parameters used in VDE-AR-N 4120; minimum information:</p> <ul style="list-style-type: none"> - Manufacturer, type, serial numbers and, if applicable, firmware of the PGU for which the following parameters were set - Protection setting values - Switch-on parameters in undisturbed network operation - Reset parameters after protection tripping - FRT mode, k-factor set if applicable and FRT entry thresholds - Active power gradient - Active power limitation (set maximum active power) - Active power adjustment at over- and under-frequency ($P(f)$ characteristic curve) - Response to a PGM controller failure <ul style="list-style-type: none"> If applicable, for plant control exclusively via the PGU: - See the PGM controller setting records for details. 	Settings record(s) <input type="checkbox"/>
<p>Setting records of the PGM controller including designation, parameters used in VDE-AR-N 4120; minimum information:</p> <ul style="list-style-type: none"> - Manufacturer, type, serial numbers and, if applicable, firmware version - Verifiable setting of the characteristic curve type required in accordance with E.7 - Description of all reference points of the characteristic curve - Specification of the (maximum) active power, if applicable, setting of an active power limit - Settling time (3 Tau) in accordance with E.7 - Response to a connection failure between the remote control system and the PGM controller in accordance with E.7 - Integration and control of any existing system components - If not set on the PGU: Active power gradient and active power adjustment in case of overfrequency and underfrequency ($P(f)$ characteristic curve), switch-on parameters in undisturbed network operation 	Settings record <input type="checkbox"/>
Arc fault qualification certificate for the switchgear or risk assessment for existing systems	Verification <input type="checkbox"/>
<p>Photographic documentation (the assignment to operating equipment shall be recognisable). The certification body may accept alternative verifications. Minimum information:</p>	Photos
<ul style="list-style-type: none"> - Type plates (with serial number) and front view of all installed protection devices and the associated test terminal strips (documentation as part of the protection test may be accepted) 	<input type="checkbox"/>
<ul style="list-style-type: none"> - Type plates of the HV switchgear 	<input type="checkbox"/>
<ul style="list-style-type: none"> - Type plates of the transformers (if used for protection/PGM controllers; type plates on the measuring cell or documentation as part of the protection test may be accepted) 	<input type="checkbox"/>

Commissioning statement for power-generating modules or storage		5 (7)
(to be completed by the plant operator; also applies to storage)		
- Type plates of transformers with tap changers		<input type="checkbox"/>
- Type plates of switchgear (e.g. circuit breakers) assigned to the protection devices		<input type="checkbox"/>
- Protection settings that are set directly on the switchgear (e.g. rotary switches/dip switches)		<input type="checkbox"/>
- Type plates of network analysis devices (if used for protection/PGM controllers)		<input type="checkbox"/>
- Type plates of PGM controller (with serial number)		<input type="checkbox"/>
- Type plates of mains-independent auxiliary power supplies/UPS (with recognisable capacity of the connected battery) of the transfer station and, if applicable, the temporarily stored protection devices		<input type="checkbox"/>
- Fuse outlets with type and size		<input type="checkbox"/>
- Nameplates for all stations		<input type="checkbox"/>
Comments:		
<p>Note: The scope of the declaration of commissioning in the individual verification procedure shall be agreed with the certification body on a project-by-project basis.</p>		
Confirmation		
<p>The actual built-in power-generating units (indicating their designation and serial number), including the main components listed in the unit certificate (including firmware versions) are listed in the section 'Commissioning of all power-generating units'.</p> <p>The built-in components/PGM controllers installed (by name and serial number) are listed in the sections 'Commissioning of the PGM controller' and 'Commissioning of additional components'.</p> <p>The operating equipment of the power-generating module (characteristic values and step settings of the operating equipment transformers, cable lengths and types) are listed as an appendix or enclosed as photographic documentation.</p> <p>The signatory confirms the accuracy of the information provided in the commissioning declaration, including the required attachments.</p>		
Date	Signature of the person who prepared the declaration of commissioning	

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)	6 (7)
Minimum information of the protection test reports at the network connection point and on the individual power-generating units or the intermediate storage protection devices	
<p>Protection test report for the protection equipment at the network connection point</p> <ul style="list-style-type: none"> - Minimum information, see Appendix *1: - System designation, installation location in the plant and date of testing - Manufacturer, type and serial number of the protection device - Transformers used with transmission ratio, accuracy class and installation location in the plant - Indication of the switchgear on which the protection device acts - For all voltage values, indicate whether the value refers to the line-line voltage or line-earth voltage - Indication that the tripping of the voltage rise protection and voltage dip protection are linked for all phases - Identification of all setting thresholds and times (in accordance with E.7) - Measurement values of all tripping thresholds (in HV: Line-to-line voltages) and tripping for all phases - Indication of whether the tripping times take into account the inherent time of the switchgear (switchgear tripped) - Measured value of the inherent time of the switchgear - Indication that the tripping time is not less than the setting time required by the network operator (not applicable if the network operator specifies a time range without a lower time value, e.g. ≤ 300 ms or $0 \dots 300$ ms) - Specification of the setting and measured values of the reset ratios of all voltage increase and voltage decrease protection thresholds - Specification of whether automatic reconnection was deactivated in the protection device or, if applicable, by external circuitry - Checking the tripping of the switchgear in the event of: <ul style="list-style-type: none"> • Failure of the auxiliary power supply • If applicable, when connecting the life contact: failure of the life contact or its connection • Failure of the measurement voltage of the protection device • Failure of the control voltage of the switchgear • If the protection device and switchgear are spatially separated: connection failure between the protection device and switchgear <p>The network operator may specify different requirements and request further tests.</p>	

Commissioning statement for power-generating modules or storage

7(7)

(to be completed by the plant operator; also applies to storage)

Protection test reports for protection equipment on the individual power-generating units or, if applicable, the intermediate storage protection devices

Minimum information:

- System designation, installation location in the plant and date of testing
- Manufacturer, type and serial number of the protection device
- for temporarily stored protection devices: firmware version of the protection device (in accordance with the component certificate)
- Transformers used with transmission ratio, accuracy class and installation location in the plant or, in the case of direct measurements: measurement location in the plant
- Specification of the transmission ratio of the transformer and the voltage U_{MV} (to determine whether U_{NV} was calculated correctly)
- Indication of the switchgear on which the protection device acts
- For all voltage values, indicate whether the value refers to the line-line voltage or line-earth voltage
- Identification of all setting thresholds and times (in accordance with E.7)
- Measured values of all tripping thresholds and times for all phases
- Indication of whether the tripping times take into account the inherent time of the switchgear (switchgear tripped)
- Measured value of the inherent time of the switchgear
- Indication that the tripping time is not less than the setting time required by the network operator (not applicable if the network operator specifies a time range without a lower time value, e.g. ≤ 300 ms or $0 \dots 300$ ms)
- Specification of the setting and measured values of the reset ratios of all voltage increase and voltage decrease protection thresholds
- Setting values of all connection parameters in undisturbed network operation or indication that this was deactivated in the protection device
- Setting values of all switch-on parameters after protection tripping
- Checking the tripping of the switchgear in the event of:
 - Failure of the auxiliary power supply
 - If the protection device and switchgear are spatially separated: connection failure between the protection device and switchgear

The network operator may specify different requirements and request further tests.

C.II.7. (E.10) Statement of compliance for power-generating modules or storage - High-voltage

This form replaces appendix E.10 of the VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE application guide.)

<p style="text-align: center;">Name of the certification body.....</p> <p>Accredited in accordance with DIN EN ISO/IEC 17065 for VDE-AR-N 4120</p>	<p style="font-size: 2em; text-align: center;">LOGO</p> <p style="text-align: right;">1 (2)</p>	
<p>Statement of compliance for power-generating modules or storage</p>		
Project description		
Connection owner		
Power data of the power-generating module or storage	Agreed active connection power $P_{AV, E}$	_____ MW
	Agreed apparent connection power $S_{AV, E}$	_____ MVA
	Agreed active connection power $P_{AV, B}$	_____ MW
	Agreed apparent connection power $S_{AV, B}$	_____ MVA
	Installed active power P_{inst}	_____ MW
Creator of the system certificate	First name, surname _____ Street, number _____ Number of verifications for the installation _____ Date of issue _____	
Creator of the commissioning statement	First name, surname _____ Street, number _____ Date of issue _____	
The power-generating module or storage (components, units, and equipment, etc.) was installed in accordance with the system certificate and the provisions of the network operator. <input type="checkbox"/> Passed NOTE _____ _____		
The component parts and settings of the power-generating module/storage installed set out in the commissioning statement are in accordance with the system certificate. <input type="checkbox"/> Passed NOTE _____ _____		
The concept for static reactive power supply, the concept for active power control, the implementation of O-/UVRT robustness and the protection concept were implemented taking into consideration the provisions of the network operator. <input type="checkbox"/> Passed NOTE _____ _____		

The power-generating module or storage described above

- meets the requirements of VDE-AR-N 4120 "TCR High-voltage"
- meets the requirements of the FNN Guideline "Technical requirements for grid-forming capabilities including the provision of inertia"
- meets the requirements of the network operator's TCC
and was installed in compliance with the system certificate indicated above.

NOTE _____

In case the harmonic oscillations are exceeded, the following aspects shall be considered.

- Installation and start of the measurement were performed
on: _____

The required functional tests of active and reactive power behaviour

- Were performed in the context of the commissioning statement.
- Could not be performed for the following reasons and will be performed in coordination with the network operator at a later point in time.

The statement of compliance includes the following attachments:

- Commissioning statement
- Additional documents reviewed in order to prepare the statement of compliance: _____

Confirmation in cases of subsequent verification measurements:

- Measurement in the time period of _____ to _____ could not provide the proof of compliance with the required harmonic levels (deadline 6 months after commissioning of the power-generating module).
- Measurement in the time period of _____ to _____ could not provide the proof required.
Reworks required.

Place, date (DD.MM.YYYY)

Confirmation by the certification body, postal address, email

- Reworks were conducted. The measurement completed within the period from _____ to _____ could provide proof of compliance with the required harmonics levels (deadline of 12 months following the failed evidence measurement).

Place, date (DD.MM.YYYY)

Confirmation by the certification body, postal address, email

Place, date (DD.MM.YYYY)

Certification body, postal address, email

This certificate shall not be used in parts.

C.III. Application for network connection - Extra-high-voltage

C.III.1. (E.6) Data sheet of power-generating modules or storage - Extra-high-voltage

This form replaces Appendix E.6 of VDE-AR-N 4130.

(This form is intended to be replicated by the user of this VDE application guide.)

Data sheet of power-generating modules or storage – Extra-high-voltage (to be completed by the connection owner)		1 (5)
Postal address of the installation	Street, number Postcode, town	
Connection owner	First name, Surname Street, number Postcode, town Phone, email	
Applicant	First name, Surname Street, number Postcode, town Phone, email	
Type of the power-generating module (multiple choice possible for energy mix)	<input type="checkbox"/> Wind energy <input type="checkbox"/> Hydro-power <input type="checkbox"/>	
	<input type="checkbox"/> PV plant <input type="checkbox"/> Free area <input type="checkbox"/> Roof area <input type="checkbox"/> Façade	
	<input type="checkbox"/> CCGT Fuel type used (e.g. natural gas, biogas, biomass)	
	<input type="checkbox"/> Thermal power plant	
	<input type="checkbox"/> Storage	
Installation type	<input type="checkbox"/> New installation <input type="checkbox"/> Extension <input type="checkbox"/> Dismantling	
Power data	Available active connection power $P_{AV, E}$	MW
	Newly to be installed active connection power $P_{AV, E}$	MW
	Rated active power of modules in PV plants for this purpose*	MWp
	Rated active power of inverters $P_{r, WE}$ (PV plants)	MW
	Total active connection power $P_{AV, E}$	MW
	Technical minimum power	MW
	Houseload of the power-generating module (including consumption power of storage)	MW
	$P_{min, dyn}$: minimum dynamic active power available for the provision of negative inertia	MW
	$P_{max, dyn}$: maximum dynamic active power available for the provision of the maximum inertia	MW
	$P_{limitneg, max}$: maximum dynamic active power for the provision of negative inertia	MW
	$P_{limitpos, min}$: minimum dynamic active power for the provision of positive inertia	MW
	Transient minimum power	MW
	T_{λ} : start up time constant	s

* Sum of existing and newly to be installed module power (maximum initial power (P_{max}) at Standard Test Conditions (STC)) in accordance with DIN EN 50380 [17].

Data sheet of power-generating modules or storage – Extra-high-voltage (to be completed by the connection owner)		2 (5)
All energy fed into the network of the network operator?		<input type="checkbox"/> yes <input type="checkbox"/> no
Island operation intended?		<input type="checkbox"/> yes <input type="checkbox"/> no
Black start capability provided?		<input type="checkbox"/> yes <input type="checkbox"/> no
Carrier-frequency utilization of the customer network intended?		<input type="checkbox"/> yes <input type="checkbox"/> no
Brief description:		
EHV/HV(MV) transformer	Upper rated voltage U_{rOS} kV	
	Lower rated voltage U_{rUS} kV	
	Rated apparent power S_r MVA	
	Short-circuit voltage u_k %	
	Vector group: Tap changer: Control range: \pm % Number of steps:	
Information on the – connection owner – own network	Operating voltage (controller voltage setpoint of the tap changer) U_{MV} kV	
	Neutral point treatment: <input type="checkbox"/> deleted <input type="checkbox"/> isolated <input type="checkbox"/> low-impedance earthing	
	<input type="checkbox"/> Schematic overview diagram of the network attached with details on the lengths and cross-sections of all cables used	
Reactive power compensation system	<input type="checkbox"/> not provided <input type="checkbox"/> provided kvar	
	Degree of choking/resonance frequency: Hz	
	Assigned: <input type="checkbox"/> to the power-generating module <input type="checkbox"/> to the power-generating units	
	<input type="checkbox"/> Schematic overview diagram and manufacturer data sheet attached	

Data sheet of power-generating modules or storage – Extra-high-voltage (to be completed by the connection owner; please, fill out one data sheet for every structurally different power-generating unit)		3 (5)	
Number of identically constructed power-generating units: units			
New power-generating unit to be installed		<input type="checkbox"/> prototype	
<input type="checkbox"/> Existing unit with capability to provide ancillary services: <input type="checkbox"/> as old installation <input type="checkbox"/> as temporary/new installation			
Number of last valid installation qualified opinion/certificate: _____ Date: _____			
NOTE 2 Where a qualified opinion /certificate is available for the existing unit, this sheet 3 (5) may be omitted for this existing unit.			
Unit type	<input type="checkbox"/> Double-fed asynchronous machine	<input type="checkbox"/> Inertia	
	<input type="checkbox"/> Synchronous machine (coupled directly)	<input type="checkbox"/> Phase shifter operation	
	<input type="checkbox"/> Network coupling with full converter*	<input type="checkbox"/> Inertia	
	others		
Unit manufacturer:	..... Type:	
Power data	Rated active power of a power-generating unit P_{rE} ** kW		
	Rated apparent power S_{rE} ** kVA		
	Contribution to the initial short-circuit AC current*** I_k'' kA at kV		
	Contribution to the sustained short-circuit current I_k kA at kV		
	<input type="checkbox"/> Cover sheet of the unit certificate prepared in accordance with VDE-AR-N 4130 and extract from the test report Network compatibility of FGW/TR 3 [5] attached		
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance %			
<input type="checkbox"/> Manufacturer data sheet attached			
Network transformer****	Rated apparent power S_r kVA	Short-circuit voltage u_k %	
	Idle-mode losses P_0 kW	Short-circuit losses P_k kW	Vector group:
	Tap changer: \pm %; Steps	Planned steps: kV/..... V	
	Rated voltage OV kV	Rated voltage UV kV	

* In the case of full converters, the network-side data of the full converters are to be entered.

** In the case of PV plants and storage, these quantities shall be indicated for the inverters.

*** For estimation purposes, the contribution of the power-generating units without inverter (I_k'') and the RMS value of the source voltage of power-generating units with inverter (I_{skPF}) (see 11.2.9) can be added.

**** If applicable, data for other relevant transformers shall be indicated.

Data sheet of power-generating modules or storage – Extra-high-voltage		4 (5)
(to be completed by the connection owner; please, use one data sheet each for every structurally different storage)		
Operating mode	<input type="checkbox"/> Houseload increase of the customer demand installation (load optimising)	
	<input type="checkbox"/> Provision of ancillary services	
	<input type="checkbox"/> Provision of control energy	
	<input type="checkbox"/> Maintaining island operation of the customer installation	
	<input type="checkbox"/> Miscellaneous	
Connection of storage	<input type="checkbox"/> via own inverter	
	<input type="checkbox"/> via the inverter of the PGU	
	<input type="checkbox"/> direct connection to the three-phase network	
	Maximum power $P_{E_{max}}$ (10 min):	..... MW
	Usable storage capacity:	..... MWh
Inverter of storage (if the battery storage has its own inverter)	Manufacturer/Type: Number:	
	Apparent power of inverter $S_{E_{max}}$:	..... kVA
	Active power of inverter $P_{E_{max}}$:	..... kW
	Rated current (AC) I_r:	..... A
	Contribution to the initial short-circuit AC current $I_{k''}$:	..... A
Power gradient of storage	Maximum power gradient in consumption mode	..... kW/s
	Maximum power gradient in feed-in mode	..... kW/s
Connection strategy	Figure number in accordance with the FNN Guideline 'Connection and operation of storage devices on the low-voltage network', Section 5:	
	Schematic circuit diagram attached (single-phase):	<input type="checkbox"/>
	Primary energy sources used (e.g. solar, wind, gas):	
	Different primary energy sources are registered separately:	<input type="checkbox"/>
	Different feed-in tariffs are accurately registered:	<input type="checkbox"/>
	Energy of storage is not consumed from the network and fed in as supported energy:	<input type="checkbox"/>
Verifications	For the inverter of storage, the extract from the test report for network compatibility in accordance with FGW/TR 3 [5] was submitted	<input type="checkbox"/>
	Unit certificates in accordance with VDE-AR-N 4130 were submitted:	<input type="checkbox"/>
Comments	..... ..... ..... ..... .....

Data sheet of power-generating modules or storage – Extra-high-voltage		5 (5)
(check list for the information to be submitted to the network operator by the connection owner; to be completed by the connection owner)		
Site map showing the location relative to places and roads, cadastral and plot designations, designation and limits of the property, and the installation site of the customer installation and the power-generating units (preferably to a scale of 1:10,000, 1:1,000 within built-up areas) attached?		<input type="checkbox"/>
Building permit for the power-generating module attached?		<input type="checkbox"/>
Preliminary building permit attached? (not required for PV plants on approved structures)?		<input type="checkbox"/>
Proof of sincerity attached? (e.g. permission as required by the Federal Immission Control Act [BImSch], decision for the development plan, sales contracts for the PGU, or similar)?		<input type="checkbox"/>
Project schedule available? (please attach)		<input type="checkbox"/>
Planned transition to continuous operation		.....
This data sheet is part of the network compatibility check and possibly the network connection acceptance. Together with the questionnaire E.7 to be completed by the network operator, it also serves as a basis for the preparation of the system certificate. Changes of any kind shall be immediately indicated in writing to the relevant network operator. These data sheets will only be processed if fully completed.		
..... Place, Date Signature of the connection owner	

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Electronic & Information e.V.

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