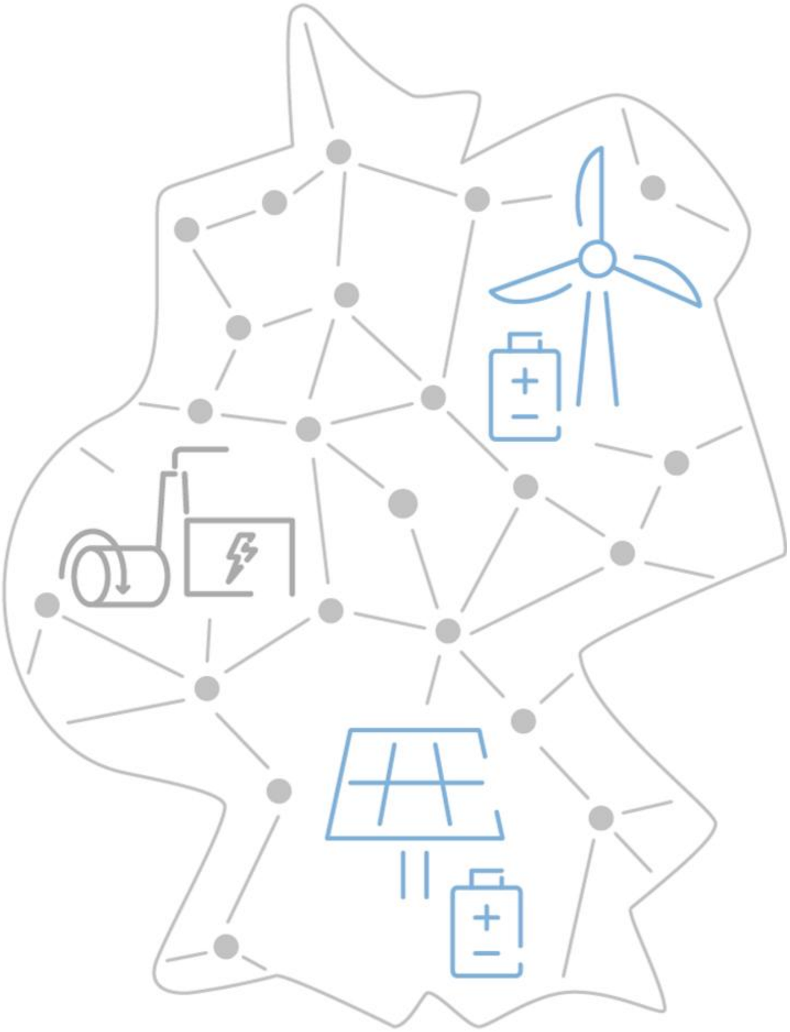

Technical requirements for grid-forming capabilities including provision of inertia

Requirements and verifications for grid-forming units and plants

Version 2.1
English version, April 2026
Original version in German first published in January 2026

VDE FNN

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Foreword

The expansion of converter-based plants 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 plants with grid-forming capabilities, which provide the inertia required for the stable operation of grid-following plants, as well as the increasing reduction of effective short-circuit power ratio also required by grid-following plants. The Network Development Plan for 2035 (based on data from 2021) and for 2037 (based on data from 2023)[1] show the need for additional inertia. 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 April 2025, the Federal Network Agency initiated a determination procedure BK6-23-0109 in accordance with Sections 12h (5) and 29 (1) of the Energy Industry Act (EnWG). This procedure defines 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 under Section 12h (1) Sentence 1 No. 2 EnWG. The German transmission system operators are responsible for procuring inertia through this new market. This determination procedure revokes the exemption from a market-based procurement for inertia granted by the Federal Network Agency on 18 December 2020. This revocation is a a prerequisite for the launch of the inertia market.

Plants participating in the inertia market shall qualify for this purpose by meeting the suitable requirements and providing the necessary verifications. These 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 requirements section of this guideline was consulted in Version 0.1 from 20 February 2024 to 20 March 2024 and published in Version 1.0 in July 2024. The verification section of this guideline was publicly consulted in Version 0.1 from 12 July 2024 to 23 August 2024 and published together with the requirements in Version 2.0 on 15 May 2025.

Note to Version 2.1

This VDE FNN Guideline (Version 2.1) replaces Version 2.0 of this FNN Guideline as of the date of publication and defines binding requirements and verifications for grid-forming units and plants formed from these units, to be complied with as a prerequisite for participating in the inertia market and contains, among other things, the significant changes listed in Overview of changes 1.

No transitional period applies for this FNN Guideline (Version 2.1). Accordingly, commissioning of a grid-forming unit is only permitted after submission of a prototype validation or unit certificate and after proof of compliance with the requirements defined in this FNN Guideline regarding the verification procedures for grid-forming plants with prototypes or plant certification. A prototype validation in accordance with Version 2.0 of the FNN Guideline may be replaced by a unit certificate in accordance with Version 2.1 of the FNN Guideline.

Nevertheless, a prototype validation including a qualified expert report for the grid-forming unit in accordance with Version 2.0 of this FNN Guideline may already be used for the submission of an offer to participate in the inertia market and for the corresponding network connection request.

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[1] https://www.netzentwicklungsplan.de/

NOTE In this case, it is the responsibility of the provider (in the market) to ensure that a corresponding upgrade of the prototype validation or unit certificate (from Version 2.0 to Version 2.1) can be submitted in time for the grid-forming unit to be used.

Overview of changes 1 - Overview of significant amendments in the FNN Guideline from Version 2.0 to Version 2.1

	Section	Amendment
Δ	2	– Completion of Table 1 with clauses in the Technical Connection Rules to be updated or replaced – Addition of grid-forming plants in the scope of application
Δ	3	Addition of necessary terms
+	4.1.1.3	Inclusion of requirements for static voltage support for Type 1 plants
Δ	4.1.2	Structural revision of PCNB requirements for Type 1 units
Δ	4.2.1.1	– Elimination of the specification for a maximum unit impedance value at high voltage level – Addition of requirements for the decay of DC current for the unit – Change of requirements for phase jump power by PGSU and storage
+	4.2.1.2, 4.2.1.3	Division of previous requirements for damping behaviour above 10 Hz into requirements for: – behaviour in the sub- and super-synchronous frequency range – behaviour in the harmonic frequency range
Δ	4.2.1.4	Extensive revision of requirements for static voltage support for Type 2 grid-forming plants
Δ	4.2.1.5	Revision and clarification of requirements for the previously used “continuous voltage control” and use of a new term: voltage source control
+	4.2.1.5.3	Addition of a control method for limited voltage source control
Δ	4.2.1.13	Addition of requirements regarding the time required to provide an effective T_{A}
Δ	4.2.2	Adjustment of PCNB requirements in VDE-AR-N 4110:2026 and VDE-AR-N 4120:2026
+	4.2.4	Inclusion of requirements for Type 2 grid-forming plants, storage and controllable consumption units
Δ	5.2	Revision and corrections to prototype rules for grid-forming units and plants, including a transitional rule for prototypes in accordance with FNN Guideline Version 2.0
+	5.2.3	Inclusion of a verification procedure for grid-forming plants with prototypes
Δ	5.3	Revision of the rule on transferability of measurements to other Type 1 units
Δ	5.4.2	Restructuring of requirements for model validation of Type 1 grid-forming units for the unit certificate procedure and the individual verification procedure
+	5.4.2.2	Introduction of specifications for model validation of start-up time constants T_{A} and of PCNB for Type 1 units as part of the unit certification
Δ	5.4.3.3.2	Adjustment of the measurement procedure for verifying PCNB
Δ	5.5.3	Revision of general modelling requirements regarding houseload of grid-forming units
Δ	5.5.4	Adjustment of measurement requirements for verifying voltage source behaviour of PGSUs und storage
Δ	5.5.5.3	Addition of verifications of phase jump power to the proof of compliance with prioritisation requirements
Δ	5.5.5.4	Revision of measurement procedure 2 for verifying effective impedance
Δ	5.5.5.5	Replacement of the verification of damping behaviour above 10 Hz with the verification of passivity properties in the harmonic frequency range
Δ	5.5.5.6.2	Revision and clarification of the verification of disturbance behaviour and linearity of the effective impedance
Δ	5.5.5.6.3	Revision of the verification of robustness and voltage source control during short-term overvoltage and undervoltage events (O/UVRT robustness)

	Section	Amendment
+	5.5.5.6.6	Inclusion of the verification of behaviour of limited voltage source control during faults
Δ	5.5.5.8	Revision of the verification of damping of power-frequency-oscillations
Δ	5.5.5.9	Revision of the verification of start-up time constants T_A and addition of an examination for proof of compliance with the prioritisation requirements
Δ	5.5.5.10	Revision of the verification of capabilities for response during overfrequency and underfrequency events in the limited setting range of the PCNB
+	5.5.6	Inclusion of an extended verification of control functions for verifying prioritisation of active power setpoints during underfrequency
+	5.5.7.1	Inclusion of a simulation-based verification of phase jump power for parameterisable gain of the voltage source control or the effective impedance
+	5.5.7.2	Inclusion of a simulation-based verification of the effective impedance for parameterisable gain of the voltage source control or the effective impedance
Δ	5.5.7.5	Inclusion of a simulation-based verification of the setpoint tracking behaviour of the voltage source control with specifications for its parameterisable gain
Δ	5.5.7.6	Inclusion of a simulation-based verification of the disturbance behaviour of the voltage source control with specifications for its parameterisable gain
+	5.5.7.7	Inclusion of a simulation-based verification of response after return into the voltage band U_r ± 10 % U_r with parameterisable gain of the voltage source control
+	5.5.7.8	Inclusion of a simulation-based verification of damping behaviour in sub- and super-synchronous frequency ranges
+	5.5.7.9	Inclusion of a simulation-based verification of the decay of the DC component of the current of a grid-forming unit
+	5.6.2.1	Additions to the relevant Technical Connection Rules that deviate from or supplement the plant certification (Section 11.4)
+	5.6.3	Introduction of an extended plant certificate for grid-forming plants within the scope of VDE-AR-N 4130
+	5.7	Introduction of specifications for a procedure for the statement of compliance for grid-forming units
Δ	A.I	Revision of criteria for determining damping
+	A.II	Inclusion of explanation on the virtual island
Δ	A.III	Revision of explanation on small-signal stability of the primary control in the unlimited setting range in accordance with VDE-AR-N 41120:2026 and VDE-AR-N 4120:2026
Δ	A.IV	Revision of the verification procedure for determining the internal impedance and the voltage source in the harmonic frequency range
+	B.IX	Inclusion of tolerance specifications for verification of the static voltage support
+	B.X	Inclusion of a schedule for the network connection process of grid-forming units
Δ: revised section +: new section		

Besides the significant changes described in Overview of changes 1, this version includes explanatory additions on measurements (see FGW TR3, Supplement 26.2) as well as various editorial corrections to improve readability.

The „*Notes for TR8*“ in this FNN Guideline serve as basis for assessment of certification and shall be incorporated into the FGW TR8 supplement associated with this FNN Guideline.

1 Introduction

This FNN Guideline describes technical requirements and verifications for an incentive scheme for the procurement of grid-forming capabilities including inertia and applies to grid-forming power-generating units (PGUs) of Type 1 or Type 2[2], grid-forming power-generating and storage units (PGSUs), grid-forming storage as well as grid-forming controllable consumption units (CCUs) (in the following referred to as grid-forming units) and the customer installations or plants formed from these units. All requirements for grid-forming plants also apply to the following grid-following units, unless particular requirements are specified: mixed plants, power-generating and storage plants, storage and controllable consumption plants.

Customer installations providing inertia[3] shall provide defined technical capabilities. These include voltage source behaviour, inertia performance and stability of the active power[4] and reactive power 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 especially counteract positive frequency gradients (increase in frequency)
3. Grid-forming units with “positive inertia”, which especially counteract negative frequency gradients (decrease in frequency)

NOTE In certain operating conditions, even in the non-procured direction of asymmetric inertia, a small power response in accordance with Sections 4.2.1.1 and 4.2.1.14 is still required.

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

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[2] [Translator´s note] The Technical Connection Rules distinguish between Type 1 and Type 2 plants (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 plants are most often synchronous in practice, whereas Type 2 plants are typically converter-based or hybrid systems.

[3] [Translator´s note] The term *Momentanreserve* is translated as “inertia”. Consequently, *markgestützen Beschaffung von Momentanreserve* is interpreted as a market for inertia. No difference is made in this FNN Guideline between mechanical and synthetic inertia.

[4] 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[5]. Sections in this FNN Guideline replace or supplement 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				
-	5.6.3.2	-	-	4.2
4.1.3	4.2.3	8.1 (Prioritisation)	8.1 (Prioritisation)	8.1 (Prioritisation)
4.1.1.1+ 4.1.2	4.2.1.10 + 4.2.2	10.2.4.3	10.2.4.3	10.2.4.3
4.1.1.3	4.2.1.4	10.2.2	10.2.2	10.2.2
-	4.2.1.6	10.2.3	10.2.3	10.2.3
-	4.2.1.5.5	10.2.3.3.4	10.2.3.3	10.2.3.3
5.4.2	5.5.3	10.6	10.6	10.6
Verifications (unit certificate)				
5.2	5.2	12	12	12
5.4.3.1 + 5.4.3.3.2	5.5.4 + 5.5.4.4.2	11.2.8	11.2.8	11.2.8
Verifications (plant 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
5.6.2.3	5.6.2.3	11.4.3	11.4.3	11.4.3
5.6.2.4	5.6.2.4	11.4.8.2	11.4.8.2	11.4.8.2
5.6.2.5	5.6.2.5	11.4.9	11.4.9	11.4.9
5.6.2.6	5.6.2.6	11.4.11	11.4.11	11.4.11
5.6.2.7	5.6.2.7	11.4.12	11.4.12	11.4.12
5.6.2.7.1	5.6.2.7.1	11.4.12.1	11.4.12.1	11.4.12.1
5.6.2.7.2	5.6.2.7.2	11.4.12.3	11.4.12.3	11.4.12.3
5.6.2.7.3	5.6.2.7.3	11.4.12.4	-	-
5.6.2.8	5.6.2.8	11.4.13	11.4.13	11.4.13
5.6.2.10	5.6.2.10	11.4.23	11.4.23	11.4.23
5.6.2.11	5.6.2.11	11.4.24	11.4.24	11.4.24
Prototype control				
5.2	5.2	12	12	12
Statement of compliance				
5.7	5.7	11.5.4	11.5.4	11.5.4
Data sheets in Appendix E				
C.I	C.I	Appendix E	-	-
C.II	C.II	-	Appendix E	
C.III	C.III	-	-	Appendix E

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[5] 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) may apply. However, there might be deviations regarding the references to the TCRs in this Guideline. These deviations will be taken into account in the next version of this FNN Guideline.

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

NOTE 1 Deviating specifications for frequency protection can be found in Sections 4.2.1.14 and 4.2.2, and deviating specifications for the parameterisation of the $P_{\mathrm{AV,E}}$ *protection device can be found in Section 4.2.4.5.*

The requirements and verifications specified in this FNN Guideline apply to the following units (and to the plants formed from these units) participating in the inertia market:

- Type 1 PGUs (Type 1 PGUs with an additional flywheel mass and/or optional phase-shifter operation)
- New Type 2 grid-forming units
- Existing Type 2 grid-following units (existing plants) 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 purposes of this Guideline, existing units or plants (i.e. units or plants to be upgraded to become grid-forming) are defined as units or plants that will be commissioned by 31 December 2027. The underlying technology of the plant is essential for the technical definition of inertia. Technological differences shall be taken into account in the procurement process (of inertia). This also applies to the use of inertia within 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:

a) the minimum technical value of the start-up time constants $T_{\mathrm{A,E,min}}$

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

A value of T_{A} in the range of 7.5 s and 12.5 s is recommended for grid-forming Battery Energy Storage Systems (BESS).

NOTE 2 No minimum requirements for $T_{\mathrm{A,min}}$ *are specified in this FNN Guideline. However, grid-forming units shall provide at least a* T_{A} *at a level that ensures compliance with requirements in this FNN Guideline, including the inherent stability of the unit (sub-network operation or stability in the virtual island network) without an additional flywheel mass in accordance with Section 4.2.2. 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 4.2.1.14.*

NOTE 3 The value specified for T_{A} *in accordance with this FNN Guideline as part of the minimum requirements (within the scope of VDE-AR-N 4120 and VDE-AR-N 4130) for grid-forming properties for BESS does not include any obligation to maintain a power headroom for operational purposes. The actual available inertia reserve power may be limited by the operating point.*

NOTE 4 A T_{A} *within 7.5 s and 12.5 s is recommended for BESS operation for the purpose of maintaining system stability. In particular, it can be assumed that BESS is technically capable of implementing very small values of* $T_{\mathrm{A,E,min}}$*. Although the grid-forming unit no longer contributes to reducing the* T_{A} *of the system once* $T_{\mathrm{A}} \geq T_{\mathrm{A,E,min}}$ *is reached, deviations from an average of approx. 12 s currently (based on Type 1 PGM) impair the inherent stability of the system during network disturbances and may lead, in particular, to a loss of synchronisation between network areas or even larger network regions.*

Special features of Type 1 grid-forming 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_rE 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:

$$T_\mathrm{A} = \frac{J_\mathrm{E} \cdot (2\pi f_\mathrm{n})^2}{P_\mathrm{rE} \cdot p^2}$$

Note 1 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 a grid-forming unit (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:

$$T_\mathrm{A} = \frac{\left(\frac{\Delta P}{P_\mathrm{rE}}\right)}{\left(\frac{\Delta f / f_\mathrm{n}}{\Delta t}\right)}$$

3.1.3

technical minimum value of start-up time constants of a grid-forming unit

$T_{A,E,min}$

minimum technical value of start-up time constants T_A of a grid-forming unit required to fully meet the grid-forming requirements of this FNN Guideline.

Note 1 to entry: The value of $T_\mathrm{A,E,min}$ does not need to be defined for the application of this FNN Guideline.

3.1.4

minimum value of start-up time constants of a grid-forming unit

$T_\mathrm{A,min}$

minimum value of start-up time constants T_A of a grid-forming unit defined and declared by the manufacturer

Note 1 to entry: Although the value of $T_\mathrm{A,min}$ is defined and specified by the manufacturer itself, it shall be greater than or equal to $T_\mathrm{A,E,min}$ in order to fully meet the requirements in this FNN Guideline, including inherent stability.

3.1.5

maximum value of start-up time constants of the grid-forming unit

$T_\mathrm{A,max}$

maximum value of start-up time constants T_A of the grid-forming unit defined and declared by the manufacturer

3.1.6

rise time

$T_{\mathrm{rise\_90\,\%}}$

time between the sudden change in a setpoint and the point at which the controlled variable first reaches 90% of the change in the setpoint; in the case of proportional control, however, this is limited to the time until 90% of the difference between the initial and final steady-state values is first reached.

Note 1 to entry: The rise time is a characteristic quantity of the step response. It also includes the time needed to detect the control deviation.

Note 2 to entry: When determining the rise time within the scope of voltage source control, the relative tolerance criterion for the setpoint leads to very long rise times and unnecessarily high accuracy requirements. Therefore, the second criterion (90% of the difference between the initial and final steady-state values) was introduced.

3.1.7

plant certificate

certificate issued in accordance with DIN EN ISO/IEC 17065 by appropriately accredited certification bodies, which proves compliance of the planned power-generating module with the requirements of VDE-AR-N 4120 as well as with the supplementary requirements of the system operator (if any)
[SOURCE: VDE-AR-N 4120:2018-11]

Note 1 to entry: The term “power-generating module document” is used for the plant certificate in the Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators.

Note 2 to entry: The plant certificate is based on unit certificates or unit verifications, component certificates or component verifications (if available) as well as network calculations and simulations.

Note 3 to entry: Unlike the unit and component certificates, the plant certificate is not a product certificate subject to regular inspection in accordance with DIN EN ISO/IEC 17067 but a certified network connection scheme.

3.1.8

extended plant certificate A

plant certificate A which confirms the existence of the qualified plant report approved by the system operator and uses the parameters determined in the qualified plant report for the (RMS) simulations and calculations required for plant certification.

3.1.9

qualified plant report

plant report prepared by a qualified body in close consultation with the system operator based on simulation studies to verify and assess compliance with requirements for the power-generating module according to a non-standardised procedure

Note to entry: These are additional simulation studies to be performed in addition to the plant certificate A for power-generating plants within the scope of VDE-AR-N 4130.

3.1.10

qualified body

technically competent institution with proven expertise in conducting and independently evaluating simulation studies on system stability of electrical energy supply systems, including RMS and EMT simulations, as well as proven experience in the context of the relevant Technical Connection Rules and the associated verification and certification procedures.

Note 1 to entry: Expertise includes, in particular, knowledge of modelling, parameterisation and analysis of grid-forming power-generating units, as well as the assessment of dynamic interactions in the transmission network.

Note 2 to entry: The qualified body shall be able to independently perform, interpret and evaluate simulations and document them in a comprehensible manner in a qualified plant report.

3.1.11
initial operating state

IOP_X

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

Note 1 to entry: *The operating state* $\mathrm{IOP}_{\mathrm{min}}$ *refers to the technical minimum power of the unit under test.*

3.1.12
rated active power

P_{rE}

active power of the power-generating unit provided by the manufacturer under nominal conditions

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

Note 1 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).*

Note 2 to entry: P_{rE} *corresponds to* P_{N} *for provision of inertia* [6].

3.1.13
maximum active power

P_{Emax}

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

Note 1 to entry: *For wind turbines, this value may be obtained (e.g. as the 600-s maximum) from the test report according to 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.*

3.1.14
maximum active power (consumption)

$P_{\mathrm{Emax,B}}$

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

3.1.15
technical minimum power of the unit (feed-in)

$P_{\mathrm{Emin,E}}$

minimum technical power of the unit which shall continuously meet the requirements defined in this FNN Guideline

Note 1 to entry: $P_{\mathrm{Emin,E}}$ *corresponds to* $\leq P_{\mathrm{ub,min}}$ *(Table 14) or to the lower limit of the setting range specified in Table 15.*

3.1.16
minimum dynamic active power available for the provision of negative inertia

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[6] Federal Network Agency (22 April 2025). Determination procedure pursuant to Sections 12h(5) and 29(1) of the Energy Industry Act (EnWG) on the specifications and technical requirements for the transparent, non-discriminatory and market-based procurement of the inherent response to active power imbalance ('inertia') as part of the non-frequency-related system service 'inertia of local grid stability' (Decision BK6-23-010; procurement concept 'inertia', as of: 24 April 2025). Federal Network Agency. Official journal 09/2025.

$P_{\mathrm{min,dyn}}$

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

$$P_{\mathrm{min,dyn}} = P_{\mathrm{limitneg,min}} - \left(T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \frac{0{,}04}{\mathrm{s}}\right)$$

3.1.17
minimum dynamic active power available for the provision of positive inertia

$P_{\mathrm{max,dyn}}$

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

$$P_{\mathrm{max,dyn}} = P_{\mathrm{limitpos,max}} + \left(T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \frac{0{,}04}{\mathrm{s}}\right)$$

3.1.18
minimum active power for the full provision of negative inertia

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

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

Note 1 to entry: Corresponds to $P_{limitneg}$ for the provision of inertia[6] *when m = 1.*

3.1.19
maximum active power for the full provision of negative inertia

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

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

Note 1 to entry: Unless technical restrictions are specified by the manufacturer, $P_{limitneg,max}$ corresponds to the value of P_{Emax}.

3.1.20
minimum active power for the full provision of positive inertia

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

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

Note 1 to entry: Unless technical restrictions are specified by the manufacturer, $P_{limitpos,min}$ is zero for PGUs and corresponds to $P_{Emin,B}$ for storage and PGSUs.

3.1.21
maximum active power for the full provision of positive inertia

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

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

Note 1 to entry: $P_{limitpos,max}$ corresponds to $P_{limitpos}$ for the provision of inertia[6] *when m = 1.*

3.1.22
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 $\Lambda = \ln(\mathrm{x}_{\mathrm{n}}/\mathrm{x}_{\mathrm{n+1}})$ of the oscillation with the smallest damping ratio

Note 1 to entry: *In this case, the variables x_n or $x_{\mathrm{n}+1}$ 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.I for an illustration of the damping ratio.*

3.1.23

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 1 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).*

3.1.24

virtual island network operation, virtual island network

network operating conditions with a stability condition that arises at a network frequency outside 50 Hz ± 200 mHz due to the intervention of the PCNB and which also produces the verification conditions for the PCNB, in which the network beyond the NCP is described exclusively by a constant load and (in the case of Type 2 PGM or storage with converters connected to the network) by an additional flywheel mass and short-circuit power, and the PGM, PGSU or storage remains connected to the NCP without signalling these operating conditions to the PGU, PGSU or storage

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 creates particular operation conditions whose stability condition corresponds to that of island network operation. There is no signalling of the islanding 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. Background information on the development of the operating conditions during virtual fictitious island network in parallel network operation can be found in Appendix A.II.*

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 or specific island network operation requirements (such as those specified in ISO 8528) that apply to the “virtual island network” or “virtual island network operation”. Rather, “virtual island network operation” is an operating condition where the network frequency is exclusively generated by the PGM, PGSU, or storage itself.*

3.1.25

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 installed at the NCP

$$SCR_\mathrm{NCP} = \frac{S''_\mathrm{k}}{P_\mathrm{inst}}$$

Note 1 to entry: *The initial short-circuit power shall be determined in accordance with the relevant Technical Connection Rules.*

3.1.26

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

3.1.27
maximum power point (MPP)
operating point of a PGU without active power limiting

Note 1 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.

3.1.28
inertia energy
energy for the provision of inertia

Note 1 to entry: The inertia energy of a Type 1 PGU corresponds to 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 Type 2 grid-forming PGU is provided by the available primary energy in electrical storage and/or by a suitable control system.

3.1.29
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 jump and by which the unit inherently counters the change of the mains voltage angle or the original power imbalance

3.1.30
grid-forming capability
capability of a PGU, PGSU, 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 1 to entry: A prerequisite for this is the capability to provide inertia power and inertia energy.

3.1.31
grid-forming unit
PGU, PGSU, storage or CCU with grid-forming capabilities

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

3.1.32.1
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

3.1.32.2
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 1 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.III).

3.1.32.3
unlimited primary control based on network security

contributions of the PCNB which are not subject to significant type and/or plant-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

3.1.32.4

limited primary control based on network security

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

3.1.32.5

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 plant-specific limitations exist which would not allow the requirements for small-signal stability of the PCNB to be fulfilled

Note 1 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 14). The unlimited setting range of the PCNB ensures that a plant is capable of compensating small displacements and keeping a stable operation from any permissible operating point in the virtual island network with defined damping.

3.1.32.6

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 plant-specific limitations

3.1.32.7

upper power limit in the unlimited setting range of the PCNB

$P_{\mathrm{ub,max}}$

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

3.1.32.8

lower power limit in the unlimited setting range of the PCNB

$P_{\mathrm{ub,min}}$

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 1 to entry: Provided that $P_{\mathrm{Emin,E}}$ is below $P_{\mathrm{ub,min}}$, as defined in Table 14, all requirements for the unlimited setting range of the PCNB shall refer to $P_{\mathrm{Emin,E}}$ instead of $P_{\mathrm{ub,min}}$.

3.1.32.9

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 f_{n}, to the value of the speed or frequency-dependent power change ΔP of the relative to the reference power P_{ref} of the PGU:

$$s = \left| \frac{\frac{\Delta f}{f_{\mathrm{n}}}}{\frac{\Delta P}{P_{\mathrm{ref}}}} \right| \quad \text{or} \quad s = \left| \frac{\frac{\Delta n}{n_{\mathrm{n}}}}{\frac{\Delta P}{P_{\mathrm{ref}}}} \right|$$

3.1.32.10

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

3.1.32.11

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

3.1.32.12

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 is reached

3.1.32.13

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

3.1.32.14

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 is reached

3.1.33

bumpless controller switching

changeover or parameter change without initiating a jump of the control variables, ensuring that system state variables take on the same values before and after the changeover

3.1.34

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 as a per-unit quantity by the rotational kinetic energy of the turboset or, alternatively, by its start-up time constant. 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 is described as a per-unit quantity by the total rotational kinetic energy of the synchronous rotating masses or, alternatively, by the start-up time constant. 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).*

3.1.35

transition period of the PT1 element

t_t

time period until the step response of the PT1 element has increased to 95 % of the final value

Note 1 to entry: This time may also be defined as 3τ *of the PT1 behaviour.*

3.1.36

temporary 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 differing from the minimum technical power at which regulatory requirements shall be continuously fulfilled

3.1.37

phase jump power

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 when transitioning to a new operating point

3.1.38

additional flywheel mass

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

3.2 Abbreviations

CCU	Controllable consumption unit (ge: regelbare Bezugseinheit)
FSM	Frequency-sensitive mode
LFSM-O	Limited frequency-sensitive mode overfrequency
LFSM-U	Limited frequency-sensitive mode underfrequency
MPP	Maximum Power Point
NCP	Network connection point (ge: Netzanschlusspunkt, NAP)
OVRT	Over Voltage Ride Through
PCNB	Primary control based on network security (ge: netzsicherheitsbasierte Primärregelung, PRNB; similar to LFSM-O/U)
PGM	Power-generating module
PGSU	Power-generating and storage unit (ge: Erzeugungs- und Speichereinheit, EZSE)
PGU	Power-generating unit (ge: Erzeugungseinheit, EZE)
SCR	Short-circuit ratio (ge: Kurzschlussleistungsverhältnis)
THD	Total harmonic distortion (ge: Gesamtoberschwingungsgehalt)
UVRT	Under Voltage Ride Through
VSM	Virtual Synchronous Machine

4 Requirements for grid-forming units and plants

4.1 Type 1 grid-forming units

4.1.1 Basic requirements

4.1.1.1 Response to steep frequency gradients (RoCoF)

Type 1 grid-forming 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 Rules apply.

4.1.1.2 Specifications for the start-up time constant

With regard to the option of operating in phase-shifter mode and the installation of an additional flywheel mass, the plant operator shall define the plant characteristics and provides these, as well as the following moments of inertia, to the system operator:

- 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 feed-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 parameterised.*

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

- 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.

4.1.1.3 Method for the provision of reactive power at the NCP

Clause 10.2.2.4 of the relevant Technical Connection Rules applies.

For Type 1 grid-forming plants, the requirement for reactive power control behaviour at the NCP shall be adjusted as follows:

"The control behaviour of reactive power according to methods a), b) and c) of VDE-AR-N 4110, or methods a) and b) of VDE-AR-N 4120 in accordance with Clause 10.2.2.4 at the NCP shall be shown in control and disturbance behaviour (in response to a step change in the control deviation of the reactive power at a constant setpoint, e.g. as a result of a sudden change in voltage) within the tolerances derived from a PT1 behaviour according to Figure 27 as specified in Section B.IX. Control behaviour that deviates from the PT1 curve as shown in Figure 27 is acceptable within the tolerance limits defined in Section B.IX (see also Figure 28). The control behaviour shall be damped within the tolerance limits as shown in Figure 27.

Any reactive power value resulting from the control behaviour predefined by the system operator shall be provided by the Type 1 grid-forming plant and be adjustable between 15 s and 45 s. The time (transition time t_t) predefined by the system operator corresponds to 3τ of a PT1 behaviour or to the time when a value of 95 % of the set-point is reached. If no specific value is predefined by the system operator, then a value of 30 s applies. The times specified here refer to the implementation of the control system without taking into account the tap setting of any internal transformer tap changer (OLTC).

NOTE 1 The permissible transition period is extended when the transformer tap changer is activated during the control process.

NOTE 2 The manufacturer may decide how the specified behaviour of the reactive power control at the NCP is implemented. This can be done, for example, by parameterising explicit times or by using controller parameters.

It is important to consider that the voltage regulation behaviour of the Type 1 grid-forming unit interacts with the initial dynamics of static voltage support. The tolerance band as shown in Figure 27 may be briefly exceeded in the process.

NOTE 3 The behaviour of the reactive power after a mains fault results from a superposition with the PGU behaviour when the voltage returns. The requirement for the above-mentioned transition period for reactive power does not apply here."

4.1.2 Requirements for the response to overfrequency and underfrequency

Sections 4.2.2.1, 4.2.2.3, 4.2.2.5, 4.2.2.6 and 4.2.2.7 (for Type 1 units with frequency measurement) apply without restrictions.

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

- Regarding the requirements for **droop and damping** in the area of the PCNB, the plant shall comply with Section 4.2.2.2, **Point 1**, where the effective PCNB shall be designed as a proportional speed control.
- Regarding the **response during overfrequency and underfrequency events** in the area of the PCNB, the plant shall comply with Section 4.2.2.2, **Point 5**. However, instead of what is specified in the Point 1 based on $P_{\mathrm{b\ inst}}$, the plant shall be capable of managing a sudden load disconnection on the lower limit value of the setting range specified in Table 15 with a maximum of 45 % of $P_{\mathrm{b\ inst}}$. Furthermore, the plant shall be capable of managing a load disconnection of arbitrary amplitude but no more than 45 % of $P_{\mathrm{b\ inst}}$ within the operating range of $P_{\mathrm{b\ inst}}$ and the technical minimum power.
- The following **special requirements** also apply to Type 1 grid-forming PGUs in the area of the PCNB:

  Each Type 1 PGU shall be capable of operate as a virtual island network based on PCNB between the operating points of temporary minimum power and maximum load P_{Amax} as specified in 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 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.

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 % $P_{\mathrm{b\ inst}}$ 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 % · $P_{\mathrm{b\ inst}}$ · (49.5 Hz – f) / 1 Hz caused by the gas or steam process is permissible with decreasing speed below 49.5 Hz and below the curve indicated in Figure 6. 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 system operator.

4.1.3 Prioritisation of the requirements

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

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

4.2.1 Basic requirements

4.2.1.1 Voltage source behaviour

From the network perspective, the grid-forming unit shall continuously behave at its terminals in a similar way to an inertial voltage source with a start-up time constant T_A behind an effective impedance (Thevenin source) corresponding to the equivalent circuit diagram for the positive sequence indicated in Figure 1. The internal 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.

NOTE 1 It is desirable that the virtual impedance is only temporarily active (e.g. within the current limit) and is as small as possible in steady-state operation, or that the effective impedance steady-state operation corresponds to the physical impedance. This does not limit the control-related capability required for stable operation to increase very small physical impedances in the low single-digit percent range.

A voltage source behind a predominantly inductive impedance responds to a sudden changes in the network as follows:

- A sudden change in voltage amplitude (Figure 1) causes primarily an instantaneous change reactive current.
- A sudden change in voltage angle (Figure 1) causes primarily an instantaneous change in active current.

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

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

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

When using

$$\delta_1 = \varphi_\mathrm{u1,PGU} - \varphi_\mathrm{u1} \tag{3}$$

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
$\varphi_\mathrm{u1,PGU}$	is the voltage angle of the positive sequence voltage at the terminals of the grid-forming unit
φ_u1	corresponds to the set start-up time constant T_A, the inertial voltage angle of the system voltage of the internal voltage source of the grid-forming unit
$p_\mathrm{1,PGU}$	is the positive sequence active power output/input at the terminals of the grid-forming unit
$q_\mathrm{1,PGU}$	is the positive sequence reactive power output/input at the terminals of the grid-forming unit
$r_\mathrm{w,1}$	is the active resistance of the positive sequence effective impedance $z_\mathrm{w,1}$ of the grid-forming unit
$x_\mathrm{w,1}$	is the inductive reactance of the positive sequence effective impedance $z_\mathrm{w,1}$ of the grid-forming unit

u_1	is the magnitude of the positive sequence voltage of the internal voltage source of the PGU
$u_{1,\mathrm{PGU}}$	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 $i_{\mathrm{Q2,PGU}}$ may be approximated using the following equation and related quantities:

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

When using

$$\delta_2 = \varphi_{\mathrm{u2,PGU}} - \varphi_{\mathrm{u2}} \tag{5}$$

Where:

δ_2	is the angle difference between the negative sequence voltage at the terminals and the negative sequence voltage of the internal voltage source of the grid-forming unit
$\varphi_{\mathrm{u2,PGU}}$	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
$x_{\mathrm{w},2}$	is the inductive reactance of the negative sequence effective impedance $x_{\mathrm{w},2}$ of the grid-forming unit
u_2	is the magnitude of the negative sequence voltage of the internal voltage source of the PGU
$u_{2,\mathrm{PGU}}$	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 2 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 4.2.1.5.4) of the grid-forming unit are not reached.

While no current limitation is activated, the effective impedance z_{w} of new plants shall be designed to ensure that, during changes of the mains voltage amplitude, the grid-forming unit does not exceed the following maximum value $z_{\mathrm{w,max}}$ by:

a) without a unit transformer (or on the low-voltage side of the unit): 0.27 p.u. or
b) including a unit transformer (or on the medium-voltage side of the unit): 0.35 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 3 The rated active power P_{rE} shall be used as the basic value for determining the impedances in p.u.

Alternatively for converted existing plants, 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 4 No requirements for the effective minimum impedance are defined in this FNN Guideline.

The following applies to grid-forming units commissioned on or after 1 January 2028: DC components in the current of the grid-forming unit shall settle to 10% of the change in the unit's DC current within 100 ms, without taking into account the influence of the unit transformer (e.g. inrush current). Persistent stationary deviations of 2% of the rated current are not taken into account.

The negative sequence effective impedance shall generally be designed to be equal to the positive sequence effective impedance in normal operation. Grid-forming units with double-fed asynchronous generator may use smaller values of the negative sequence impedance values if a converter with a higher rating would otherwise be required.

NOTE 5 It is recommended to select the smallest possible R/X ratio of the control impedance (approximately 0.1).

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

$$\Delta i_{\mathrm{P1,PGU,max}} = -\frac{1}{z_{\mathrm{w,max}}}\left(\sin(\delta_{\mathrm{n1}}) - \sin(\delta_{\mathrm{v1}})\right) \tag{6}$$

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 $\Delta i_{\mathrm{P,PGU}}$:

- At least 50 % of $\Delta i_{\mathrm{P1,PGU,max}}$ (70% for PGSU and storage) shall be provided in the procured direction, where the power change may be limited to values ≥ 45 % P_{Emax} (70% for PGSU and storage).
- At least 5 % of $\Delta i_{\mathrm{P1,PGU,max}}$ shall be provided in the non-procured direction, where the power change may be limited to values ≥ 5 % P_{Emax}. There are no requirements for existing plants regarding the provision of $\Delta i_{\mathrm{P1,PGU,max}}$ in the non-procured direction.

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

NOTE 6 It is assumed that the phase jump power 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 4.2.1.5.4), current clipping is permitted up to 40 ms after voltage angle jumps and sudden changes in the voltage amplitude. In order to avoid persistent current clipping, the current may be regulated down to 95 % of the current at which current clipping would occur, but at least to I_{r}.

NOTE 7 Current clipping is characterised by a significant distortion of the output current of the grid-forming unit. Current clipping in the case of asymmetrical faults is not taken into account in this version of the FNN Guideline. The currents shall be limited to such an extent that they remain sinusoidal after a maximum of 40 ms despite the emerging 100 Hz fluctuations.

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

NOTE 8 In line with 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 shall be considered provided by verifying inherent stability in the virtual island network.*

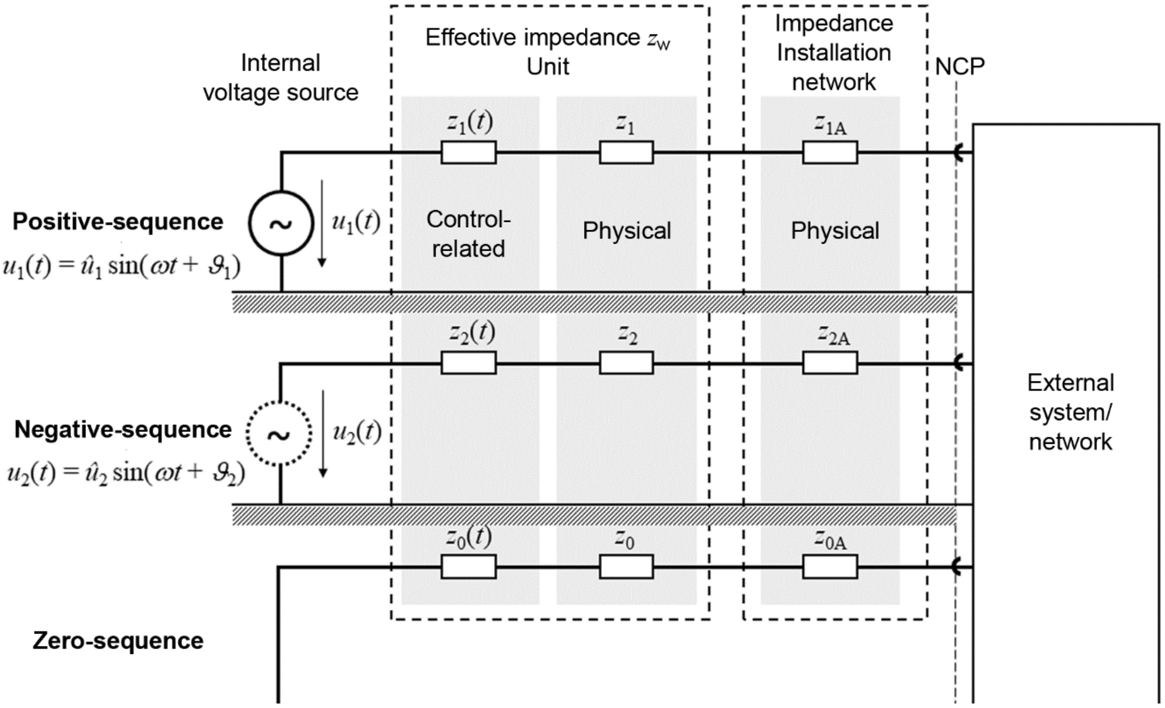


Figure 1 - Schematic representation of the fundamental frequency voltage source behaviour of a grid forming unit at the NCP with optional negative sequence voltage source

4.2.1.2 Requirements for behaviour in the sub- and super-synchronous frequency range

The grid-forming unit shall have a damping effect in the area of sub- and super-synchronous oscillations. The sub- and super-synchronous frequency range extends from 3 Hz to 50 Hz (exclusively) in the rotating reference system.

NOTE In the stationary reference system, frequencies from > 0 Hz to 47 Hz are included in the sub-synchronous range and from 53 Hz to < 100 Hz in the super-synchronous range.

4.2.1.3 Requirements for behaviour in the harmonic frequency range

The grid-forming unit shall operate passively in the harmonic frequency range. The harmonic frequency range extends from 100 Hz to 2.5 kHz inclusive in the stationary reference system.

4.2.1.4 Method for the provision of reactive power at the NCP

Clause 10.2.2.4 of the relevant Technical Connection Rules applies. The first sentence, however, shall be omitted: “The provision of reactive power shall not impair the dynamic network support.”

It shall be replaced by the following: “The static voltage support shall not impair the voltage source control at the grid-forming units and the UVRT/OVRT behaviour of grid-forming units in accordance with Section 4.2.1.6 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_C).”

For grid-forming PGMs, the requirement for reactive power control response at the NCP is adjusted as follows: "The control behaviour of reactive power according to methods a), b) and c) of VDE-AR-N 4110, or methods a) and b) of VDE-AR-N 4120 and VDE-AR-N 4130 in accordance with Clause 10.2.2.4 at the NCP shall be within the tolerances derived from PT1 behaviour as shown in Figure 27 in Section B.IX, both in terms of setpoint tracking and disturbance behaviour (e.g. in response to a step change in the control deviation, e.g. ΔQ in Figure 2). Control response may deviate from the PT1 curve within the tolerance limits defined in Figure 27. The tolerance requirements shall be met for an SCR value in the range of 10 to 50 at the NCP. The control behaviour shall be damped within the tolerance limits as shown in Figure 27.

NOTE 2 This does not present a limitation for the control dynamics for power-frequency-oscillations specified in Section 4.2.1.12.

Any reactive power value resulting from the control response specified by the system operator shall be adjustable by the grid-forming PGM within the specified limits in Table 2. The time predefined by the system operator corresponds to 3τ of a PT1 behaviour or, respectively, to the time when a value of 95 % of the set-point is reached. If no specific value is predefined by the system operator, the standard value in Table 2 applies. This also determines the dynamics for the setpoint $U_{\mathrm{ref,PGU}}$ in Figure 2. The times specified in Table 2 refer to the implementation of the control system without taking into account the tap setting of any internal transformer tap changer.

Furthermore, with transition times of less than 5 s and low SCR values, the tolerance band may be exceeded in specific scenarios (e.g. setpoint behaviour in $Q(U)$ procedures). In such cases, alternative acceptance criteria may be applied in coordination with the system operator, e.g. minimum damping requirements (see Appendix A.I).

NOTE 3 The permissible settling time is extended when the transformer tap changer responds during the control process.

NOTE 4 The manufacturer may decide how the specified behaviour of the reactive power control at the NCP is implemented. This can be done, for example, by parameterising explicit times or by using controller parameters.

Table 2 - Overview of required transition periods for the control response of static *voltage support for grid-forming PGMs (Type 2)*

	Required transition period t_t in s			
	$Q(U)$ characteristic curve	**$Q(P)$ characteristic curve[a)]**	**Voltage limitation function**	**cos(φ) specification**
MV	5 to 45, standard 20	5 to 45, standard 20	5 to 45, standard 20	5 to 45, standard 20
HV	3 to 45, standard 20	-	5 to 45, standard 20	5 to 45, standard 20
EHV	1 to 45, standard 5	-	5 to 45, standard 20	5 to 45, standard 20

The specified transition periods apply to an SCR value in the range from 10 to 50. For lower SCR values, the acceptance criteria are determined in coordination with the system operator.

a) Only relevant for plants within the scope of VDE-AR-N 4110.

It is important to consider that the response of the voltage source control interacts with the initial dynamics of the static voltage support in the setpoint tracking and disturbance behaviour. The tolerance band as shown in Figure 27 may be briefly exceeded in the process.

NOTE 5 The behaviour of the reactive power after a mains fault results from a superposition with the PGU behaviour when the voltage returns. The requirement for the above-mentioned transition period for reactive power does not apply."

The following applies to PGMs within the scope of VDE-AR-N 4120 and VDE-AR-N 4130: If the installed capacity of the grid-forming units is more than 10% and less than 90% of the installed capacity of its PGM (P_{Amax}), the implementation of static voltage support for the entire plant shall be performed in coordination with the system operator. In particular, interactions between the non-grid-forming and grid-forming parts of the PGM shall be minimised and the grid-forming properties of the units at plant level shall not be undermined as a result.

NOTE 6 If this limit value of 10% is not reached, static voltage support may be implemented for the grid-forming units by means of a Q setpoint.

4.2.1.5 Voltage source control for grid-forming units

4.2.1.5.1 General information

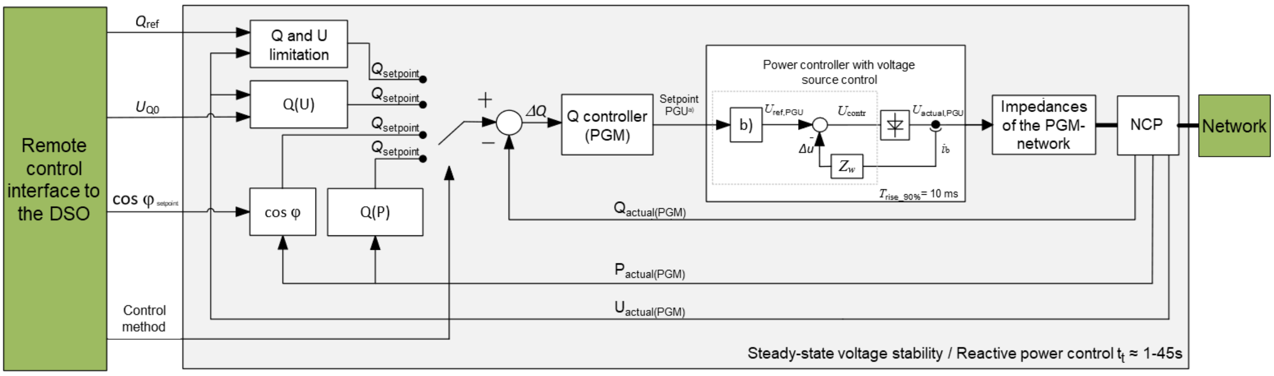
The voltage source control encompasses all control processes regarding the amplitude of the voltage source including the effective impedance specified in Section 4.2.1.1.

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

NOTE 1 The superordinate requirements for static voltage support defined in Clause 10.2.2 of the relevant Technical Connection Rules relate to the grid-forming plant.

NOTE 2 An illustrative representation of the static voltage support and the voltage source control during implementation in the grid-forming unit can be found in Figure 2.

Requirements for voltage source control outside the quasi-steady-state operating range apply to grid-forming units which, due to the availability of primary energy, only feed active power of ≤ 5 % P_{Emax}, as far as technically feasible.



a) e.g. $U_{setpoint}$ or $Q_{setpoint}$
b) If applicable, processing of the setpoint value

Figure 2 - An illustrative representation of the static voltage support of the voltage source control during implementation in the grid-forming unit

A prerequisite for stable voltage source 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 plant and the impedance of the external network (see Figure 1). The voltage source control shall meet specified stability requirements for a value range of the short-circuit power ratio at the terminals of the grid-forming unit of SCR ≥ 1 or for virtual island network operation.

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

These requirements only apply if the prerequisites of static voltage support 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 behind 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 3 The proportional behaviour corresponds to the k-factor used in the context of the grid-following plant or the reciprocal value of the effective impedance in steady state.

A response in the current should follow after an amplitude jump of the voltage at the terminals of the grid-forming unit, which indicates a constant voltage source behind a constant impedance. This is satisfied if, starting from an operating point in the unlimited working range, the doubling of voltage magnitude 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.

The manufacturer may design the voltage source control gain or the effective impedance of a grid-forming unit to be parameterisable. The nominal value shall be indicated.

NOTE 4 The parameterisable impedance should enable individual requirements of network conditions to be taken into account, such as in the case of fault-induced islanding or sub-network conditions.

A tolerance of $(\Delta u_\mathrm{I}/\Delta i_\mathrm{I})/(\Delta u_\mathrm{II}/\Delta i_\mathrm{II})$ = 100 % ± 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.

4.2.1.5.2 Dynamic requirements

In the event of a change of the setpoint for the voltage source 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 Rules.

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 source control:

- Rise time of the apparent current: $T_\mathrm{rise\_90\,\%} \leq$ 10 ms
- Settling time of the reactive current: $T_\mathrm{settling\_\Delta x} \leq$ 60 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 $\Delta i_\mathrm{Q} > 0$ or -20 % I_r and +10 % I_r for $\Delta i_\mathrm{Q} < 0$, whereby Δi_Q corresponds to the reactive current 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 start 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 αβ 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.

4.2.1.5.3 Limited voltage source control during network faults

The following applies to grid-forming units within the scope of VDE-AR-N 4110 and connection at network level 5:

Grid-forming PGMs (Type 2) commissioned on or after 1 January 2028 shall be capable, at the request of the system operator, of suspending voltage source control at the grid-forming units in the event of network voltage dips of values ≤ 0.7 U_c. The voltage source control shall be maintained for a period of 150 ms after the smallest PGU conductor-conductor terminal voltage has fallen below 0.7 U_{LV}. After a maximum of 210 ms after the PGU terminal voltage falls below 0.7 U_{LV}, the maximum conductor current shall not exceed 20% of the rated current I_r. After 250 ms it shall also not exceed 10% I_r.

NOTE 1 The voltage at the terminals of the PGU unit shall be used as reference point for transitioning into limited voltage source control.

NOTE 2 Limited voltage source control may be required by the system operator in order to ensure the effectiveness of automatic reclosing (no feed-in upon the arc of the fault) and to prevent measurement values from being distorted by intermediate feed-in effects.

NOTE 3 In the current reduction state, the grid-forming properties of the unit may be or become limited.

Type 2 plants with double-fed asynchronous generators cannot suppress current feed-in in the negative-sequence $\Delta i_{B2} = k \cdot \Delta u_2$ in proportion to the negative-sequence voltage in the event of unbalanced network faults. This behaviour is accepted.

NOTE 4 If this behaviour of Type 2 plants with double-fed asynchronous generators is not sufficient to support the effect in the network as described above, the system operator may prevent the PGU from feeding electricity into the network during voltage dips by specifying appropriate settings for the loss of mains protection in the PGU.

For plants commissioned by 31 December 2027, no limitation of the fault current is also permitted on a permanent basis. The system operator may instead require that the loss of mains protection on the PGUs prevents power feed-in, whereby the setting or delay time shall be at least 150 ms in network sections without automatic reclosing. In network sections with automatic reclosing, the following settings may be selected for voltage reduction protection:

- *U* << : 0.45 U_{LV}, Setting or delay time: 0 ms to 150 ms
- *U* <: 0.8 U_{LV}, Setting or delay time: 300 ms

Shorter setting or delay times are not permitted.

NOTE 5 This is to ensure that automatic reclosing remains effective (no feed-in to the fault arc) and to prevent measurement values from being distorted by intermediate feed-ins.

4.2.1.5.4 Behaviour when reaching and leaving current limits

In addition to the requirements defined 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 meet 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 of the respective requirements for the dynamic behaviour of the grid-forming unit at that point in time.

4.2.1.5.5 Behaviour upon return to the voltage band of U_c ± 10 % U_c or U_n ± 10 % U_n

If, after a fault according to Section 4.2.1.6, the mains voltage returns to a value within the voltage band U_c ± 10 % U_c or U_n ± 10 % U_n (for the VDE-AR-N 4120 and VDE-AR-N 4130) 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 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 procured inertia. 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 active power behaviour are exempt from this requirement. The final steady-state 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.

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

The following requirements apply to Type 2 grid-forming plants instead of those specified in Clause 10.2.3 of the relevant Technical Connection Rules 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 meet 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 meet 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 curves[7]. 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).

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[7] Also referred as “FRT limit curves”.

- The occurrence of the following event defines the start of the 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):
    - voltages > 1.1 U_c or < 0.9 U_c

  The following event defines the criterion for the end of the fault:
    - return of all line-to-line voltages to the range of U_c +/- 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 $P_\mathrm{Emax} \cdot 2$ 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 Rules define the minimum requirements for the PGM to remain connected to the network. These are not designed to be used for parameterising unddervoltage protection.

After 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 Rules (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 value over 1 min, U_1min, at the start 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).

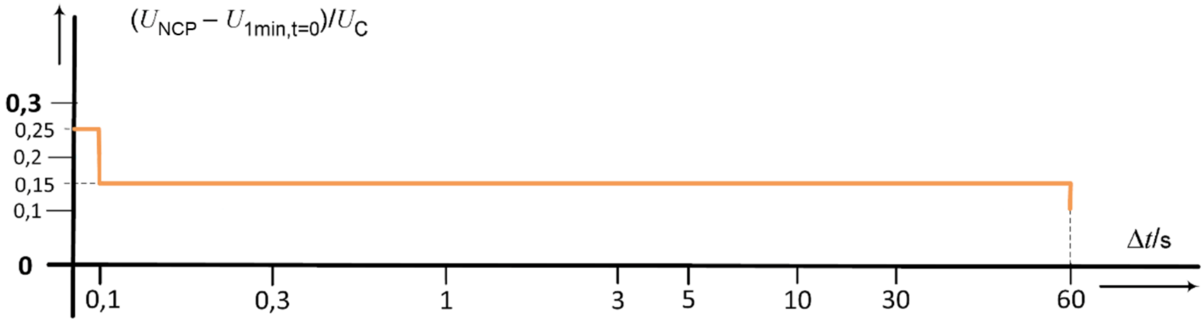

Figure 3 - Limit curve for relative voltage increases (Figure 12 in VDE-AR-N 4110 or Figure 10 in VDE-AR-N 4120)

For customer installations with grid-forming units, the requirements for dynamic network support (Type 1 PGU) and O/UVRT robustness (Type 2 grid-forming units, PGSU and storage) are specified separately in accordance with the requirements applicable to the respective types.

The system operator may require technical specifications 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.

4.2.1.7 Fast protection during high during high voltages

4.2.1.7.1 General information

During galvanic separation of a sub-network with one or more grid-forming units together with a high effective capacitance (e.g. cable or compensation device), their interaction can 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 network users if the mentioned disconnection above the HVRT characteristic is supplemented by a disconnection requirement.

4.2.1.7.2 Requirement for fast protection during high voltages

The requirement for fast protection during high voltages only applies to Type 2 grid-forming units 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 4.2.1.6 shall not be undermined.

4.2.1.8 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. Below residual voltages of 20 % at the unit terminals, this requirement applies only as far as technically feasible. The requirements specified in Section 4.2.1.6 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 Rules applies to Type 2 plants in the event of control instability of the unit or the plant.

4.2.1.9 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.

4.2.1.10 Response to steep frequency gradients (RoCoF)

Grid-forming units shall be able to ride 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 Rules 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 4.2.1.14 in Figure 4 without disconnecting the plant from the network.

4.2.1.11 Capability of parallel network 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 meet 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 SCR of 1.0, 3.0 and 25.0 at the PGU terminals.

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

4.2.1.12 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 in the rotating reference system.

NOTE 1 In the stationary reference system, the frequencies from 50 ± 10 Hz to 50 ± 0.05 Hz are included.

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 meet 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 2 The damping behaviour relates to the control loop of the power synchronisation control of the unit acting on the fundamental component 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.

4.2.1.13 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 providing direction-dependent inertia, the start-up time constant for positive inertia $T_\mathrm{A} = T_\mathrm{A,pos}$ or start-up time constant for negative inertia $T_\mathrm{A} = T_\mathrm{A,neg}$ 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 4.2.1.14. Grid-forming units providing both positive and negative inertia shall be designed to be symmetric regarding the start-up time constants with $T_\mathrm{A} = T_\mathrm{A,pos} = T_\mathrm{A,neg}$.

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

NOTE 1 As long as Section 4.2.1.14 does not specify any permissible limitations, the relationship $T_\mathrm{A} \cdot \mathrm{d}\omega/\mathrm{d}t = p_\mathrm{gen} - p_\mathrm{actual} - p_\mathrm{D}$ *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.

4.2.1.14 Requirements for inertia power and inertia energy

The grid-forming unit shall meet the requirements specified in Section 4.2.1.5 (Voltage source control), Section 4.2.1.6 (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 under 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 source control or OVRT, UVRT, robustness, PCNB, and the reference frequency-response curve according to Figure 4 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) in Figure 4 shows the reference frequency curve which applies for 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 NCP[8]. In both cases, the respective $\mathrm{T_A}$ 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 $\mathrm{T_A}$ applies only as far as technically feasible. For the market-based procurement of symmetric inertia, curves (a) and (b) shall both be followed in the same way while maintaining the $\mathrm{T_A}$.

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

The power changes resulting from the effective T_A as a consequence of the reference frequency curves as shown in Figure 4 shall settle within 800 ms ($T_\mathrm{A} \leq 10$ s) or 1.3 s ($T_\mathrm{A} > 10$ s) after the start of the respective sequence, with a tolerance of ± 5 %.

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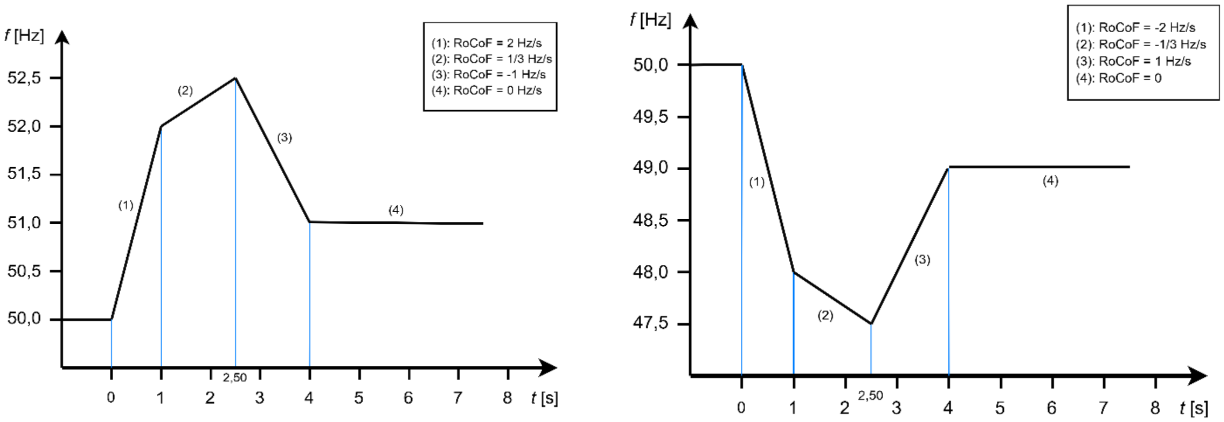
[8] Upon reaching a frequency maximum or minimum, inertia shall also be provided in the opposite direction with the corresponding start-up time constant to counter the frequency drop or frequency rise in the same way.

NOTE 2 Damping significantly determines the dynamics of the power supplied as a result of a frequency change or the change in frequency as a result of a power change.

NOTE 3 The power changes resulting from the effective T_A as a consequence of the reference frequency curves as shown in Figure 4 are inherently determined by the effect of the inertial voltage signal of the internal voltage source of the grid-forming unit. It shall not be formed from the mathematical relationship shown in Section 5.5.5.9.3.2 (equation (21)).

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



Market-based procurement of negative inertia
(a)

Market-based procurement of positive inertia
(b)

Figure 4 - Reference frequency curves for verifying inertia power and energy

NOTE 4 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 network. In that case, the following applies to plants 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 5 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 (primary control based on network security)

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 ± 200 mHz.

NOTE 1 Such an event, which causes the system to operate outside the frequency range of 50 Hz ± 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. The frequency band of 50 Hz ± 200 mHz is harmonised throughout Europe, but the threshold value shall be adjustable in accordance with Section 4.2.2.2.

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 range specified for a particular plant.

In the primary control based on network security, a distinction may be made between the control speed in the unlimited and limited setting ranges. The unlimited and the limited setting ranges of the actuating speed are different for each technology based on the parameters in Table 14 and Table 15. Within the respective type-specific active power setting ranges, the unlimited actuating speed range specified in Table 14 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. In accordance with the specifications in Table 3, the droop adjustment range of the frequency-dependent active power feed-in shall be adjustable, the droop standard value shall be provided, and the reference value P_{ref} shall be taken into account.

   For PGUs, PGSUs and storage, the final steady-state value of the active power adjustment resulting from the standard settings of the droop settings in the PCNB range is shown in Figure 5.

Table 3 - Specifications for droop settings in the area of the primary control based on network security

PGU technology	**Droop setting range**$^{(1)}$	**Droop standard value**	**Reference value P_{ref}**
Type 1 PGU	2 % to 12 %	5 %	$P_{\mathrm{b\ inst}}$
Type 2 PGU	2 % to 12 %	5 %	$P_{\mathrm{mom}}{}^{(2)}$
Power-generating and storage unit	Overfrequency: 2 % to 12 % Underfrequency: 0.2 % - 5 %	Overfrequency: 5 % Underfrequency: 1.6 %	P_{Emax}
Storage			
Controllable consumption unit$^{(4)}$	-	Overfrequency: 5 %$^{(3)}$ Underfrequency: 5 %	$P_{\mathrm{mom}}{}^{(2)}$

(1) The droop of the frequency-dependent active power feed-in shall be adjustable (where applicable, separately for the overfrequency and the underfrequency range).

(2) 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 200 ms.

(3) The requirement in the overfrequency range applies to CCUs as far as technically feasible.

(4) Provided that their consumption is continuously frequency-dependent and controllable within the time range relevant to the PCNB and has been agreed with the system operator.

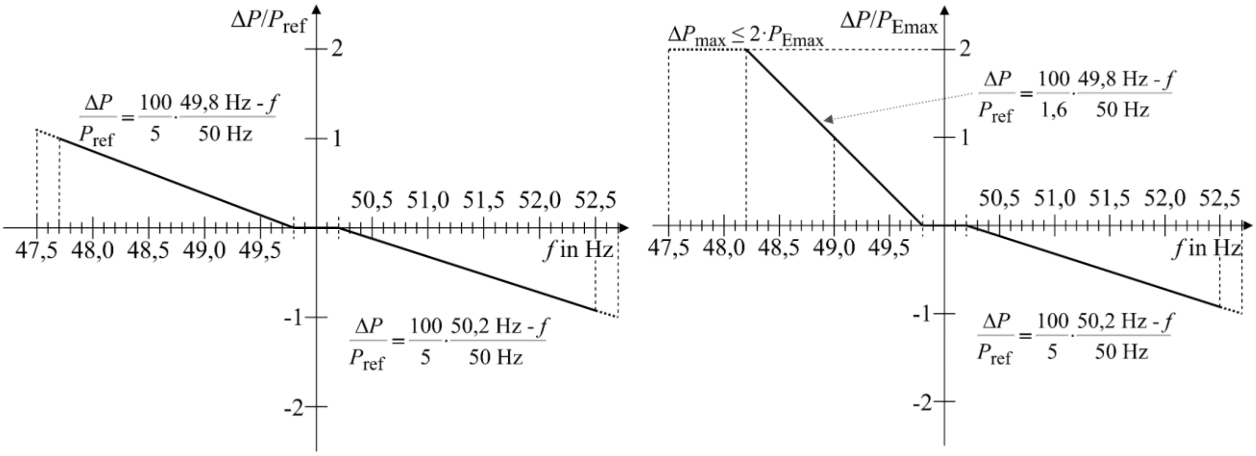
Structure and parameterisation of the speed or frequency control

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

- The frequency control shall have a damping factor within the unlimited setting range according to Table 14 between minimum and maximum load ($P_{\text{ub,min}}$ and $P_{\text{ub,max}}$) in accordance with the specifications in Table 14. For PGSUs and storage, this applies in the range from maximum charging to discharging power (and vice versa).
- 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 overfrequency 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.



(a)

(b)

Figure 5 - Final steady-stage value of the active power adjustment within the scope of PCNB for (a) PGUs and (b) PGSU and storage in accordance with the required droop settings

NOTE 3 The increase in power during underfrequency up to > 2· P_{Emax} as shown in Figure 5 is only required within the operating ranges specified in Table 14 and does not constitute a requirement for overload capacity.

NOTE 4 If the storage as shown in Figure 5 is at maximum capacity at the time of the frequency drop, it shall be reduced depending on the frequency and increased to the maximum possible feed-in. If the storage is capable of handling overload, the power output should be increased further in accordance with the characteristic curve (dashed area).

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) can 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 14 apply to the PCNB. The actuating speeds in the limited setting range are specified in Table 15. Actuating speeds higher than those specified in Table 15 are permissible and shall be indicated by the manufacturer or plant operator.

4) In the virtual island network, grid-forming PGSUs and storage shall be capable of handling a sudden transition from charging to discharging mode and vice versa by at least 100 % (in accordance with Table 14) based on a setpoint step change.

5) In virtual island network operation, grid-forming units shall meet the following requirements in the event of sudden load disconnection (**overfrequency event**):

   Grid-forming PGUs:

   - A Type 2 PGU shall handle a sudden 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 15.
   - Grid-forming PGUs shall be capable of reducing the active power from the power output value prior to the 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 14 and Table 15). Values of the minimum power that are technically possible and which are lower than those indicated in Table 14 and Table 15 are permissible.

   Grid-forming PGSUs and storage:

   - In discharging operation, PGSUs and storage shall be capable of handling a sudden load reduction 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 meet the following requirements in the event of sudden power demand (power increase or **underfrequency event**) caused by the network frequency dropping into the range of the PCNB:

   - Grid-forming PGUs shall meet the requirements specified in Table 14, grid-forming PGUs shall increase their power output within the unlimited, and beyond that, in the limited setting range specified in Table 15. 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 sudden 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 system 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

Technology-specific values of the active power output within the PCNB shall be used according to Table 14 and Table 15. 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, the requirement for a maximum transient frequency of 52.5 Hz in the PCNB area cannot be met in accordance with Point 5 of Section 4.2.2.2. Therefore, a sudden 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 % $P_{\text{b inst}}$. During virtual island network operation (as far as technically feasible) the amount of sudden load disconnection and connection may be limited to values up to the amplitudes specified in Table 14, so that the frequency does not exceed 52.5 Hz or fall below 47.5 Hz. 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 (as far as technically feasible) be greater than 52.5 Hz or lower than 47.5 Hz for load disconnection and connection according to Table 14. It considers the start from an operating point between $P_{\text{b inst}}$ and technical minimum power or temporary minimum power.

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

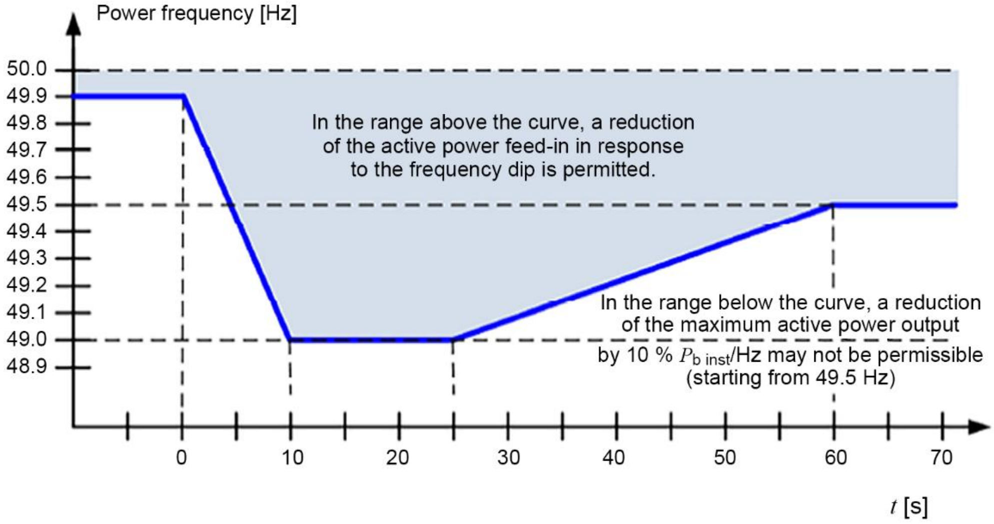


Figure 6 - Requirement for the output power of the PGM in the dynamic short-term range

Figure 6 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 for 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 Hz ± 200 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 Hz ± 200 mHz for an uninterrupted period of at least 30 s.

Adjusting the active power setpoint to any increase in available primary energy shall be limited to a gradient not exceeding 10 % $P_{\mathrm{b\ inst}}/\mathrm{min}$ (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 Hz ± 100 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 Parameterisation of the deadband of the PCNB

If there is a connection to the telecontrol system of a system operator, the grid-forming unit shall have a signal interface to allow the system operator to deactivate (setpoint = 0 mHz) or reactivate[9] the deadband of the PCNB of the grid-forming unit during a critical network state (e.g. during network restoration or sub-network operation).

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

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 “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 (following the characteristic curve), a sliding measurement window of 3 to 5 periods with a corresponding evaluation method may be used in conjunction with frequency determination for the implementation of the PCNB (for an example see the aforementioned FNN Guideline).

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 as part of a PGM, 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 relevant Technical Connection Rules have priority. They still shall be supplemented with the requirements for grid-forming behaviour specified in this FNN Guideline. The following requirements deviating from the prioritisation requirements[10] in Clause 8.1 of VDE-AR-N 4130, apply:

1. *Avoiding or limiting 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 behaviour[11], including synchronicity, angular stability, damping of power-frequency-oscillations, and damping behaviour for higher frequencies specified in Section 4.2.1

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[9] 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.

[10] Existing passages in accordance with the Technical Connection Rules are indicated in italics.

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

4. Requirements for the start-up time constant specified in Sections 4.2.1.13 and 4.2.1.14
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 system 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 static voltage support specified in Section 4.2.1.4
10. Specifications of operational setpoints for active power and reactive power including limitations to demand 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. *Avoiding or limiting damages to the grid-forming unit, plants 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*
2. Voltage source behaviour[11], 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 4.2.1.13 and 4.2.1.14
4. *Specifications for the network security management of the system operator specified in Clause 10.2.4.2 and the requirements for* $P_{\mathrm{AV,E}}$ *of the relevant Technical Connection Rules*
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 static voltage support specified in Section 4.2.1.4*
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 including limitations to demand power

4.2.4 Grid-forming plants (Type 2, storage and CCUs)

4.2.4.1 General information

The requirements defined below apply to Type 2 grid-forming PGUs, PGSUs, storage and CCUs that form a grid-forming PGM, in addition to the requirements of Sections 4.2.1, 4.2.2 and 4.2.3.

4.2.4.2 Requirements for effective impedance of the plant

While no current limitation is activated, the effective impedance $z_{\mathrm{w,A}}$ of new plants shall be designed to ensure that, during changes of the mains voltage amplitude, the grid-forming PGM does not exceed the following maximum value $z_{\mathrm{w,A,max}}$ by:

a) high-voltage network: 0.50 p.u.
b) extra high-voltage network: 0.40 p.u.

In coordination with the transmission system operator, deviations from the value in b) are permitted.

For PGMs within the scope of VDE-AR-N 4130, a maximum value of 0.15 applies to the R/X ratio at plant level.

4.2.4.3 Requirements for behaviour in the sub- and super-synchronous frequency range at plant level

The requirements for behaviour in the sub- and super-synchronous frequency range with regard to the NCP of the PGM only apply to PGMs within the scope of VDE-AR-N 4130. The requirements for the grid-forming unit specified in Section 4.2.1.2 shall also be met at plant level.

4.2.4.4 Requirements for the behaviour in the harmonic frequency range at plant level

The requirements for behaviour in the harmonic frequency range with regard to the NCP of the PGM only apply to PGMs within the scope of VDE-AR-N 4130. The requirements for the grid-forming unit specified in Section 4.2.1.3 shall also be met at plant level.

4.2.4.5 Requirements for the $P_{\mathrm{AV,E}}$ protection device

When $P_{\mathrm{AV,E}}$ monitoring is provided for the PGM, the corresponding $P_{\mathrm{AV,E}}$ protection device shall be parameterised in such a way that, at an active power operating point of the PGM at $P_{\mathrm{AV,E}}$, it does not trip when the phase jump power required by this FNN Guideline occurs in conjunction with the transient behaviour of the inertia power, based on the set start-up time constants of the grid-forming units.

5 Verification of electrical properties for grid-forming units

5.1 Principles of the verification process

The verifications defined 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 Rules, using the individual verification procedure (plant 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 Rules, which are replaced in accordance with Section 2 Table 1, may be omitted for new unit certificates.

A supplement to an existing plant 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 Rules. The verifications in accordance with Clause 11 of the relevant Technical Connection Rules are partially replaced by the corresponding verifications in Section 2 Table 1 (for grid-forming capabilities). Verifications for the minimum technical requirements, which are replaced in accordance with Section 2 Table 1, may be omitted for new plant certificates.

A complete verification in accordance with this FNN Guideline is provided for grid-forming units that require a plant certificate in accordance with the German Ordinance on the Verification of Electrical Properties of Energy Systems (abbreviated in German as NELEV) by means of a plant certificate A in accordance with the relevant Technical Connection Rules as well as the requirements of this FNN Guideline. The statement of compliance may be submitted subsequently within the deadlines specified in the relevant Technical Connection Rules. A plant certificate C or C2 alone is not sufficient verification in accordance with this FNN Guideline. Verification is only provided upon submission of the extended statement of compliance.

Verifications in this FNN Guideline contain only provisions 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 provisions 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 TR8[12].
- Details on the design of the measurement-based verifications as well as the documentation of the measurement results are defined in this FNN Guideline as well as in FGW TR3[12]. Any additions to the FGW TR3 guideline shall neither undermine nor specify more stringent requirements as those laid out in this Guideline, which serves as a supplement to the relevant Technical Connection Rules. Measurements

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[12] Generally, the current version of the FGW TR3, TR4 or TR8 guidelines may apply. The relevant Supplements for TR3 and TR4 shall be used in combination with this FNN Guideline as soon as they have been published. The relevant Supplement for TR8 should be taken into account as soon as it has been published

of grid-forming units and associated components shall be conducted by an accredited testing or measuring institute in accordance with DIN EN ISO/IEC 17025. To this end, the laboratory shall provide proof of successful participation in the interlaboratory tests and training courses organised by the FGW.

- Details on the design of modelling, simulation and model validation are defined in this FNN Guideline and supplemented with the FGW TR4[12]. Any additions to the FGW TR4 guideline shall neither undermine nor specify more stringent requirements as those laid out in this Guideline, which serves as a supplement to the relevant Technical Connection Rules.

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. Specifically, this means the provision of:

- Clear reference to the company issuing the certificate
- Stamp and signature of the 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 Prototype requirements for grid-forming units and plants

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 Rules. A prototype validation shall be issued for grid-forming units in combination with a qualified expert report.

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 validation for grid-forming units are stricter than the requirements in Clause 12 of the relevant Technical Connection Rules.

The existing requirements of the relevant Technical Connection Rules (as specified in the Section 2) shall also be verified in accordance with the verifications specified in this FNN Guideline.

Type 1 grid-forming 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 expert report in which the requirements laid out in this FNN Guideline are verified.

For wind turbines, a prototype procedure similar to Section 12 of the relevant Technical Connection Rules will be submitted in version 2.2 of this FNN Guideline for the purpose of measurement, submitting the network connection request and commissioning, as well as electrical planning in accordance with the relevant Technical Connection Rules. This does not apply to the qualification for participating in the inertia market.

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.

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 validation 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 Rules) confirms full compliance with the requirements based on a qualified expert report. The measurements required for the qualified expert report 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 defined in this FNN Guideline. Based on the qualified expert report, the certification body shall demonstrate in a comprehensible manner in the prototype validation whether the prototype can meet the requirements of this FNN Guideline. Furthermore, the certification body shall state in the prototype validation whether the requirements for the provision of verification specified in this FNN Guideline were met during measurements and model validation.

NOTE 1 Eligibility to participate in the inertia market and to submit the corresponding network connection request is subject to compliance of the grid-forming unit with the requirements defined for the unit in this FNN Guideline (Version 2.0). However, the grid-forming unit may only be commissioned if it complies with the requirements defined in Version 2.1 (or newer) of this FNN Guideline. Accordingly, a prototype validation issued for Version 2.0 shall be updated according to Version 2.1 (or newer) before commissioning, or a unit certificate shall be issued in accordance with this FNN Guideline in Version 2.1.

In addition, the behaviour of a Type 2 grid-forming unit shall be monitored using a disturbance recorder for the period of validity of the prototype validation by evaluating measured currents and voltages at its terminals. Requirements in Section 5.2.4 apply.

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

NOTE 2 For a grid-forming prototype with prototype validation in accordance with this FNN Guideline in Version 2.0, a unit certificate in accordance with this FNN Guideline in Version 2.1 (or newer) may be issued directly (see also NOTE 1 above).

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

When performing a technical network assessment at plant level, a prototype plant report (as defined in VDE-AR-N 4110:2018, VDE-AR-N 4120:2018, and VDE-AR-N 4130:2018 as ‘electrical planning of the generation plant’) shall be issued by a body accredited in accordance with DIN EN ISO/IEC 17065 (for the relevant Technical Connection Rules) upon request of the system operator prior to the planned conversion or commissioning of the grid-forming units.

NOTE 3 After conversion or commissioning of the grid-forming units, an extended commissioning declaration shall be submitted, taking into account Section 5.2.3.

5.2.3 Verification procedure for grid-forming plants with prototypes

For verification at plant level, a plant report for prototypes of grid-forming units shall be submitted when prototypes are used (after conversion or for new units). The deadlines specified in Clause 12 (Prototype Regulation) of the relevant Technical Connection Rules apply.

After the conversion or commissioning of an existing unit or new unit, an extended commissioning declaration shall be submitted for the PGM. The following documents shall be provided for this purpose:

- Prototype validation for the units to be converted or new units in accordance with this FNN Guideline.
- Confirmation of the implementation of necessary software updates for all converted units through a relevant extract from the event log.
- Manufacturer's declaration certifying the replacement of necessary hardware components.
- Parameter extract of the converted units.
- Measurement-based verification based on internally switchable signals on a unit freely selectable by the certification body in the field by means of the following measurements: according to Section 5.5.5.3, 5.5.5.8 and 5.5.5.9 (evaluation according to Section 5.5.5.9.3.3).

- As an alternative to a measurement-based verification, a verification document may be submitted for the converted unit with the help of disturbance recorder evaluations in accordance with the criteria defined in the Section 5.2.4. In this case, the specifications in Section 5.2.4 on monitoring in a plant with several identical grid-forming units apply.
- The measurement-based verification or its alternative (monitoring by means of a disturbance recorder) may be omitted if the conversion of the unit was performed solely on the basis of a software update.

In addition, it shall be verified that all converted units in the plant correspond to the status of the tested or monitored unit.

Verification at plant level shall be provided by a certification body accredited in accordance with DIN EN ISO/IEC 17065 (for the relevant Technical Connection Rules). The necessary measurements shall be performed by a testing institute accredited in accordance with DIN EN ISO/IEC 17025 (for FGW TR3, Revision 26). The requirements defined in Clause 12 of the relevant Technical Connection Rules apply to the subsequent submission of the plant certificate and the statement of compliance.

5.2.4 Monitoring by means of a disturbance recorder

The following requirements apply to the monitoring of a grid-forming unit (new unit or converted existing unit) using a disturbance recorder:

In the case of several grid-forming units of the same type (Type 1 or Type 2) within a plant, the disturbance recorder shall be provided for any unit of this type within the plant. Connection of the disturbance recorder to the system operator’s control centre is not required. The party owning the disturbance recorder shall make the recorded data available to the certification body twice a quarter and then every six months, as well as to the system operator upon request. The data recorded by the disturbance recorder shall be evaluated by the certification body, reviewed for technical comprehensibility and verified according to the requirements of this FNN Guideline.

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

The certification body shall also inform the plant operator if the recordings of the disturbance recorder are not compliant. The plant operator (or by the party performing the certification on request) shall then inform the system operator. In the case of a connection in the distribution network, the plant operator (or by the certification body on request) shall also inform the relevant transmission system operator. The system operator shall grant a reasonable period for rectification in case of non-compliance. Otherwise, the monitoring period within the scope of the prototype validation by the certification body shall end no later than upon issuance of the statement of compliance. At the discretion of the system operator, the monitoring period may be terminated earlier after a sufficient number of representative network 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 disturbance recorder of Type 2 grid-forming units. 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 disturbance 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 αβ coordinate system. The instantaneous values of the measured currents and voltages are to be filtered with a moving arithmetic average over 5 ms.

- Fundamental component 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 start 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 system operator. Upon request of the system 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 disturbance 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.

5.2.5 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 verification of electrotechnical are demonstrated by means of the individual verification procedure. For these units, verification of the requirements specified in this FNN Guideline may be performed based on a qualified expert report as part of the individual verification procedure within two years of publication of Version 2.0 of this FNN Guideline in May 2025.

NOTE The qualified expert report is limited exclusively to the verification of the requirements in this FNN Guideline that replace or supplement the requirements of the relevant Technical Connection Rules. The process for verifying compliance with the requirements defined in the relevant Technical Connection Rules remains unaffected.

The qualified expert report shall be issued by a testing institute accredited in accordance with DIN EN ISO/IEC 17065 (for the relevant Technical Connection Rules) and shall confirm compliance with the requirements defined in this FNN Guideline. The measurements required for the qualified expert report 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 defined in this FNN Guideline. Based on the qualified expert report, the certification body shall demonstrate in a comprehensible manner whether the Type 1 grid-forming unit is able to meet the requirements of this FNN Guideline. Furthermore, the certification body shall demonstrate whether the requirements for the verification procedure defined 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 disturbance recorder in accordance with the specifications in Clause 11.6.5 of VDE-AR-N 4120, taking into account the relevant Technical Connection Rules.

A plant certificate C in accordance with this FNN Guideline shall be provided for new or converted 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/√10 times and √10 times (for Type 1 units) or between 1/√10 times and twice (for Type 2 units) of the rated apparent power of the measured grid-forming unit.
3) For verifications of quasi-steady-state operation and static voltage support, the manufacturer's specifications mentioned under Point 2 may be extended, if the concept of the grid-forming unit and the components used are technically equivalent. Under these prerequisites, the measurements may be transferred for Type 2 grid-forming units of rated apparent power from 100 kVA to 10 MVA.

For transferability in Type 1 units, the following also applies with regard to the start-up time constants. For each type (or each type variant relevant for certification), complete evidence of the start-up time constants, including measurement or validation of the calculation method used to determine the start-up time constants, shall be provided by the certification body. Validation of the procedure requires that the calculation method used by the manufacturer is provided in the manufacturer's declaration in a comprehensible manner. The certification body can then confirm that the information is provided in a comprehensible manner if the manufacturer's declaration contains the mass moment of inertia of the entire PGU drive train based on a multi-body simulation model description, including the necessary parameter specifications and corresponding simulation reports. It shall contain the following information:

- the mass moments of inertia of the individually separated component assemblies (e.g. torsional vibration damper, crankshaft, cylinder assembly, flywheel, flexible coupling, generator, etc.) of the complete shaft train;
- the topology of the model (e.g. multiple components connected by gears);
- the nominal speed of the individual components.

5.4 Type 1 grid-forming units

5.4.1 General information

If the additional flywheel mass can be decoupled from the generator, all verifications defined in this FNN Guideline as well as the FRT capability shall be performed in accordance with the relevant Technical Connection Rules 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 Rules.

The following measurement tests should take into account the general requirements for measurement setup or technology and test conditions specified in TR3 Revision 26, Chapter 3 (Chapters 3.2.1 to 3.2.3 and Chapters 7.1.3 to 7.1.5).

5.4.2 Requirements for simulation models and model accuracy

5.4.2.1 General model requirements

In the event that the relevant system operator requests simulation models of the Type 1 unit, the following applies:
For Type 1 grid-forming units, FGW TR4, Revision 10, Chapter E.5.2 shall be taken into account with regard to the requirements for simulation models and model accuracies relating to the verification of the requirements for primary control based on network security in accordance with Section 5.4.3.3 and the verification of start-up time constants in accordance with Section 5.4.3.2.3.

5.4.2.2 Validation of the simulation model – standard procedure (unit certification)

5.4.2.2.1 Start-up time constant in accordance with the test in Section 5.4.3.2.3

The value of the start-up time constant in accordance with the manufacturer's specifications shall be used in the simulation model.

Note for TR8:
The value of the start-up time constant in accordance the manufacturer's specifications shall be used in the simulation model.

5.4.2.2.2 Behaviour of the PCNB in accordance with the test in 5.4.3.3.2

The test described in Section 5.4.3.3.2 (Measurements 1 and 3) shall be represented in the same way for the simulation model. The following steps are required:

1) The PGU simulation model is initialised to the starting point of the measurements with regard to active power output, speed, reactive power feed-in and generator voltage. It shall be confirmed that the respective intermediate values, such as the output signal of the primary controller (u_R) and (if this is represented in the model) the position of the actuators (y_Ti), are within the permissible tolerances (see FGW TR4 Revision 10, Chapter E.5.2.1.1). The operating mode of the generator control and the drive unit control are selected according to the measurement conditions specified in Section 5.4.3.3.2.2.
2) The droop settings of the PCNB shall be determined in accordance with Measurement 3 and be based on the initial and final steady state. In this case, a maximum deviation of ± 5 % from the value set on the unit shall be verified. The active power ramp rate shall be determined. Speeds in the limited adjustment range shall correspond at least to the characteristic values specified in Table 15.
3) The damping and frequency of the settling response of the frequency or speed shall be determined for the simulation-based test (Measurement 1). Damping may be determined using the method described in Appendix A.I. The damping ratio required for the respective technology in accordance with Table 14 (Appendix B.I) and the frequency of the transient response of the speed shall be maintained by the simulation model with an accuracy of ± 15 % relative to the measured value. As an alternative to the damping ratio, the corresponding amplitude ratio may also be evaluated directly, taking into account the accuracy of ± 15% of the measured amplitude ratio.
4) If during the simulation-based test (Measurement 1) of the speed of the unit the settling process 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 speed 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, Point 2, Section (3) applies to the frequency of the grid-forming unit, whereby the tolerance band ε_dyn[13] = ± 15 % shall be considered for the frequency.

Note for TR8:
The model shall be considered validated regarding the correct representation 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 set in the grid-forming unit with a maximum deviation of ± 5 %.*
- *Compliance with at least the active power ramp rates in accordance with Table 15.*
- *The simulated damping or the corresponding amplitude ratio of the PCNB as well as the frequency of the settling process of the speed corresponds to the measured value with a maximum deviation of ± 15 % of the measured amplitude ratio.*
- *If the procedure according to FGW TR4, Revision 10, Chapter E.5.2.1.1, point 2, paragraph (3) is applied, the frequency of the simulation model of the grid-forming unit is within the permissible tolerance band.*

5.4.2.3 Validation of the simulation model – individual verification procedure

5.4.2.3.1 Start-up time constant in accordance with the test in Section 5.4.3.2.3

The specifications of Section 5.4.2.2.1 apply.

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[13] See equations E-3 to E-6 and Point 2, paragraph (3) in FGW TR4, Revision 10, Chapter E.5.2.1.1.

5.4.2.3.2 Behaviour of the PCNB in accordance with Section 5.4.3.3.3.2

5.4.2.3.2.1 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, where applicable) 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 of the controlled actuator is the mechanical drive power.

The basic test setup is presented in Figure 7. In this case, the load of the virtual island network is 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 accordance with FGW TR4 (Specifications for active power output) and FGW TR8 in the closed control loop of the virtual island network. This also applies in particular to the output variable of the primary controller. If required for compliance with the model accuracy, additional variables such as a controller output, valve position, mass flow, etc. may also be included in the model comparison.

5.4.2.3.2.2 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 plant in accordance with Section 5.4.3.3.3.2 as well as with Test 4 in Section 5.4.3.3.2.2. The agreement between the model and the PGU or PGM shall be assessed.

Requirements for model accuracy

The model shall meet 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 represented 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.

5.4.3 Verifications

5.4.3.1 Response to steep frequency gradients (RoCoF) (Section 4.1.1.1)

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

Note for TR8:
Verification shall be considered demonstrated if the manufacturer's declaration proves that the unit is able to ride through required RoCoF values 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.

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

5.4.3.2.1 General information

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 5.4.3.2.2.

- The additional flywheel mass, including the generator-side clutch where applicable, through a manufacturer's declaration in accordance with Section 5.4.3.2.2.
- The complete shaft train (overall system consisting of generator, turbines, additional flywheel mass, etc.) through measurement-based verification in accordance with Section 5.4.3.2.3.

5.4.3.2.2 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 shall be 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 shall be 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 in accordance with 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, where 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:

Verification of the mass inertia values or start-up time constants shall be considered demonstrated when the information from the manufacturer and the measured or calculated values are indicated in the manufacturer's declaration and are presented in a technically comprehensible manner for:

- T*he generator with an excitation device*.
- T*he additional flywheel mass, including the generator-side clutch, where applicable.*

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

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

5.4.3.2.3.1 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 manufacturer's specifications using the measured values.

5.4.3.2.3.2 Measurement procedure

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

5.4.3.2.3.3 Evaluation

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

5.4.3.2.3.4 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:
Verification of the start-up time constants of the complete shaft train (complete system consisting of generator, turbines, additional flywheel mass, etc.) shall be considered demonstrated 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%.

5.4.3.3 Verification of the primary control based on network security

5.4.3.3.1 General information

Verification of the primary control based on network security may be provided by means of measurement-based verification (type testing) in accordance with Section 5.4.3.3.2 as 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 5.4.3.3.3 as part of the individual verification procedure. In the individual verification procedure, Measurement 4 in Section 5.4.3.3.2.2 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.

5.4.3.3.2 Measurement-based verification (type test) as part of the unit certification

5.4.3.3.2.1 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, where applicable) or 49.8 Hz to 47.5 Hz. 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. The design of the primary control based on network security as proportional speed control shall also be confirmed in the manufacturer's declaration.

5.4.3.3.2.2 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 meet 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 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 7. Alternatively, 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. It is recommended that the switch position S_{network} is measured and that an additional measuring point is provided at the point of delivery or at the load.

Any existing control system for the load or load bank shall not influence the control system of the PGU. The load or load bank should remain passive during the measurement period. With a passive ohmic load or load bank, it should be noted that the power of the load or load bank changes quadratically with the voltage and is also influenced by the temperature.

NOTE 1 The active power in the virtual island is largely determined by the load or load bank.

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 parameterised 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 2 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 reached with an accuracy of ± 10 mHz. The specified initial effective power shall maintain a tolerance of ± 5 % $P_{\text{b inst}}$. The deviation shall be taken into account in the evaluation.

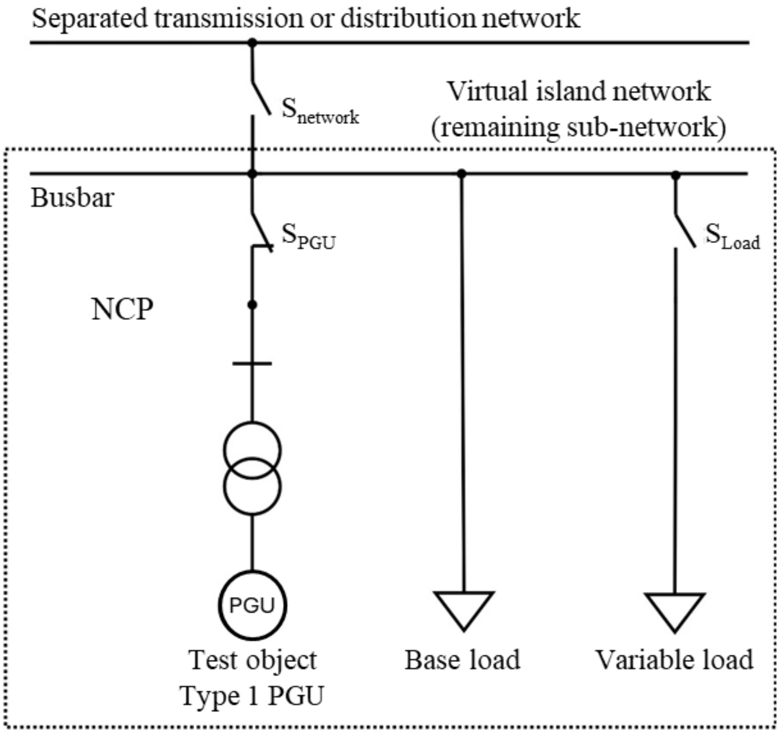

Figure 7 - Virtual island network for verifying the characteristics of a Type 1 PGU

Performing the 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 network operation at $P_{\text{b inst}}$, 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 15 to a maximum of 55 % $P_{\mathrm{b\ inst}}$ of the test object at nominal voltage. In addition, perform the following repetitions by setting the load of the virtual island network to:

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

  NOTE *3* 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 step of at least 5 % $P_{\mathrm{b\ inst}}$ during the transition to virtual island network operation. The transition to virtual island network operation takes place from a previous network parallel operation at $P_{\mathrm{b\ inst}}$, 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 % $P_{\mathrm{b\ inst}}$, 75 % $P_{\mathrm{b\ inst}}$, 85 % $P_{\mathrm{b\ inst}}$ as well as $P_{\mathrm{Emin,E}}$.

The measurement should start at least 10 seconds before switching from network parallel operation to virtual island network operation and end no earlier than 30 seconds after reaching the steady-state operating point (settling process completed).

Measurement 2

Starting from steady-state operation 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 14 (amplitude in the unlimited control range). Ensure that the steps of the variable load have a tolerance of 2 % $P_{\mathrm{b\ inst}}$. Select the last step so that, in the steady-stae condition, $P_{\mathrm{b\ inst}}$ minus the specified step amplitude according to Table 14 is reached. 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 4 With regard to step levels, for example with a step level of 10 % $P_{\mathrm{b\ inst}}$, the output at the end of the last step should be 90 % $P_{\mathrm{b\ inst}}$, i.e. for gas turbines > 2 MW, the following steps: 55 %, 65 %, 75 %, 85 %, 90 % $P_{\mathrm{b\ inst}}$.

NOTE 5 During Measurement 2, the frequency band of 50 Hz ± 200 mHz may be traversed.

The measurement duration per step should be at least 30 seconds, ensuring that the frequency at the end of the step corresponds to a target frequency that matches the droop. The measurement may be started at a frequency above 50 Hz in order to avoid underfrequency disconnection during the measurement.

Measurement 3

Starting in steady-state operation 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
- actual frequency + 300 mHz; actual frequency - 300 mHz
- actual frequency + 0 Hz; actual frequency - 0 Hz

Perform the measurements with a simulated frequency increase at an initial power of 100 % $P_{\mathrm{b\ inst}}$ 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 ramp rates can be verified in accordance with Table 15.

The measurements are preferably performed in a continuous sequence (50 Hz → 50.3 Hz → 50.8 Hz → 51.3 Hz → 50.3 Hz → 50.0 Hz or 50 Hz → 49.7 Hz → 49.2 Hz → 48.0 Hz → 49.7 Hz → 50.0 Hz), whereby the steady-state condition is required before each frequency change.

NOTE 6 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.

NOTE 7 For the measurement accuracy of the frequency or speed, it should be noted that the mains frequency may also fluctuate slightly. This fluctuation shall be taken into account in the evaluation and distinguished from the tolerance of the simulated signal. In addition to the simulated frequency, the mains frequency should also be recorded throughout the entire measurement.

Measurement 4
The maximum insensitivity of the frequency-dependent active power adjustment around the measured frequency value may be determined similarly to the procedure defined in FGW TR 3 (Chapter 7.2.1.6 or Chapter 7.2.2.3.3 in Revision 26) for "Determining the effective deadband", whereby the deadband of 200 mHz shall be set to zero.

NOTE 8 PCNB should be deactivated for this.

5.4.3.3.2.3 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.

It is recommended that the selection of amplitude maxima to be evaluated be agreed with the manufacturer. Overall, damping behaviour shall be demonstrated, whereby a temporary violation of the damping criterion is permitted for individual amplitudes.

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 ramp rate) 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.

5.4.3.3.2.4 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 ramp rate 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 shall be 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 ≥ 0.06.*

Measurement 2 shall be considered passed if the speed curve of the test object meets the requirement for the damping ratio D ≥ 0.06 in each case. The damping ratio shall be determined in accordance with the definition in Section 3.1.22 while taking into account Appendix A.I.

Measurement 3 shall be considered passed if the final steady-state values of the active power deviate by a maximum of ± 5 % of the expected power change or ± 0.5 % $P_{\mathrm{b\ inst}}$ *from the values resulting from the set droop and comply with at least the active power ramp rates according to Table 15.*

Measurement 4 shall be considered passed if the determined insensitivity complies with the required limit value of ± 10 mHz with a maximum deviation of ± 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.

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

5.4.3.3.3.1 General information

Simulation-based verification of the unit's primary control based on network security in accordance with Section 5.4.3.3.3.3 (Simulation-based verification in the individual verification procedure for Type 1 plants) based on a simulation model of the *P*(*f*) behaviour validated in accordance with Section 5.4.2.3.2 requires the performance of corresponding measurement-based tests on the operational unit in accordance with Section 5.4.3.3.3.2. This measurement of the unit is performed in synchronous network operation.

NOTE 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 plant in the case of connected generation units that cannot be separated (e.g. CCGT systems).

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

5.4.3.3.3.2.1 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 $P_{\mathrm{Emin,E}}$ to maximum output ($P_{\mathrm{b\ inst}}$) is divided into several sections with different parameters as shown in Table 14 and Table 15, 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.

5.4.3.3.3.2.2 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 14 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 condition, cancel the change in the frequency difference. After the steady-state condition 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 condition. If different unlimited setting ranges are specified for a unit in Table 14 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 $P_{\mathrm{Emin,E}}$.

Once the steady-state condition 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 $P_{\mathrm{Emin,E}}$, 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 condition is reached. The measurement is complete when the steady-state condition is reached again.

Instructions for performing the measurement

The test object is connected to a rigid network with a correspondingly constant mains frequency. In the following description, the control structure shown in Figure 21 in Appendix A.III is assumed .

In order to increase the output power of the PGU, the frequency difference $\Delta f = f_{\mathrm{setpoint}} - f_{\mathrm{actual}}$ shall be positive, which results in two options:

a) The setpoint f_{setpoint} is increased, which means that Δf becomes positively larger at a constant f_{actual} (with $f_{\mathrm{actual}} < f_{\mathrm{setpoint}}$).

b) The actual value f_{actual} is manipulated and reduced, whereby Δf becomes positively larger at a constant f_{setpoint} (with $f_{\mathrm{actual}} < f_{\mathrm{setpoint}}$).

The opposite applies to power reduction, whereby Δf shall be negative for power reduction:

a) The setpoint f_{setpoint} is reduced, which means that with a constant f_{actual} (with $f_{\mathrm{actual}} > f_{\mathrm{setpoint}}$), the value of Δf becomes negatively larger.

b) The actual value f_{actual} is manipulated and increased, whereby the value of Δf becomes negatively larger when f_{setpoint} remains constant (with $f_{\mathrm{actual}} > f_{\mathrm{setpoint}}$).

5.4.3.3.3.2.3 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.

5.4.3.3.3.2.4 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 ramp rate of the limited setting range of the PCNB shall be indicated.

Note for TR8:
Verification of the PGUs behaviour in the limited setting range shall be considered demonstrated if the final steady-state values of the active power deviate by a maximum of ± 5 % of the expected power change or ± 0.5 % $P_{b\ inst}$ *from the values resulting from the set droop and comply at least with the active power ramp rates according to Table 15. There is no assessment of the behaviour of the PGU in the unlimited setting range.*

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

5.4.3.3.3.3.1 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 Rules and Section 5.4.3.3.2 (with exception of Measurement 4) of this FNN Guideline may be omitted.

5.4.3.3.3.3.2 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 where 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.

5.4.3.3.3.3.3 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 $P_{\mathrm{L+}} = P_{\mathrm{L}} + \Delta P_{\mathrm{L}}$ or $P_{\mathrm{L-}} = P_{\mathrm{L}} - \Delta P_{\mathrm{L}}$.

Defining 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 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 $P_{\mathrm{Emin,E}}$ ($\mathrm{IOS}_{\mathrm{min}}$). The value of the load $P_{\mathrm{L+}}$ and $P_{\mathrm{L-}}$ to be switched on and off corresponds to the magnitude of the unlimited setting range of the PGU as specified in Table 14.

Test 1 - Damping of the closed control loop
Starting from a steady-state condition 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 14 (amplitude in the unlimited control range). Select the last step so that P_{rE}, in steady-state operation, minus the specified step amplitude according to Table 14 is reached. Subsequently reduce the load in the virtual island network in corresponding steps to one step above the technical minimum power. Ensure the steady-state condition is reached before introducing a new step.

NOTE 1 With regard to step levels, for example with a step level of 10 % $P_{\mathrm{b\ inst}}$, the output at the end of the last step should be 90 % $P_{\mathrm{b\ inst}}$ i.e. for gas turbines > 2 MW, the following steps: 55 %, 65 %, 75 %, 85 %, 90 % $P_{\mathrm{b\ inst}}$.

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 % $P_{\mathrm{b\ inst}}$. In addition, perform repetitions for step load disconnection ΔP_{L} by 35 % $P_{\mathrm{b\ inst}}$, 25 % $P_{\mathrm{b\ inst}}$ and 15 % $P_{\mathrm{b\ inst}}$.

NOTE 2 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 $\mathrm{IOP}_{\mathrm{min}}$, 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 IOP_{75} at nominal frequency, perform a load connection $\Delta \mathrm{P}_{\mathrm{L}}$ 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 deadband is traversed without bumps relative to the power actuator.

5.4.3.3.3.3.4 Evaluation and presentation of the test report

The active power and frequency or speed curve shall be shown 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 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 ramp rate for the limited setting range of the PCNB shall also be indicated.

Note for TR8:
The tests shall be 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 / VDE-AR-N 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 final steady-state values of the active power deviate by a maximum of ± 5 %* $P_{\text{b inst}}$ *from the values resulting from the set droop settings and at least the active power ramp rates comply with the values specified in Table 15,*
- *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.III).*

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 4):

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.

When performing measurements, the temporary connection of a grid-forming unit without prototype validation is permitted in coordination with the system operator.

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 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-HIL[14] and P-HIL[15]) with missing components such as rotor and generator (these are replaced by simulation). Verification may be also based on the C-HIL level[16]. 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 regarding properties under test. The adapted requirements for performing tests on test benches, including the specifications for DC sources for PV PGUs and PGSUs, are specified in Appendix D of FGW TR3. Network emulators shall be used accordingly.

Table 4 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. Verifications are also allocated to the test situation of the virtual island network or synchronous

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[14] M-HIL: Mechanical Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)
[15] P-HIL: Power Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)
[16] C-HIL: Controller Hardware-in-the-Loop (for further details refer to IEC TC 61400-21-4)

network operation. Measurement-based verifications are also subdivided into field measurements and test bench measurements using a network emulator.

Table 4 - Overview: Requirements and associated verifications for grid-forming units (Type 2, storage and controllable consumption units)

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	Voltage source behaviour	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	Phase jump power	-		Section 5.5.5.3 b)		-	Section 5.5.7.1 d)	-
4.2.1.1	Effective impedance	-		Section 5.5.5.4 b)		-	Section 5.5.7.2 d)	-
4.2.1.1	Settling DC component (current)	-		-		-	Section 5.5.7.9	-
4.2.1.2	behaviour in the sub- and super-synchronous frequency range	-		-		-	Section 5.5.7.8	-
4.2.1.3	behaviour in the harmonic frequency range	-		-		-		Section 5.5.5.5 b)
4.2.1.5	Voltage source control - set-point tracking behaviour	-		Section 5.5.5.6.1 b)		-	Section 5.5.7.5 b), d)	-
4.2.1.5	Voltage source control – Disturbance response and linearity of the effective impedance	-		Section 5.5.5.6.2 b)		-	Section 5.5.7.6 b), d)	-
4.2.1.6	Robustness through short-term overvoltage and undervoltage events (OVRT/UVRT robustness)	-		Section 5.5.5.6.3 b)		-		-
4.2.1.5.4	Behaviour at the current limits	-		Section 5.5.5.6.4 b)		-		-
4.2.1.5.5	Behaviour when resuming a value within the voltage band	-		Section 5.5.5.6.5 b)		-	Section 5.5.7.7 d)	-
4.2.1.5.3	Behaviour of the limited voltage source control	-		Section 5.5.5.6.6 b)		-		-
4.2.1.7	Fast protection during high during high voltages	-		-		-		Section 5.5.5.6.7 b)
4.2.1.10	Response to steep frequency gradients (RoCoF)	-		-		-		Section 5.5.5.7 a)
4.2.1.11	Capability of parallel network operation	-		-		-	Section 5.5.7.10 b)	-
4.2.1.12	Damping of power-frequency-oscillations (0.05 Hz – 10 Hz)	-		Section 5.5.5.8 a)		-	Section 5.5.7.3 c)	
4.2.1.13 + 4.2.1.14	Provision of inertia (T_A)	-		Section 5.5.5.9 a)		-	Section 5.5.7.4 c)	
4.2.2.2	Behaviour in the underfrequency and overfrequency ranges (PCNB) – limited setting range	-		Section 5.5.5.10 a)		-		-
4.2.3	Prioritisation of the requirements (units)	-		Sections: 5.5.5.3 b), 5.5.5.9 a)		-		-

a) The measurements shall be performed for $T_A = T_{A,min}$ and $T_A = T_{A,max}$ as well as the nominal value of the voltage source control gain or effective impedance specified by the manufacturer.

b) The measurements shall be performed at a T_A value selected by the certification body and at the nominal value of the voltage source control gain or effective impedance specified by the manufacturer.

c) If $T_{A,min} < T_A < T_{A,max}$ can be parameterised, additional simulation-based tests shall be performed using the nominal value of the voltage source control gain or effective impedance specified by the manufacturer.

d) In the case of different voltage source control gain or effective impedance values specified by the manufacturer, the marked tests shall also be performed based on simulation.

Existing plants 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 1 If the existing plant to be converted to grid-forming technology is based on grid-forming units that were certified in accordance with this FNN Guideline, the procedure defined in this FNN Guideline may also be applied to existing plants 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 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 4 (see footnotes).

NOTE 2 Some verifications shall be performed with T_{Amin} and T_{Amax} and, if required, for additional values of T_{A} in the setting range. Verifications of a parameterised T_{A} in the range between $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$ may be provided by simulation.

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.

If a final steady-state value is required to be determined during the measurement-based tests, but no procedure is specified at the specific test point, the definition of the final steady-state value from TR3, Revision 26 may be used, provided that it is applicable in that specific case. In general, the steady-state condition is considered to be reached when the amplitudes of the fluctuations within the permissible tolerance do not tend to increase.

Supplementary simulation-based verifications in accordance with Section 5.5.7 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 5.5.7.10 shall be performed in a network environment defined in accordance with Section 2 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	αβ components of the voltage space vector
i_α, i_β	αβ components of the current space vector[17]
$u_{\alpha\beta}$	Magnitude of the voltage space vector in the αβ coordinate system[17]
$i_{\alpha\beta}$	Magnitude of the current space vector in the αβ coordinate system[17]
$i_{\mathrm{P},\alpha\beta}$	Magnitude of the active current vector in the αβ coordinate system[17]
$p_{\alpha\beta}$	Active power in the αβ coordinate system
$q_{\alpha\beta}$	Reactive power in the αβ coordinate system
$u_{\alpha\beta,5ms}$	Magnitude of the voltage space vector in the αβ coordinate system as a 5 ms average value[17]
$i_{\alpha\beta,\mathrm{5ms}}$	Magnitude of the current space vector in the αβ coordinate system as a 5 ms average value[17]
$i_{\mathrm{P},\alpha\beta,\mathrm{5ms}}$	Magnitude of the active current pointer in the αβ coordinate system as a 5 ms average value[17]
$p_{\alpha\beta,\mathrm{5ms}}$	Active power in the αβ coordinate system as a 5 ms average value[17]
$q_{\alpha\beta,\mathrm{5ms}}$	Reactive power in the αβ coordinate system as a 5 ms average value[17]
$i_{\mathrm{P},1}$, $i_{P,2}$	Fundamental component of the current vectors (active component) in the positive and negative sequence
$i_{\mathrm{Q},1}$, $i_{\mathrm{Q},2}$	Fundamental component of the current vectors (reactive component) in the positive and negative sequence
$i_{\mathrm{P},1,\mathrm{100ms}}$, $i_{\mathrm{P},2,\mathrm{100ms}}$	Fundamental component of the current vectors (active component) in the positive and negative sequence as 100 ms average value
$i_{\mathrm{Q},1,\mathrm{100ms}}$, $i_{\mathrm{Q},2,\mathrm{100ms}}$	Fundamental component of the current vectors (reactive component) in the positive and negative sequence as 100 ms average value
u_1, u_2	Fundamental component of the voltage vectors in the positive and negative sequence
p_1, p_2	Fundamental component of the active power in the positive and negative sequence
q_1, q_2	Fundamental component of the reactive power in the positive and negative sequence
$i_{\mathrm{S},1}$, $i_{\mathrm{S},2}$	Fundamental component of the apparent current vectors in the positive and negative sequence
f_1	Fundamental component in the positive sequence frequency

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

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[17] For determining the αβ components of current and voltage, see Appendix B.V.

The fundamental component 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, it 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 load power shall not fluctuate by more than ± 5 % of the power expected from the average voltage resulting in the virtual island in steady-state operation 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 islanding 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 disconnecting from the test object. This is also the case when the requirement 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. These models shall be submitted to the system operator as part of the inspection of the network connection.

NOTE Appropriate simulation models as part of the certification process shall be provided to the relevant system operator for example, for the assessment of connection requests, for the detailed determination of the dynamic behaviour of plants 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 represents 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 part of the model which can be switched off.
2) Protection functions (loss of mains protection on the unit such as overvoltage protection, undervoltage protection, frequency step-up protection, frequency step-down protection) shall be implemented in a model part which can be switched off, 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 (under normal operating conditions without occasional consumers, in accordance with the manufacturer's specifications) of less than 3% P_{Emax} and for units with a P_{Emax} < 50 kW is not required. The average internal load may be modelled in a simplified manner, e.g. as an impedance load.
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 represents 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 to be able to represents the entire operating range of the unit between $P_{\mathrm{Emin,E}}$ 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.

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 parameterisable 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 sequences, 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 (manufacturer's declaration).

   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 represent the entire operating range of the grid-forming unit between $P_{\mathrm{Emin,E}}$ 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 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.

6) The user shall be able to change the parameters of the grid-forming unit defined as parameterisable 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 system 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 system operators.

   NOTE 2 If the system operator providing the connection (distribution system operator) uses a simulation environment that deviates from the specifications of the German transmission system 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 represented 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)[18]. 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

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[18] The following paper provides an overview on VSM and 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

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 meet all requirements for the grid-forming unit (e.g. phase jump power, 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 represent the entire operating range of the grid-forming unit between $P_{\mathrm{Emin,E}}$ 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 Rules do 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:

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 (Plant models for system 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 phase jump power (Section 5.5.5.3)
5) Examination of the effective impedance (Section 5.5.5.4)
6) Examination of the behaviour of the voltage source 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 represented 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 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 αβ 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 component of the positive sequence vectors ($iP_{,1}$, $u1$, $p1$, $q1$ or $iP_{,1,S}$, $u1_{,S}$, $p1_{,S}$, $q1_{,S}$), 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 of the positive sequence voltage $u1_{,S}$ and the positive sequence current $|iP_{,1,S}|$ before the start of the test shall be determined by taking the average value over a time window of 1 s. During

this time window, the positive sequence voltage shall remain within a tolerance band of ± 0.25% normalized 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 $p1_{,\mathrm{S}}$ and $q1_{,\mathrm{S}}$.

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 ± 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 5.5.3.6.2.2.2. Proceed as follows to validate the model:

1) The steady-state voltage at the terminals $u1_{,\mathrm{S}}$ of the grid-forming unit of the EMT model or detailed RMS simulation model after islanding may deviate from the measured value by a maximum of ± 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 shall be 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 ± 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 5.5.3.6.2.2.2. 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 verifying 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 $p1_{,\mathrm{S}}$ in the simulation model deviates from those in the measurement $p1$ by a maximum of ± 40% relative to the measured frequencies. In the case of wind turbines, 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. 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 shall be considered validated regarding the correct representation 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 may deviate by a maximum of ± 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 and final steady state. In this case, a maximum deviation of ≤ ± 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 14 (Appendix B.I) and the frequency of the transient response of the frequency shall be maintained by the simulation model with an accuracy of ± 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 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 Point 2, Paragraph 3, applies to the frequency of the grid-forming unit, whereby a value of ± 15 % relative to the steady-state frequency deviation shall be taken into account for the tolerance band (ε_dyn[19]) of the frequency.

Note for TR8:
The model shall be considered validated regarding the correct representation 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 ± 5 %.*
- *Compliance with at least the active power ramp rates in accordance with Table 15. As long as no minimum requirements are specified for the grid-forming unit in accordance with Table 15, verification of the actuating speeds shall be considered demonstrated through their identification.*

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[19] See equations E-3 to E-6 and Point 2, paragraph (3) in FGW TR4, Revision 10, Chapter E.5.2.1.1.

- *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 ± 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 ± 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 Phase jump power 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 $p\alpha\beta_{,\mathrm{S}}$ of the EMT model. The maximum value of the phase jump power of the simulation model may deviate by a maximum of - 10 % / + 25 % from the measured maximum value of the phase jump power in the procured direction and by a maximum of ± 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 shall be considered validated regarding the correct representation of the phase jump power of the grid-forming unit under the following conditions:

- *The simulated maximum value of the phase jump power 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 ± 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.

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 ± 5 % from the measured value. The measured effective impedance shall be specified for the detailed RMS simulation model.

Note for TR8:
The model shall be considered validated regarding the correct representation 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 ± 5 %.

In addition, the provisions of Section 5.5.3.6.2.1 apply.

5.5.3.6.2.2.8 Voltage source control in accordance with the test specified in Section 5.5.5.6

The measurements described in Section 5.5.5.6 shall be simulated.

NOTE The short-circuit ratio (SCR) at the terminals of the grid-forming unit in the simulation environment should correspond with sufficient accuracy to the SCR in the test environment.

Setpoint tracking behaviour 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 $u1$ or $u1_{,\mathrm{S}}$, or alternatively the reactive current $i\mathrm{Q}_{,1}$ or

$iQ_{,1,\mathrm{S}}$ shall be compared with the result of the measurement. The simulated rise time shall not deviate from the measured value by more than ± 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 ± 5 %.

Note for TR8:
The model shall be considered validated regarding the correct representation of the setpoint tracking behaviour of the voltage source 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 ± 5 % or ± 50 ms,*
- *the simulated steady-state currents and voltages correspond to the measured currents and voltages with a maximum deviation of ± 5 %.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

Disturbance 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 $iQ_{,1,\mathrm{S}}$ determined with the EMT model and RMS model and the damping of the settling process shall not deviate by more than ± 15 % from the measured values. The profile of the reactive current shall lie within the curve in accordance with Figure 10 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 ± 5 %.

Note for TR8:
The model shall be considered validated regarding the correct representation of the disturbance behaviour of the voltage source 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 ± 15 % and the profile of the reactive current is always within the curve in accordance with Figure 10,*
- *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 ± 15 %,*
- *the simulated steady-state currents and voltages correspond to the measured currents and voltages with a maximum deviation of ± 5 %.*

In addition, the provisions of Section 5.5.3.6.2.1 apply.

OVRT or UVRT robustness of the voltage source 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 shall be 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 ± 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 ± 20 % from the measured value.

Note for TR8:
The model shall be 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 ± 20 %,*
- *the simulated settling time of the positive sequence reactive current corresponds to the measured settling time with a maximum deviation of ± 20 %,*

- *the simulated damping of the settling process of the positive sequence reactive current corresponds to the measured value with a maximum deviation of ± 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 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 shall be 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 band of U_c ± 10 % U_c in accordance with 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 meets 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 positive sequence overvoltages (overshoot) do not exceed the final steady-state value of the voltage by more than 5 %, notwithstanding a value of 2.5 % for the final steady-state voltage 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 shall be considered validated regarding the correct representation of the behaviour of the grid-forming unit when returning to the voltage band of U_c ± 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 positive sequence overvoltages (overshoot) do not exceed the final steady-state value of the voltage by more than 5 %, notwithstanding a value of 2.5 % for the final steady-state voltage 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 tests in Section 5.5.5.6.7

It shall be verified by simulation using the EMT model and the detailed RMS model in accordance with the specifications in Section 5.5.5.6.7 that the functionality of the fast protection during high voltages (amplitude jump of the voltage 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 4.2.1.7.2.

Note for TR8:
The model shall be 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.*

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 meet the requirements of the relevant Technical Connection Rules 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 4.2.1.14 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 shall be 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 network or losing stability. 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 network or losing stability.*

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 sequence active power $p1$ shall be compared with the corresponding simulated fundamental component of the positive sequence active power $p1_{,\mathrm{S}}$ (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 damping based on a frequency or phase jump power may be determined in accordance with the procedure 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 $p1$ 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 $p1_{,\mathrm{S}}$. 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 $p1_{,\mathrm{S}}$ may deviate by a maximum of ± 5 % from the value $p1$ determined from the test.
3) In the event that the settling process of the measured power $p1$ is heavily damped and a damping ratio cannot be determined, the settling process of the power $p1_{,\mathrm{S}}$ of the simulation model shall be compared with the active power $p1$ measured on the test object, starting from the initial until the final steady state is reached. The procedure according to FGW TR4, Revision 10, Chapter E.5.2.1.1, Point 2, Paragraph 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 shall be 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 %,*
- *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 $iP_{,1,\mathrm{S}}$, $u1_{,\mathrm{S}}$ and $p1_{,\mathrm{S}}$ shall be used for validation of the RMS type model.

The 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 phase jump power 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 condition 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 % shall 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 meet 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 parameterisation 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 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 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) Based on a complete project definition, the tests performed on the operational plant shall be documented alongside the corresponding simulations using the validated model types (EMT model, detailed RMS model and RMS type model). Selected measured values or signals of the grid-forming unit, such as voltages and currents as well as the intermediate variables identified as required, shall be presented in a uniform graphical representations as a comparison of the signals.
4) All parameters used to define types of grid-forming units within a family, including their parameterisations 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 5.5.7 for non-measured values of the start-up time constant T_A shall be included in the model documentation, including any additional parameterisations 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 system 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, system 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 system 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 meet requirements for model accuracy for all simulation-based verifications based on a uniform model parameterised for a defined T_A. If required, the parameter used for different T_A shall be documented. The signals listed in Section 5.5.2.1 and the intended parameterisations shall be made available if they are required for the corresponding verifications.

5.5.3.9 Models used by the system operator

The simulation models of the plant to be provided in accordance with the relevant Technical Connection Rules or individual Technical Connection Conditions of the system 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 meet 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 system 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 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. As part of the measurements according to Point 1, the effectiveness of the parameterised T_{A} shall also be verified.

5.5.4.2 Test environment for measurements in virtual island network 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. The short-circuit power ratio should be SCR ≥ 3[20].

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 $P_{\mathrm{Emin,E}}$ to the maximum active power P_{Emax}.

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

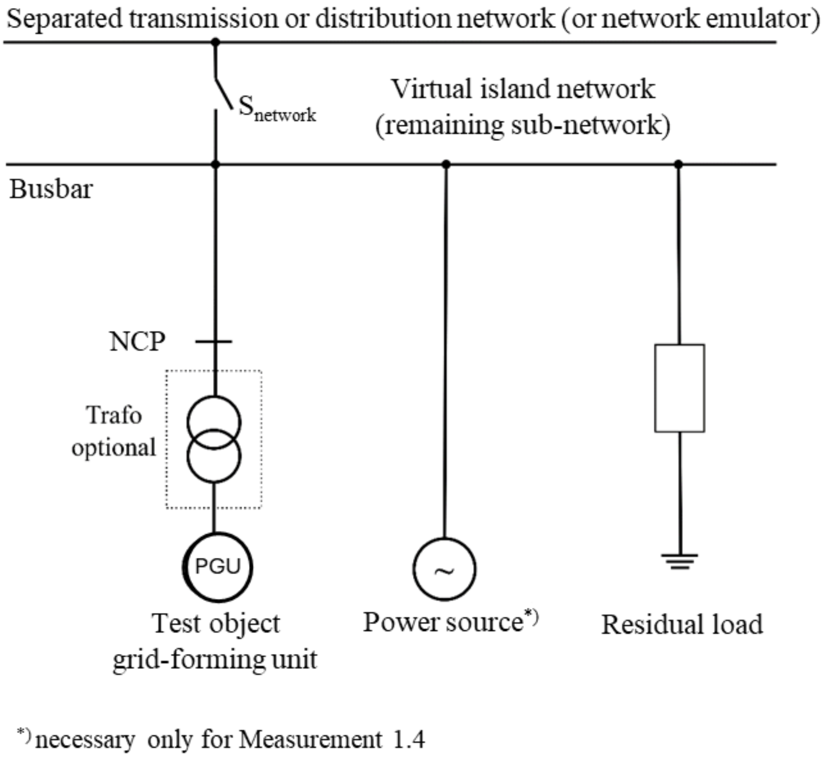

Figure 8 - Example test environment for measurements in the virtual island network

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 meet requirements for voltage source behaviour in accordance with Section 4.2.1.1 and to meet PCNB requirements in accordance with Section 4.2.2. For both properties, it shall be determined based on the measurement-based tests in Table 5 whether the test object in the virtual island network meets the requirements for stability of small and large signal behaviour. Based on the measurement procedures

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[20] The test results obtained with a low SCR value may be used.

described in this section, both properties shall be evaluated individually in Section 5.5.4.4 and documented individually in Section 5.5.4.5.

Table 5 - Measurements in virtual island network for verifying 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} **(-)**	Q_{residual} **/** P_{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_{Emax} e))	0.0	45 % P_{Emax} to 65 % P_{Emax} alternatively - 45 % P_{Emax} to - 65 % P_{Emax} when performing Measurment 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 14 Appendix B.I. regarding the power amplitude, these may be applied.

d) Does not apply if the inertia is procured in both positive and negative directions.

e) This corresponds to at least half of the phase jump power 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.

Performing 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 5), generate the operating condition of virtual island network according to Figure 8 for all measurements specified in Table 5 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 5). Set the values for the residual load according to Table 5 for the respective measurements before the start of the virtual island network operation.

It is recommended that the switch position S_{network} is measured and that an additional measuring point is provided at the point of delivery or at the load. The measurement should start at least 10 seconds before the S_{network} is opened.

Any control system for the load bank output shall not influence the control system of the grid-forming unit. The load bank should behave as passively as possible during the measurement period. It should be noted that the power of a passive ohmic load bank changes quadratically with the voltage and is also influenced by the temperature.

NOTE 1 The active power in the virtual island is largely determined by the load or load bank.

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.

For PGSU or storage, a droop between 2% and 2.5% shall be provided when performing Measurement 1.4.

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 $p1$, reactive power $q1$, frequency $f1$ and voltage $u1$ shall be determined for all measurements in accordance with Table 5.

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.

In addition, the value of the set start-up time constant shall be checked for plausibility for Measurement 1.1. To do this, check the frequency curve to ensure that the set T_{A} is effective. The frequency gradient $\Delta f1/\Delta t$ shall be determined from the start of the measurement (beginning of islanding operation) to the time of damping decay. The effective T_{A} shall be determined using equation (7), taking into account the $\Delta p1$ measured at the terminals of the unit during the same period.

$$T_{\mathrm{A}} = \left| \frac{\Delta p_1}{P_{\mathrm{rE}} \cdot \left(\frac{\Delta f_1 / f_{\mathrm{n}}}{\Delta t} \right)} \right| \qquad (7)$$

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 $p1$ and frequency $f1$ shall be determined for all measurements according to Table 5.

In the case of wind turbnies, 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 5 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 of $D > 0.5$.

5.5.4.5 Presentation in the measurement report

5.5.4.5.1 Voltage source behaviour

The measured or calculated positive sequence variables of active power $p1$, reactive power $q1$, frequency $f1$ and the positive and negative sequence components of the voltage $u1$,$u2$ 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 ia, ib, ic and phase voltages ua, ub, uc 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 to 30 network periods.

The T_A value determined for Measurement 1.1 shall be represented graphically and indicated.

Note for TR8:
Verification shall be considered successful, provided the following conditions are fulfilled:
Starting from an operating state at rated frequency, a steady-state condition 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 Rules, which would lead to a complete disconnection of the grid-forming unit.

The T_A value determined or validated for Measurement 1.1 corresponds to the set value with a tolerance of 50%.

5.5.4.5.2 Response to overfrequency and underfrequency (PCNB) in the unlimited setting range

The measured positive sequence components of the active power $p1$ and frequency $f1$ 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:
Verification shall be considered demonstrated 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 by a maximum of 10 s,*
- *the settling behaviour of the measured frequency meets the required damping ratio according to Table 14.*

Verification shall be considered demonstrated when the measured frequency profile as part of Measurement 2.1 meets the requirement for the damping ratio in accordance with Table 14. 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) Requirements for phase jump power and 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) Required behaviour of the voltage source control including robustness against short-term overvoltage and undervoltage events (O/UVRT robustness) as well as fast protection during high voltages in accordance with Sections 4.2.1.5 to 4.2.1.7
4) Robustness against steep frequency gradients (ROCOF) in accordance with Section 4.2.1.10
5) Basic network parallel operation capability in accordance with Section 4.2.1.11

6) Damping of power-frequency-oscillations in accordance with Section 4.2.1.12

7) Inertia power and energy in accordance with Section 4.2.1.14 corresponding to the start-up time constant T_A in accordance with Section 4.2.1.13

8) 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 described 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 9. Part of the test environment is an FRT test device, which consists, for example, of a switchable d-axis and q-axis inductance.

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 described in this section applies to all tests specified in Section 5.5.5.1, Points 1) to 8).

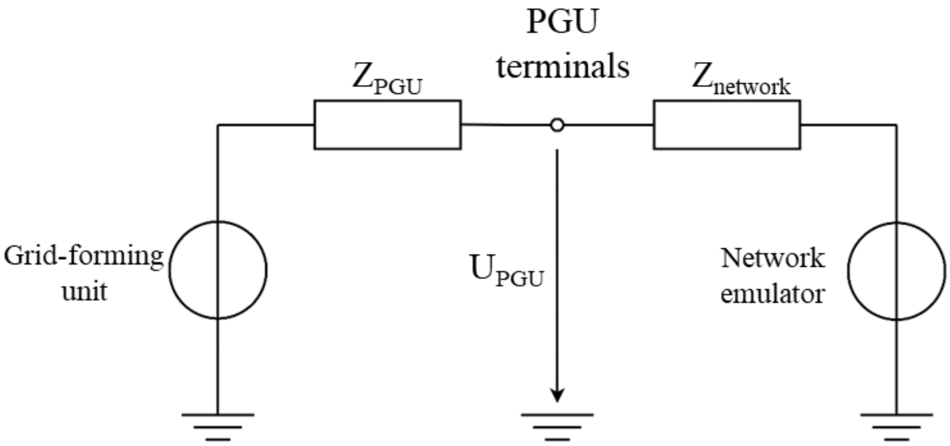

Figure 9 - Example test environment for measurements in synchronous operation

5.5.5.3 Verification of the phase jump power (Section 4.2.1.1)

5.5.5.3.1 Aim of the measurement

The aim of the measurement is to determine the phase jump power provided by the grid-forming unit. This involves checking compliance with the requirements in Section 4.2.1.1. In addition, it shall be determined whether the voltage source behaviour is given higher priority according to Section 4.2.3 over specifications by third parties or the network security management of the system operator. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, the measurement shall be performed for the nominal value specified by the manufacturer. For the minimum and maximum of the parameterised values, the simulation-based verification shall be performed in accordance with Section 5.5.7.1.

5.5.5.3.2 Measurement procedure

Based on an operating point of 50 % P_{Emax} ± 5 % P_{Emax}, 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 ± 5 % (relative to P_{Emax}). In doing so, a power limiting setpoint shall be provided by the highest-priority limitation setpoint according to Section 4.2.3 (e.g. interface that would be used within the framework of an network security management command) in such a way that the limited value is exceeded due to resulting phase jump power.

Measurement procedure 1 - Activating a phase step

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

Measurement procedure 2 - Applying a phase change

Apply a phase step 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_{Emax} can be measured at the terminals of the grid-forming unit in the procured direction. Repeat this measurement starting from the same operating point ± 5 % P_{Emax} with the identical phase angle step with a negative sign - $\Delta\theta_{\mathrm{setpoint}}$ ± 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 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 condition. 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. phase jump power) and change in active current $\Delta i_{\mathrm{P,PGU}}$ shall be determined as an instantaneous value based on the initial steady-state condition.

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

$$\left(\sin(\delta_{\mathrm{n1}}) - \sin(\delta_{\mathrm{v1}})\right) \approx \sin(\Delta\delta_1) \tag{8}$$

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

$$\Delta i_{\mathrm{P1,PGU,max}} = -\frac{1}{z_{\mathrm{w,max}}}\sin(\Delta\delta_1) \tag{9}$$

where the values for $z_{\mathrm{w,max}}$ 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. phase jump power) and change in active current $\Delta i_{\mathrm{P,PGU}}$ shall be determined as space vector $iP_{,\alpha\beta}$ values based on the initial steady-state condition. At the time when the maximum change in active power occurs, the angle difference between the voltage at the terminals of the grid-forming unit and its initial value shall be determined ($\Delta\delta_1$)(see Appendix B.VI). Equation (6) is used to determine the required maximum value $\Delta i_{\mathrm{P1,PGU,max}}$. The assumption described for Equation (8) is permissible.

This means that the maximum value $\Delta i_{\mathrm{P1,PGU,max}}$ of the active current response $\Delta i_{\mathrm{P,PGU}}$ 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 (9).

5.5.5.3.4 Presentation in the measurement report

The measured active power $p\alpha\beta$ and the measured active current $iP_{,\alpha\beta}$ 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. In addition, the active power limiting setpoint shall be shown.

Note for TR8:
The test shall be considered passed if the maximum change in active current $\Delta i_{P,PGU}$ *in the procured direction is at least 50 % (70 % for PGSU and storage) 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. The test shall be considered passed in the non-procured direction, if the maximum change in active power is at least 5 %* P_{Emax}*. The phase jump power is not restricted by the active power limiting setpoint.*

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 ($z_{\mathrm{w,max}}$) in accordance with Section 4.2.1.1 when the voltage amplitude at the terminals of the grid-forming unit changes. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, the measurement shall be performed for the nominal value specified by the manufacturer. For the minimum and maximum of the parameterised values, the simulation-based verification shall be performed in accordance with Section 5.5.7.2.

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 operating states in accordance with Table 6.

Active power throttled operation is permitted, and the active power shall be kept as constant as possible during the measurements (± 10 % P_{n}).

Table 6 - Initial operating conditions for Measurements 1 and 2 for determining the effective impedance

Number	Active power output	Output reactive power	Short-circuit power ratio
1	> 55 % P_{Emax}	10 % (± 5 %) relative to P_{Emax}	SCR ≥ 3[21]
2	> 55 % P_{Emax}	- 10 % (± 5 %) relative to P_{Emax}	
3a)	15 % to 45 % P_{Emax}	- 10 % to + 10 % relative to P_{Emax}	
a) The voltage setpoint step $\Delta u_{\mathrm{setpoint}}$ according to Measurement 1 shall occur in the negative direction.			

Measurement procedure 1 - Excitation by activating a setpoint step

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

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

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[21] 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 ≥ 3, the measurement may also be performed with a value of SCR ≥ 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 correspondingly small steps of the quadrature 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 source control, 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. Δu_{I} = 0.03 - 0.05 p.u. and Δu_{II} = 0.07 – 0.1 p.u.). To avoid external influences, these two steps should be performed in quick succession. Phase jumps associated with the connection of the voltage magnitude step are already taken into account in the evaluation.

NOTE 3 No current limitation should apply during measurements.

5.5.5.4.3 Evaluation

Measurement procedure 1

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

$$\underline{z}_{\mathrm{w},1} = \frac{\underline{u}_{1,\mathrm{n}} - \underline{u}_{1,\mathrm{v}} \pm \Delta\underline{u}_{\mathrm{setpoint}}}{\underline{i}_{\mathrm{S}1,\mathrm{n}} - \underline{i}_{\mathrm{S}1,\mathrm{v}}} \quad (10)$$

It shall be noted that 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 therefore be evaluated in order to determine the internal voltage change in terms of magnitude and phase.

Measurement procedure 2

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

$$\underline{z}_{\mathrm{w},1} = \frac{\underline{u}_{1,\mathrm{n}} - \underline{u}_{1,\mathrm{v}}}{\underline{i}_{\mathrm{S}1,\mathrm{n}} - \underline{i}_{\mathrm{S}1,\mathrm{v}}} \quad (11)$$

The values are considered stationary if all positive sequence values averaged over 100 ms have not changed by more than ± 2% of the respective nominal value over a period of 2 seconds. The values to be used in equation (11) correspond to the positive sequence values averaged over 2 s for the evaluation time window under consideration.

5.5.5.4.4 Presentation in the measurement report

The time progression of the measured positive sequence terminal voltages $u1$ of the grid-forming unit and the active and reactive components $iP_{,1}$, $iQ_{,1}$ of the positive sequence apparent current $iS_{,1}$ 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 $\underline{u}_{1,\mathrm{v}}$, $\underline{u}_{1,\mathrm{n}}$ and currents $\underline{i}_{\mathrm{S}1,\mathrm{v}}$, $\underline{i}_{\mathrm{S}1,\mathrm{n}}$ shall be labelled and their values shall be indicated.

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

Note for TR8:
Verification shall be considered demonstrated if the values of the determined impedance $|\underline{z}_{w,1}|$ *correspond to the specifications for the maximum value* $z_{w,max}$ *in Section 4.2.1.1.*

5.5.5.5 Verification of passive properties in the harmonic frequency range (Section 4.2.1.3)

Verification of passive characteristics in the frequency range from 100 Hz to 2.5 kHz in the stationary reference system is provided on the basis of a manufacturer's declaration (evaluation of impedance in the required frequency range).

The specifications given here regarding procedures and evaluation shall be taken into account. Alternatively, if available, a corresponding procedure developed by FNN or FGW may be selected.

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

The step size for determining impedance shall not exceed 5 Hz. The excitation of the grid-forming unit shall be monofrequent, i.e. with only one frequency component in the exciting signal.

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

Regardless of the method chosen, all control systems shall be activated in their standard parameterisation in accordance with the requirements of this FNN Guideline (in particular for PCNB). Starting from this configuration, the parameters shall then be varied within the relevant range.

The manufacturer may decide whether the specified frequency-dependent 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. Verification shall be provided when claiming that the resistive component of the unmeasured unit transformer could compensate for any non-passivity of the unit.

In the selected procedure, both the operating points of the unit (voltage, active power, reactive power) and the control modes shall be varied if these lead to a change in the frequency-dependent impedance of more than 15% for at least one frequency within the relevant frequency range.

Evaluation and presentation in the manufacturer's declaration
The frequency-dependent impedance shall be determined and presented in terms of magnitude and phase in the positive and negative sequences. The impedance curve shall include both the physical impedance and the contribution of the control-related impedance, as well as any additional influences of the converter control that are effective within the frequency range under investigation.

According to small-signal theory, frequency-dependent impedance is a differential determination based on the change in current at the measured frequency in relation to the change in voltage at the measured frequency as a result of targeted single-frequency excitation.

Note for TR8:

The manufacturer's declaration shall be considered technically comprehensible if the frequency-dependent impedance of the grid-forming unit is specified, has a positive real part in the frequency range from 100 Hz to 2.5 kHz and the method used by the manufacturer to determine the impedance values is comprehensible and justified.

5.5.5.6 Verification of voltage source control and FRT behaviour (Sections 4.2.1.5 to 4.2.1.6)

5.5.5.6.1 Verification of setpoint tracking behaviour

5.5.5.6.1.1 Aim of the measurement

The aim of the measurement is to determine the behaviour of the voltage source control when the setpoint changes. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, the measurement shall be performed for the nominal value specified by the manufacturer. For other parameterisable values, the simulation-based verification shall be performed in accordance with Section 5.5.7.5.

5.5.5.6.1.2 Measurement procedure

Verification of the behaviour of the grid-forming unit in response to a change in the setpoint step shall be demonstrated similarly to Measurement 1 in Section 5.5.5.4.2 by applying a setpoint step under initial operating conditions and excitation conditions specified there.

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 ≥ 3, a value of SCR ≥ 1 may be used for verification.

5.5.5.6.1.3 Evaluation

The rise time of $u1$ relative to the final value shall be determined from the time profile of the positive sequence voltage $u1$. 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 $iQ_{,1}$ of the PGU may be then used to evaluate the rise time.

NOTE The start-up time to be determined is usually defined as the time taken to reach 90% of the setpoint step. However, since the output voltage will not reach the setpoint (P control), the calculation of the rise time here refers to the final steady-state value of the voltage change.

5.5.5.6.1.4 Presentation in the measurement report

The profile of the setpoint and the variable ($u1$ or $iQ_{,1}$) used for evaluation shall be documented graphically. The determined rise time shall be indicated.

Note for TR8:
Verification shall be considered demonstrated if the determined rise time of the voltage $u1$ (or alternatively of the current $iQ_{,1}$) is < 1 s.

5.5.5.6.2 Verification of the disturbance behaviour 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. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, the measurement shall be performed for the nominal value specified by the manufacturer. For other parameterisable values, the simulation-based verification shall be performed in accordance with Section 5.5.7.6.

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. In this case, the mains voltage is within the rated range of the unit (e.g. U_r ± 10 % U_r).

NOTE Measurement 1 in Section 5.5.5.4.2 may only be performed 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 of at least two grid-forming units analogous to the configuration mentioned above. 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 αβ 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 evaluation of the current rise time (apparent current) is performed using $i\alpha\beta_{,5\mathrm{ms}}$(see Appendix B.V) for the period between the start time (10% of the voltage change) and 90% of the change in current (determined from the final steady-state value of the current).

The value of $\Delta i_{\mathrm{Q,End}}$, as the final steady-state value of the reactive current change, is determined in the same way as the steady-state apparent currents $\underline{i}_{\mathrm{S1,v}}$ and $\underline{i}_{\mathrm{S1,n}}$ for use in equation (11) 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 $iQ_{,1}$. The settling tolerances are +20 % I_r and -10 % I_r for $\Delta i_{\mathrm{Q,End}} > 0$ or -20 % I_r and +10 % I_r for $\Delta i_{\mathrm{Q,End}} < 0$.

The envelope curve in Figure 10 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 $\Delta i_{\mathrm{Q,End}}$ of the reactive current component $iQ_{,1}$ determined from $\mathrm{i}_{\mathrm{S1,v}}$ or $\underline{i}_{\mathrm{S1,n}}$ in a similar way as described in Section 5.5.5.4.3.

NOTE 1 Figure 10 is used only for calculating damping. The value of t_2' is set in Figure 10 at 80 ms and is used to construct the envelope curve.

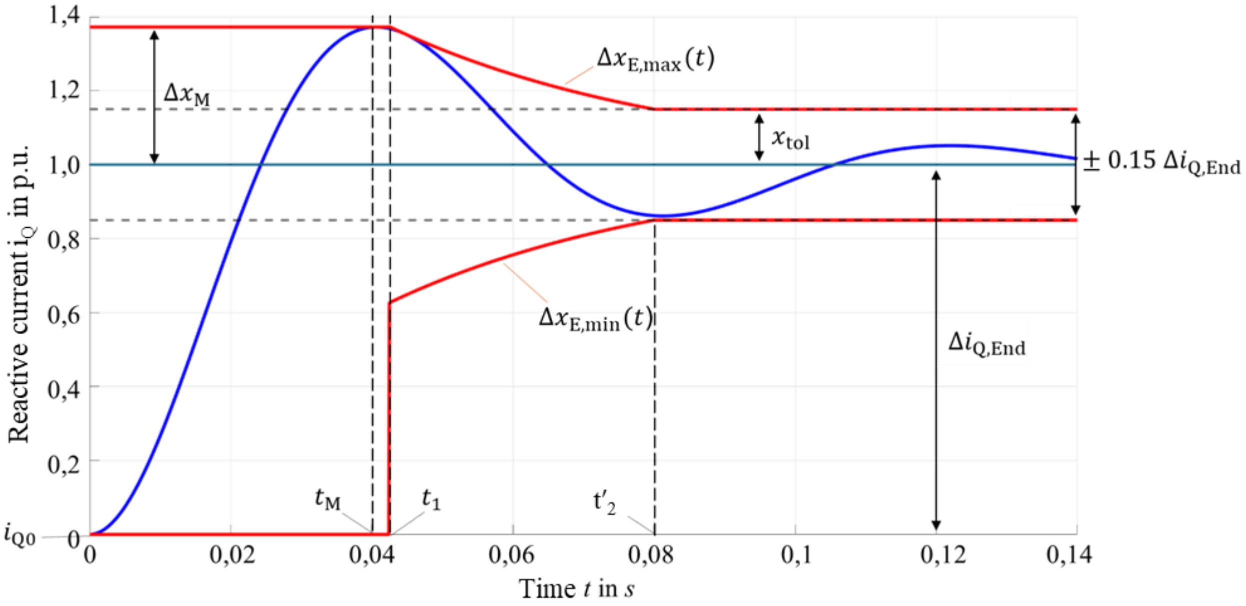


Figure 10 - Envelope curve for determining the damping of the voltage source control (i_Q is related to $\Delta i_{Q,End}$)

Equations (12) to (17) apply for the defining points of the envelope elements in Figure 10.

$$\Delta x_M = e^{-\frac{D}{\sqrt{1-D^2}}\cdot\pi} \cdot \Delta i_{Q,End} = 0.03723 \cdot \Delta i_{Q,End} \qquad (12)$$

$$\Delta x_{E,max}(t) = \left(1 + \frac{e^{-\frac{D\cdot\pi}{T_M\cdot\sqrt{1-D^2}}\cdot t}}{\sqrt{1-D^2}}\right) \cdot \Delta i_{Q,End} \qquad (13)$$

$$\Delta x_{E,min}(t) = \left(1 - \frac{e^{-\frac{D\cdot\pi}{T_M\cdot\sqrt{1-D^2}}\cdot t}}{\sqrt{1-D^2}}\right) \cdot \Delta i_{Q,End} \qquad (14)$$

$$t_2' = t_{\text{settling}\,\Delta x} + 20\text{ ms} = 80\text{ ms} \qquad (15)$$

$$t_1 = 42.6\text{ ms} \qquad (16)$$

$$t_M = 40.65\text{ ms} \qquad (17)$$

NOTE 2 The tolerance band for the settling time differs in its reference value from the steady-state band for evaluating damping. Figure 10 shows only the band for evaluating damping. In equation (15), $T_{\text{settling}\,\Delta x}$ corresponds to the maximum value of the settling time in accordance with the requirements of Section 4.2.1.5.2.

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 (18).

$$L_Z = \frac{\Delta u_I \cdot \Delta i_{Q,II}}{\Delta u_{II} \cdot \Delta i_{Q,I}} \qquad (18)$$

Where Δu_I and Δu_{II} are the measured differences in the positive sequence terminal voltages $u1$ 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 $iS_{,1}$ analogous to Measurement procedure 2 in Section 5.5.5.4.3, where the following applies:

$$\Delta i_{\mathrm{Q,I}} = i_{\mathrm{Q1,n}} - i_{\mathrm{Q1,v}} \text{ as a response to the voltage magnitude step } \Delta u_{\mathrm{I}} \tag{19}$$

$$\Delta i_{\mathrm{Q,II}} = i_{\mathrm{Q1,n}} - i_{\mathrm{Q1,v}} \text{ as a response to the voltage magnitude step } \Delta u_{\mathrm{II}} \tag{20}$$

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 ia, ib, ic and phase voltages ua, ub, uc at the terminals of the grid-forming unit shall be shown starting with two network periods before the sudden voltage change over a total of 15 - 30 network periods.

The time profiles of the variables $u\alpha\beta_{,5ms}$, $i\alpha\beta_{,5\mathrm{ms}}$ and $iQ_{,1}$ shall be documented graphically.

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

The time progression of the measured positive sequence terminal voltages $u1$ of the grid-forming unit and the active and reactive components $iP_{,1}$, $iQ_{,1}$ of the positive sequence apparent current $iS_{,1}$ 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 $iQ_{,1}$ 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 shall be considered fulfilled if the moving average instantaneous value of the current $i\alpha\beta_{,5\mathrm{ms}}$ *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 shall be considered fulfilled if the reactive current $iQ_{,1}$ *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 shall be considered fulfilled if the curve of the reactive current component as a result of the sudden voltage change (in accordance with the specifications of Measurement procedure 2 in Section 5.5.5.4.3) lies within the envelope curve according to Figure 10.

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

5.5.5.6.3 Verification of robustness and voltage source control during short-term overvoltage and undervoltage events (OVRT or UVRT robustness) in Section 4.2.1.6

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. In addition, verifications of multiple fault control shall be provided in accordance with Clause 11.2.5.2 of the relevant Technical Connection Rules and the associated verification procedures in accordance with FGW TR3, Revision 26. These shall be evaluated in accordance with FGW TR8, Revision 10.

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). An overview of the measurements is provided in FGW TR3, Revision 26, Chapter 4.6.3.1. The column for the k-factor does not apply.

NOTE 1 Tests that are explicitly repeated for different k-factors in accordance with Chapter 4.6.3.1 of FGW TR3, Revision 26, are omitted accordingly.

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) starting with cos $\varphi \approx 1$ or $Q \approx 0$ respectively. In addition, a test shall be conducted with the PGU underexcited and overexcited at the maximum possible reactive power specified by the manufacturer. If the PGU has a capacity exceeding a cos φ of 0.95, then testing with a cos φ of 0.95 is considered sufficient.

NOTE 2 For symmetrical voltage dips in the range of ≤ 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) apply.

NOTE 3 For PGSU and storage, measurements shall be performed for both 'energy supply' and 'energy consumption' operating modes. In both operating modes, full load and partial load refer to the nominal power for that particular operating mode.

The behaviour of the voltage source control of the grid-forming unit during overvoltages shall be verified by applying 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 phase-to-phase voltage for asymmetrical voltages increases, with a duration of ≥ 5 s. For PGSU and storage, the measurement shall be performed at the minimum possible DC voltage specified by the manufacturer.

NOTE 4 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 αβ coordinates (see Appendix B.V).

The rise time of the current is evaluated using $i\alpha\beta_{,5\mathrm{ms}}$ (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 $i\alpha\beta_{,5\mathrm{ms}}$ (see Appendix B.V). An evaluation based on operating points at full load does not apply.

It is recommended to determine the final value of the reactive current change $\Delta i_{\mathrm{Q,End}}$ from the average value of the current between 350 ms and 500 ms (or the last 150 ms before voltage recovery in low voltage dip tests with short dip times) after the sudden voltage change. 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.

NOTE 1 The reason for this is that any corrective measures that may be necessary during the further course of the voltage dip should not influence the determination of the final 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 $iQ_{,1}$, $iQ_{,2}$. In the event of mains voltage drops of Δu to a value < 0.05 p.u., the apparent current may also be used for evaluation instead of the reactive current. 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 2 These values may be used to determine damping.

Above 120 % U_n, voltage source control is required as far as technically feasible. This capacity shall be specified in the unit certificate.

5.5.5.6.3.4 Presentation in the measurement report

The instantaneous values (abc) of the phase currents ia, ib, ic and phase voltages ua, ub, uc at the terminals of the grid-forming unit shall be shown starting from two network periods before the sudden voltage change over a total of 15 to 30 network periods.

The time profiles of the variables $u\alpha\beta_{,5ms}$, $i\alpha\beta_{,5ms}$, $iQ_{,1}$ and $iQ_{,2}$ over this specified time period shall be documented graphically.

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

The time progression of the measured positive sequence terminal voltages $u1$ of the grid-forming unit and the active and reactive components $iP_{,1}$, $iQ_{,1}$ of the positive sequence apparent current $iS_{,1}$ 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 $iQ_{,1}$ shall be indicated.

The maximum difference between the reactive current in the positive or negative sequence from the steady-state value, referenced to that steady-state value, shall be determined and reported for the time intervals from 80 ms to 130 ms after the sudden voltage change, and 130 ms after the sudden voltage change until voltage recovery.

The assumptions regarding the relevant influencing variables and any restrictions shall be indicated to show whether it is possible to control a symmetrical voltage magnitude 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:
Verification of compliance with the requirement for robustness against overvoltage and undervoltage events shall be considered demonstrated 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 ($iQ_{,1}$ and $iQ_{,2}$) 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 fulfilled if, 80 ms after the sudden voltage change, the positive and negative components of the terminal voltage of the grid-forming unit ($u1$*,* $u2$*) can be verified 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 ($iQ_{,1}$ and $iQ_{,2}$*) remain, 80 ms after the sudden voltage change, within a band of ± 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 ± 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 damping.*

The additional requirement presented in Figure 12 (VDE-AR-N 4110) or Figure 10 (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. If the indicated requirements are verified by a suitable test (FGW TR3, Revision 26, Chapter 4.6.3.1), they shall be considered fulfilled and a corresponding manufacturer declaration is not required.

Verification that a symmetrical voltage magnitude 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 shall be considered demonstrated if indicated in a corresponding manufacturer's declaration.

5.5.5.6.4 Verification of behaviour when reaching and leaving current limits (Section 4.2.1.5.4)

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 specifications 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 4.2.1.5.4 shall be evaluated as follows:

For each symmetrical voltage dip, the THD (up to 2.5 kHz with a resolution of 25 Hz) of the currents ia, ib, ic of the grid-forming unit shall be determined 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 ia, ib, ic 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, the time profile of the apparent current $iS_{,1}$, $iS_{,2}$ as well as the active and reactive components $iP_{,1}$, $iP_{,2}$, $iQ_{,1}$, $iQ_{,2}$ of the positive and negative sequence components of the current of the grid-forming unit shall be evaluated. The average value of the apparent current $iS_{,1}$, $iS_{,2}$ exchanged with the network over the duration of the voltage dip or overvoltage shall be determined.

The average value of the active and reactive current $iP_{,1}$, $iQ_{,1}$ measured between 150 ms and 300 ms after the sudden voltage change shall be determined 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 ia, ib, ic and phase voltages ua, ub, uc 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 to 30 network periods.

For all measurements relating to symmetrical overvoltage and undervoltage tests, the instantaneous values of the phase voltages ua, ub, uc and phase currents ia, ib, ic 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 $iP_{,1}$, $iQ_{,1}$ and $iP_{,2}$, $iQ_{,2}$ of the current of the grid-forming unit in the positive and negative sequences shall be shown graphically.

The average values $i_{\mathrm{P1,End}}$, $i_{\mathrm{P2,End}}$, $i_{\mathrm{Q1,End}}$, $i_{\mathrm{Q2,End}}$ of the active and reactive current $iP_{,1}$, $iP_{,2}$, $iQ_{,1}$, $iQ_{,2}$ 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 $i_{\mathrm{P1,End,25}}$, $i_{\mathrm{P1,End,50}}$ and $i_{\mathrm{P1,End,75}}$ 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 $iS_{,1}$, $iS_{,2}$ exchanged with the network over the duration of the voltage dip or overvoltage shall be indicated.

Note for TR8:
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 shall be considered demonstrated 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, verification shall be considered demonstrated.

Proof of compliance with the requirements for current limitation in terms of magnitude (or when no direct reactive current prioritisation takes place) shall be considered demonstrated 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 for effective current behaviour until further notice.

Verification that the unit immediately switches to the operating state without current limitation (when current limitation is no longer required) shall be considered demonstrated if, the reactive current does not exceed a steady-state tolerance of ± 10 % I_r *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 *± 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_r ± 10 % U_r (Section 4.2.1.5.5)

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. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, the measurement shall be performed for the nominal value specified by the manufacturer. For other parameterisable values, the simulation-based verification shall be performed in accordance with Section 5.5.7.7.

5.5.5.6.5.2 Measurement procedure

The measurement shall be performed in accordance with Section 5.5.5.6.3. Pre-fault values should be determined over a period of 10 seconds before the fault occurs.

5.5.5.6.5.3 Evaluation

The evaluation is based on the positive and negative sequence components of the terminal voltage $u1$,$u2$ as well as the active and reactive current $iP_{,1}$, $iP_{,2}$, $iQ_{,1}$, $iQ_{,2}$ of the grid-forming unit.

The reference time for voltage recovery is the time at which the positive sequence voltage $u1$ 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 $iP_{,1}$ or $p1$ over the last seconds before the sudden voltage change.

To determine the rise time of the active current $iP_{,1}$ after the end of the fault, a tolerance band of ± 0.1 p.u. of the rated current of the unit is applied close to the pre-fault active current to be regulated. The rise time of the active current $iP_{,1}$ 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 positive sequence overvoltages at the terminals of the unit, the positive sequence voltage $u1$ 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 positive sequence value averaged over these 2 s of the evaluation time window under consideration is the final steady-state value of the voltage (final steady-state value $U_{1,\mathrm{End}}$ of the positive sequence voltage after voltage recovery).

5.5.5.6.5.4 Presentation in the measurement report

The instantaneous values of the phase currents ia, ib, ic and phase voltages ua, ub, uc at the terminals of the grid-forming unit shall be shown graphically from two network periods before voltage recovery over a total of 15 to 30 network periods.

The time progression of the measured positive sequence terminal voltages $u1$ of the grid-forming unit as well as the active and reactive components $iP_{,1}$, $iQ_{,1}$ of the positive sequence apparent current $iS_{,1}$ 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 $u1$ is reached after voltage recovery.

The time of voltage recovery and the time at which the active current $iP_{,1}$ 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 $u_{1,\mathrm{End}}$ to be used for the evaluation and the maximum value of the positive sequence voltage $u1$ after voltage recovery shall be labelled and their values shall be indicated.

Note for TR8:
Verification of correct behaviour for active current return after the end of the fault is provided when the pre-fault active current is reached again after 1 second. It shall be justified if the active current cannot reach this time due to technical restrictions.

Proof of compliance with the requirements for behaviour regarding temporary overvoltages after voltage recovery shall be considered demonstrated if the determined positive sequence overvoltages $u1$ does 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 Evidence of the behaviour of limited voltage source control during network faults (Section 4.2.1.5.3)

5.5.5.6.6.1 Aim of the measurement

The purpose of the measurement is to test the response of the grid-forming unit with regard to the implementation of effective limited voltage source control during network faults in accordance with the requirements defined in Section 4.2.1.5.3. In this context, it shall be determined whether the limited voltage source control effectively limits the conductor current of the grid-forming unit. The measurement shall only be performed for grid-forming units within the scope of VDE-AR-N 4110 commissioned after 1 January 2028.

5.5.5.6.6.2 Measurement procedure

The measurement shall be performed in accordance with FGW TR3, Revision 26, Chapter 4.6.3.1. However, instead of the tests specified in Table 4-80, the measurements specified in Table 7 in this FNN Guideline shall be performed.

Table 7 - Measurements for verifying limited voltage source control during network faults

Test number	**Remaining line-to-line voltage** U/U_n in p.u.	**Fault type**	**Fault duration** in ms	**Load**	**Reactive power** Q/P_n
50.3. FL.Lim	0.45 – 0.60	three-phase	≥ 1371 (for U = 0.45 p.u.) ≥ 1982 (for U = 0.60 p.u.)	Full load	0 to ± 10 %
50.3.FL.OE.Lim				Full load	20 % to max. bis max. overexcited
50.2.FL.Lim		two-phase	≥ 1610 (for U = 0.45 p.u.) ≥ 2305 (for U = 0.60 p.u.)	Full load	0 to ± 10 %
80.3.FL.Lim	0.65 – 0.75	three-phase	≥ 2593 (for U = 0.65 p.u.) ≥ 3000 (for U = 0.75 p.u.)	Full load	0 to ± 10 %
80.2.FL.Lim		two-phase	≥ 3000	Full load	0 to ± 10 %

5.5.5.6.6.3 Evaluation

The evaluation is performed in accordance with FGW TR3, Revision 26, Chapter 4.6.3.2, whereby the following applies in place of the section on ‘Limited dynamic network support’:

For the operating mode ‘limited voltage source control in the event of mains faults’, the following evaluation shall also be performed for voltage dips ≤ 0.8 U_n.

The maximum conductor currents shall be determined as single-period values for the following time ranges for the positive sequence value of the apparent current, the negative sequence value of the apparent current and the fundamental RMS values of the apparent currents of the three phases:

- 60 ms after $t \leq 0.8\,U_\mathrm{n}$ to 20 ms before fault clearance t2'.
- 100 ms after $t \leq 0.8\,U_\mathrm{n}$ to 20 ms before fault clearance t2'.

Time $t \leq 0.8\,U_\mathrm{n}$ is the time at which the smallest outer conductor voltage is ≤ 0.8 U_n.

5.5.5.6.6.4 Presentation in the measurement report

The presentation in the measurement report is in accordance with FGW TR3, Revision 26, Chapter 4.6.3.3, whereby for numbers 77 to 86 in Table 4-82, voltage dips ≤ 0.8 U_n shall be taken into account and the time $t \leq 0.8\,U_\mathrm{n}$ shall be used.

Note for TR8:
Verification shall be considered demonstrated when:

- *All necessary tests in accordance with FGW TR3 Revision 26 have been performed in full, taking into account the tests specified in Table 7 relating to the limited voltage source control.*
- *The voltage source control is maintained for all mains voltage dips below 0.8 U_n for a period of 150 ms.*
- *The maximum apparent current (of the three conductor currents) for all mains voltage dips below 0.8 U_n does not exceed 20% of the rated current I_r after a maximum of 210 ms.*
- *The maximum apparent current (of the three conductor currents) for all mains voltage dips below 0.8 U_n does not exceed 10% of the rated current I_r after a maximum of 250 ms.*

5.5.5.6.7 Verification of fast protection during high voltages (Section 4.2.1.7)

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 demonstrate in a comprehensible manner 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 4.2.1.7.2 are fulfilled.

Note for TR8:
Verification shall be considered demonstrated 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 4.2.1.7.2.*
- *The criteria used for shutdown shall be specified.*

5.5.5.7 Response to steep frequency gradients (RoCoF)(Section 4.2.1.10)

The requirement, that PGUs shall be able to ride through fast frequency changes in accordance with Section 4.2.1.10 without disconnecting from the network shall be verified by means of a manufacturer's declaration in accordance with the specifications in Clause 11.2.8 of the relevant Technical Connection Rules.

Note for TR8:
Verification shall be considered demonstrated if the manufacturer's declaration proves that the unit is able to ride through the RoCoF values required in accordance with Section 4.2.1.10 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 4.2.1.12)

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 8 shall be performed in each case.

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 setup or the impedance of the test equipment is unknown, a simulation-based verification (in accordance with Section 5.5.7.3) 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 % to 75 % P_{Emax}. The power factor cos φ shall be set to 1.0. If several settings are provided for the start-up time constant, the test shall be performed for $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$. For intermediate values, verification may be simulated in accordance with Section 5.5.7.3 as an alternative to measurement-based verification.

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 plants

- The active power curve may be influenced by a time-varying primary energy supply. To avoid this influence, the operating points defined in Table 8 should be reached in a throttled state.
- In the case of wind turbines, 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 of approximately 250 mHz to 500 mHz (see Table 8, column: Disturbance after measurement procedure 1). Select the amplitude of the frequency step 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 8 - Tests to verify damping of power-frequency-oscillations

Test	Active power	PCNB	Disturbance after measurement procedure 1	Disturbance after measurement procedure 2
1	50 - 75 % P_{Emax} a)	deactivated	+Δf_{ref}	$\Delta\theta_{\text{pd}}$ c)
2	50 - 75 % P_{Emax} a)	deactivated	- Δf_{ref}	$\Delta\theta_{\text{npd}}$ c)
3	50 - 75 % P_{Emax} a)	activated b)	+Δf_{ref}	$\Delta\theta_{\text{pd}}$ c)
4	50 - 75 % P_{Emax} a)	activated b)	- Δf_{ref}	$\Delta\theta_{\text{npd}}$ c)

a) For bidirectional units, the tests shall be performed for both power directions (charging and discharging operation).
b) The frequency deadband 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 step
Apply a phase step to the grid-forming unit and evaluate the active power response of the unit (see Table 8, column: Disturbance after measurement procedure 2). The excitation by a phase step may be generated by various methods:

- application through a network emulator,
- connecting a phase 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.

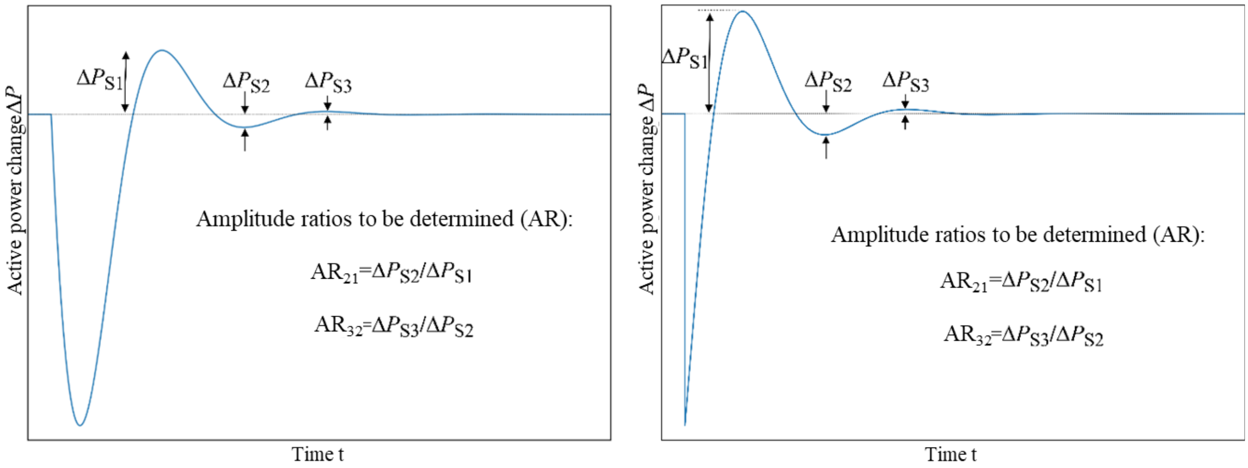
Select the magnitude of the phase angle step so that it results in a change in active power of 15 % to 30 % P_{Emax} in the procured direction or 2 % to 4 % P_{Emax} in the non-procured direction.

Ensure that the change in active power in response to the phase 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 $p1$ 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 illustrated in Figure 11 for amplitude ratios AR_{21} and AR_{32}, based on the active power change ΔP (difference between the actual value and the initial steady-state value of the active power at the start of the active power measurement). If Measurement 1 is used, its influence may be eliminated when evaluating damping for measurements with activated PCNB.

NOTE The signal path of the active power change in Figure 11 is based on a second-order system with a damping ratio of 0.45. The influence of the PCNB may be neglected.



a) b)

Figure 11 - Calculation example of damping of frequency-power-oscillations; a) excitation by means of frequency step, b) excitation by means of phase step

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 $p1$ 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 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 shall be considered fulfilled if the determined damping factor does not fall below the value specified in Section 4.2.1.12 by more than 10% (i.e. $D \geq 0.45$). If a total of three maxima and minima can be identified from the profile of the positive sequence active power, the two determined amplitude ratios of the successive minima and maxima (AR_{21} and AR_{32}) shall be less than 0.2. If fewer than three maxima and minima can be identified from the course of the active power of the positive sequence, then the condition shall also be considered fulfilled.

5.5.5.9 Verification of the start-up time constants T_A and the inertia power and energy (Sections 4.2.1.13 and 4.2.1.14)

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. In addition, it shall be determined whether higher priority is given to inertia power in accordance with Section 4.2.3 before specifications by third parties or the network security management of the system operator.

5.5.5.9.2 Measurement procedure

If verification is demonstrated for a setting range of T_A, the following measurements shall be performed at least with the minimum and maximum setting values $T_\mathrm{A,min}$ and $T_\mathrm{A,max}$. For the range between these values, a simulation-based verification in accordance with Section 5.5.7.4 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 9 and a reactive power of 0 ± 5 % relative to P_{Emax}, perform the measurement 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 9), 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.

For Measurements 1.1 to 1.4, use an active power limiting setpoint as the highest-priority limiting setpoint in accordance with Section 4.2.3 (e.g. interface that would be used within the framework of a network security management command) so that the limited value is exceeded due to the existing inertia power. For this purpose, throttling in accordance with footnote a) Table 9 may be implemented through the highest-priority limiting setpoint.

If positive inertia is procured only through the market, Measurements 1.1 to 1.4 are not required.

Ensure that the grid-forming unit is 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. Use a constant primary energy supply when performing this test on a test bench. For free-field measurements, continuously record the available primary power which is being continuously determined on the PGU side or a representative substitute variable for grid-forming PGUs. Repeat the measurement if the available primary power or the power derived from it changes by more than ± 5 % P_{Emax} during the measurement. Alternatively, measurements 1.1 and 1.2 may be performed in a throttled state.

The minimum value $P_{\mathrm{limitneg,min}}$ and maximum value $P_{\mathrm{limitneg,max}}$ for the full provision of inertia as well as the value $P_{\mathrm{min,dyn}}$ shall be determined by the manufacturer and indicated in the unit certificate.

NOTE 1 The specified power values $P_{\mathrm{limitneg,min}}$, $P_{\mathrm{limitneg,max}}$ and $P_{\mathrm{min,dyn}}$ are determined as part of the verification process on the basis of an operating point of the unit at $Q \approx 0$ and ambient conditions (e.g. temperature/air pressure) that do not impose any restrictions on the nominal conditions (see Section 3.1.8). When reactive power is supplied at the same time, these may be lower due to apparent current limits. This influence is accepted but shall be disclosed as part of the plant certification process.

Perform Measurements 1.3 and 1.4 only if T_{A} in segment (3) in Figure 4 (a) could not be verified through Measurements 1.1 and 1.2.

Table 9 - 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	$\mathrm{P}_{\text{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	deactivated	Throttled state permitted for PGUs	Testing of T_{A} in segments (1) and (2) and, if required, (3)
1.2	$\mathrm{P}_{\text{limitneg,max}}$: Maximum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	deactivated		
1.3	$\mathrm{P}_{\text{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	deactivated	Throttled state permitted for PGUs a)	Testing of T_{A} in segment (3)
1.4	$\mathrm{P}_{\text{limitneg,max}}$: Maximum value for the full provision of inertia b) (tolerance ± 5 % $_{\text{Emax}}$)	deactivated		
1.5	$\mathrm{P}_{\text{limitneg,min}}$ or $P_{\text{limitpos,min}}$: Minimum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	activated	Throttled state permitted for PGUs	Testing of 1.5 times the energy amount Where applicable, testing of T_{A} in segment (3) with disclosure of internal signals
1.6	$\mathrm{P}_{\text{limitneg,max}}$ or $P_{\text{limitpos,max}}$: Maximum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	activated		

a) 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_{Emax}.

b) The active power output 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).

Table 10 - 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	$P_{\mathrm{limitpos,min}}$: Minimum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	deactivated	Testing of T_{A} in segments (1) and (2) and, if required, (3)
2.2	$P_{\mathrm{limitpos,max}}$: Maximum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	deactivated	
2.3	$P_{\mathrm{limitpos,min}}$: Minimum value for the full provision of inertia [a](tolerance ± 5 % P_{Emax})	deactivated	Testing of T_{A} in segment (3)
2.4	$P_{\mathrm{limitpos,max}}$: Maximum value for the full provision of inertia [a] (tolerance ± 5 % P_{Emax})	deactivated	
2.5	$P_{\mathrm{limitpos,min}}$ or $P_{\mathrm{limitneg,min}}$: Minimum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	activated	Testing of 1.5 times the energy amount Where applicable, testing of T_{A} in segment (3) with disclosure of internal signals
2.6	$P_{\mathrm{limitpos,max}}$ or $P_{\mathrm{limitneg,max}}$: Maximum value for the full provision of inertia (tolerance ± 5 % P_{Emax})	activated	

c) The active power output 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. $P_{\mathrm{Emax,B}}$ 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 10 and a reactive power of 0 ± 5 % relative to P_{Emax}, perform this measurement 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.

For Measurements 2.1 to 2.4, use an active power limiting setpoint as the highest-priority limiting setpoint in accordance with Section 4.2.3 (e.g. interface that would be used within the framework of a network security management command) so that the limited value is exceeded due to the existing inertia power.

If only negative inertia is procured, Measurements 2.1 to 2.4 are not required.

Ensure that the grid-forming unit is in normal operating condition in both variants. A constant primary energy supply is assumed for Measurements 2.1 and 2.2. Do not perform the measurements at an active power operating point with power reduction. Use a constant primary energy supply when performing this test on a test bench. For free-field measurements, continuously record the available primary power which is being continuously determined on the PGU side or a representative substitute variable for grid-forming PGUs. Repeat the measurement if the available primary power or the power derived from it changes by more than ± 5 % P_{Emax} during the measurement.

The minimum value $P_{\mathrm{limitpos,min}}$ and maximum value $P_{\mathrm{limitpos,max}}$ for the full provision of inertia as well as the value $P_{\mathrm{max,dyn}}$ shall be indicated by the manufacturer in the unit certificate.

NOTE 2 The specified power values $P_{\mathrm{limitpos,min}}$, $P_{\mathrm{limitpos,max}}$ and $P_{\mathrm{max,dyn}}$ are determined as part of the verification process on the basis of an operating point of the unit at $Q \approx 0$ and ambient conditions (e.g. temperature/air pressure) that do not impose any restrictions on the nominal conditions (see Section 3.1.8). When reactive power is supplied at the same time, these may be lower due to apparent current limits. This influence is accepted but shall be disclosed as part of the plant certification process.

Perform Measurements 2.3 and 2.4 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, then repeat the respective test of segment 1 at an adjusted active power operating point. Do this until the tolerance limit of -5% relative to the magnitude of the inertia power expected for the original active-power operating point (see Table 10) 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 verifying 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 for 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 active power output $p1$ 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 (21) for each segment or time period in Figure 4 (a).

$$\Delta P = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{\Delta f / f_{\mathrm{n}}}{\Delta t}\right) \tag{21}$$

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 (22) to (24).

$$\Delta P_1 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{2\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{22}$$

$$\Delta P_2 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{1/3\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{23}$$

$$\Delta P_3 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{-1\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{24}$$

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 12):

$$\Delta P_{01} = \Delta P_1 \tag{25}$$

$$\Delta P_{12} = \Delta P_2 - \Delta P_1 \tag{26}$$

$$\Delta P_{23} = \Delta P_3 - \Delta P_2 \tag{27}$$

To check that the expected values were achieved, a tolerance band of ± 5 % of the expected change in inertia power (ΔP_{01}, ΔP_{12} and ΔP_{23}) according to equations (25) to (27) is used, provided that the T_{A} to be verified is < 10 s. It shall be determined whether the measured power *p1* 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 % no later than 1 s after the start of the segment,
- Segments (2) and (3): a tolerance band of ± 5 % 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. This shall be done until in the time period of segment (1) the tolerance limit of -5% relative to the magnitude of the inertia power expected for the original active power operating point (see Table 10) 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 *p1* in Measurements 1.5 and 1.6 remains continuously below the active power output (active power operating point of the grid-forming unit according to Table 9) from the end of segment (3) Figure 4 (a). If the active power *p1* exceeds its initial value from the end of segment (3) Figure 4 (a), ΔE_{neg} and ΔE_{pos} shall be determined according to:

$$\Delta E_{\mathrm{neg}} = \int_{t_{\mathrm{n1}}}^{t_{\mathrm{n2}}} (P(t) - P_0)\,\mathrm{d}t \tag{28}$$

$$\Delta E_{\mathrm{pos}} = \int_{t_{\mathrm{p1}}}^{t_{\mathrm{p2}}} (P(t) - P_0)\,\mathrm{d}t \tag{29}$$

where the intermediate variables are defined as follows:

$P(\mathrm{t})$	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

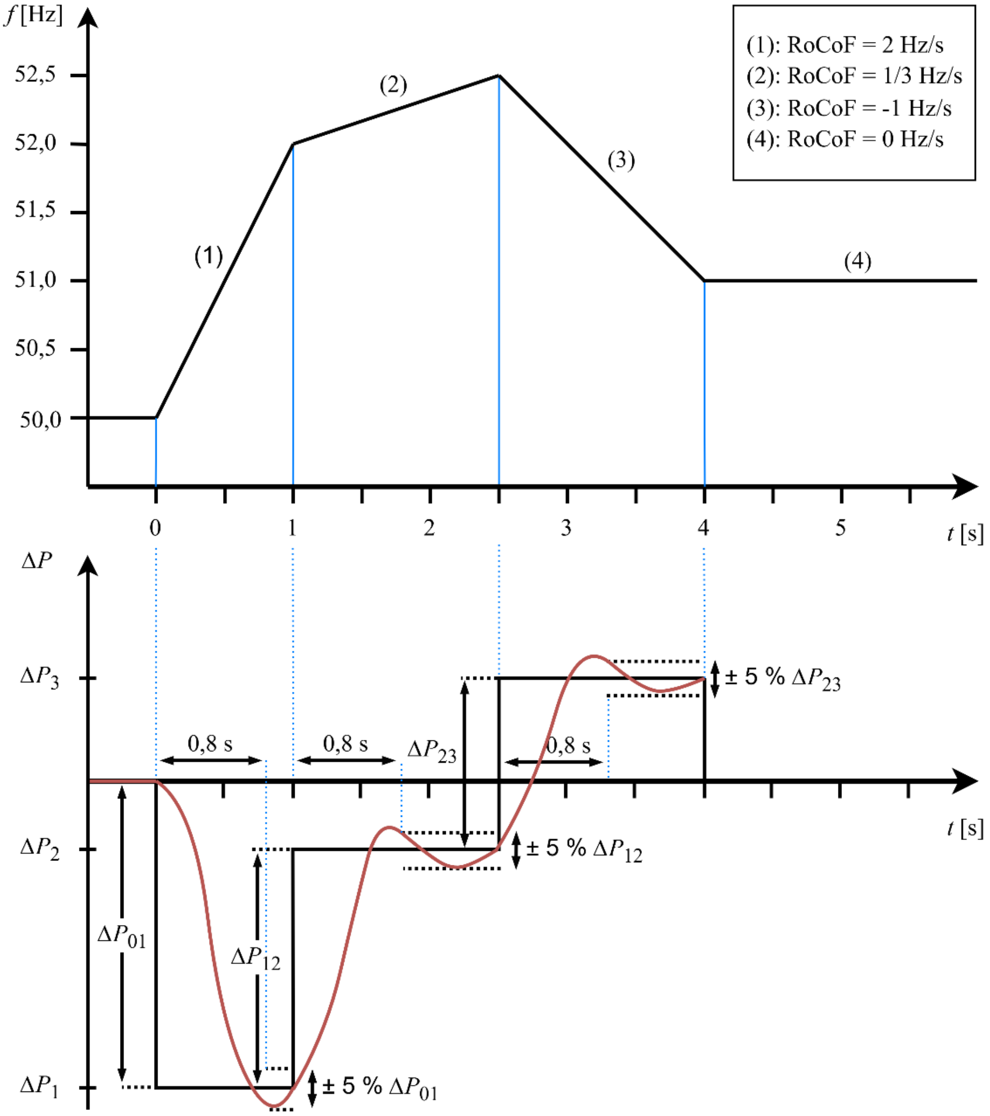


Figure 12 - Example of an evaluation of the start-up time constants and the inertia power during the market-based procurement of negative inertia for T_A < 10 s

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 time 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 condition is reached after segment (3) with a tolerance band of ± 5 % P_{Emax}.

3) In segments (1) and (2) in Figure 4 (a), for the periods in which the active power $p1$ is above or below the active power output (active power operating point of the grid-forming unit according to Table 9), an integral value ($\Delta E_{\text{pos},12}$ or $\Delta E_{\text{neg},12}$ according to equation (29) or (28)) shall be determined for the deviation of the active power $p1$ from the initial value.

4) In segment (3) in Figure 4 (a), for the time periods in which the active power $p1$ is above or below the active power output, an integral value ($\Delta E_{\text{pos},3}$ or $\Delta E_{\text{neg},3}$ according to equation (29) or (28)) shall be determined based on the deviation of the active power $p1$ from the initial value.

5) From the end of segment (3) in Figure 4 (a) until the end of the evaluation time window $T_{\mathrm{Assessment}}$, an integral value ($\Delta E_{\mathrm{pos},4}$ or $\Delta E_{\mathrm{neg},4}$ according to equation (29) or (28)) shall be determined again for the periods in which the active power $p1$ is above or below the active power output, based on the deviation of the active power $p1$ 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 using the active power output $p1$ for periods (1) and (2) as shown in Figure 4 (b) when performing Measurements 2.1 and 2.2, and for period (3) when performing Measurements 2.3 and 2.4. If the verification of T_{A} in segment (3) in Section 5.5.5.9.2 were 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 (30) for each segment or time period in Figure 4 (b).

$$\Delta P = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{\Delta f / f_{\mathrm{n}}}{\Delta t}\right) \tag{30}$$

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 (31) to (33).

$$\Delta P_1 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{-2\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{31}$$

$$\Delta P_2 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{-1/3\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{32}$$

$$\Delta P_3 = -T_{\mathrm{A}} \cdot P_{\mathrm{rE}} \cdot \left(\frac{+1\ \mathrm{Hz/s}}{50\ \mathrm{Hz}}\right) \tag{33}$$

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 (25) and (27).

To check that the expected values were achieved, a tolerance band of ± 5 % of the expected change in inertia power (ΔP_{01}, ΔP_{12} and ΔP_{23}) according to equations (25) to (27) is used, provided that the T_{A} to be verified is < 10 s. It shall be determined whether the measured power $p1$ 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 % no later than 1 s after the start of the segment,
- Segments (2) and (3): a tolerance band of ± 5 % 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. This shall be done until, within the time interval of segment 1, the tolerance limit of −5% relative to the magnitude of the inertia power expected for the original active power operating point (see Table 10) 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 $p1$ in Measurements 2.5 and 2.6 remains continuously above the active power output (active power operating point of the grid-forming unit according to Table 10) from the end of segment (3) in Figure 4 (b). If the active power $p1$ exceeds its initial value from the

end of segment (3), ΔE_{pos} and ΔE_{neg} shall be determined using equation (29) or (28) taking Figure 4 (b) into account.

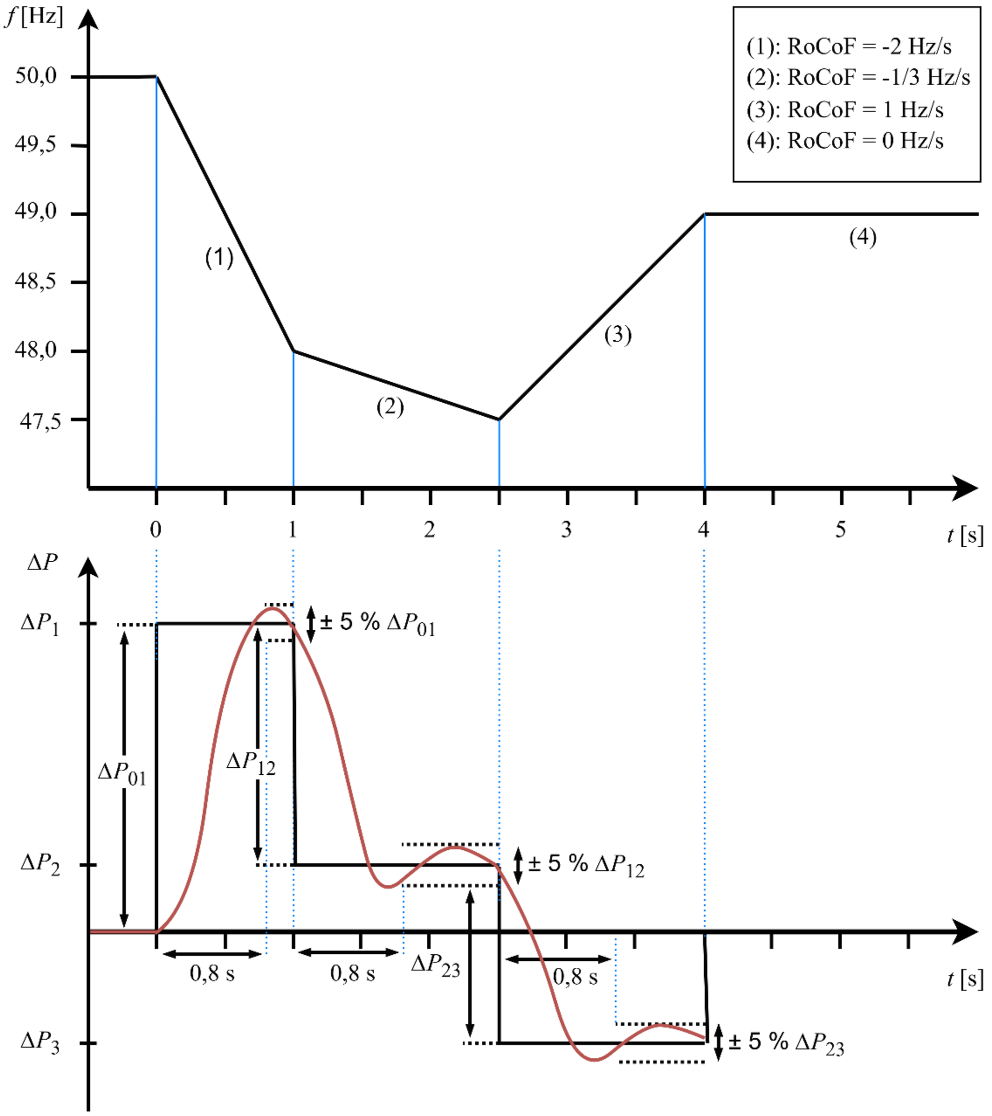


Figure 13 - Example of an evaluation of the start-up time constants and the inertia power during the market-based procurement of positive inertia for T_A < 10 s

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 time window $T_{\mathrm{Evaluation}}$ 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 condition is reached after segment (3) with a tolerance band of ± 5 % P_{Emax}.

3) In segments (1) and (2) in Figure 4 (b), for the time periods in which the active power $p1$ is above or below the active power output, an integral value ($\Delta E_{\mathrm{pos,12}}$ or $\Delta E_{\mathrm{neg,12}}$ according to equation (29) or (28)) shall be determined for the deviation of the active power $p1$ from the initial value.

4) In segment (3) in Figure 4 (b), for the time periods in which the active power $p1$ is above or below the active power output, an integral value ($\Delta E_{\text{pos},3}$ or $\Delta E_{\text{neg},3}$ according to equation (29) or (28)) shall be determined for the deviation of the active power $p1$ 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 $p1$ is above or below the active power output, an integral value ($\Delta E_{\text{pos},4}$ or $\Delta E_{\text{neg},4}$ according to equation (29) or (28)) shall be determined based on the deviation of the active power $p1$ from the initial value.

5.5.5.9.3.3 Evaluation of an 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 by a recalculation from the recorded time responses based on the gradients of the speed or frequency and the input variables of the frequency-forming quantities (often state variables).The determination shall be performed in accordance with the specific implementation used to realise the start-up time constant. When evaluating the tests, it shall be ensured that the start-up time constant T_A actually governing the system behaviour 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, documenting the determination of the start-up time constant in the test report is not required.

The general approach 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: $T_A = (p_{\text{gen}} - p_{\text{actual}} - p_D) / (\mathrm{d}\omega/\mathrm{d}t)$, 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 damping contributions may be combined in the signal P_D. A clear description 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 $u1$, the positive sequence active current $iP_{,1}$ and the positive sequence active and reactive power $p1$, $q1$ at the terminals of the grid-forming unit shall be shown. In addition, the active power limiting setpoint 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 $f1$ 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 shall be 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) (where 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 shall be considered verified if the determined value does not deviate by more than 5 % from the agreed value,*
- *the inertia power is not restricted by the active power limiting setpoint (prioritisation),*
- *the evaluation of Point 3) of Measurement procedure 1 shows that* $\Delta E_\mathrm{pos} \leq 1.5\,\Delta E_\mathrm{neg}$*.*

Measurement procedure 1 shall be 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*
  $(|\Delta E_\mathrm{pos,12}| + |\Delta E_\mathrm{neg,3}| + |\Delta E_\mathrm{pos,4}| + |\Delta E_\mathrm{neg,4}|) \leq 1.5 \cdot (|\Delta E_\mathrm{neg,12}| + |\Delta E_\mathrm{pos,3}|)$.

Measurement procedure 2 shall be 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) (where 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 shall be considered verified if the determined value does not deviate by more than 5 % from the agreed value,*
- *the inertia power is not restricted by the active power limiting setpoint (prioritisation),*
- *the evaluation of Point 3) of measurement procedure 2 shows that* $\Delta E_\mathrm{neg} \leq 1.5\,\Delta E_\mathrm{pos}$*.*

Measurement procedure 2 shall be 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*
  $(|\Delta E_{neg,12}| + |\Delta E_{pos,3}| + |\Delta E_{neg,4}| + |\Delta E_{pos,4}|) \leq 1.5 \cdot (|\Delta E_{pos,12}| + \Delta E_{neg,3}|)$.

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. The measurement shall be performed for all PGU technologies, regardless of whether a limited setting range is required according to Table 15.

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 delayed signal or offset 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 % P_{Emax}. Provide the following frequency steps for the offset to be applied to the frequency setpoint:

- Step 1: Setpoint - actual frequency + 300 mHz
- Step 2: Setpoint - actual frequency + 800 mHz
- Step 3: Setpoint - actual frequency + 1.3 Hz
- Step 4: Setpoint - actual frequency + 300 mHz
- Step 5: Setpoint - 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 the active power output corresponding to the minimum power. Proceed with the intended frequency steps as follows:

- Step 1: Setpoint - actual frequency – 300 mHz
- Step 2: Setpoint - actual frequency – 800 mHz
- Step 3: Setpoint - actual frequency – 2.0 Hz
- Step 4: Setpoint - actual frequency – 300 mHz
- Step 5: Setpoint - 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 active power output (active power ramp rate) shall be determined from the entire time profile of the active power $p1$ of the grid-forming unit for each measurement (step). 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 $p1$ 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 and the active power gradients shall be labelled, and their values shall be indicated. In addition, the T_{A} used to parameterise the grid-forming unit during the measurements shall be specified.

Note for TR8:
The measurement shall be considered passed if the final steady-state values of the active power $p1$ deviate by a maximum of ± 5 % of the expected power change or ± 0.5 % P_{Emax} from the values resulting from the set droop. The unit shall also comply at least with the active power ramp rates according to Table 15. If no minimum requirements are specified for the grid-forming unit in accordance with Table 15, verification of the actuating speeds shall be considered demonstrated through their identification.

5.5.6 Supplementary verification of controller functions

5.5.6.1 Prioritisation of active power setpoints in the event of underfrequency

5.5.6.1.1 Aim of the measurement

The aim of the measurement is to verify the effective implementation of the prioritisation requirements in accordance with Section 4.2.3 corresponding to the relevant Technical Connection Rules. A distinction shall be made between the following types of verification:

a) the prioritisation of primary control based on network security in the event of an underfrequency event (see point 5, Section 4.2.3) and

b) the prioritisation of voltage source behaviour (see Points 3 and 2 in Section 4.2.3) or behaviour based on start-up time constants (see Points 4 and 3 in Section 4.2.3).

In both cases setpoints are issued simultaneously by third parties (e.g. a direct marketer) or by the network security management of the system operator.

In case a), the measurement is performed in accordance with the criteria described below on the basis of Supplement 26.1 of TR3, taking into account the additions and deviations specified below.

In case b), proof shall be provided in the verifications specified in Sections 5.5.5.3 and 5.5.5.9.

5.5.6.1.2 Measurement procedure

As this is purely a functional test of prioritisation, this measurement may generally be performed on appropriate test benches. For measurements on components, the control variable of active power may also be used as the output variable instead of the actual active power.

NOTE As already described in the TR3 supplement, the tests described here are purely functional and do not require the determination of dynamic parameters and control accuracies.

The measurement is performed on the basis of Chapter 2.2 (Test Procedure) of Supplement 1 to FGW TR 3 Revision 26. In deviation from the supplement, the following parameters are specified for the measurement:

- Standard droop in accordance with Table 3
- Instead of the gradients defined in the supplement (‘$\Delta P/\Delta f$...’), the specifications according to Table 14 and Table 15 apply
- The requirements regarding start-up and settling times for the ‘$P(f)$ control’ described in the supplement do not apply.

If components beyond the unit (e.g. PGM controller) are used for the full implementation of the PCNB function (including measurement and control), compliance with the requirements shall be demonstrated for the respective combination of unit and components. The verification may have been provided as part of the unit certificate with an external component.

5.5.6.1.3 Evaluation

The evaluation is based on Section 2.3 (Evaluation) of Supplement 1 to FGW TR 3 Revision 26.

5.5.6.1.4 Presentation in the measurement report

The presentation in the measurement report is based on Section 2.4 (Presentation) of Supplement 1 to FGW TR 3 Revision 26. Notwithstanding this, the following applies instead of the fourth point: “The final steady-state value of the active power adjustment resulting from the simulated or specified frequency and the droop as the setpoint for active power in the range of the PCNB.“

5.5.7 Supplementary verifications based on simulations

5.5.7.1 Simulation-based verification of phase jump power (Section 4.2.1.1)

5.5.7.1.1 General information

If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, a simulation-based test in accordance with this section shall be performed for the minimum and maximum values in addition to the measurement-based verification in accordance with Section 5.5.5.3 (in which the gain nominal value of the voltage source control is specified).

5.5.7.1.2 Aim of the test

The aim of the simulation-based test is to determine the phase jump power provided by the grid-forming unit. This involves checking compliance with the requirements in Section 4.2.1.1.

5.5.7.1.3 Test procedure

Test environment
The simulation-based test is performed based on the detailed RMS model, which has been 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 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. In the grid-forming unit, the minimum and maximum gain values of the voltage source control and the effective impedance shall be set for all tests in accordance with the manufacturer's specifications.

Performing the test
The test shall be simulated in accordance with Section 5.5.5.3.2, whereby the measurement method used for measurement-based verification shall be used.

5.5.7.1.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications in Section 5.5.5.3.3, taking into account the simulated values of$\Delta\delta_{1,\mathrm{S}}$, $\Delta i_{\mathrm{P,PGU,S}}$, $\delta_{\mathrm{n1,S}}$, $\delta_{\mathrm{v1,S}}$, $\Delta i_{\mathrm{P1,PGU,max,S}}$, $p\alpha\beta,\mathrm{S}$ and $iP_{,\alpha\beta},\mathrm{S}$.

The test report shows the minimum and maximum values of the parameterised gain of the voltage source control and the effective impedance of the grid-forming unit for the respective simulated values and simulated curves in accordance with Section 5.5.5.3.4.

Note for TR8:
The simulation-based test shall be considered passed if the following criteria are fulfilled for the minimum and maximum values of the voltage source control gain and the effective impedance:

- *The maximum active current change $\Delta i_{P,PGU,S}$ is at least 50% (70% for PGSU and storage) in the procured direction and at least 5% of the determined maximum value $\Delta i_{P1,PGU,max,S}$ in the non-procured direction. A tolerance of 1 % of the nominal active current may be assumed.*
- *The maximum active power change is at least 5% P_{Emax} in the non-procured direction.*
- *The phase jump power is not restricted by the active power limiting setpoint.*

5.5.7.2 Simulation-based verification of the effective impedance (Section 4.2.1.1)

5.5.7.2.1 General information

If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, a simulation-based test in accordance with this section shall be performed for the minimum and maximum values in addition to the measurement-based verification in accordance with Section 5.5.5.4 (in which the nominal value of the voltage source control gain or the effective impedance is provided).

5.5.7.2.2 Aim of the test

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

5.5.7.2.3 Test procedure

Test setup

The simulation-based test is performed based on the detailed RMS model, which has been 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 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. In the grid-forming unit, the minimum and maximum gain values of the voltage source control and the effective impedance shall be set for all tests in accordance with the manufacturer's specifications.

Performance of the test

The test shall be simulated in accordance with Section 5.5.5.4.2, whereby the measurement method used for measurement-based verification shall be used.

5.5.7.2.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications in Section 5.5.5.4.3, taking into account the simulated values of $\underline{u}_{1,\mathrm{v}}$, $\underline{u}_{1,\mathrm{n}}$, $\underline{i}_{\mathrm{S1,v}}$, $\underline{i}_{\mathrm{S1,n}}$, $\Delta u_{\mathrm{setpoint}}$ and $z_{\mathrm{w,1}}$.

The test report shows the minimum and maximum values of the parameterised gain of the voltage source control and the effective impedance of the grid-forming unit for the respective simulated values and simulated curves in accordance with Section 5.5.5.4.4.

Note for TR8:
The simulation-based verification shall be considered demonstrated if, for the minimum and maximum values of the voltage source control gain or the effective impedance, the magnitudes of the determined impedance $|\underline{z}_{w,1}|$ *correspond to the specifications for the maximum value* $z_{w,max}$ *in accordance with Section 4.2.1.1.*

5.5.7.3 Simulation-based verification of damping of power-frequency-oscillations (Section 4.2.1.12)

5.5.7.3.1 General information

The tests described below shall only be performed if the manufacturer of the grid-forming unit has specified more than two parameterisations of the start-up time constant T_{A}, meaning $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$, for the grid-forming unit under test. 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 setup or test equipment is unknown. As a prerequisite, the required model validation shall include the test environment. If the requirements in Section 4.2.1.12 were verified for the values to be reported between $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$ by means of a measurement-based verification in accordance with Section 5.5.5.8, it is not required to perform the simulation-based tests described below.

5.5.7.3.2 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 $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$. If, instead of a measurement-based verification of the damping of power-frequency-oscillations for $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$ in accordance with Section 5.5.5.8.2, a simulation-based verification is used, the damping of power-frequency-oscillation for values of $T_{\mathrm{A,min}}$ and $T_{\mathrm{A,max}}$ shall be determined.

5.5.7.3.3 Test procedure

Test environment

The simulation-based test is performed based on the detailed RMS model, which has been validated in accordance with Section 5.5.3.6.2, in a simulation-based test environment that corresponds to the test environment in Figure 9. The network emulator shown in Figure 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. The test environment shall be parameterised so that the simulation-based tests of the grid-forming unit are performed 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 also require 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 defined in Table 8 (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 plants” in Section 5.5.5.8.2 also apply to the simulation-based verification.

5.5.7.3.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications of Section 5.5.5.8.3, taking into account the simulated active power $p1_{,\mathrm{S}}$. Alternatively, the damping of frequency-power-oscillations may also be determined taking into account Appendix A.I based on the simulated active power $p1_{,\mathrm{S}}$. Intrinsic value determination may be used, provided that the intrinsic values determined for $T_\mathrm{A,min}$ and $T_\mathrm{A,max}$ do not deviate from the measurement results by more than ± 10 %.

The signal used to excite the power-frequency-oscillations and the profile of the active power $p1_{,\mathrm{S}}$ 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 shall be considered fulfilled if the determined damping factor does not fall below the value specified in Section 4.2.1.12 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 shall also be considered fulfilled, provided that the first amplitude ratio (*AR_{21}*) is less than 0.25.*

5.5.7.4 Simulation-based verification of the start-up time constants as well as the inertia power and energy (Sections 4.2.1.13 and 4.2.1.14)

5.5.7.4.1 General information

The tests described below shall only be performed if the manufacturer of the grid-forming unit has specified more than two parameterisations of the start-up time constant T_A, meaning $T_\mathrm{A,min}$ and $T_\mathrm{A,max}$, in the grid-forming unit under test. It is not required to perform the simulation-based tests described below if the requirements in Section 4.2.1.14 are verified for the values between $T_\mathrm{A,min}$ and $T_\mathrm{A,max}$ through a measurement-based verification in accordance with Section 5.5.5.9.

5.5.7.4.2 Aim of the test

The aim of the simulation-based test is to determine the start-up time constant set or parameterised 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 meet the requirements in Sections 4.2.1.13 and 4.2.1.14.

5.5.7.4.3 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 Figure 9. The network emulator shown in Figure 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised 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 verifying the start-up time constant T_A meet the requirements in Section 5.5.5.9.

5.5.7.4.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications of Section 5.5.5.9.3, taking into account the simulated active power $p1_{,\mathrm{S}}$.

The test report shall show the time sequence of the simulated positive sequence voltage $u1_{,\mathrm{S}}$, positive sequence current $iP_{,1,\mathrm{S}}$ and positive sequence active power $p1_{,\mathrm{S}}$ and reactive power $q1_{,\mathrm{S}}$ 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 $f1_{,\mathrm{S}}$ 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 shall be 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) (where 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 shall be considered demonstrated 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 $\Delta E_\mathrm{pos} \leq 1.5\, \Delta E_\mathrm{neg}$.*

The simulated measurement procedure 1 shall be 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* $(|\Delta E_\mathrm{pos,12}| + |\Delta E_\mathrm{neg,3}| + |\Delta E_\mathrm{pos,4}| + |\Delta E_\mathrm{neg,4}|) \leq 1.5 \cdot (|\Delta E_\mathrm{neg,12}| + |\Delta E_\mathrm{pos,3}|)$.

The simulated measurement procedure 2 shall be 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) (where 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 shall be 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* $\Delta E_{\mathrm{neg}} \leq 1.5\, \Delta E_{\mathrm{pos}}$.

The simulated measurement procedure 2 shall be 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* $(|\Delta E_{\mathrm{neg},12}| + |\Delta E_{\mathrm{pos},3}| + |\Delta E_{\mathrm{neg},4}| + |\Delta E_{\mathrm{pos},4}|) \leq 1.5 \cdot (|\Delta E_{\mathrm{pos},12}| + \Delta E_{\mathrm{neg},3}|)$.

5.5.7.5 Simulation-based test of the setpoint tracking behaviour of voltage source control (Section 4.2.1.5)

5.5.7.5.1 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. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, a simulation-based test in accordance with this section shall be performed for the parameterisable values.

5.5.7.5.2 Aim of the test

The aim of the simulation-based test is to determine the setpoint tracking behaviour of the voltage source 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.

5.5.7.5.3 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 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised 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 $Z_{\mathrm{Network}}= 0.05$ 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_{Emax} is not required.

5.5.7.5.4 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 $u1_{,\mathrm{S}}$ and the simulated reactive current $iQ_{,1,\mathrm{S}}$ and active current $iP_{,1,\mathrm{S}}$.

The test report shall show the time profile of the setpoint and the evaluated variable ($u1_{,\mathrm{S}}$ or $iQ_{,1,\mathrm{S}}$). The determined rise time shall be indicated.

Note for TR8:
Verification shall be considered demonstrated if the determined rise time of the simulated voltage (or alternatively of the simulated current) is < 1 s.

5.5.7.6 Simulation-based verification of the disturbance behaviour of the voltage source control (Section 4.2.1.5)

5.5.7.6.1 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. If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, a simulation-based test in accordance with this section shall be performed for the parameterisable values.

5.5.7.6.2 Aim of the test

The aim of the simulation-based test is to determine the disturbance behaviour of the voltage source control of the grid-forming unit as well as to check compliance with the dynamic requirements for voltage source control 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 voltage source control of the grid-forming unit in parallel operation with another grid-forming unit shall be determined if required.

5.5.7.6.3 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 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised 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 shown in Figure 9 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_{Network} = 0.05 p.u. and 0.3 p.u. relative to S_{Emax} of the grid-forming unit (corresponds to SCR = 20 or SCR = 3 at the PGU). A reactive power change of more than 30 % relative to P_{Emax} is not required. If required, repeat the test in parallel operation with a grid-forming unit of the same type.

5.5.7.6.4 Evaluation and presentation of the test report

The simulation-based tests shall be evaluated in accordance with the specifications in Section 5.5.5.6.2.3, taking into account the simulated voltages $u\alpha\beta_{,5ms,\mathrm{S}}$, $u1_{,\mathrm{S}}$ and the simulated currents $i\alpha\beta_{,5\mathrm{ms},\mathrm{S}}$, $iQ_{,1,\mathrm{S}}$.

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 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 $iQ_{,1,S}$ *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 10 after the sudden voltage change (in accordance with the specifications 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 … 1.15.*

5.5.7.7 Simulation-based verification of response after return to the voltage band of U_r ± 10 % U_r (Section 4.2.1.5.5)

5.5.7.7.1 General information

If the manufacturer allows setting parameters for the voltage source control gain or the effective impedance of the grid-forming unit, a simulation-based test in accordance with this section shall be performed for the parameterisable values, with the exception of the nominal value.

5.5.7.7.2 Aim of the test

The aim of the simulation-based test 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.

5.5.7.7.3 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 9 shall be replaced by a network equivalent in the simulation-based environment. The elements of the test environment shall be parameterised in accordance with the real test environment so that the simulation-based test environment reflects the real test conditions. In the grid-forming unit, the voltage source control gain or effective impedance shall be set in accordance with the manufacturer's specifications.

Performance of the test

The test shall be performed as a simulation in accordance with Section 5.5.5.6.3.2.

5.5.7.7.4 Evaluation and presentation of the test report

The simulation-based test shall be evaluated in accordance with the specifications in Section 5.5.5.6.5.3, taking into account the simulated positive sequence voltage $u1_{,S}$, $u2_{,S}$ and the simulated reactive current $iQ_{,1,S}$, $iQ_{,2,S}$ and active current $iP_{,1,S}$ and $iP_{,2,S}$.

The test report shall show the respective parameterised voltage source control gains and the effective impedance of the grid-forming unit for the respective simulated values and the respective simulated curves in accordance with Section 5.5.5.6.5.4.

Note for TR8:
Simulation-based verification of correct behaviour for active current return after the end of a fault is provided if, for the voltage source control gains parameterised according to the manufacturer's specifications or the effective impedance (with the exception of the nominal value specified by the manufacturer) the pre-fault active current is reached again after 1 s. It shall be justified if the active current cannot reach this time due to technical restrictions.

The simulation-based verification of the requirements for behaviour regarding temporary overvoltages after voltage recovery is provided as long as the voltage source control gain parameterised according to manufacturer's specifications or the effective impedance (with the exception of the nominal value specified by the manufacturer) do not exceed the determined positive sequence overvoltages $u1_{,S}$ *of 5% (or 2.5% if* *the unit is put into service after 31 December 2027) relative to the final steady-state value* $u_{1,\mathrm{End}}$ *of the voltage.*

5.5.7.8 Simulation-based verification of damping behaviour in the sub- and super-synchronous frequency range (Section 4.2.1.2)

5.5.7.8.1 Aim of the test

The aim of the simulation-based test is to determine the damping behaviour in the sub- and super-synchronous frequency range. The damping behaviour is tested in the rotating reference system and covers frequencies from 3 Hz to 50 Hz.

5.5.7.8.2 Test procedure

In order to show that the grid-forming unit under assessment has damping characteristics in sub- and super-synchronous frequency ranges 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. The EMT model of the grid-forming unit validated in accordance with Section 5.5.3.6.2.2 shall be used for the test. For testing, the EMT model of the unit may either be operated in accordance with the test setup described in Section 5.5.7.10 or, alternatively, directly connected to an ideal voltage source (infinite bus). In the test setup, the supply frequency of the voltage source at the network node 'EHV-1' or, alternatively, the ideal voltage source shall be varied sinusoidally in the range from 3 Hz to 50 Hz as specified in Section 5.5.7.10. Determine the Bode plot (frequency and phase response) of the transfer function $G_{\mathrm{PGU}}(s)$ = $P_{\mathrm{PGU}}(s)\,/\,f_{\mathrm{PGU}}(s)$. The operating point of the grid-forming unit shall be selected in accordance with Test 4 as specified in Table 19.

NOTE If the test setup described in Section 5.5.7.10 is used, only the EMT model of the grid-forming unit should be activated.

To create the Bode plot, the supply frequency of the voltage source at node 'EHV-1' or the ideal voltage source at the terminals of the grid-forming unit may be modulated sinusoidally with an amplitude Δf of 0.1 Hz and a frequency f_{excite} in the range 3 Hz to 50 Hz in steps from ≤ 1 Hz (in the rotating coordinate system with $f = 50\ \mathrm{Hz} + \Delta f \cdot \sin(2\pi f_{\mathrm{excite}} \cdot t)$).

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 plot.

Deactivate the PCNB for the tests. This may be achieved by increasing the frequency deadband or by adjusting the droop settings.

5.5.7.8.3 Evaluation and presentation of the test report

The phase angle and amplitude of the $G_{\mathrm{PGU}}(s)$ transfer function in the generator sign convention in the frequency range from 3 Hz to 50 Hz shall be displayed. . The respective phase reserve at the ± 90° limits shall be indicated.

The essential variables shall be represented in x-t-diagrams with labelling or marking of relevant states. In addition, the determined Bode plots indicating the resonance point and phase reserve in the frequency range between 3 Hz and 50 Hz. If mechanical resonances were taken into account in the case of wind turbines, these shall be shown in the Bode plot with the corresponding tolerance band.

Note for TR8:
The simulation test shall be considered passed for grid-forming units if:

- *the amplitude and phase of the transfer function $G_{PGU}(s)$ of the EMT model of the grid-forming unit is shown in the frequency range from 3 Hz to 50 Hz,*
- *the respective phase reserve at the ± 90° limits is indicated in the test report.*
- *the essential variables are represented within x-t-diagrams,*
- *the Bode plots show the resonance points and phase reserve for the frequency range from 3 Hz to 50 Hz,*
- *if mechanical resonances were taken into account in the case of wind turbines, these are shown in the Bode plot with the corresponding tolerance band.*

5.5.7.9 Simulation-based verification of the settling process of the DC component (Section 4.2.1.1)

5.5.7.9.1 General information

The simulation-based test described below replaces a measurement-based test and refers to the requirement specified in Section 4.2.1.1 on the decay of the DC component of the current. Verification shall be provided for grid-forming units commissioned on or after 1 January 2028.

5.5.7.9.2 Aim of the test

The aim of the simulation-based test is to prove that, in the event of a relevant network fault, the DC components of the currents of the grid-forming unit decay to less than 10% of the change in the DC current of the unit within 100 ms.

5.5.7.9.3 Test procedure

Test environment

The simulation-based test is performed on the basis of the EMT simulation model validated in accordance with Section 5.5.3.6.2.2 in a simulation-based test environment consisting of the grid-forming unit, which is directly connected to an NCP at the corresponding voltage level. A unit transformer shall always be taken into account. Transformer saturation shall be omitted.

Performance of the test

Based on the nominal operation of the PGU ($P = P_n$, $Q = 0$, $U = U_n$), simulate a 3-phase short-circuit with a short-circuit impedance of 0 Ω at the NCP, with the short-circuit occurring at a zero-crossing of the voltage of phase a. Set the simulation duration after the fault at 150 ms. Fault clearing is not required. The SCR at the NCP is irrelevant in this context.

5.5.7.9.4 Evaluation and presentation of the test report

The simulation shall be evaluated as follows:

1) For phase currents a, b and c, the upper and lower envelopes and their mean values shall be plotted using graphical approximation (optional).
2) For all currents of phases a, b and c, the mean value between the upper and lower envelopes at 100 ms after the fault occurs shall be determined and indicated for each phase. The mean value corresponds to the DC component in the phase.

The simulated fault currents and the envelopes as well as their mean values determined for phases a, b and c shall be documented graphically.

Note for TR8:
Verification shall be considered demonstrated if it can be determined for all mean values of phases a, b and c at the time 100 ms that their magnitude does not exceed a value of 10 % of the change in the DC current of the unit. Permanent stationary deviations of 2 % of the rated current are not evaluated. Verification shall be provided for grid-forming units commissioned on or after 1 January 2028.

5.5.7.10 Verifications for parallel operation (Section 4.2.1.11)

5.5.7.10.1 General information

The simulation-based tests described below shall be performed.

5.5.7.10.2 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. Verifications shall be simulated. The detailed RMS models or EMT models shall be used according to Section 5.5.3. Verifications are based on a standardised benchmark model network described in Appendix 0.

5.5.7.10.3 Test procedure

Description of the test environment and its initialisation

The test environment for verifying 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 under test. The internal interconnection of the PGU in the PGM of the benchmark-network is shown in Appendix B.VII. 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.VII 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 in a way 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 represented 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. This considers the voltage source control, FRT behaviour, PCNB behaviour and 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 - 10 Hz occurring in the upstream network.

Conducting tests

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 source control requirements are fulfilled. If no corresponding interface is considered 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. The excitation is applied once to the first PGU of the 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 and with a residual voltage from 22 % to 25 % (3K) or 20 % to 22 % (2K) 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 condition.

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, including within an extended test environment, by applying the reference profiles in accordance with Section 4.2.1.14, 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 condition.

Use the detailed RMS model for these tests.

Test 4

Determine the frequency responses for various test configurations in this simulation-based test 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. Modulate the supply frequency ($f_{\mathrm{SP}}(s)$) of the voltage source at the network node 'EHV-1' sinusoidally in the range from 0.05 Hz to 10 Hz. Determine the Bode plot (frequency and phase response) of the transfer function $G_{\mathrm{p}}(s) = P_{\mathrm{PGU}}(s) / f_{\mathrm{SP}}(s)$ und $G_{\mathrm{PGU}}(s) = P_{\mathrm{PGU}}(s) / f_{\mathrm{PGU}}(s)$.

Perform the following calculations:

Determination of the frequency response relative to the electrical power of a 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 10 Hz in steps from ≤ 0.05 Hz (in the rotating coordinate system with $f = 50\ \mathrm{Hz} + \Delta f \cdot \sin(2\pi f_{\mathrm{excite}} \cdot t)$).

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 plot.

Deactivate the PCNB for the tests. This may be achieved by increasing the frequency deadband or by adjusting the droop settings.

Use the detailed RMS model for this test.

5.5.7.10.4 Evaluation

Test 1

It shall be shown, that compliance with the requirements for voltage source control 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 also lead to stable operation of the grid-forming PGUs in a plant 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 4.2.1.6 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 a plant within the defined network environments. Furthermore, it shall be shown, that the introduction and removal of power limitations of the grid-forming units occur 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 4.2.1.14, 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 10 Hz, the phase angle of the PGU's active power in the generator sign convention remains within the range of -180° ± 90° with respect to the phase angle of the voltage source. The respective phase reserve at the ± 90° limits shall be indicated.

5.5.7.10.5 Presentation in the test report

Verification of network parallel operation capability shall be provided in a test report. The report shall have the following content:

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) as well as 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 plots indicating the resonance point and phase reserve at frequencies of 0.05 Hz and 10 Hz. If mechanical resonances were taken into account in the case of wind turbines, these shall be shown in the Bode plot 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 shall be considered passed if the results are clearly documented in the test report.

5.6 Procedure for plant certification

5.6.1 General information

For customer installations with grid-forming units, a plant certificate shall be submitted to the system 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 plant certification in accordance with Clause 11.4 of the relevant Technical Connection Rules are described below.

5.6.2 Deviations from TCR requirements within the scope of plant certification

5.6.2.1 Deviations from requirements in Clause 11.4.1 (General information)

5.6.2.1.1 General information

Clause 11.4.1 of the relevant Technical Connection Rules applies. In addition to Section 11.4.1, the requirements defined in the following subsections apply.

5.6.2.1.2 Plant certification for new units

Unit certificates in accordance with this FNN Guideline in Version 2.1 (or newer) shall be used when certifying plants with grid-forming capabilities.

5.6.2.1.3 Plant certification for the conversion of existing plants

The conversion of existing grid-following Type 2 units (existing plants) to Type 2 grid-forming units is always considered a significant change. For these, a new plant certificate shall be created based on the unit certificates of the converted units in accordance with this FNN Guideline in Version 2.1 (or newer). In addition to Clause 11.4.1 of the relevant Technical Connection Rules, the following applies to these plants:

“For the issuance of the statement of compliance, the following requirements apply to existing plants that are being converted to Type 2 grid-forming units:

- 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 that is freely selectable by the certification body, 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 defined shall be verified.
- As an alternative to a measurement-based verification, a verification document may be submitted for the converted unit with the help of disturbance recorder evaluations in accordance with the criteria defined in the Section 5.2.4. In this case, the specifications in Section 5.2.4 on monitoring in a plant with several identical grid-forming units apply. This verification shall be provided after the statement of compliance. The grid-forming unit shall be monitored for a period of at least one year. In this case, instead of a final operating licence, the system operator issues an operating licence that is limited to the monitoring period. The final operating licence is issued after proof of compliance through evaluation of disturbance recorder data.
- The measurement-based verification or its alternative (monitoring by means of a disturbance recorder) may be omitted if the conversion of the unit was performed solely on the basis of a software update.
- The certification body has checked that all units in the plant correspond to the status of the tested or monitored unit.“

- The necessary measurements shall be performed by a testing institute accredited in accordance with DIN EN ISO/IEC 17025 (for FGW TR3, Revision 26).

- If the required measurement-based verification has been provided as part of the verification of grid-forming plants with prototypes in accordance with Section 5.2.3, this verification may also be used for the statement of compliance.

5.6.2.2 Deviations from the requirements in Clause 11.4.2 (Documents to be provided by the connection owner for the plant 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 Rules:

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)

5.6.2.3 Deviations from requirements in Clause 11.4.3 (Feed-in power)

In addition to Clause 11.4.3 of the relevant Technical Connection Rules, the following applies:

When designing the plant, it shall be ensured that compliance with the reactive power supply requirements specified in Section 11.2.2 of the relevant Technical Connection Rules does not restrict the ability to provide inertia. The plant certificate shall indicate the extent to which the sum of the power $(\sum P_{\mathrm{limitneg,min}}, \sum P_{\mathrm{limitneg,max}})$ of the units installed in the plant is restricted for the full provision of inertia through the reactive power provision at maximum required in over- or underexcited operation (in accordance with the system operator questionnaire) at the NCP at nominal voltage (U_{n} or U_{c}).

NOTE This may be performed on the basis of a load flow calculation using the respective PQ diagrams of the units.

5.6.2.4 Requirements deviating from Clause 11.4.8.2 (inter-area oscillations and phase swinging)

Instead of the second paragraph of Clause 11.4.8.2 of the relevant Technical Connection Rules, the following applies:

“For Type 2 grid-forming plants, this requirement is fulfilled by successful testing of the damping of frequency-power oscillations in accordance with Section 5.5.5.8 of this FNN Guideline as part of the of unit certification.”

5.6.2.5 Requirements deviating from Clause 11.4.9 (Verification of island operation and sub-network operation)

Capability of sub-network operation

Verification of sub-network operation in accordance with the relevant Technical Connection Rules is not required. Instead, the following applies:

"For grid-forming units, this requirement is fulfilled by the unit certificate in accordance with this FNN Guideline. The capability of the grid-forming units of the plant to operate in a sub-network shall be indicated in the plant certificate. A corresponding technical justification shall be provided for Type 1 PGMs and the procedure shall be agreed with the system operator, unless the entire active power control range is covered by the required amplitude specified in Table 14 as part of the primary control based on network security.

It shall also be demonstrated that the operating concept of the PGM allows the fed-in power to be reduced to the minimum technical power as specified in Table 15."

5.6.2.6 Requirements deviating from Clause 11.4.11 (steady-stage voltage support / reactive power provision)

5.6.2.6.1 General information

The actual control behaviour of static voltage support is influenced by the impedance of the grid (SCR), communication times and the PGM (generation units + park network).

Clause 11.4.11 of the relevant Technical Connection Rules applies. With regard to the verification of control response, the following applies to Type 1 plants within the scope of VDE-AR-N 4110 and VDE-AR-N 4120 and to Type 2 grid-forming plants that deviate from this:

With regard to control behaviour, the grid-forming units and components of the PGM shall be evaluated to determine the extent to which the PGM can reach a reactive power jump from the maximum required underexcited to the maximum required overexcited reactive power feed-in within the required times according to Section 4.1.1.3 (Type 1 plants) or Section 4.2.1.4 (Type 2 plants) of this FNN Guideline. This range may be restricted if the use of the step controller was necessary. The time setpoint (3τ of the PT1 behaviour) can be found in the questionnaire of the system operator E.7 [VDE-AR-N 4120 and VDE-AR-N 4130] or E.9 [VDE-AR-N 4110]. Compliance with requirements for the transition period (3τ of the PT1 behaviour) shall be demonstrated both in the setpoint tracking and disturbance behaviour for Type 2 plants in accordance with Section 4.2.1.4 and for Type 1 plants in accordance with Section 4.1.1.3 of this FNN Guideline. The tolerance setpoints shown in Figure 27 in Appendix B.IX apply here. Damped behaviour shall be demonstrated for the control response within the tolerance limits. Alternatively, if the tolerance band is exceeded during the verification process, an alternative acceptance criterion may be defined in coordination with the system operator in the case of transition times of less than 5 s and low SCR values (e.g. based on a suitable minimum damping, see also Appendix A.I).

When evaluating the dynamic behaviour, it should be noted that the behaviour of the voltage source control of Type 2 grid-forming units or the voltage regulator of Type 1 grid-forming units interacts with the initial dynamics of static voltage control in terms of setpoint tracking and disturbance behaviour. The start of the evaluation of the disturbance behaviour shall be based on a state after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1).

NOTE 1 The initial response of the unit's voltage source control is understood to be the process until a near-steady state is reached with the superimposed reactive power control deactivated. For Type 2 units, for example, the requirement *for the settling time may be used as the starting point for evaluating the disturbance behaviour of the static voltage support.*

NOTE 2 In the case of mixed grid-following and grid-forming units within a PGM, the aforementioned verification for the response of the plant shall only be considered for the grid-forming part of the PGM.

For PGMs within the scope of VDE-AR-N 4120 and VDE-AR-N 4130, in which the installed capacity of the Type 2 grid-forming units is more than 10% P_{Amax} or less than 90% P_{Amax}, the following applies:
The concept for static voltage support of the entire PGM shall be submitted and presented as agreed with the system operator. A measurement-based verification of the overall behaviour of the plant shall be performed upon request of the system operator.

Verification of the control response of the static voltage support may be provided using one of the following methods:

Method A) Measurement-based verification of the behaviour of the entire plant:
The measurement-based verification is performed as part of the statement of conformity in accordance with Section 5.7.2 by a testing institute accredited in accordance with DIN EN ISO/IEC 17025. This procedure shall be indicated accordingly in the plant certificate.

Method B) Simulation-based verification taking into account the unit models and the PGM controller model:
The simulation-based verification is performed in accordance with Section 5.6.2.6.2.

Method C) Verification of the control response of the grid-forming unit with associated PGM controller as part of component certification
Verification of the control response of the static voltage support is performed as part of the component certification of the PGM controller, taking into account the grid-forming unit. It shall be ensured that the required setting values of the PGM controller are specified in the component certificate under the conditions of the parameters relevant to the PGM (e.g. SCR value of the network, impedances of the PGM), thus ensuring compliance of the control response of the static voltage support for the PGM. If verification of the control response of the static voltage support of the grid-forming unit and the PGM controller has been provided as part of the component certification, this shall be stated in the plant certificate and compliance for the PGM shall be confirmed.

Procedure D) Evaluation of the control response based on the component and unit certificates and corresponding manufacturer documentation
Verification of the control response of the static voltage support for the PGM is provided on the basis of the evaluation of the assets specified for the components (PGM controller) and grid-forming units as part of the component or unit certificates.

NOTE 3 In this case, the manufacturer shall document for the component (PGM controller), e.g. on the basis of a validated simulation model (e.g. in tabular form), under which conditions and with which parametisations the required control response can be implemented for the PGM. The impedance of the PGM, communication times between the PGM controller and units, the SCR value at its NCP and a variation in the delay of the reactive current behaviour of the grid-forming unit shall be taken into account.

Note for TR8:
Verification of the static voltage support may be provided using one of the following methods and shall be evaluated accordingly:

- *Method A) Measurement-based verification of the behaviour of the entire plant*
- *Method B) Simulation-based verification taking into account the unit models and the PGM controller model*

- *Method C) Verification of the control response of the grid-forming unit with associated AC converter controller as part of component certification*
- *Method D) Evaluation of the control response based on the component and unit certificates and corresponding manufacturer documentation*

The method used for verification shall be indicated in the plant certificate.

Regardless of the chosen method, verification of static voltage support shall be considered demonstrated if, for the transition period (3τ) required by the system operator, the control behaviour of the static voltage support of the entire plant (both in terms of setpoint tracking and disturbance behaviour) is within the required tolerance ranges specified in Figure 27 in Appendix B.IX. This may be demonstrated by measurement (Method A) or simulation (Method B) or demonstrated in a comprehensible manner on the basis of the evaluation of the relevant information in the component and unit certificates (Methods C and D). A damped response shall be demonstrated for the control response within the tolerance limits. When using Methods A and B, the start of the evaluation of the disturbance behaviour is considered to be the state after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1).

For PGMs within the scope of VDE-AR-N 4120 and VDE-AR-N 4130, in which the installed capacity of the Type 2 grid-forming units is more than 10% P_{Amax} *or less than 90%* P_{Amax}*, a concept for static voltage support shall be agreed with the system operator and presented in a comprehensible manner.*

5.6.2.6.2 Simulation-based verification of static voltage support (overall plant behaviour)

5.6.2.6.2.1 Aim of the test

The aim of the simulation-based test is to determine the overall plant behaviour with regard to static voltage support for the reactive power control method specified by the system operator and to verify compliance with the requirements defined in Sections 4.1.1.3 (Type 1 units) and 4.2.1.4 (Type 2 units). Compliance with the required tolerance bands shown in Figure 27 and the transition period specified by the system operator for the control response of the static voltage support shall be determined.

5.6.2.6.2.2 Test procedure

The simulation-based test shall be performed using the RMS model of the PGM, assuming an SCR value of 10 [VDE-AR-N 4120] or 20 [VDE-AR-N 4110] at the NCP. Also assumed is the SCR value specified for the NCP of the PGM. The test shall be performed in accordance with the specifications of Measurement 1 (setpoint tracking behaviour) and Measurement 2 (disturbance behaviour) in accordance with Section 5.7.2.1.2.

5.6.2.6.2.3 Evaluation and presentation of the test report

The evaluation and documentation of the simulation-based test shall be performed in accordance with the specifications in Section 5.7.2.1.3 or 5.7.2.1.4.

Note for TR8:

The simulation-based test shall be considered passed if the step response for all tests performed is within the corresponding tolerance bands and if damped behaviour is demonstrated for control response within the tolerance bands. The evaluation of disturbance behaviour begins after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1).

5.6.2.7 Deviations from requirements in Clause 11.4.12 (Dynamic network support)

5.6.2.7.1 Deviations from requirements in Clause 11.4.12.1 (General information)

Instead of Clause 11.4.12.1 of the relevant Technical Connection Rules, the following specifications apply:

For grid-forming units of a Type 2 PGM or Type 2 PGM consisting solely of grid-forming units, verifications in this section apply at plant level. For Type 2 PGMs with grid-forming and grid-following plants, verification at plant level shall be taken into account in each case in a type-specific manner (for grid-forming units in accordance with Section 5.6.2.7 in this FNN Guideline and for grid-following units in accordance with Clause

11.4.12 of the relevant Technical Connection Rules). This may also require an assessment of the behaviour of the individual units at their terminals in the PGM.

The behaviour of the PGM is verified by simulation based on the validated detailed RMS-simulation models of the PGUs and components. If there is no model available for the PGM controller that complies with the requirements imposed on it, the conceptual behaviour of the PGM controller may be taken into account as an alternative.

In this case, voltage increases due to the voltage source control of the PGU shall be indicated as follows:

- > 110 % U_c [VDE-AR-N 4110] or > 110 % U_n [VDE-AR-N 4120] at the NCP. If these increases occur for periods of more than 50 ms, this shall be coordinated with the system operator.
- > 110 % U_{ref} [VDE-AR-N 4130] shall be indicated at the NCP and agreed with the system operator.

In addition to that, any impact that underexcited operation of the PGM may have on the functionality of the Q-U protection shall be reported and possible alternatives shall be presented.

If a Q-U protection trip be detected, it is not considered to be an erroneous function of the PGM.

For Type 2 plants it shall be determined whether the voltage source protection may lead to tripping of the Q-U protection. For this purpose, the calculation shall be performed with a symmetrical voltage dip to a value between:

- 70% U_c and 80% U_c [VDE-AR-N 4110], with the PGM supplying active power feed-in at P_{inst} and reactive power at the maximum (underexcited)agreed with the system operator.
- 70% U_c and 80% U_c [VDE-AR-N 4120 and VDE-AR-N 4130], with the PGM supplying an active power feed-in between 20 % and 30 % P_{inst} and reactive power (underexcited) at the maximum required by the system operator.

NOTE The previous three paragraphs (regarding Q-U protection) do not apply when VDE-ARN 4110:2026 and VDE-AR-N 4120:2026 are applied.

Riding through multiple faults shall be verified in the unit and component certificate.

The following calculations of voltage dips and voltage increases shall be performed for faults in the voltage level of the network connection point (fault on the same network) [VDE-AR-N 4110, VDE-AR-N 4120, VDE-AR-N 4130] and for faults in the next higher voltage level (fault in the upstream-network) [VDE-AR-N 4110, VDE-AR-N 4120].

The following applies to PGMs within the scope of VDE-AR-N 4110: single-phase fault cases shall be simulated in accordance with FRT limit curves for the neutral-point treatment methods of solidly grounded, low-resistance grounded, and temporarily low-resistance grounded neutrals, both on the same network and the upstream network. In networks operated in isolation and in networks with earth fault compensation, single-phase faults cannot be simulated. Nevertheless, the PGM shall not disconnect from the network in the event of an earth fault.

The following applies to PGMs within the scope of VDE-AR-N 4120 and VDE-AR-N 4130: for networks with earth-fault compensation, single-phase faults are not to be considered.

The limits specified in Clause 10.2.3.3 of the relevant Technical Connection Rules for the short-circuit power of Type 2 plants after a network fault shall be disregarded for verification.

5.6.2.7.2 Deviations from requirements in Clause 11.4.12.3 (Dynamic network support for a Type 2 PGM)

In the relevant Technical Connection Rules, the following text of Clause 11.4.12.3 does not apply:

"Furthermore, the k-factor resulting at the network connection point shall be specified and evaluated for compliance with the requirements specified in Section 10.2.3 and the system operator questionnaire".

"Where the system operator specifies such a k-factor and the calculations show that a k-factor higher than 6 would have to be set at the PGUs which do not permit the setting of higher factors, a factor of 6 is considered sufficient".

In addition, the following specification applies:

It shall be verified, that the static voltage support outside of the quasi-steady-state operating range of the PGM for grid-forming units as shown 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, does not impair the voltage source control of the grid-forming units. It shall also be verified, that the UVRT/OVRT behaviour of grid-forming units in accordance with Section 4.2.1.6 is not impaired.

5.6.2.7.3 Deviations from requirements in Clause 11.4.12.4 (Limited dynamic network support for a Type 2 PGM)

Instead of Clause 11.4.12.4 of VDE-AR-N 4110, the following specifications apply:

Verification of the required reducibility of the apparent current (limited voltage source control) in accordance with Section 5.5.5.6.6 shall be provided in the unit certificate for grid-forming PGMs with a commissioning date after 1 January 2028. For grid-forming PGMs commissioned after this date, the loss of mains protection shall be parameterised in accordance with the specifications of the system operator, unless verification in accordance with Section 5.5.5.6.6 has been provided as part of the unit certificate.

The feasibility of the limited voltage source control or the effectiveness of the disconnection protection in accordance with Section 4.2.1.5.2 shall be assessed in the plant certificate.

5.6.2.8 Deviations from requirements in Clause 11.4.13 (Active power output)

The concept for implementing the prioritisation requirements of Section 4.2.3 shall be evaluated for the PGM. It shall be ensured that the control strategy of the plant does not restrict the provision of inertia. In addition, and in accordance with the requirements of Section 4.2.4.5, the $P_{\mathrm{AV,E}}$ protection device shall be parameterised in such a way that it does not get triggered (for an active power operating point of the PGM at $P_{\mathrm{AV,E}}$) when the phase jump power required in this FNN Guideline occurs in conjunction with the transient curve of the inertia power based on the set start-up time constants of the grid-forming units.

5.6.2.9 Deviation from requirements in Clause 11.4.15 (Active power feed-in as a function of network frequency during overfrequency and underfrequency)

Proof of compliance shall be provided when issuing the unit certificate or the individual verification procedure.

With regard to proof of compliance (verification) with the prioritisation requirements, the following applies to Type 2 plants instead of Clause 11.4.15 of the relevant Technical Connection Rules:

Compliance with the prioritisation specifications in accordance with Section 4.2.3 shall be checked in particular in the event of overfrequency/underfrequency when active power setpoints are issued simultaneously by the system operator (network security management) and/or by third parties (e.g. direct marketers). Verification of the unit's technical capability to implement the relevant prioritisation specifications are provided in accordance with Section 5.5.6.1 as part of unit certification.

5.6.2.10 Deviations from the requirements in Clause 11.4.23 (PGM model)

In addition to the requirements of Clause 11.4.18 of the relevant Technical Connection Rules, the following specifications apply:

If the system operator requires the connection owner to provide a PGM model in accordance with Clause 10.6 of the relevant Technical Connection Rules or Section 5.5.3.9 in this FNN Guideline, this shall be submitted with the connection application, if available. If no PGM model is available, this shall also be submitted to the system operator together with the plant certificate.

5.6.2.11 Deviations from requirements in Clause 11.4.24 (VDE-AR-N 4110) (Plant certificate B)

The following applies to PGMs within the scope of VDE-AR-N 4110: a plant certificate A shall be submitted in all cases.

5.6.3 Extended plant certification procedure (extra-high-voltage)

5.6.3.1 General information

For PGMs with grid-forming units connected to the public extra-high-voltage network, the requirements for plant certification in accordance with Sections 5.6.1 and 5.6.2 shall be met, as well as the requirements in the following subsections.

5.6.3.2 Network connection process in the extended plant certification procedure

5.6.3.2.1 General information

For PGMs with grid-forming units connected to the public extra-high-voltage network, the network connection process is performed as part of the extended plant certification procedure as shown in Figure 14. This serves as an addition to the network connection process defined in VDE-AR-N 4130. Accordingly, unless otherwise specified, the requirements for the process flow specified in VDE-AR-N 4130 remain unaffected.

5.6.3.2.2 Preparation and planning of the network connection and extended replacement network data

The network connection process is started by the connection owner submitting the connection application (‘Start’). The ‘transmission of network data at the NCP’ by the system operator to the connection owner takes place as part of the connection offer in accordance with Clause 4.2.2 of VDE-AR-N 4130.

Based on the network data specified by the system operator, the connection owner plans the PGM and designs the network connection (‘PGM planning and design of the network connection’), taking into account the corresponding unit certificates of the grid-forming units planned within the plant in accordance with this FNN Guideline. Detailed planning of the plant includes:

- Specification and design of the plant structure and dimensioning of the planned operation equipment.
- Performance of the necessary load flow and short-circuit current calculations to verify the properties and parameters specified in the network connection agreement.
- Defining control structures (PGU/PGM control).

Once the detailed planning of the plant is completed, the ‘detailed planning data’ and the ‘EMT and RMS models’ of the grid-forming units are handed over to the system operator for use in network studies. The system operator may request a preliminary model of the plant based on the detailed planning data and the unit models.

For the purpose of conducting studies to confirm compliance of the plant in accordance with Section 5.6.3.2.4, the system operator transmits ‘extended equivalent network data at the NCP’ or an extended equivalent network model for the NCP of the customer installation to the connection owner. This extended replacement network model maps the steady-state and dynamic properties of the surrounding network that are relevant for the dynamic behaviour at the NCP. This may include the frequency- and voltage-dependent impedance, the R/X ratio, short-circuit power at the NCP described by a detailed equivalent network, relevant voltage harmonics and interharmonic components, existing series and shunt compensation stages, and the time-dependent behaviour of protection and control devices in the upstream network (network protection, reactive power control, etc.).

NOTE In the course of the detailed network studies conducted by the system operator in accordance with Section 5.6.3.2.3, the extended equivalent network model for verifying resonance stability shall be specified in more detail. Nevertheless, the studies to confirm PGM compliance by the connection owner and the detailed network studies by the system operator may be conducted at the same time.

5.6.3.2.3 Detailed network studies by the system operator and specification of the extended replacement network

If necessary, the system operator will perform '*detailed network studies*' (interaction studies) based on the detailed unit models of the PGM. Based on these studies, the extended equivalent network model provided to the connection owner for the NCP of the planned PGM is further specified with regard to specific resonance characteristics for the NCP of the customer installation. The extended replacement network realistically reflects the critical operating conditions identified in the interaction studies. Critical interactions identified with the planned parameterisation of the grid-forming units are presented by the system operator and taken into account in the replacement network model. Any modified replacement network model shall be handed over to the connection owner for use in the '*Study to confirm PGM compliance*'.

NOTE 1 If the network studies are conducted by third parties, the requirements for model transfer in accordance with Section 5.5.3.9 shall be taken into account.

NOTE 2 In coordination with the system operator, the connection owner may also be responsible for conducting the detailed studies. In this case, the system operator shall provide a suitable infrastructure for conducting the studies.

5.6.3.2.4 Study to confirm plant compliance

Compliance of the plant with the requirements of this FNN Guideline shall be confirmed by means of a simulated 'study'. The study shall be conducted in accordance with the specifications in Section 5.6.3.3 on the basis of a detailed model of the PGM and the '*extended replacement network data at the NCP*' (replacement network model) provided by the system operator in accordance with Section 5.6.3.2.2 and, if necessary, further specification of these equivalent network data in accordance with Section 5.6.3.2.3 as part of a qualified plant report.

NOTE If the studies are performed by third parties, the requirements for model transfer in accordance with Section 5.5.3.9 shall be taken into account.

If no critical interactions are identified with the planned parameterisation of the grid-forming units either in the interaction studies conducted by the system operator or in the study to confirm PGM compliance, the connection owner shall provide the system operator with the qualified plant report, which demonstrates compliance of the plant with the requirements at the NCP, taking into account the extended replacement network data. The system operator shall review and subsequently approve the qualified plant report. Upon completion of this process, compliance of the plant is confirmed.

Based on the interaction studies conducted by the system operator and the study by the connection owner, it shall be confirmed that the connection owner was able to select a '*suitable parameterisation within the parameter space of grid-forming units*' (or the parameter space permitted in the unit certificate) that avoids or sufficiently minimises the expected interactions. After submission of the qualified plant report created in accordance with the final selected parameterisation, this is checked and approved by the system operator. Upon completion of this process, compliance of the plant is confirmed.

5.6.3.2.5 Final set-up of the PGM

Once the plant compliance has been confirmed, the PGM and the grid-forming units within the PGM shall be parameterised in accordance with the final parameterisation specified in Section 5.6.3.2.4. The final parameterisation of the PGM shall be stated in the plant certificate.

5.6.3.2.6 Completion of the extended plant certification procedure and provisional operating licence

The existence of the qualified plant report approved by the system operator shall be assessed by the certification body as part of the plant certificate in accordance with the criteria defined in the Section 5.6.3.3.1. In addition, the '*final EMT and RMS models of the PGM*' shall be handed over to the system operator by the connection owner. The process ends with the certification body issuing the '*extended plant certificate*' and the system operator subsequently issuing the '*provisional operating licence*' (ge: VBE).

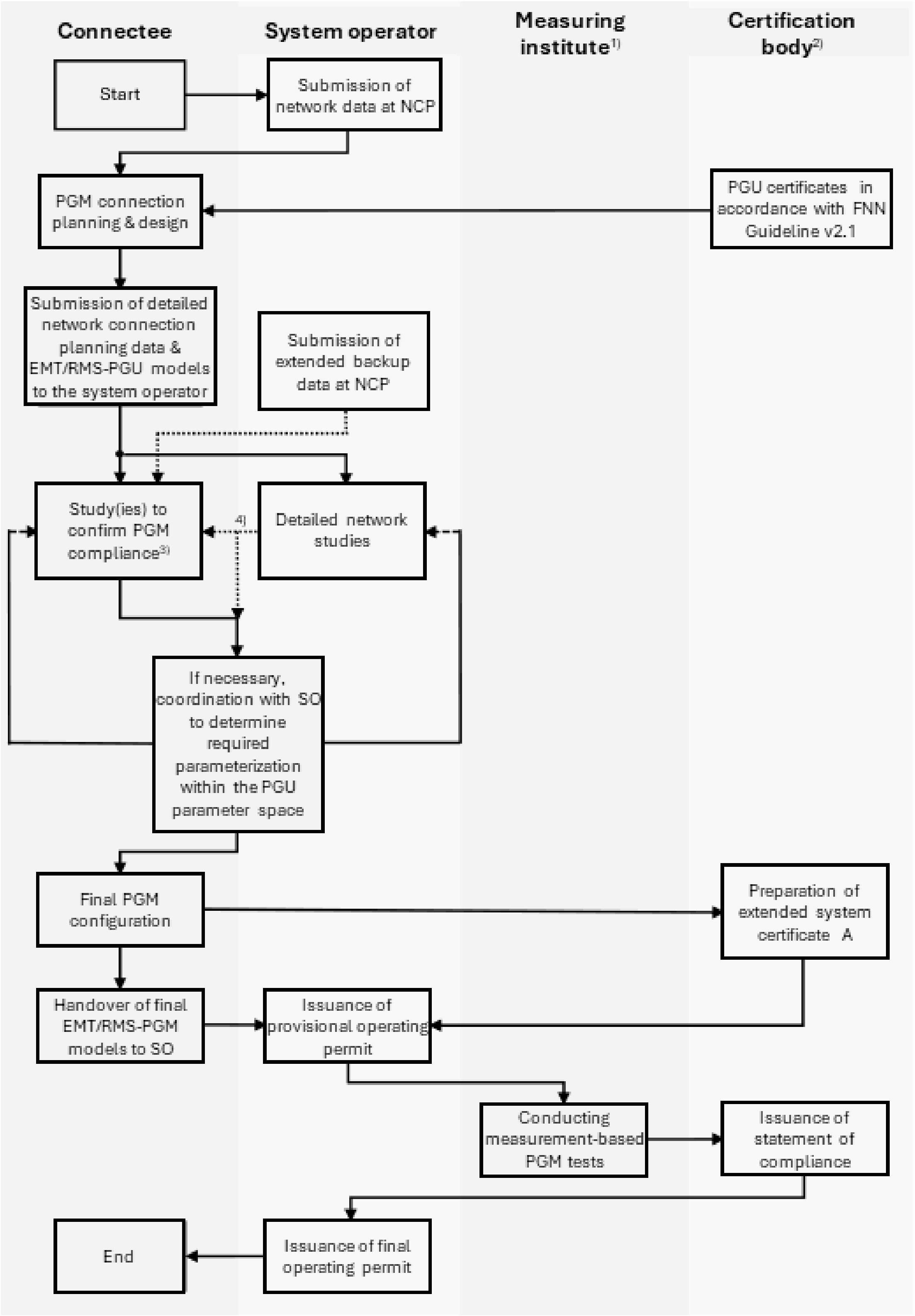
NOTE The requirements for the issuance of the provisional operating licence in accordance with VDE-AR-N 4130 remain unaffected by this.

5.6.3.2.7 Issuance of the statement of compliance and final operating licence

After the certification body has issued the '*extended plant certificate*' and the provisional operating licence has been obtained, '*measurement-based tests*' may be performed on the operational PGM as part of the statement of compliance in accordance with Section 2. If an adjustment to the parameterisation of the grid-forming units has been agreed, the statement of compliance shall verify whether the parameterisation settings of the grid-forming units in the PGM and the PGM itself comply with this agreement.

The network connection process in the extended plant certification procedure ends with the issuance of the statement of compliance, with which the system operator issues the '*final operating permit*' (ge: EBE) for the PGM.

NOTE The requirements for the issuance of the final operating permit in accordance with VDE-AR-N 4130 remain unaffected by this.



[1] Accredited in accordance with DIN EN ISO/IEC 17025.
[2] Accredited in accordance with DIN EN ISO/IEC 17065.
[3] See qualified plant report in accordance with Section 5.6.3.3.
[4] In order to verify individual requirements, the system operator may, in the course of detailed network studies, adjust the extended replacement network data, which shall be taken into account in the studies to confirm PGM compliance (see Section 5.6.3.2.3).

Figure 14 - Network connection process in the extended plant certification procedure for connecting grid-forming plants to the extra-high-voltage network

5.6.3.3 Qualified plant report

5.6.3.3.1 General information

For PGMs with grid-forming units connected to the public extra-high-voltage network, the requirements for plant certification in accordance with Section 5.6.1 and 5.6.2 as well as the additional requirements in this section shall be fulfilled:

The plant certificate in accordance with VDE-AR-N 4130 and the additions or deviations formulated in accordance with Sections 5.6.1 and 5.6.2 of this FNN Guideline shall be extended to include a qualified plant assessment for the PGM. In this assessment, the requirements for the PGM specified in Section 4.2.4 shall be reviewed and evaluated by a qualified body on the basis of a simulation study in accordance with the following criteria. The qualified body shall be commissioned by the connection owner to conduct the study in coordination with the system operator. The qualified plant report prepared by the qualified body shall be submitted to the system operator, who shall review its content and approve it.

Verification of these requirements is provided on the basis of a confirmation from the system operator. During the certification process, the certification body only checks that this valid confirmation from the system operator has been provided. Submission of the qualified plant report approved by the system operator is a prerequisite for the issuance of the plant certificate.

Note for TR8:
Compliance of the PGM with the requirements defined in Section 4.2.4 at plant level is confirmed through a qualified plant report in accordance with the criteria defined in Section 5.6.3.3 (evaluation criterion: True/False).

The criteria to be verified in the study are listed in the following subsections.

5.6.3.3.2 Verification of the effective impedance

It shall be verified by calculation that the requirements for effective impedance are fulfilled in accordance with the specifications in Section 4.2.4.2 both in steady-state operation and during a transient compensation process (without triggering the current limitation). Verification may be limited to a representative part of the plant. Any simulations that may be necessary may be performed using the detailed RMS plant model. The effective impedance of the system ($z_{\mathrm{w,A}}$) shall be indicated. The R/X ratio shall be determined and indicated in accordance with the specifications in Section 5.5.5.4 for the impedance of the plant $z_{\mathrm{w,A}}$.

5.6.3.3.3 Verification of minimum phase jump power

Based on the phase jump power requirements for the grid-forming unit (see Section 4.2.1.1), it shall be demonstrated by simulation that, assuming an SCR = 3 at the NCP, the active current response $\Delta i_{\mathrm{P,PGU}}$ can be verified in accordance with the effective impedance related to the plant.

In addition to this, the expected value of the SCR at the NCP shall be used for the simulation-based test. The determined phase jump power shall be indicated.

The testing method shall be agreed with the system operator.

5.6.3.3.4 Verification of the damping of oscillations (0.1 Hz to 10 Hz) of frequency-active power oscillations and voltage-reactive power oscillations

Based on the requirements for the grid-forming unit with regard to the damping of frequency-power oscillations (see Section 4.2.1.12), it shall be demonstrated by simulation that, assuming an SCR = 3 at the terminals of the grid-forming unit of the PGM furthest away from the NCP, the damping demonstrated for the grid-forming unit for frequency-active power oscillations remains within the specified tolerance. The test shall also be performed under the same assumptions for voltage-reactive power oscillations.

In order to verify the damping characteristics of the PGM in relation to the generator or network oscillations present in the extended NCP replacement network, frequency responses for various test configurations shall be determined in this simulation-based verification for the following tests:

Test 1 – Frequency-active power oscillations
Vary the supply frequency of a voltage source to be specified within the extended equivalent network sinusoidally in the range from 0.05 Hz to 10 Hz and provide a Bode plot (frequency and phase response) of the transfer function $G_\mathrm{p}(s) = P_\mathrm{PGU}(s) / f_\mathrm{NCP}(s)$ for a representative selected grid-forming unit within the PGM. The supply frequency of the voltage source may be modulated sinusoidally with an amplitude Δf of 0.1 Hz and a frequency f_excite in the range 0.05 Hz to 10 Hz in steps from ≤ 0.05 Hz (in the rotating coordinate system with $f = 50\ \mathrm{Hz} + \Delta f \cdot \sin(2\pi f_\mathrm{excite} \cdot t)$).

Show that, in the frequency range from 0.05 Hz to 10 Hz, the phase angle of the active power of the representative selected grid-forming units in the generator sign convention remains within the range of -180° ± 90° with respect to the phase angle of the voltage source. Indicate the respective phase reserve at the ± 90° limits.

In wind turbines, this excitation can lead to mechanical interactions. The wind turbine manufacturer may specify up to three frequencies (f_res) for the unit to be certified, including a tolerance band of ± 0.1 Hz or ± 20 % of f_res with regard to mechanical resonances.

Deactivate the PCNB for the verification described. This may be achieved by increasing the frequency deadband or by adjusting the droop settings.

Test 2 – Voltage-reactive power oscillations
Vary the amplitude of a voltage source to be specified within the extended equivalent network sinusoidally in the range from 0.05 Hz to 10 Hz and provide a Bode plot (frequency and phase response) of the transfer function $G_\mathrm{Q}(s) = Q_\mathrm{PGU}(s) / U_\mathrm{NCP}(s)$ for a representative selected grid-forming unit within the PGM. The plant controller shall be taken into account here. The amplitude of the supply frequency of the voltage source may be modulated sinusoidally with an amplitude Δu of 0.05 p.u. and a frequency f_excite in the range 0.05 Hz to 10 Hz in steps from ≤ 0.05 Hz (in the rotating coordinate system with $U = U_\mathrm{n} + \Delta u \cdot \sin(2\pi \mathrm{f}_\mathrm{excite} \cdot t)$).

Shown that, in the frequency range from 0.05 Hz to 10 Hz, the phase angle of the reactive power of selected representative grid-forming units in the generator sign convention remains within the range of -180° ± 90° with respect to the amplitude of the voltage source. Indicate the respective phase reserve at the ± 90° limits.

NOTE The excitation in the voltage amount can trigger changes in active power and thus also frequency-active power oscillations. This effect shall be taken into account in the evaluation.

Use the detailed RMS plant model for this simulation-based verification.

5.6.3.3.5 Verification of the damping of specific sub- and super-synchronous torsional interaction (3 Hz to 100 Hz)

It shall be verified by simulation for the PGM that the requirements for behaviour in the sub- and super-synchronous frequency range according to Section 4.2.1.2 are also fulfilled at plant level. For this purpose, the simulation-based verification according to Section 5.5.7.8 shall be represented by simulation at plant level.

5.6.3.3.6 Verification of passive properties in the harmonic frequency range (100 Hz to 2.5 kHz)

A simulation for the PGM shall prove that the requirements for behaviour in the harmonic frequency range according to Section 4.2.1.3 for the unit are also fulfilled at plant level. For this purpose, the verification procedure according to Section A.IV shall be simulated at plant level.

5.6.3.3.7 Verification of voltage support

The behaviour of the PGM control system for voltage support in accordance with the requirements of Section 4.2.1.4 in conjunction with the voltage source control of the grid-forming unit in accordance with Section 4.2.1.5 (where applicable) shall be verified by simulation. For this purpose, the measurement-based verifications described in Section 5.7.2 shall be simulated on the basis of the detailed RMS simulation model of the plant for both setpoint tracking and disturbance behaviour.

5.7 Procedure for the statement of compliance

5.7.1 General information

Clause 11.5.4 of the relevant Technical Connection Rules applies. The following applies instead of the first paragraph:
"Based on the plant certificate and the commissioning statement provided by the operator of the PGM, a certification body properly accredited in accordance with DIN EN ISO/IEC 17065 confirms the compliance of the installed PGM with the requirements of FNN Guideline in combination with the relevant Technical Connection Rules as well as the specifications of the system operator (for document review refer to E.12 in VDE-AR-N 4110 and E.10 in VDE-AR-N 4120 as well as in VDE-AR-N 4130). The creator of the statement of compliance shall be independent of the creator of the commissioning statement (four-eyes principle)."

In addition, the additions specified in the following sections shall be observed when issuing the statement of compliance.

5.7.2 Measurement-based verification of the plant behaviour with regard to voltage support within the scope of the statement of compliance

5.7.2.1.1 Aim of the measurement

The aim of the measurement is to determine the overall plant behaviour with regard to static voltage support for the reactive power control methods specified by the system operator and to verify compliance with the requirements defined in Section 4.1.1.3 (Type 1 units) and Section 4.2.1.4 (Type 2 units). Compliance with the required tolerance bands shown in Figure 27 and the transition period specified by the system operator for the control response of the static voltage support shall be determined.

The measurement is only necessary if method A) in Section 5.6.2.6.1 has been selected or specified in the plant certificate for verifying steady-state voltage support (overall plant behaviour).

5.7.2.1.2 Measurement procedure

The system behaviour with regard to static voltage support is checked on the operational PGM in accordance with Measurement 1 (setpoint tracking behaviour) and Measurement 2 (disturbance behaviour) described below. Both measurements shall be performed for the reactive power control methods required by the system operator. The internal automatic tap changers of the transformer tap changers shall be deactivated or operated in manual mode when performing the measurements.

Unless otherwise agreed with the system operator (see Section 4.2.1.4), the measurements shall only relate to the grid-forming part of the PGM. Accordingly, all non-grid-forming units within the PGM shall be operated with $Q = 0$ or $\cos\varphi = 1$. The system operator shall be informed about the performance of this test.

The PGM shall be operated with an active power of ≥ 40 % $P_{\mathrm{b\ inst}}$ for the reactive power control methods Q, $Q(U)$ and $\cos\varphi$. The PGM shall also be operated with an active power of > 90 % $P_{\mathrm{b\ inst}}$ for the control method $Q(P)$. If one of the operating points required in Measurements 1 and 2 cannot be reached, it may be omitted. This shall be justified.

Before changing the setpoint or manipulating the actual value during the measurements, the PGM shall be operated stably with regard to active power within a tolerance band of ± 2 % $P_{\mathrm{b\ inst}}$ (for PGMs < 300 kVA ± 4 % $P_{\mathrm{b\ inst}}$).

Measurement method 1 – Setpoint tracking behaviour (setpoint specification)
The measurement method is based on the specification of external setpoints in the PGM controller. When performing the measurement method, the following distinctions shall be made with regard to the control methods specified by the system operator:

Control method: Reactive power-voltage characteristic $Q(U)$;

Set the characteristic curve in accordance with the system operator questionnaire. Approach the reactive power levels specified in Table 11 (column 2) by adjusting the parameters in the controller, whereby the specifications refer to the active power $P_{\mathrm{b\ inst}}$ in operation. Adding or subtracting an offset to the measured voltage value or replacing the measured voltage value with a suitable signal is also permitted.

Control method: Reactive power with voltage limiting function

Set the characteristic curve in accordance with the system operator questionnaire. Approache the reactive power levels specified in Table 11 (column 4) by adjusting the parameters in the controller, whereby the specifications refer to the active power $P_{\mathrm{b\ inst}}$ in operation.

Control method: Displacement factor cos φ

Configure the transition time for static voltage support required by the system operator in the PGM controller. Approach the setpoints specified in Table 11 (column 5) for the displacement factor cos(φ) one after another.

Control method: Characteristic curve $Q(P)$ (VDE-AR-N 4110 only)

Configure the transition time for static voltage support required by the system operator in the PGM controller for this control method. Set the characteristic curve should be set in accordance with the system operator questionnaire. If possible, perform a jump in the active power output recorded by the PGM controller at the NCP from 90% to 30% $P_{\mathrm{b\ inst}}$ by adding or subtracting an offset to the actual active power value. This should generate a reactive power jump in accordance with the characteristic curve. If the above procedure cannot be applied, this measurement may be omitted. In this case, specify the same transition period as for $Q(U)$ control or cosφ control, for example, if the controller functions or controller cores are identical and this is confirmed by a manufacturer's declaration (as part of component certification).

NOTE 1 If the active power is set by an external active power setpoint, two control functions are superimposed in this measurement. By reducing the active power, a continuous profile of the reactive power setpoint is generated, which means that the parameterised transition time cannot be determined.

Table 11 - Measurements for checking the plant behaviour regarding static voltage support as part of the statement of compliance

Num ber	**Reactive power control methods**			
	$Q(U)$ characteristic curve	**$Q(P)$ characteristic curve**[a)]	**Voltage limitation function**	**cos(φ) setpoint**
	Q_{setpoint} related to $P_{\mathrm{b\ inst}}$	P_{setpoint} related to $P_{\mathrm{b\ inst}}$	Q_{setpoint} related to $P_{\mathrm{b\ inst}}$	$\cos\varphi_{\mathrm{setpoint}}$
1	± 0.05	0.9 → 0.3	± 0.05	1.0
2	0.33 (underexcited)	-	≥ 0.33 (underexcited)	0.95 cap.
3	0.33 (overexcited)	-	≥ 0.33 (overexcited)	0.95 ind.
4	± 0.05	-	± 0.05	1.0

a) Only relevant for plants within the scope of VDE-AR-N 4110.

NOTE The setpoints shall be agreed with the system operator and adjusted if necessary to avoid unwanted voltage reactions.

Measurement method 2 – Disturbance behaviour

The measurement method is based on the manipulation of the measurement signal or the actual feedback value of the PGM controller, which may vary depending on the controller function. When performing the measurement procedure, proceed as described in Measurement procedure 1, but instead of setting an external setpoint as shown in Table 11, perform the specified measurements by manipulating the measurement signal or the feedback actual value of the PGM controller.

If oscillations are observed in Measurement procedures 1 and 2, their cause shall be determined. This may be done, for example, by switching the PGM controller off and on again.

5.7.2.1.3 Evaluation

For Measurement methods 1 and 2, the tolerance bands for the tested operating points shall be determined in accordance with Appendix B.IX. It shall be determined whether the step response lies within the tolerance bands and whether they are damped within these bands. The evaluation of the disturbance behaviour according to Measurement method 2 shall start after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1).

NOTE A step response profile that deviates from PT1 behaviour is permissible provided that the tolerance bands are maintained.

The transition time $t_t = 3\,\tau$, at which the step response has reached a value of 95 % of the final value or the setpoint, shall be determined. The entire step response shall be taken into account.

5.7.2.1.4 Presentation in the measurement report

For Measurement methods 1 and 2, the setting values of all relevant parameters of the PGM controller shall be documented. For all control modes, the step response and tolerance bands shall be displayed and the relevant variables to be evaluated shall be marked. If, in coordination with the system operator, deviations from the specified test points in Table 11 are made, the test points tested shall be indicated. The start time for the evaluation of the disturbance behaviour according to Measurement method 2 shall be displayed, from which the disturbance behaviour is evaluated after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1).

Control mode: Reactive power-voltage characteristic $Q(U)$

The time profile of the calculated reactive power setpoint, the measured reactive power and the measured voltage shall be documented. In addition, the set characteristic curve shall be displayed.

Control mode: Reactive power with voltage limiting function

The time profile of the reactive power setpoint and the measured reactive power shall be documented. In addition, the set characteristic curve shall be displayed.

Control mode: Displacement factor cos φ

The time profile of the setpoint of the displacement factor and the measured displacement factor shall be documented. In addition, the time profile of the calculated reactive power setpoint, the measured reactive power and the deadband used shall be documented.

Control mode: Characteristic curve $Q(P)$ (only VDE-AR-N 4110)

The time profile of the calculated reactive power setpoint, the measured reactive power and the active power shall be documented. In addition, the set characteristic curve shall be displayed.

Note for TR8:

The test shall be considered passed if the step response for all tests performed is within the corresponding tolerance bands and the control behaviour is damped within the tolerance bands. The evaluation of disturbance behaviour begins after the initial response of the voltage source control (Type 2) or the voltage regulator (Type 1). If the measurements were performed with an SCR < 10 and the tolerance specifications were not met, a simulation-based test in accordance with Section 5.6.2.6.2 may be used instead for compliance assessment.

A. Appendix (informative)

A.I. Qualitative considerations for determining the damping ratio

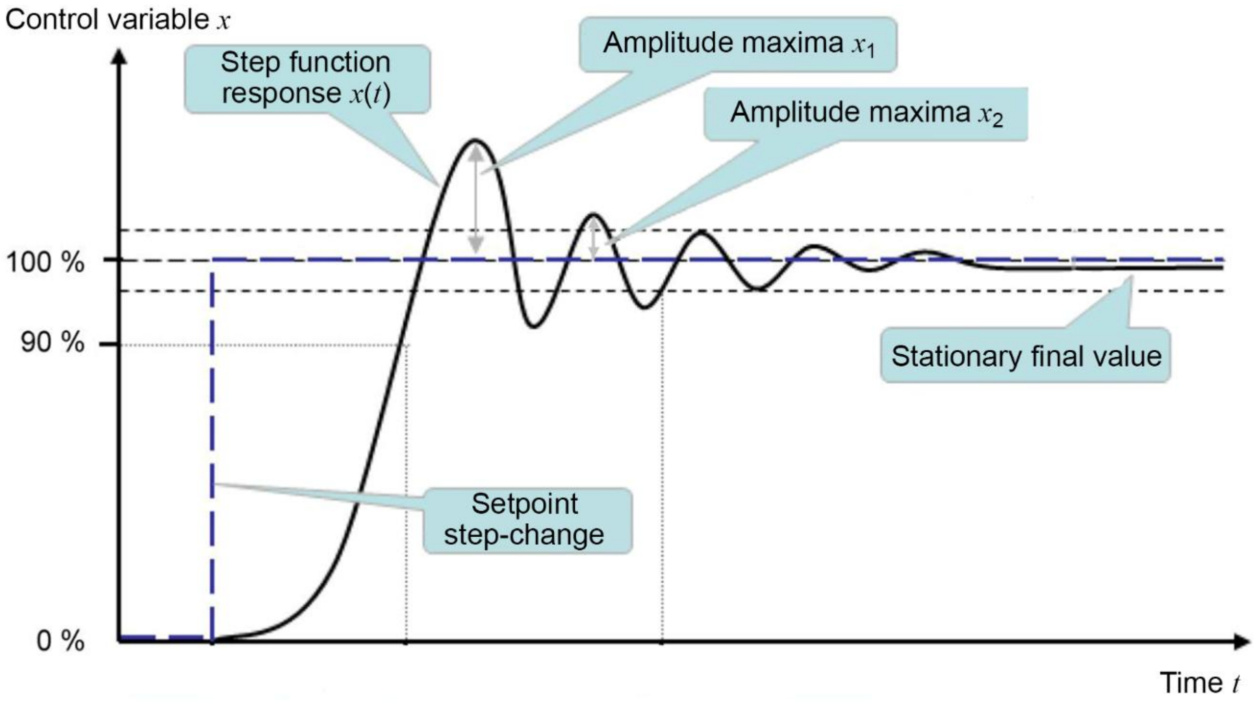


Figure 15 - Step response of a closed-loop control system for the quantitative determination of the damping factor

Based on the amplitude maximum x_1 and the amplitude maximum x_2 as shown in Figure 15, the amplitude ratio yields the following logarithmic decrement:

$$\Lambda = \ln\left(\frac{x_{\mathrm{n}}}{x_{\mathrm{n+1}}}\right) \tag{34}$$

The damping ratio D may be derived from the logarithmic decrement Λ:

$$D = \frac{\Lambda}{\sqrt{(2\pi)^2 + \Lambda^2}} \tag{35}$$

NOTE Based on practical experience, the second and third amplitude maxima or amplitude minima should be evaluated.

The maximum and minimum amplitudes are determined based on the respective difference to the final steady-state value.

Alternatively, the damping factor may be determined by evaluating successive extrema, as shown in Figure 16. The logarithmic decrement of two successive maxima and minima is determined as follows:

$$\Lambda_k = \ln\left(\frac{\Delta x_{\mathrm{n}}}{\Delta x_{\mathrm{n+1}}}\right) = \ln\left(\frac{x_{\mathrm{max,n}} - x_{\mathrm{min,n}}}{x_{\mathrm{max,n+1}} - x_{\mathrm{min,n+1}}}\right) \tag{36}$$

The damping ratio D_k is determined according to equation (35), taking into account the kth logarithmic decrement. The damping ratio D is then calculated from the average value of ideally three consecutive oscillation periods according to:

$$D = \frac{1}{N}\sum_{k=1}^{N} D_k \tag{37}$$

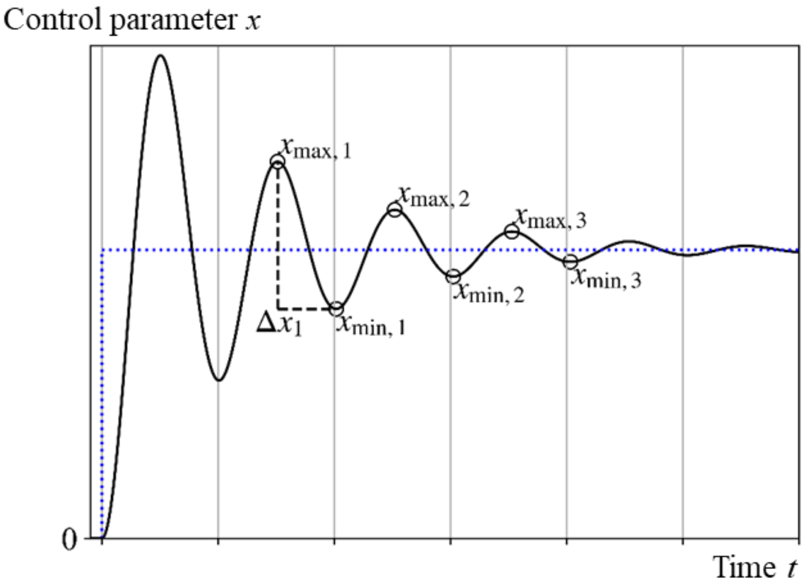


Figure 16 - Step response of a control loop for quantitative determination of the damping ratio based on the absolute differences between successive extrema

A.II. Considerations for the virtual island

All PGMs, PGSUs, as well as storage and CCUs participate in primary control based on network security (PCNB) when the mains frequency rises or falls outside the frequency band of 50 Hz ± 200 mHz. Such an event, which causes a particular plant to operate outside the frequency range of 50 Hz ± 200 mHz, may occur when a large power imbalance is no longer compensated by the market-based primary and secondary controls.

In this situation, the unit no longer sees a rigid network behind its NCP but, instead, finds itself in virtual island network operation. This creates a relevant stability condition for the unit with respect to the closed PCNB control loop (i.e. considering both the unit itself and the network), which consists of the sum of all grid-forming and grid-following units. This situation is simplified and exemplified for Type 2 PGUs in Figure 17. The start-up time constant still available in the virtual island network is then reduced to a stability-relevant level. It is essential that Type 1 units with their own flywheel mass and Type 2 units with the effectively available start-up time constant of the network (provided flywheel mass) are able to regulate and maintain a stable operating point under these operating conditions in accordance with the requirements for primary control based on network security defined in Section 4.1.2 or 4.2.2.2. For Type 1 PGU, an exemplary explanation of the dynamic behaviour of the PCNB can be found in Appendix A.III.

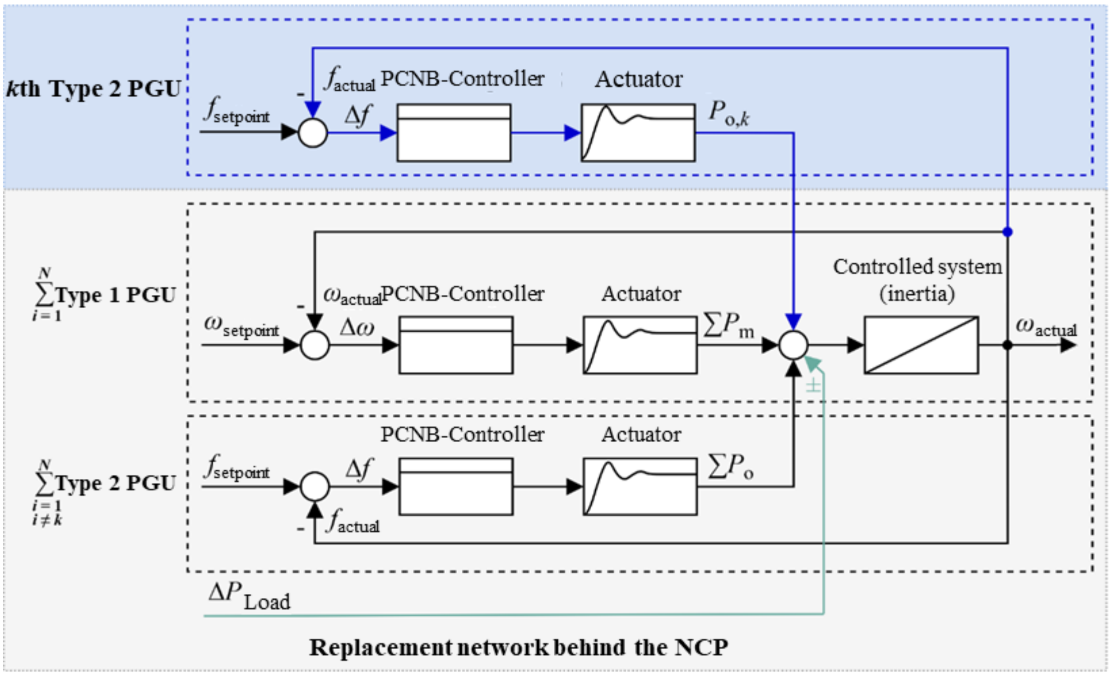


Figure 17 - Simplified power balance representation of the primary control based on network security by considering the summation in a virtual island network

A.III. Considerations for small-signal stability of the primary control in the unlimited setting range and recommendations for controller stability of Type 1 plants

Small-signal stability describes behaviour of a dynamic system during small deflections around an operating point. In the case of non-linear relationships between input and output signals, “small” signals are those which have an approximate linear transfer behaviour in the range that is essential for the task at hand.

In an interconnected system that includes rotating masses (e.g. synchronous machines), an imbalance between the generation power and the power consumed in the electrical network is manifested in an initial frequency gradient, as the current imbalance acts as an acceleration moment on the rotating masses. Therefore, the frequency (speed), which is identical to the network frequency excluding short-term dynamic oscillations, is an integrating control variable resulting from the power imbalance that is available throughout the entire network.

The primary control (market-based or based on network security) in the network is therefore an essential task that shall be constantly performed to maintain power balance between generation and consumption. The primary control may be structured into the following sub-tasks requiring different actions:

1) Maintaining stability at the operating point (small-signal stability[22])
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 planned 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, briefly up to 52.5 Hz), with a foreseeable impairment of the function of the system (e.g. frequency-dependent disconnection of a consumer load)

Maintaining small-signal stability means that a frequency gradient $\mathrm{d}f / \mathrm{d}t$ caused by a slight power imbalance is stabilised to $\mathrm{d}f / \mathrm{d}t = 0$ during undisturbed operation and, in particular in virtual island network operation, and, above all, that no ringing oscillations occur. Small-signal stability constitutes therefore a basic prerequisite for any practical operation. As all variables with an influence on frequency, it results from the

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[22] The terms controller stability and small-signal stability are used here interchangeably.

accumulated effect of all plants with frequency or speed control in a synchronous zone. This also applies to small-signal stability of large interconnected systems.

A plant without the capability to maintain a stable operating point with constant speed or frequency in standalone operation (or in island operation, sub-network operation) relies on the stabilising support of the network in parallel operation (stability provided through an external source). This is always the case when the control system active during network operation does not allow standalone operation while maintaining small-signal stability.

Unlimited setting range

Regardless of process-related limitations on active power control speeds (load change speed), small-signal stability can only be ensured if the key unit parameters such as start-up time constant and process-related behaviour (e.g. delays) during active power supply, as well as the control speed of the actuator (e.g. turbine inlet valve) are coordinated in such a way that small-signal stability is guaranteed. Since this requirement can lead to significantly higher active power ramp rates than those permitted according to Section 4.1.2 or Table 15, the control range specified for this purpose as defined in Table 14 may be reduced and designated as the ‘unlimited setting range’. For this reduced setting range, the actuation speed shall be set so that small-signal stability is guaranteed in the virtual island network while complying with the specified damping.

Limited setting range

As soon as the unlimited setting range has been passed during a control process, the load change speeds of the ‘limited setting range’ may be activated in accordance with Section 4.1.2 or Table 15. At the same time, the operating point of the unlimited setting range shall be maintained with the respective activated load change rate of the limited setting range. This is necessary, so that the steady-state condition is again available in the unlimited setting range. Thus, small-signal stability is also fully restored after passing through a limited setting range.

Example of the dynamic behaviour of primary control based on network security

The following section provides an exemplary explanation of the dynamic behaviour of PCNB for different faults in the virtual island network. For this purpose, the basic controller structure as shown in Figure 21 is used with a valve control system designated ‘PCNB control unit (example 1)’ for the limited and unlimited setting range of Type 1 PGU. The input for the PCNB control unit is the signal u_i, which represents the sum of the output signals of the upstream power and speed controllers. The output y of the PCNB control unit corresponds to the effective valve position, which is adapted within the PCNB control unit via two different control speeds in accordance with the specification of the input signal u_i and which regulates the turbine or mechanical power P_m accordingly.

NOTE The effective valve position y shown in Figure 21 is not identical to the individual valve positions but should be regarded as a simplified substitute variable.

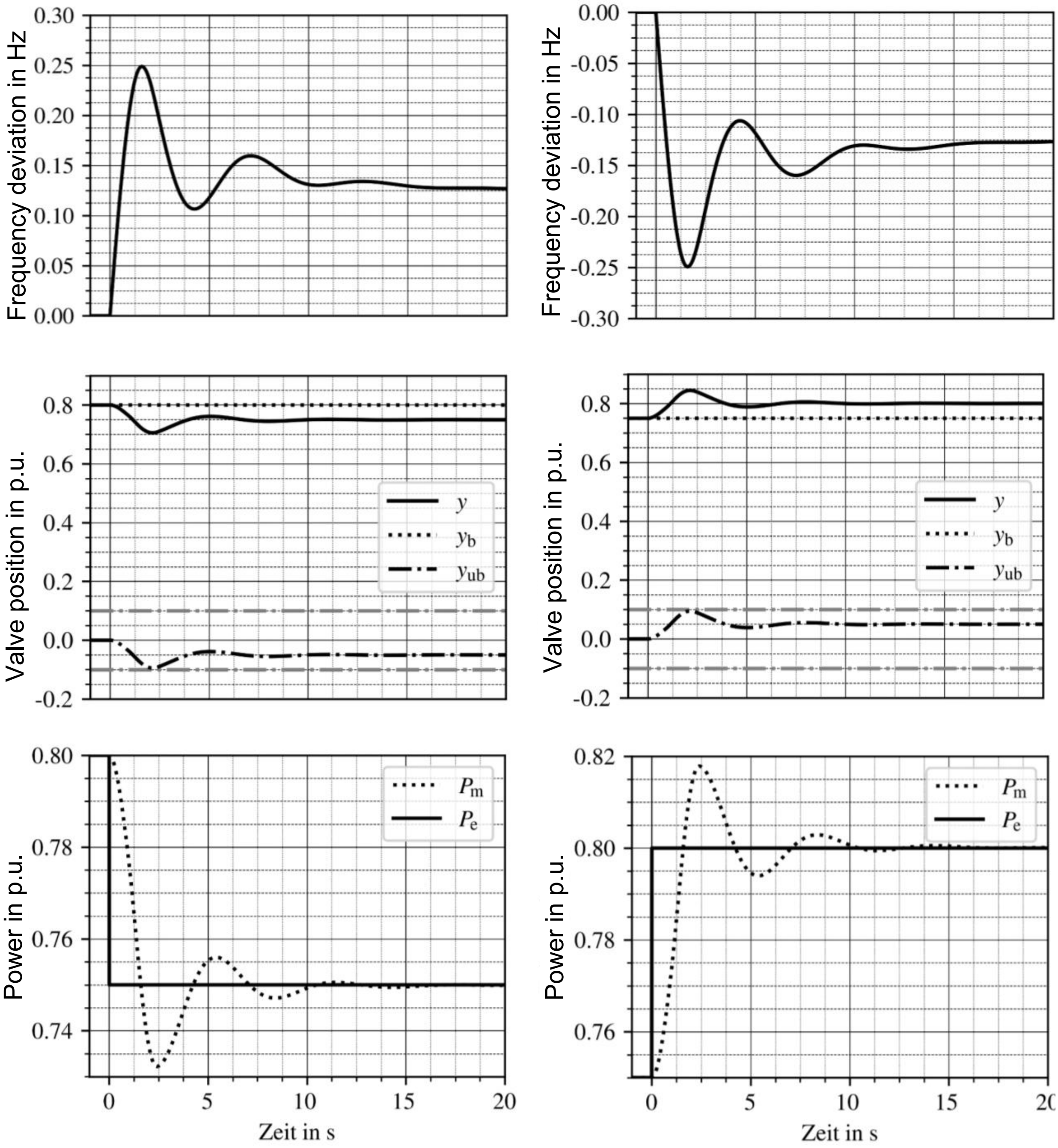
The control speeds are selected so that they meet dynamic requirements of the PCNB with regard to compliance with the requirements for small signal stability. This means that a sufficiently fast control speed is implemented for the unlimited setting range (u_i -y ≤ | 0.1 p.u.|) and a slow control speed for the unlimited setting range (u_i -y > | 0.1 p.u.|). The output signal or valve position y is therefore the sum of a synthesised unlimited (y_ub) and a limited (y_b) component.

Figure 18 and Figure 20 show the resulting dynamic behaviour with active PCNB for two different sizes of disturbance: a sudden load change of ± 5 % $P_\mathrm{b\ inst}$ (Figure 18) and a sudden load change of ± 10 % $P_\mathrm{b\ inst}$ (Figure 20).

In the case of the 5 % disturbance, the frequency response and the mechanical power P_m curve show dynamically stable and sufficiently damped behaviour. The disturbance is completely controlled in the PCNB control unit by the unlimited setting range, which is why the curve of the effective valve position y is fully described by its unlimited component y_ub, which remains within the defined limits of ± 0.1 p.u. The limited component y_b, on the other hand, does not undergo any change. In stationary operation, depending on the disturbance and a droop of 5%, a frequency deviation of |0.125 Hz| results when the threshold value for activating the PRNB is set to 0 Hz.

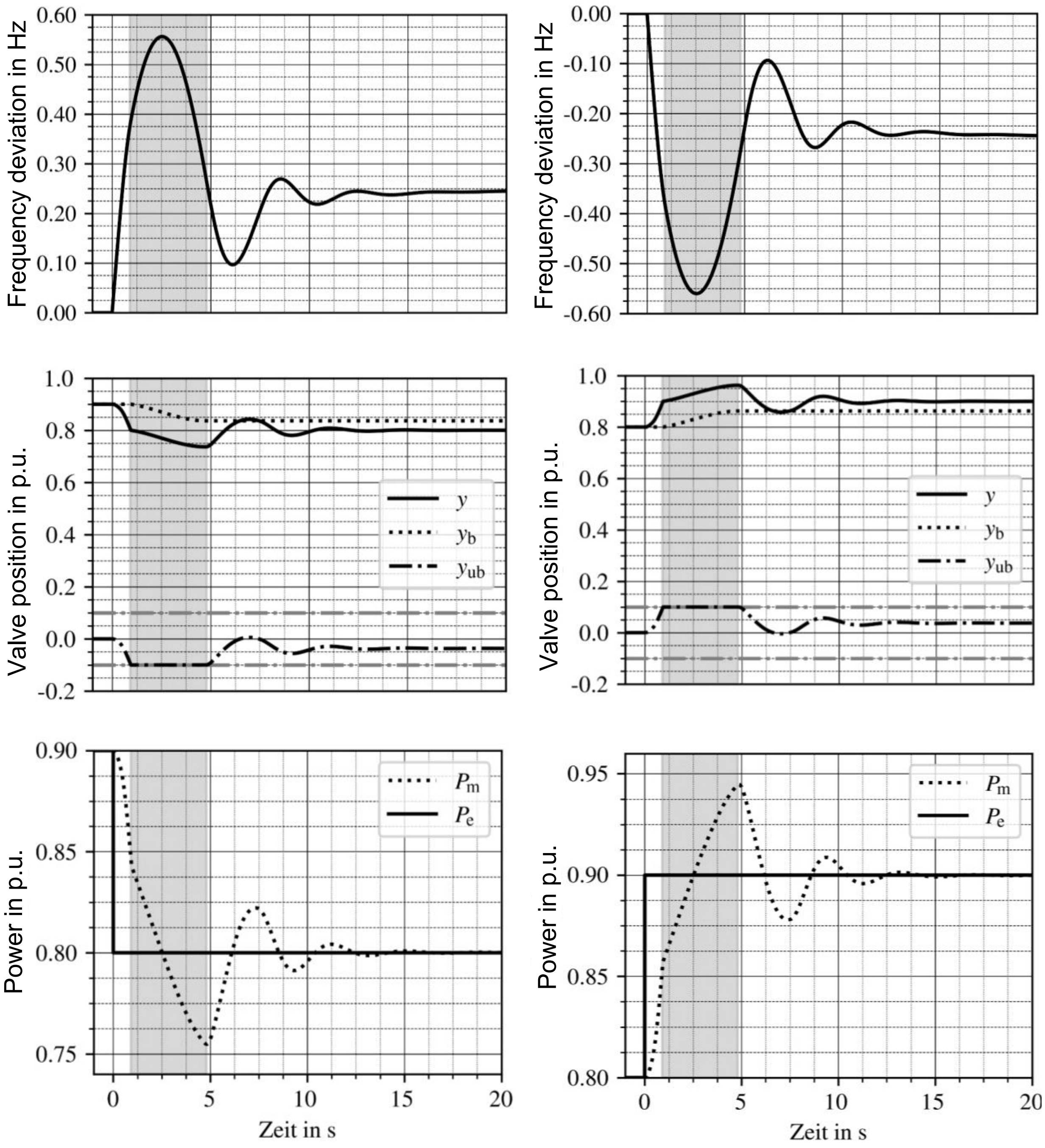
In contrast in Figure 20, the occurrence of the 10% disturbance causes the limited setting range to be temporarily activated in addition to the unlimited setting range. The respective temporarily active period of the limited setting range is shaded in grey. In this range, the unlimited component y_ub of the output signal is at its respective maximum value of ± 0.1 p.u. The response of the limited setting range is due to the fact that process-related delays in the PGU, corresponding to the available flywheel mass, lead to an increase or decrease in speed which (in connection with the set controller droop) temporarily exceed the required final steady-state value of +10% (and thus the unlimited setting range). This is particularly evident in the slower change in mechanical power P_m. As soon as the control deviation (u_i -y) is back within the limits of the unlimited setting range, the unlimited component y_ub becomes active again and the mechanical power P_m is regulated again by the valves at a faster control speed. Thanks to this coordinated valve control, the frequency or speed curve and the mechanical power curve are overall sufficiently stable and damped. In steady-state condition, the 10% disturbance and 5% droop result in a frequency deviation of |0.25 Hz| when the threshold value for activating the PCNB is set to 0 Hz.

After reaching a new steady-state operating point, the unlimited setting range shall be fully available again for further power changes. This is illustrated in Figure 20 for the +10% disturbance in Example 2 where the unlimited setting component y_ub being replaced by the limited setting component y_b. This is achieved with the slower control speed of the limited setting range. In steady-state condition, the limited component y_b thus corresponds to the valve position y, since the unlimited component y_ub then reaches the value zero and is therefore fully available again in the event of a new disturbance.



(a) (b)

Figure 18 - Example 1: Dynamic behaviour of a Type 1 plant (gas turbine) in the PCNB area (in the virtual island network) after a sudden load change of (a) - 5 % $P_{b\ inst}$ and (b) + 5 % $P_{b\ inst}$



(a) (b)

Figure 19 - Example 2: Dynamic behaviour of a Type 1 plant (gas turbine) in the PCNB area (in the virtual island network) after a sudden load change of (a) - 10 % $P_{b\ inst}$ and (b) + 10 % $P_{b\ inst}$ (the temporarily active limited setting range is shaded in grey)

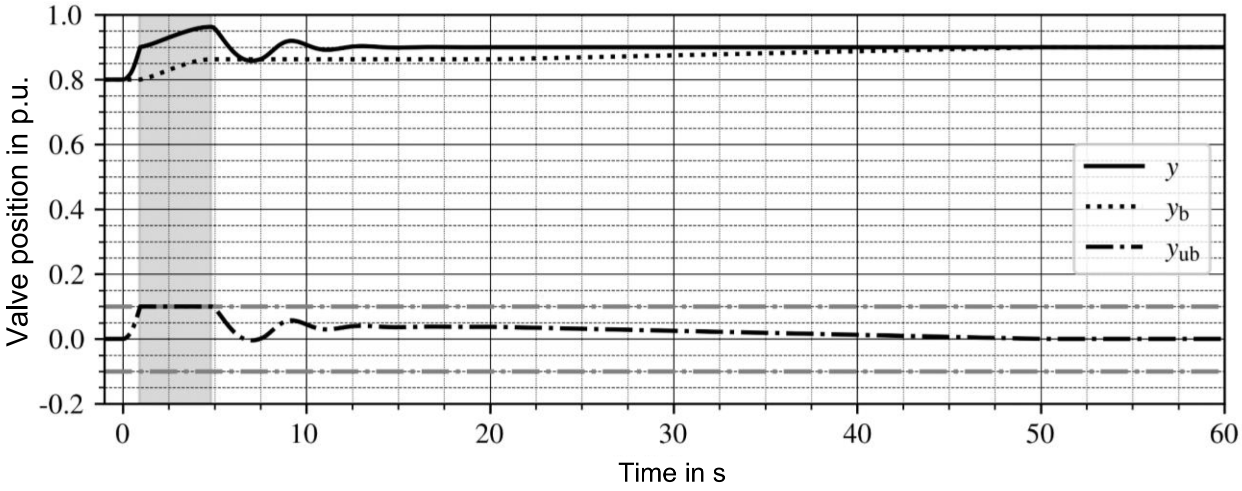


Figure 20 - Example 3: Feedback of the synthesised valve position components in the PCNB control unit

Recommendations for the controller structure

Speed control is not only required for island operation of a plant (e.g. during start-up until synchronisation with the network or during operation of the houseload network), but it is also essential for the primary control in the interconnected system. By contrast, the power control is not capable of ensuring stable primary control and is subject to limitations with respect to network dynamics, which apply even when the control does not directly act on frequency. The following remarks on power control may be derived only in part from aspects of network dynamics that are beyond the scope of this document. Nevertheless, they should still be considered in the development of controller structures and the specification of parameters:

1) False control effect: After a sudden load connection, the electrical power output of the generator (P_e or 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 plant 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 ($f_\mathrm{nadir}, f_\mathrm{zenith}$).
2) Negative contribution to the damping of the primary control: When operating in parallel with other PGUs, mutual accelerations are required between individual plants with different dynamics during a dynamic primary control process of the primary control in order to maintain synchronism. These mutual accelerations lead to dynamic power changes which affect fast power control adversely. The result is an opposing control response which reduces the damping of the primary control.
3) Negative damping of inter-area oscillations and phase swinging: Network dynamics studies show that the damping of both local phase swinging and widespread inter-area oscillations are usually adversely affected by fast power control.

A basic structure for power-controlled PGMs is described as follows in order to meet requirements for small-signal stability of the frequency control by applying a suitable parameterisation and taking into account the aspects mentioned above.

The controller structure shown in Figure 21 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 condition,

- 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 meet damping requirements.

The characteristic of the influence of the frequency regarding the deadband is defined in the f deadband block.

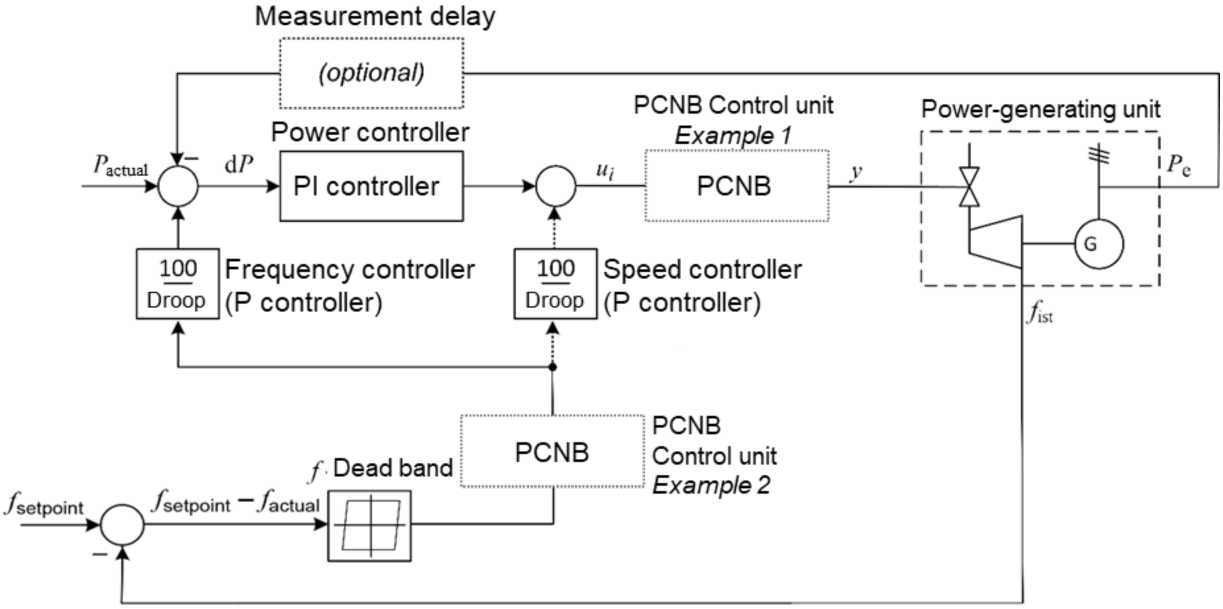


Figure 21 - Basic control structures in power-regulated PGMs with examples uses of PCNB

The power control, which serves as a P-I control to ensure compliance with the steady-state frequency-power characteristic, shall be designed to react slowly ($T_I \geq 10$ s, $K_p \leq 0.1$) so that it is dynamically decoupled from the frequency control as well as from inter-area oscillations and phase swinging and thus avoids the effects mentioned in Points 1 to 3.

In order to avoid the effects described in Points 1 to 3, the measured electrical power may be fed as input to the setpoint/actual value comparison of the power controller via a delay (see Figure 21), where the time constant of the delay is, for the reasons of dynamic decoupling mentioned above, at least 2.5 s (Point 1) and ideally 10 s (Points 1 to 3). If required, the instantaneous measurement signal of the electrical power shall be used for other functions in control systems. If the speed controller affecting the convergence point (dashed line) is not used, then the proportional gain of the power controller shall be $K_p \approx 1$ to ensure that the direct frequency action has a direct effect on the control variable.

The dynamics of the primary control may be influenced by the frequency controller acting on the power setpoint. Optionally, an additional frequency controller may be used to add its output signal to the output signal of the power controller. Both frequency controllers may include dynamic correction devices in order to meet damping requirements. The PCNB control units shown in Figure 21 are examples for uses of the primary control based on network security.

Additional functions of the turbine controller that are necessary during load shedding to maintain houseload supply after disconnecting from the network are not indicated here. For example, this may entail the deactivation of the power setpoint (P_{setpoint}) and deadbands in the frequency detection.

A.IV. Example of a verification procedure for determining the internal impedance and voltage sources in the harmonic frequency range

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 required 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 ($V_{\mathrm{GFI}}(f)$ in Figure 22) of the grid-forming unit. For this purpose, the test object is subjected to an additional small-signal harmonic excitation during operation (see Figure 22).

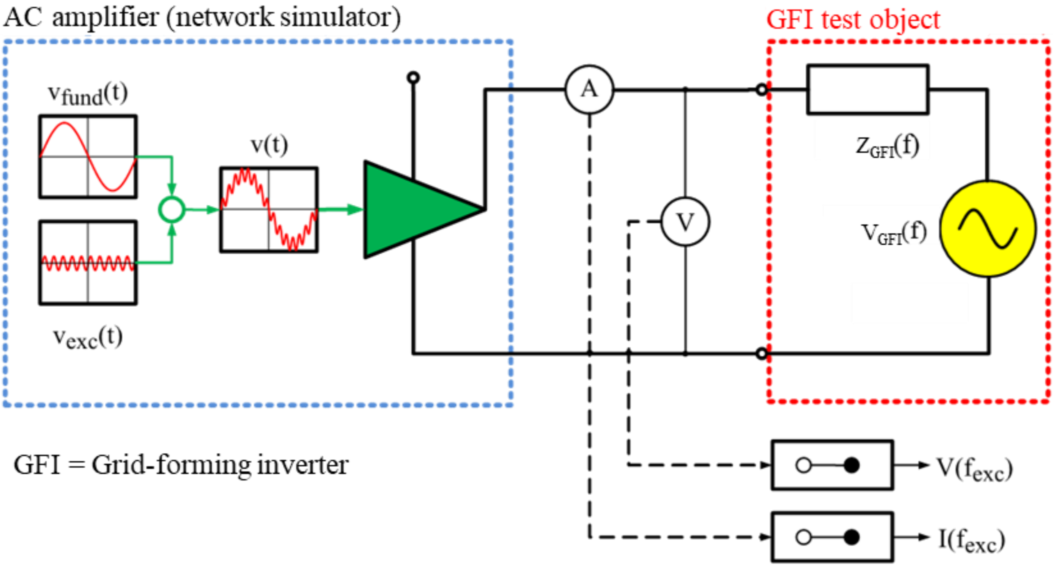


Figure 22 - Principle of differential impedance spectroscopy for determining the internal impedances and harmonics sources of a unit

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 consume or supply at least the maximum apparent power and the maximum current of the test object and, in addition to the fundamental frequency, regulate angles and amplitudes of additional excitation voltages in the required frequency range (100 Hz to 2.5 kHz).

Test setup 2 – Mains operation 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, a harmonic source is operated (in parallel or in series) 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[23,24].

Perform an impedance spectroscopy for each of the operating points in Table 12. Ensure that the test object is operated at its rated voltage (± 5 %). The frequency range to be investigated is between 100 Hz and 2.5 kHz with a maximum step size of 5 Hz.

Table 12 - Measurements to verify passivity in the harmonic frequency range

Measurement	**Active power** [% P_n]	**Reactive power** [% P_n]
1	0 - 25	0
2	25 – 50	0
3	50 - 75	0 / max. ind./ max cap.
4	75 - 100	0

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 is does not exceed 3 % of the fundamental component amplitude.

NOTE 1 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 2 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 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.

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[23] S. Rogalla, S. Kaiser, B. Burger und B. Engel, „Measured Impedance Characteristics of Solar Inverters up to 1 MW“, *19th Wind Integration Workshop*, 2020
[24] 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

NOTE 3 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 12, follow two independent excitation signals (e.g. with different amplitude or phase angle of the excitation voltage) with frequencies from 5 Hz to 2.5 kHz in steps of maximum 5 Hz in the positive and negative sequences.

Table 13 - Steps for tests to verify passivity in the harmonic frequency range

Frequency range	**Step size Δf**	**Symmetrical component**	**Window size t_a**
100 Hz to 2.5 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. It can be determined by the necessary resolution of the Fourier transform and depends on the step size Δf. In general, the following applies:

$$t_a = \frac{1}{\Delta f} \tag{38}$$

For the maximum step size of 5 Hz required in this document, this results in a window size of 200 ms.

NOTE 4 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 $t_b = 3 \cdot t_a$.

Excitation duration:
The excitation duration per frequency step is also at least three windows of duration t_a therefore $t_b = 3 \cdot t_a$.

NOTE 5 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 $I_{a1,2}(f)$, $I_{b1,2}(f)$ per symmetrical component differing in phase or amplitude of the excitation may then be obtained from the spectrum. The formulas (39) to (42) 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.

$$\underline{Z}_1(f) = \frac{\underline{U}_{a1}(f) - \underline{U}_{b1}(f)}{\underline{I}_{a1}(f) - \underline{I}_{b1}(f)} \tag{39}$$

$$\underline{Z}_2(f) = \frac{\underline{U}_{\mathrm{a2}}(f) - \underline{U}_{\mathrm{b2}}(f)}{\underline{I}_{\mathrm{a2}}(f) - \underline{I}_{\mathrm{b2}}(f)} \quad (40)$$

$$\underline{U}_1(f) = \frac{\underline{U}_{\mathrm{a1}}(f) \cdot \underline{I}_{\mathrm{b1}}(f) - \underline{U}_{\mathrm{b1}}(f) \cdot \underline{I}_{\mathrm{a1}}(f)}{\underline{I}_{\mathrm{b1}}(f) - \underline{I}_{\mathrm{a1}}(f)} \quad (41)$$

$$\underline{U}_2(f) = \frac{\underline{U}_{\mathrm{a2}}(f) \cdot \underline{I}_{\mathrm{b2}}(f) - \underline{U}_{\mathrm{b2}}(f) \cdot \underline{I}_{\mathrm{a2}}(f)}{\underline{I}_{\mathrm{b2}}(f) - \underline{I}_{\mathrm{a2}}(f)} \quad (42)$$

The last window is generally considered in the evaluation.

NOTE 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 may 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 terms of magnitude and phase

The determined impedances are each displayed in a diagram in terms of 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 in terms of 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 using Prony analysis[25] for filtering out oscillations with known frequencies, caused by mechanical resonances, from active power or frequency signals. 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 $p1(t)$ for correcting the active power curve and $f1(t)$ for the frequency curve):

1) **Removing the signal path before the event**

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[25] Further information on Prony analysis can be found in: J. Machowski, Z. Lubosny, J. W. Bialek, und J. R. Bumby, *Power System Dynamics: Stability and Control*, 3. Hoboken Publisher House, NJ, USA: John Wiley & Sons, 2020.

Remove the section before the start of the event from the signal path so that the time $t = 0$ corresponds to the start of the event.

2) **Dividing the signal path into several components (Prony analysis)**

Divide the signal path $g(t)$ resulting from Step 1 into several vibration components with different frequencies using Prony analysis. Determine the i-th amplitudes $\mathrm{A_i}$, frequencies f_i, phase angles φ_i and damping parameters d_i of the n identified vibration components. 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 $g(t)$:

$$g_{\text{prony}}(t) = \sum_{i=1}^{n} A_i e^{d_i \cdot t} \cos\left(2\pi f_i t + \varphi_i\right) \tag{43}$$

3) **Comparing identified frequencies with frequencies of mechanical resonances**

Compared frequencies f_i of the vibration components identified by the Prony analysis 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.

B. Appendix (normative)

B.I. Parameters for the primary control based on network security

Table 14 - Dynamic requirements for 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	
		$P_{\mathrm{ub,min}}$	$P_{\mathrm{ub,max}}$	Amplitude	Damping ratio
Gas turbine ≤ 2 MW(2)	1	10 % $P_{\mathrm{b\ inst}}$	100 % $P_{\mathrm{b\ inst}}$	± 10 % $P_{\mathrm{b\ inst}}$	≥ 0.06
Gas turbine > 2MW(2)		55 % $P_{\mathrm{b\ inst}}$(9)	100 % $P_{\mathrm{b\ inst}}$(9)	± 10 % $P_{\mathrm{b\ inst}}$ (8)	≥ 0.06
Steam turbine(6)		20 % $P_{\mathrm{b\ inst}}$(9)	100 % $P_{\mathrm{b\ inst}}$(9)	± 10 % $P_{\mathrm{b\ inst}}$ (8)	≥ 0.06
Combined-cycle power plant		55 % $P_{\mathrm{b\ inst}}$(9)	100 % $P_{\mathrm{b\ inst}}$(9)	± 10 % $P_{\mathrm{b\ inst}}$ (8)	≥ 0.06
Internal combustion engines (for power generation) (3)		50 % P_{Emax}	100 % P_{Emax}	- 10 % / + 5 % P_{Emax}	≥ 0.06
Gas engine (4)		50 % P_{Emax}	100 % P_{Emax}	- 5 % / + 2,5 % P_{Emax}	≥ 0.06
Hydroelectric power plants in turbine and, where applicable, pump operation		(7)	(7)	(7)	
Geothermal energy		10 % P_{Emax}	100 % P_{Emax}	± 10 % P_{Emax}	≥ 0.06
Battery storage	2	-100 % P_{mn}(5)	100 % P_{mn}(5)	± 100 % P_{mn}(5)	≥ 0.2
Fuel cell		No requirements			
PV plant		10 % P_{Emax}	100 % P_{Emax}	± 90 % P_{Emax}	≥ 0.2
Wind power plant		45 % P_{Emax}	100 % P_{Emax}	- 10 % / + 1 % P_{Emax}	≥ 0.06
		15 % P_{Emax}	45 % P_{Emax}	- 10 % P_{Emax}	

1) Unlimited setting range: Range of the small-signal stability of the primary control based on network security (see definition in Section 3.1.32.2) for cos $\varphi = 1$.

2) This applies to natural gas. Other values may be agreed between the system 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 system 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). The value may depend on the operating conditions and is determined by the maximum possible power in charging mode when the feed-in is reduced (+ΔP) and the maximum possible power in discharging mode when the feed-in is increased (-ΔP).

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 system operator on a project-by-project basis and determined through the hydraulic characteristics of the plant. For plants with a P_{Amax} > 45 MW, additional coordination with the transmission system operator is required. Designs with ineffective working and associated setting ranges are not permissible.

8) For Type 1 units or plants with $P_{\mathrm{b\ inst}}$ > 350 MW, the maximum amplitude is: $\pm \frac{35\ \mathrm{MW}}{P_{\mathrm{b\,inst}}} \cdot 100\ \%$.

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 system operator in accordance with Appendix B.II.

NOTE For PGUs based on a new type of technology, the total setting range and the amplitude of the unlimited setting range of the PCNB shall be agreed between the system operator and the plant operator on a project-specific basis.

Table 15 - Dynamic requirements for 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(2)	Minimum actuating speed	Setting range(2)	Minimum actuating speed	Setting range(2)	Minimum actuating speed	Setting range(2)	Minimum actuating speed
Gas turbine ≤ 2 MW(3)	1	10 % - 100 %	66 % $P_{\text{b inst}}$ /min	10 % - 100 %	66 % $P_{\text{b inst}}$ /min	10 % - 100 %	66 % $P_{\text{b inst}}$ /min	10 % - 100 %	66 % $P_{\text{b inst}}$ /min
Gas turbine > 2 MW(3)(6)		55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min
Steam turbine(4)		20 % - 100 %	20 % $P_{\text{b inst}}$ /5 min	20 % - 100 %	20 % $P_{\text{b inst}}$ /5 min	20 % - 100 %	45 % $P_{\text{b inst}}$ /8s	20 % - 100 %	45 % $P_{\text{b inst}}$ /8s
Combined-cycle power plant(6)		55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min	55 % - 100 %	20 % $P_{\text{b inst}}$ /min
Internal combustion engines (for power generation) ≤ 2 MW(3)		50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min
Internal combustion engines (for power generation) > 2 MW(3)		50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min
Geothermal energy		10 % - 100 %	20 % $P_{\text{b inst}}$ /5 min	10 % - 100 %	20 % $P_{\text{b inst}}$ /5 min	10 % - 100 %	45 % $P_{\text{b inst}}$ /8 s	10 % - 100 %	45 % $P_{\text{b inst}}$ /8s
Hydropower		(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)
Fuel cell ≤ 2 MW	2	50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min	50 % - 100 %	66 % $P_{\text{b inst}}$ /min
Fuel cell > 2 MW		50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min	50 % - 100 %	20 % $P_{\text{b inst}}$ /min
Wind power plant		65 % - 100 % 45 % - 65 % 15 % - 45 %	6 % $P_{\text{b inst}}$ /s 4 % $P_{\text{b inst}}$ /s 2 % $P_{\text{b inst}}$ /s	65 % - 100 % 45 % - 65 % 15 % - 45 %	6 % $P_{\text{b inst}}$ /s 4 % $P_{\text{b inst}}$ /s 2 % $P_{\text{b inst}}$ /s	15 % - 100 %	25 % $P_{\text{b inst}}$ /s	15 % - 100 %	25 % $P_{\text{b inst}}$ /s

1) Limited setting range: (large signal behaviour); consideration of the open control loop
2) The setting range is relative to P_{Emax}, but for Type 1 units of gas turbine, steam turbine and gas and steam plant technologies it is relative to $P_{\text{b inst}}$.
3) All fuels, including: diesel, natural gas, digester gas, heating oil, kerosene, synthesis gas. Other values may be agreed between the system 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 incineration”.
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 plant. For plants with a P_{Amax} > 45 MW additional coordination with the transmission system operator is required. Designs with ineffective working and associated setting ranges are not permissible.
6) 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 system operator in accordance with Appendix B.II.

NOTE For PGUs based on a new type of technology, the total setting range and the amplitude of the limited setting range of the PCNB shall be agreed between the system operator and the plant operator on a project-specific basis.

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% $P_{\text{b inst}}$.

For example, a 10 % $P_{\text{b inst}}$ load connection (requirements for fast output power) starting from a power point of 90 % $P_{\text{b inst}}$ 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 23. The power range from approx. 95% to 100% $P_{\text{b inst}}$ 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% $P_{\text{b inst}}$ (CCGT).

In the transient setting range > approx. 80% $P_{\text{b inst}}$ (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 as shown in Figure 23 in the lower setting range < approx. 70 % $P_{\text{b inst}}$ (CCGT).

This behaviour requires an adjustment of the requirements (actuating speed or amplitude) in the boundary zones of the limited and unlimited setting range as shown in Figure 23.

Both scenarios (load disconnection in the lower setting range or load connection in the upper setting 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 23 should only be seen as an example.

NOTE For Type 1 units or plants with $P_{\text{b inst}}$ *> 350 MW, the maximum amplitude is:* $\pm \frac{35\,MW}{P_{b\,inst}} \cdot 100\,\%$.

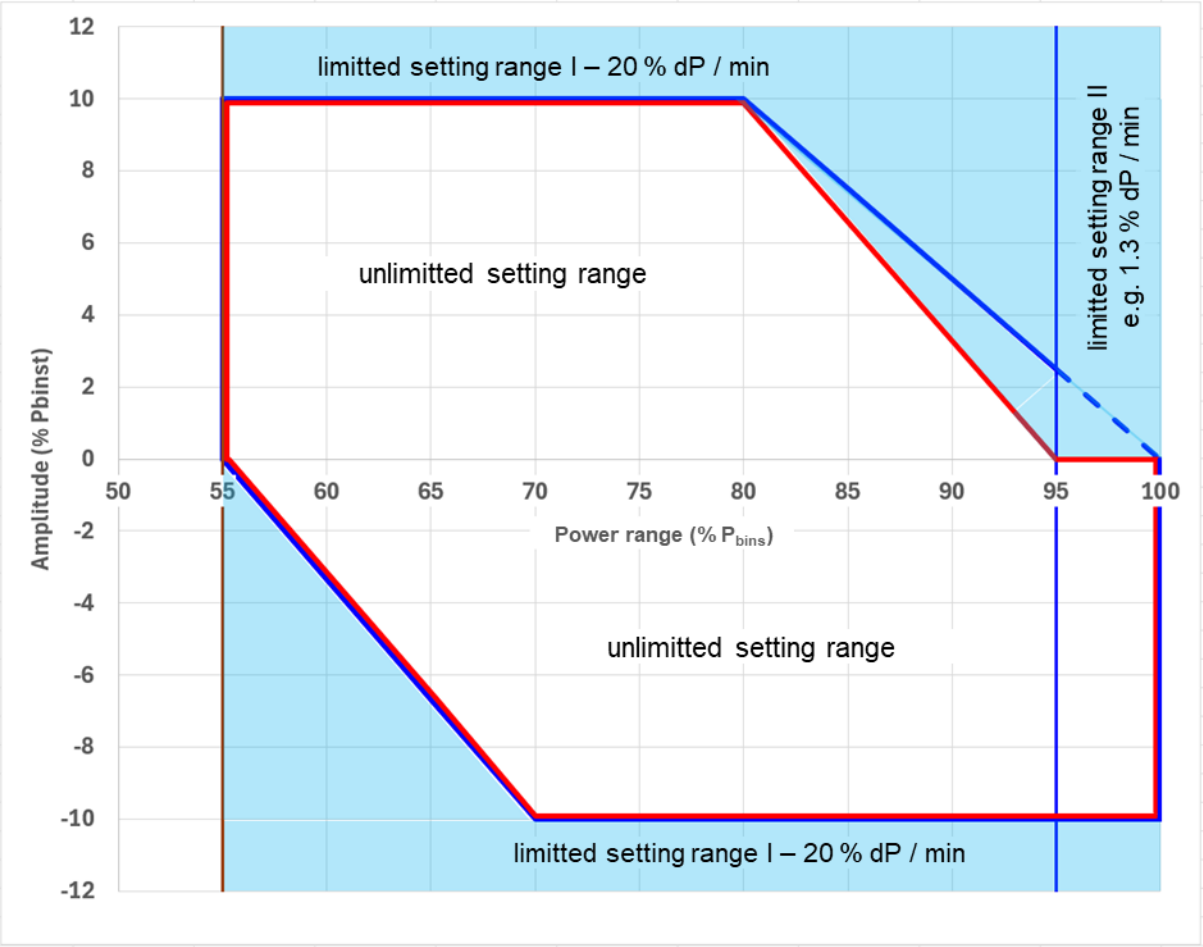


Figure 23 - Technological limitations of the setting ranges (example CCGT)

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 23, the blue and red characteristic curves diverge at approx. 80 % $P_{\text{b inst}}$ (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% $P_{\text{b inst}}$ (CCGT), a control reserve of 2.5% $P_{\text{b inst}}$ (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 16.

Table 16 - 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 of values/resolution**	**Unit**
[…]	[…]	[…]	[…]	[…]
Deactivation of the deadband of the primary control based on network security (Section 4.2.2.6)	Setting command	M	2 x binary	
Activation of the deadband of the primary control based on network security (Section 4.2.2.6)	Setting command	M	2 x binary	
[…]	[…]	[…]	[…]	[…]
Feedback messages (for checking the transmitted values)	**Function**	**Requirement** O… Optional M… Minimum	**Range of values/resolution**	**Unit**
[…]	[…]	[…]	[…]	[…]
Activation of the deadband of the primary control based on network security (Section 4.2.2.6)	Setting command	M	2 x binary	
Activation of the deadband of the primary control based on network security (Section 4.2.2.6)	Setting command	M	2 x binary	
[…]	[…]	[…]	[…]	[…]

B.IV. Construction of the envelope curve for determining the damping of voltage source control

The basis for evaluating the damping requirements for the disturbance behaviour of the voltage source control 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 ± 15 % relative to the final value (Δx_{tol} = 15 % · $\Delta i_{\mathrm{Q,End}}$) no later than 80 ms after a sudden change in the terminal voltage of the unit (see Figure 10). Figure 10 is shown again below for illustrative purposes.

NOTE The key points of the requirement were selected based on the +20 / -30 % I_{r} 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 $\Delta i_{\mathrm{Q,End}}$ is first determined relative to the pre-fault reactive current in accordance with Section 5.5.5.6.2.3 or Section 5.5.5.4.3.

The overshoot Δx_{M} for the required damping ratio of D = 0.3 is generally a maximum of

$$\Delta x_{\mathrm{M}} = e^{-\frac{D\cdot\pi}{\sqrt{1-D^2}}}\cdot\Delta i_{\mathrm{Q,End}} = 0.3723\cdot\Delta i_{\mathrm{Q,End}} \tag{44}$$

and limits the envelope curve in the first section upwards until time t_1.

The time t_M of the first maximum is around

$$t_M = \frac{-1}{\ln\left(\Delta x_{tol} \cdot \sqrt{1-D^2}\right)} \cdot \frac{D \cdot \pi}{\sqrt{1-D^2}} \cdot t'_2 = 40.65 \text{ ms} \tag{45}$$

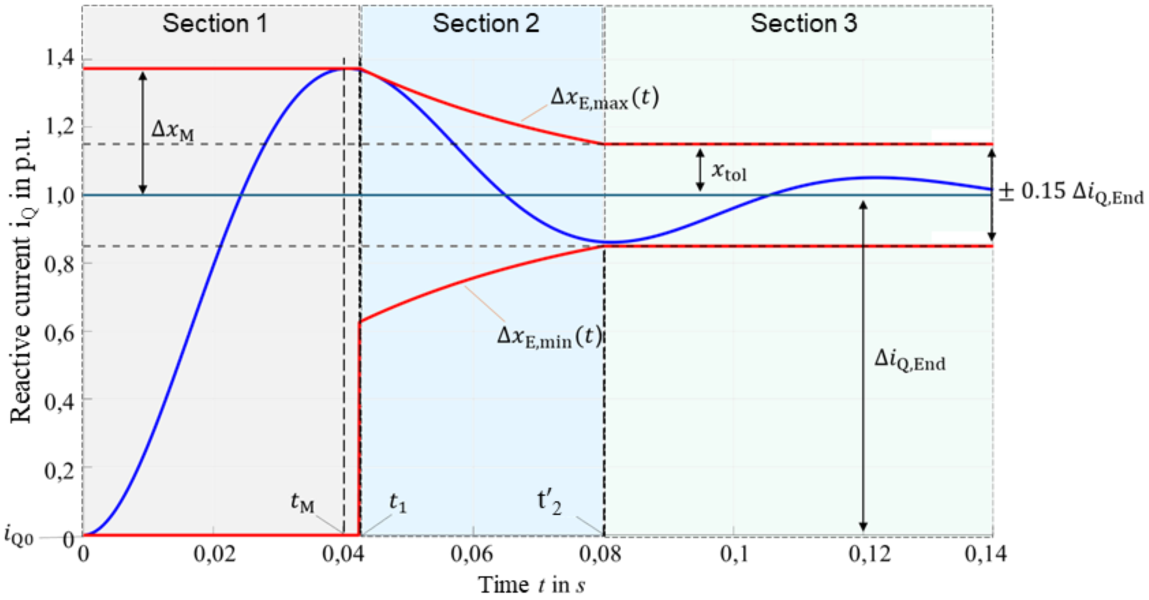


Figure 10 - (Repetition) Envelope curve for determining the damping of continuous voltage control

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 value in order to tangentially match the transient response of the PT2 element:

$$t_1 = \left(1 - \frac{\sqrt{1-D^2}}{\pi \cdot D} \cdot \ln\left(\sqrt{1-D^2}\right)\right) \cdot t_M = 42.6 \text{ ms} \tag{46}$$

Based on this, the upper and lower envelopes $\Delta x_{E,max}(t)$ or $\Delta x_{E,min}(t)$ in the form of e-functions in the second section of the envelope curve are:

$$\text{(upper envelope) } \Delta x_{E,max}(t) = \left(1 + \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} \cdot t}}{\sqrt{1-D^2}}\right) \cdot \Delta i_{Q,End} \tag{47}$$

$$\text{(lower envelope) } \Delta x_{E,min}(t) = \left(1 - \frac{e^{-\frac{D \cdot \pi}{T_M \cdot \sqrt{1-D^2}} \cdot t}}{\sqrt{1-D^2}}\right) \cdot \Delta i_{Q,End} \tag{48}$$

In the third section, a tolerance band of Δx_{tol} of ± 15 % · $\Delta i_{Q,End}$ 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 ± 5 % · $\Delta i_{Q,End}$ 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'_2 = 80 ms (see Figure 24).

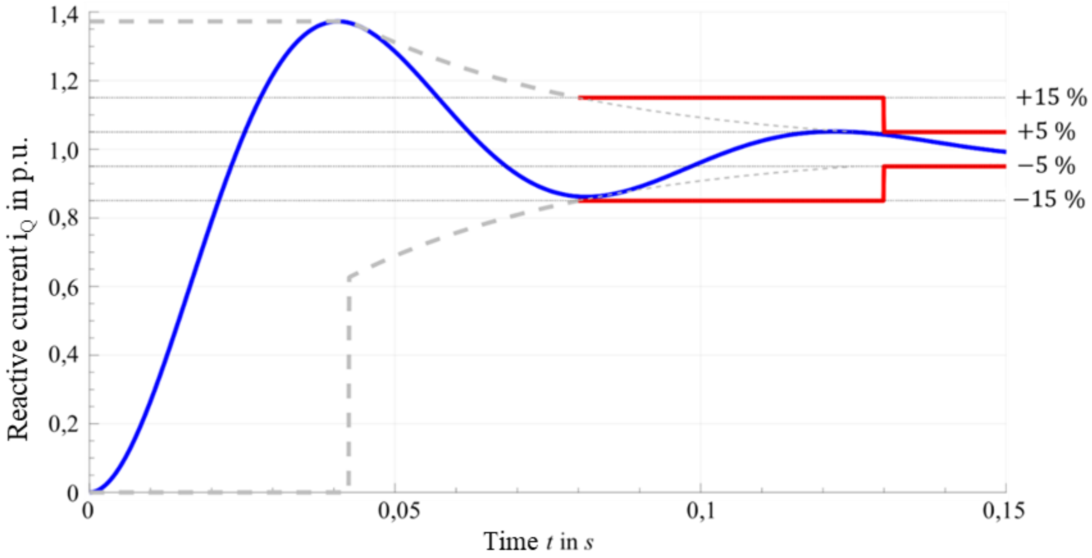


Figure 24 - Envelope curve for evaluating the damping behaviour during large signal changes in the voltage amplitude at the terminals of the grid-forming unit

B.V. Determination of instantaneous values

Instantaneous values are determined using αβ coordinates with the aid of the Clarke transformation. The αβ coordinates of the voltages are determined as follows:

$$u_\alpha = \frac{\sqrt{2}}{3} \cdot (u_\mathrm{a} - 0.5 \cdot u_\mathrm{b} - 0.5 \cdot u_\mathrm{c}) \tag{49}$$

$$u_\beta = \frac{\sqrt{2}}{3} \cdot \left(\frac{\sqrt{3}}{2} \cdot u_\mathrm{b} - \frac{\sqrt{3}}{2} \cdot u_\mathrm{c}\right) \tag{50}$$

$$u_0 = \frac{\sqrt{2}}{3} \cdot \left(\frac{1}{\sqrt{2}} \cdot u_\mathrm{a} + \frac{1}{\sqrt{2}} \cdot u_\mathrm{b} + \frac{1}{\sqrt{2}} \cdot u_\mathrm{c}\right) \tag{51}$$

The αβ coordinates of the currents are determined as follows:

$$i_\alpha = \frac{\sqrt{2}}{3} \cdot (i_a - 0.5 \cdot i_\mathrm{b} - 0.5 \cdot i_\mathrm{c}) \tag{52}$$

$$i_\beta = \frac{\sqrt{2}}{3} \cdot \left(\frac{\sqrt{3}}{2} \cdot i_\mathrm{b} - \frac{\sqrt{3}}{2} \cdot i_\mathrm{c}\right) \tag{53}$$

$$i_0 = \frac{\sqrt{2}}{3} \cdot \left(\frac{1}{\sqrt{2}} \cdot i_\mathrm{a} + \frac{1}{\sqrt{2}} \cdot i_\mathrm{b} + \frac{1}{\sqrt{2}} \cdot i_\mathrm{c}\right) \tag{54}$$

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 αβ coordinate system is calculated as the RMS value using:

$$|u_{\alpha\beta}| = \sqrt{(u_\alpha^2 + u_\beta^2)} \tag{55}$$

$$\left|i_{\mathrm{\alpha\beta}}\right| = \sqrt{\left(i_{\mathrm{\alpha}}^2 + i_{\mathrm{\beta}}^2\right)} \tag{56}$$

The modulus bars of $|u_{\mathrm{\alpha\beta}}|$ and $|i_{\mathrm{\alpha\beta}}|$ have been omitted from this document for the sake of simplicity.

The instantaneous active power in the three-phase system is defined as:

$$p = u_{\mathrm{a}} \cdot i_{\mathrm{a}} + u_{\mathrm{b}} \cdot i_{\mathrm{b}} + u_{\mathrm{c}} \cdot i_{\mathrm{c}} \tag{57}$$

The active power determined using equation (57) corresponds to the active power in the αβ coordinate system, i.e.:

$$p_{\mathrm{\alpha\beta}} = p = 3 \cdot (u_{\mathrm{\alpha}} \cdot i_{\mathrm{\alpha}} + u_{\mathrm{\beta}} \cdot i_{\mathrm{\beta}}) \tag{58}$$

The magnitude of the active current vector in the αβ coordinate system may be determined as the RMS value as follows:

$$|i_{\mathrm{P,\alpha\beta}}| = \frac{p}{3 \cdot \left|u_{\mathrm{\alpha\beta}}\right|} \tag{59}$$

The modulus bars of $|i_{\mathrm{\alpha\beta}}|$ have been omitted from this document for the sake of simplicity.

The instantaneous reactive power in the αβ coordinate system is defined as:

$$q_{\mathrm{\alpha\beta}} = 3 \cdot \left(-u_{\mathrm{\alpha}} \cdot i_{\mathrm{\beta}} + u_{\mathrm{\beta}} \cdot i_{\mathrm{\alpha}}\right) \tag{60}$$

To suppress measurement noise, a moving average over 5 ms is formed for the evaluation of these variables in this FNN Guideline according to:

$$u_{\mathrm{\alpha\beta,5ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} u_{\mathrm{\alpha\beta}} \cdot \mathrm{d}t \tag{61}$$

$$i_{\mathrm{\alpha\beta,5ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} i_{\mathrm{\alpha\beta}} \cdot \mathrm{d}t \tag{62}$$

$$i_{\mathrm{P,\alpha\beta,5ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} i_{\mathrm{P,\alpha\beta}} \cdot \mathrm{d}t \tag{63}$$

$$p_{\mathrm{\alpha\beta,5ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} p_{\mathrm{\alpha\beta}} \cdot \mathrm{d}t \tag{64}$$

$$q_{\mathrm{\alpha\beta,5ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} q_{\mathrm{\alpha\beta}} \cdot \mathrm{d}t \tag{65}$$

B.VI. Determination of the angular change over time

The angular change over time may be determined by the following steps:

1) Determining the αβ components u_α, u_β from the three-phase voltages using αβ transformation (see equations (49) and (50)).
2) Calculating the phase angle:

$$\varphi_{\mathrm{u},\alpha\beta} = \begin{cases} \mathrm{atan}\left(\frac{u_\beta}{u_\alpha}\right) + \left(\frac{3\pi}{2}\right) & , \mathit{if}\ u_\alpha < 0 \\ \mathrm{atan}\left(\frac{u_\beta}{u_\alpha}\right) + \left(\frac{\pi}{2}\right) & , \mathit{if}\ u_\alpha \geq 0 \end{cases} \tag{66}$$

3) Determining the raw phase angle change, including changes due to the sawtooth waveform:

$$\Delta\varphi_{\mathrm{u},\alpha\beta} = \varphi_{\mathrm{u},\alpha\beta}^{(2\ldots n)} - \varphi_{\mathrm{u},\alpha\beta}^{(1\ldots(n-1))} \tag{67}$$

where n corresponds to the number of data points.

4) Removing the influence of the sawtooth waveform in the phase angle change:

$$\Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{korr0}} = \begin{cases} \Delta\varphi_{\mathrm{u},\alpha\beta}^{(-2\pi)} & , \text{if } \Delta\varphi_{\mathrm{u},\alpha\beta} > \pi \\ \Delta\varphi_{\mathrm{u},\alpha\beta} & , \text{if } \Delta\varphi_{\mathrm{u},\alpha\beta} \leq \pi \end{cases} \tag{68}$$

$$\Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{korr}} = \begin{cases} \Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{corr0}}^{(+2\pi)} & , \text{if } \Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{corr0}} < -\pi \\ \Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{corr0}} & , \text{if } \Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{corr0}} \geq -\pi \end{cases} \tag{69}$$

5) Determining the instantaneous (noise-affected) frequency:

$$f = \frac{\Delta\varphi_{\mathrm{u},\alpha\beta,\mathrm{corr}}}{2\pi \cdot \Delta t} \tag{70}$$

where Δt corresponds to the time resolution of the data points.

6) Calculating frequency averages with two moving time windows of 5 ms and 1 s:

$$f_{5\mathrm{ms}} = \frac{1}{5\ \mathrm{ms}} \cdot \int_{t-5\ \mathrm{ms}}^{t} f \cdot \mathrm{d}t \tag{71}$$

$$f_{1\mathrm{s}} = \frac{1}{1\ \mathrm{s}} \cdot \int_{t-1\ \mathrm{s}}^{t} f \cdot \mathrm{d}t \tag{72}$$

7) Determining the difference between the two aforementioned frequency averages (in steady state, this difference is zero):

$$\Delta f = f_{5\mathrm{ms}} - f_{1\mathrm{s}} \tag{73}$$

8) Calculating the integral of the frequency difference over time and conversion from rad to degrees:

$$\varphi_{\mathrm{rad}} = 2\pi \cdot \int_{t-1\ s}^{t} \Delta f \cdot \mathrm{d}t \tag{74}$$

$$\varphi_{\mathrm{grad}} = \frac{\varphi_{\mathrm{rad}}}{\pi} \cdot 180° \tag{75}$$

B.VII. Benchmark system for verifying network parallel operation capability

The benchmark network model (BN) to be used to verify network parallel operation capability is shown in Figure 25 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 25.

PGM-1 corresponds to a plant 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 17.

Table 17 - Rated voltages of the nodes in the benchmark system (verification of network parallel operation capability)

Nodes	Nominal voltage
EHV-1	380 kV
HV-0, HV-1, HV-2	110 kV
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-based, 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 parameterised 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 18.

Table 18 - (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 a plant is greater than half the rated apparent power S_r 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 network node ‘MV-1’ or ‘MV-2’ is achieved in accordance with Test 2c shown in Section 5.5.7.10.3. 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 as shown in Figure 25,
   - a parallel connection of the PGU on the low-voltage side of a common PGU transformer as shown in Figure 26, 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_r across all sections.
   c) R/X value of the partial section according to the following formula: R/X [p.u.] = (0.3 · I_r [kA])$^{-1,5}$.

    d) Maximum voltage drop along the entire bundle conductor is < 1% at rated active power or compliance with an impedance of the bundle conductor is < 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:
    a) Minimum possible cross-sectional dimensioning per section individually or identical across all sections.
    b) Compliance with the nominal line load capacity I_r across all sections.
    c) R/X value of the partial section according to the following formula: R/X [p.u.] = $(0.28 \cdot I_r\,[\text{kA}])^{-1,67}$.
    d) 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:
    a) 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.
    b) 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).
    c) Tap changers may be represented 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.
    d) 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.

1) Table 19 applies for the active and reactive power operating points of the PGU in the initial state. For PGSUs (storage), the specified active power operating points shall also be checked in the event of a negative sign (consumption).
2) 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.
3) 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 19 - 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)**						**Initiali-sation**
			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)

*Consumption of active power: nominal apparent power

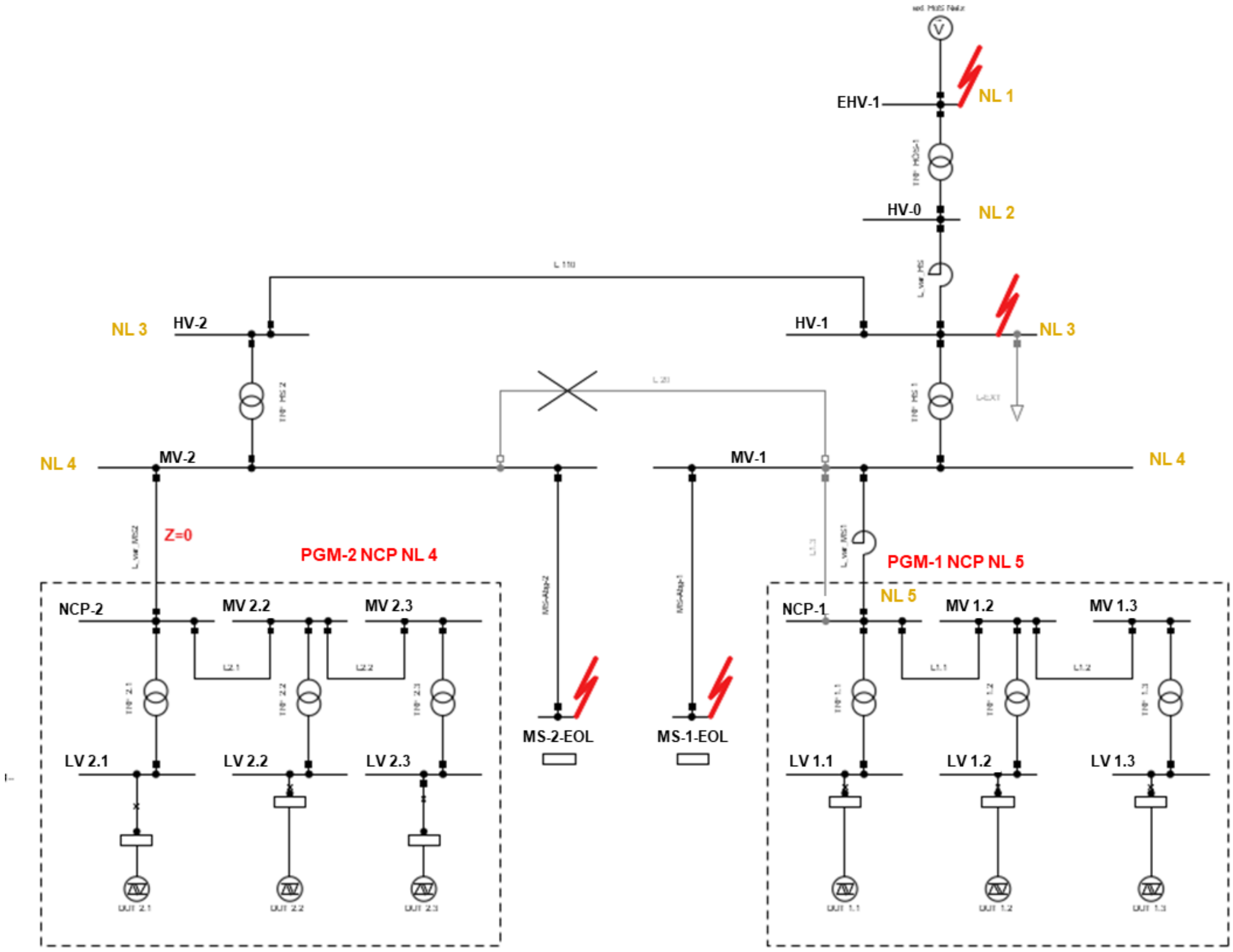


Figure 25 - Benchmark system for verifying network parallel operation capability

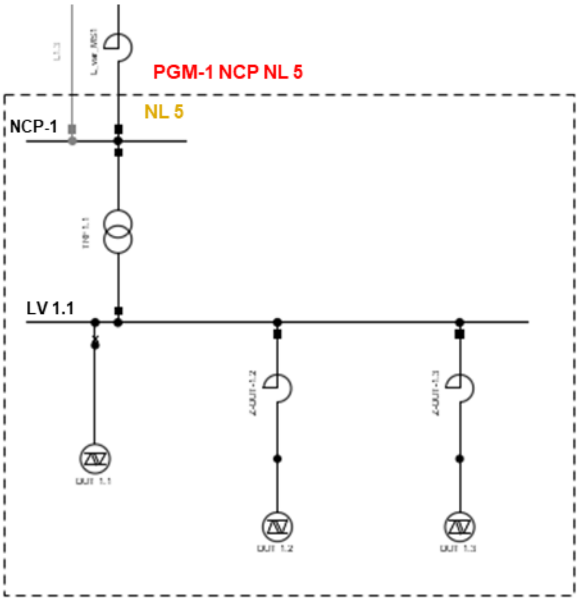


Figure 26 - Alternative configuration of the PGM 1 (same for PGM 2)

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, appropriate adjustments are necessary. A continuous determination of the THD with a step size of 1 ms shall be used for evaluation. No grouping is applied. 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:

$$f(t) = c_0 + \sum_{k=1}^{\infty} c_k \sin\left(\frac{k}{N}\omega_1 t + \varphi_k\right) \tag{76}$$

$$c_k(t_1) = |b_k(t_1) + j a_k(t_1)| = \sqrt{b_k(t_1)^2 + a_k(t_1)^2} \tag{77}$$

$$Y_{C,k}(t_1) = \frac{c_k(t_1)}{\sqrt{2}} \tag{78}$$

$$b_k(t_1) = \frac{2}{T_N} \int_{t_1 - T_N}^{t_1} f(t) \times \sin\left(\frac{k}{N}\omega_1 t\right) \mathrm{d}t \tag{79}$$

$$a_k(t_1) = \frac{2}{T_N} \int_{t_1 - T_N}^{t_1} f(t) \times \cos\left(\frac{k}{N}\omega_1 t\right) \mathrm{d}t \tag{80}$$

$$c_0(t_1) = \frac{1}{T_N} \int_{t_1 - T_N}^{t_1} f(t)\, \mathrm{d}t \tag{81}$$

The time profile of THD is then determined from:

$$THD(t_1) = \sqrt{\sum_{k=N+1}^{h_{\max} \times N} \left(\frac{Y_{C,k}(t_1)}{Y_{H,1}(t_1)}\right)^2} = \sqrt{\sum_{k=N+1}^{h_{\max} \times N} \left(\frac{Y_{C,k}(t_1)}{Y_{C,N}(t_1)}\right)^2} \tag{82}$$

When using

ω_1	Angular frequency of the fundamental component, $\omega_1 = 2 \cdot \pi \cdot f_{H,1}$
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 component
$f_{H,1}$ = 50 Hz	Frequency of the fundamental component 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 Hz
N = 2	Number of fundamental component 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

B.IX. Tolerance specifications for verifying static voltage support

The following requirements apply to the envelope curve as shown in Figure 27, which depends on the respective transition period ($t_t = 3\ \tau$) for evaluating the requirements for static voltage support:

- The tolerance specifications apply to an SCR value range of 10 to 50 at the NCP.
- The reactive power is the controlled variable.
- The network connection point is used as reference point.
- The tolerances shown refer to deviations between the reactive power setpoint and the actual reactive power value and are based on $P_{b\ \mathrm{inst}}$.
- The tolerance in amplitude during the transient process is shown in Figure 27 (a) for an example step $A \cdot \sigma(t)$ with amplitude (A) 0.325 (where $\sigma(t)$ corresponds to the unit step). The upper limit ($y_{\max}(t)$) of the tolerance range is derived from a tolerance of +5 % $Q/P_{b\ \mathrm{inst}}$ based on the PT1 step response and a shift of Δt_x (which results in a tolerance of 80 % of the amplitude A at t = 0) according to:

$$y_{\max}(t) = \begin{cases} 0.02 & t < 0 \\ A \cdot \sigma(t) \cdot \left(1 - e^{-\frac{t-\Delta t_x}{\tau}}\right) + 0.05 & 0 \le t \le 5\tau \\ \left(y_{\max}(5\tau) - (A + 0.02)\right) \cdot e^{-\frac{t}{\tau_{II}}} + (A + 0.02) & t > 5\tau \end{cases} \tag{83}$$

$$\tau_{II} = \frac{\tau}{4} \tag{84}$$

$$\Delta t_x = \ln\left(1 - \frac{0.8 \cdot \sigma(t) - 0.05}{\sigma(t)}\right) \cdot \tau \tag{85}$$

- The lower limit ($y_{\min}(t)$) of the tolerance range is calculated from a tolerance of -5% $Q/P_{b\ \mathrm{inst}}$ based on the PT1 step and the subsequent shift by the initial delay Δt_0 as follows:

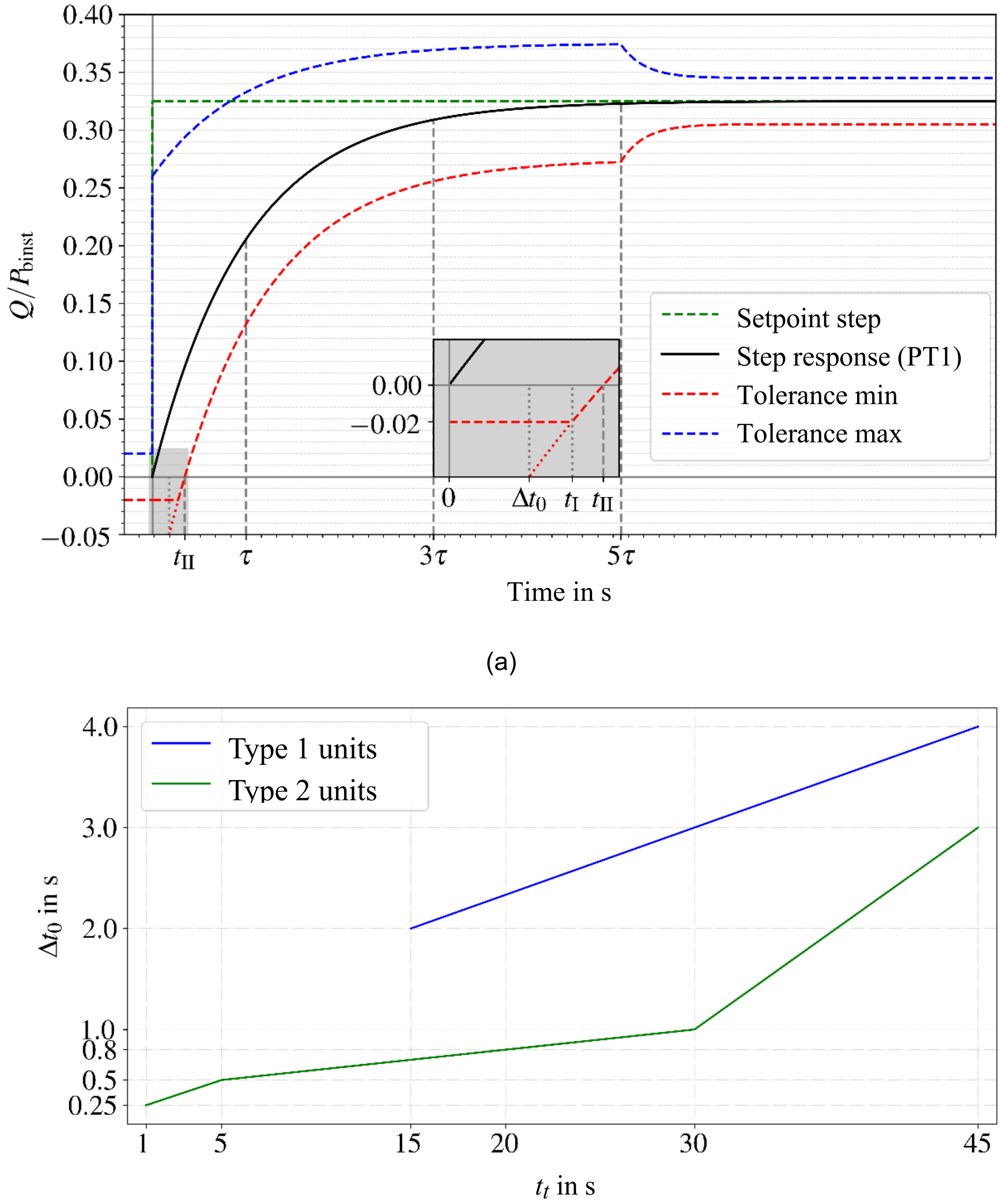
$$y_{\min}(t) = \begin{cases} -0.02 & t < t_I \\ A \cdot \sigma(t) \cdot \left(1 - e^{-\frac{t-\Delta t_0}{\tau}}\right) - 0.05 & t_I \le t \le 5\tau \\ \left(-y_{\min}(5\tau) + (A - 0.02)\right) \cdot \left(1 - e^{-\frac{t}{\tau_{II}}}\right) + y_{\min}(5\tau) & t > 5\tau \end{cases} \tag{86}$$

$$t_I = \Delta t_0 - \ln\left(1 + \frac{0.02 - 0.05}{A}\right) \cdot \tau \tag{87}$$

The value of Δt_0 shall be set depending on the selected transition time according to Figure 27 (b).

The controlled variable shall be within a band of ±2 % $Q/P_{b\ \mathrm{inst}}$ at the start of the step.

- After $t > 5\,\tau$, the settling process is considered to be completed and the requirement for quasi-steady-state operation apply. From this point onwards, the tolerance band is reduced in accordance with equations (83) and (86) in a PT1 shape with the transition time τ_{II} auf ±2 % $Q/P_{\mathrm{b\ inst}}$.



(a)

(b)

Figure 27 - (a) Step response of the static voltage support with design-relevant tolerance bands for an exemplary setpoint step of 0.325·$\sigma(t)$ and (b) initial delay Δt_0 as a function of the transition time t_t

NOTE The value of t_{II} corresponds to the point in time at which the minimum tolerance curve of the step response reaches the value of $Q/P_{\mathrm{b\ inst}} = 0$ and is calculated below:

$$t_{\mathrm{II}} = \Delta t_0 - \ln\left(1 - \frac{0{,}05}{A}\right) \cdot \tau \qquad (88)$$

Figure 28 shows an example of permissible PT2 behaviour of static voltage support within the tolerance bands relevant to the design for an exemplary setpoint step of 0.325·$\sigma(t)$, an initial delay Δt_0 of 3 s and a transition time t_t of 30 s of the PT1 behaviour for a Type 1 plant.

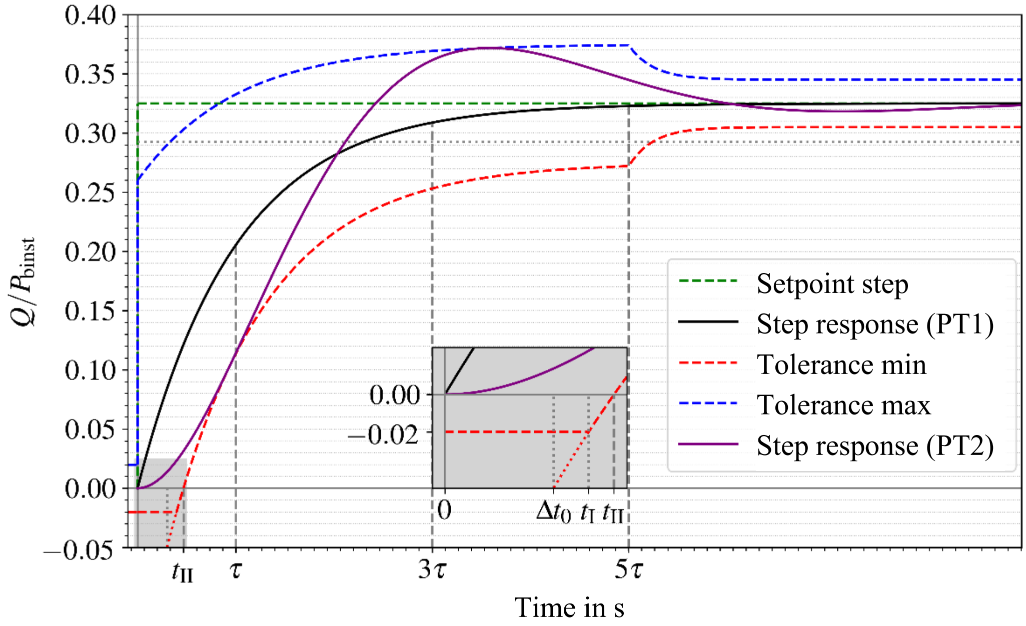
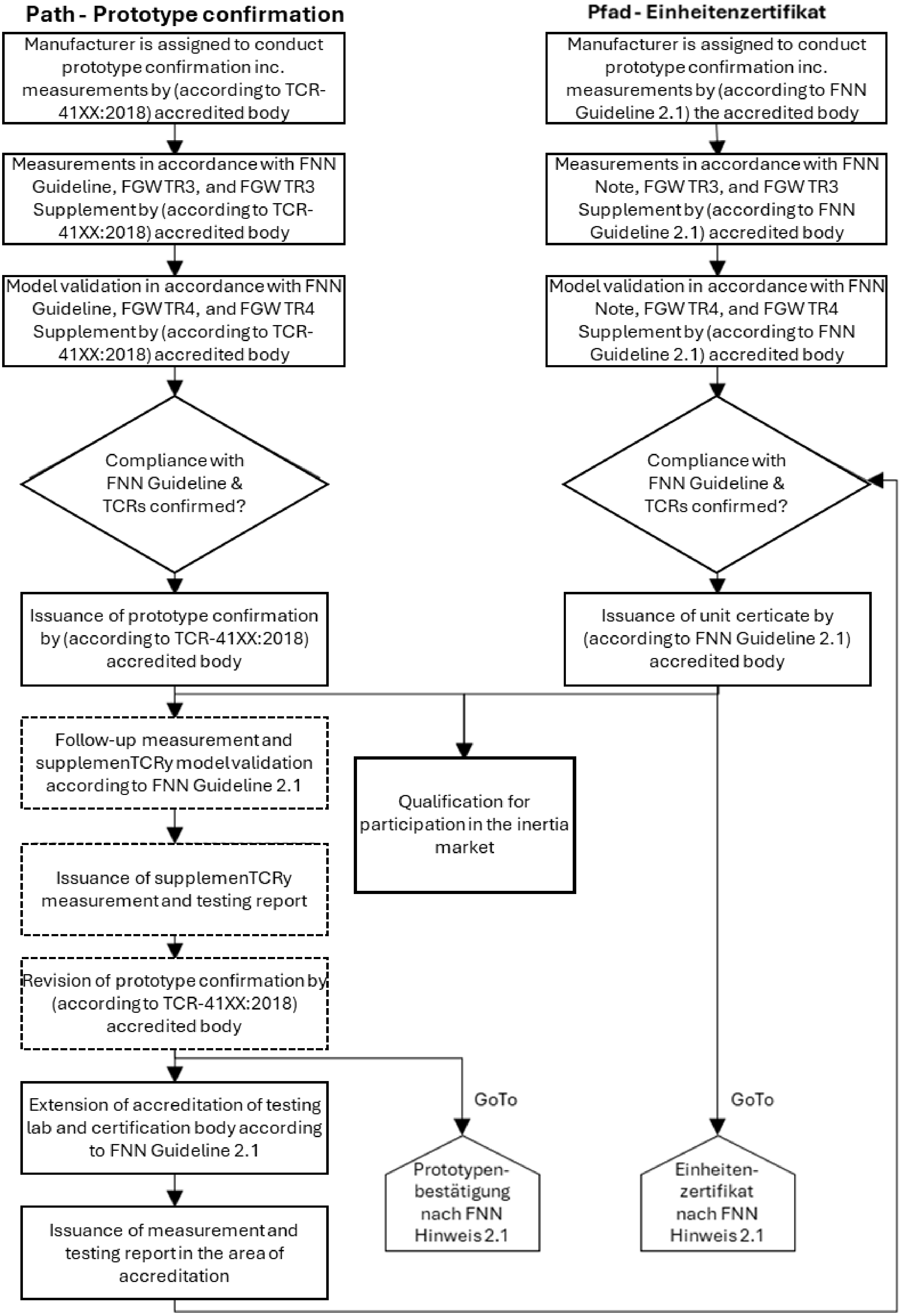
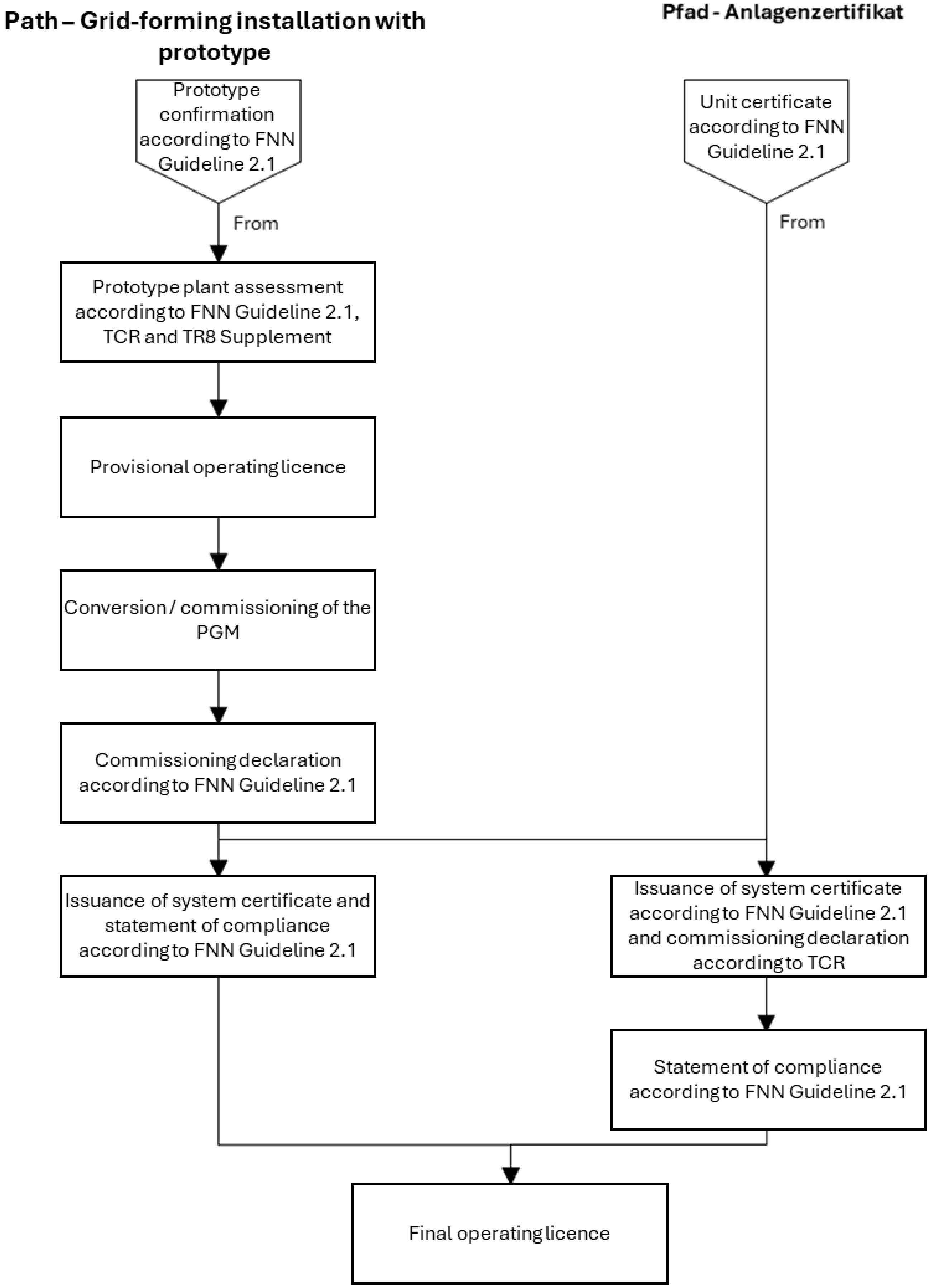


Figure 28 - Step response of static voltage support (Type 1 plants) for PT1 and PT2 behaviour within the permissible tolerances for an exemplary setpoint step of 0.325·$\sigma(t)$, Δt_0 = 3 s and t_t = 30 s

B.X. Schedule for the network connection process of grid-forming units




Path – Grid-forming installation with prototype
Pfad - Anlagenzertifikat
Prototype confirmation according to FNN Guideline 2.1
From
Prototype plant assessment according to FNN Guideline 2.1, TCR and TR8 Supplement
Provisional operating licence
Conversion / commissioning of the PGM
Commissioning declaration according to FNN Guideline 2.1
Issuance of system certificate and statement of compliance according to FNN Guideline 2.1
Unit certificate according to FNN Guideline 2.1
From
Issuance of system certificate according to FNN Guideline 2.1 and commissioning declaration according to TCR
Statement of compliance according to FNN Guideline 2.1
Final operating licence

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 Rules in the operating licence procedure for grid-forming units and grid-forming plants.

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 rule)

Application for network connection (medium-voltage) (to be completed by the connection owner)	1 (4)

Designation of the construction project		______________________
Location of the plant	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	☐ Connection owner is the property owner ☐ Authority the property owner is supplied with the application	
Plant installer (if known)	Company, postcode, town	______________________
	Phone, email	______________________
Plant type	☐ Demand facility ☐ Power-generating module ☐ Mixed customer site	☐ Charging system for electric vehicles ☐ Storage ☐ Temporary connection (e.g. power for a construction site) ☐ Emergency power generator

Allocation of network connection	☐ New plant	☐ Extension or modification	☐ 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 customer sites the location of the power-generation units shall be clearly indicated.	☐ yes ☐ no

Anticipated active connection power $P_{\text{AV, B}}$ and $P_{\text{AV, E}}$ [kW]

	Previous values	Total value required hereafter (in final stage after measure)
Consumption active power $P_{\text{AV, B}}$		
Feed-in active power $P_{\text{AV, E}}$ *		

For power-generating modules, mixed customer sites 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: ☐ basic MPOs
☐ other MPOs________

Power expected to be consumed on site	☐ no	If yes: Power _____ kW	Starting date _____

Is a data sheet for assessing system perturbations (Form E.2) for the connection of a demand facility attached?	☐ yes ☐ no
Time schedule for the construction works attached?	☐ yes ☐ 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 (medium-voltage)
(to be completed by the connection owner of power-generating modules, mixed customer sites or storage)

2 (4)

Type of the power-generating module (multiple choice possible for energy mix)	☐ Wind energy	☐ Hydropower	☐ ……………….........	
	☐ Photovoltaics	☐ Ground area	☐ Roof area	☐ Other
	☐ CHP plant	Fuel type used (e.g. natural gas, biogas, biomass) ……………………………………………………................ ……..		
	☐ Thermal power plant			
	☐ Storage	Operating mode: ☐ Peak load coverage / Optimisation of houseload consumption ☐ Balancing energy market / Ancillary services ☐ Island operation ☐ Other: ________________________		
Operating mode	☐ Peak load coverage / Optimisation of houseload consumption ☐ Balancing energy market / Ancillary services ☐ Island operation ☐ Inertia ☐ Other: ________________________			
	☐ Stand-by generator with > 100 ms parallel network operation ☐ Stand-by generator with ≤ 100 ms parallel network operation	Operating mode: ☐ Trial operation in accordance with DIN 6280-13 or VDE 0100-560 (VDE 0100 560) ☐ Peak consumption coverage ☐ Balancing energy market ☐ ________________________		
Measure for a power-generating module	☐ New plant	☐ Extension or modification		☐ Dismantling
Power data	Available (existing)	New plant / extension / dismantling	Final configuration (new planned total value)	
Maximum generation active power, cumulated $\sum P_{\mathrm{Amax}}$ *	………………….kW	……………...kW	…………….kW	
Maximum generation apparent power, cumulated $\sum S_{\mathrm{Amax}}$ *	………………..kVA	… ……..kVA	… ……..kVA	
For PV: module power [kWp]				
Houseload of the power-generating module ………kW				
All energy fed into the network of the system operator?				☐ yes ☐ no
Is feed-in monitoring ($P_{\mathrm{AV,E}}$ – monitoring) planned at the network connection point?				☐ yes ☐ 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 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 storage)	3 (4)

Number of identically constructed power-generating units or storage: .... units

Unit certificate available ☐ yes ☐ no. When no: ☐ Prototype ☐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	☐	Double-fed asynchronous machine	☐ Inertia
	☐	Synchronous machine (coupled directly)	☐ Phase shifter operation
	☐	Network connection with full converter (no storage)*	☐ Inertia
	☐	Storage	☐ 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_{Emax} **	.... kW
	$P_{\mathrm{min,dyn}}$: minimum dynamic active power available for the provision of negative inertia	.... kW
	$P_{\mathrm{max,dyn}}$: maximum dynamic active power available for the provision of the maximum inertia	.... kW
	$P_{\mathrm{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia	.... kW
	$P_{\mathrm{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia	.... kW
	Temporary 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.
	where applicable, at high-voltage level: 0.50 p.u.	................p.u.
	Contribution to the initial short-circuit AC current I_{K} “........ kA ***	at V
	☐ 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 .... %
☐ Manufacturer data sheet attached

Additional data for storage

Connection of storage		☐ via its own inverter ☐ via the inverter of another Power-generating unit (in a PGSU) ☐ direct connection to the AC-network or three-phase network
Operation of storage	☐ Consumption and feed-in from/into the network of the system operator	Feed-in from the storage into the network of the system operator planned simultaneously with power-generating units ☐ yes ☐ no
	☐ No consumption, but feed-in into the network of the system operator	
	☐ No consumption and no feed-in from/into the network of the system operator	
	☐ Consumption, but no feed-in into the network of the system 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		☐ public ☐ 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*	☐ yes ☐ no
Information of each identically constructed charging device	Number of charging devices	Maximum charging capacity of the charging device	Charging technology
		.... kW	☐ AC ☐ DC** ☐ Bidirectional*** ZEREZ ID:
			☐ AC ☐ DC**
			☐ AC ☐ DC**
Metering	Is a separate metering of the charging devices requested by the responsible party or a third-party metering point operator?		☐ yes*** ☐ no

* The system operator may require a device to control the active power.

** The reactive power specifications of the system 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 rule)

Commissioning report (medium-voltage) (to be completed by the operator of the transfer station)		1 (1)
Postal address of the plant	Station name or field number Street, number Postcode, town	....
Plant operator	First name, Surname Phone, email	....
Installer of the electrical installation	Company, place Phone, email	....
Metering point operation	The measuring equipment is 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 agreement):	
Station data	☐ Stub ☐ Double stub ☐ Looping-in ☐ Demand installation ☐ Feeder ☐ Mixed customer site/storage	
TF blocks (blocker for audio-frequency ripple control)	Required in the connection offer: ☐ yes ☐ no	
	Installed: ☐ yes ☐ no	Test protocol available: ☐ yes ☐ no

Documentation: Updated project documents handed over to the system operator at least 2 weeks prior to commissioning of the transfer station ☐ yes ☐ no

☐ Commissioning order (E.5) is available
☐ Network sales prerequisites are satisfied
☐ Network control agreement is available
☐ Schematic circuit diagram, wiring diagrams for secondary technical equipment, if any
☐ Test protocol of the transfer protection and for PGMs of the primary loss of mains protection
☐ Joint commissioning (with the system operator)
☐ Protection checked by switch tripping
☐ Calibration certificates for the transducers
☐ Protocol of the earth connection measurement

☐ Confirmation in accordance with DGUV Regulation 3
☐ For power-generating modules: Equipment for network security management checked
Optional for telecontrol systems:
☐ Measurement value transmission checked
☐ Reports checked
☐ Remote control checked (including emergency-stop circuit breaker)
☐ For power-generating modules: Measurement value transmission P, Q 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 system 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 qualified electricians or persons trained in electrical engineering. 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	.... System 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 rule.)

Data sheet for a power-generating module – Medium-voltage (to be completed by the connection owner, also applies to mixed customer sites and storage)		1 (4)
Feeder number of the connection owner ________________		
Location of the plant	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 system operator, a new network compatibility assessment by the system operator may be required.		☐ yes, Date E.1____________ ☐ no
Are existing power-generating modules or storage connected to the network connection point? ☐ yes ☐ no Final plant certificate number: ________________________________ Date: ________________ NOTE If no plant 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?		☐ yes, ………………….kW ☐ no
Island operation intended?		☐ yes ☐ no
Black start capability provided?		☐ yes ☐ 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 (where applicable)	• 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_{bUV} in kV • Short-circuit voltage u_{k} in % • Switching group • Control range of the tap changer ± in % • Number of steps
Generator transformer	• Rated apparent power S_{r} in kVA • Short-circuit voltage u_{k} in % • Switching group • Control range of the tap changer ± 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	• 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)	• 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 plant certificate)			3 (4)
Number of identically constructed power-generating units or storage: .... units			
Unit type	☐ Double-fed asynchronous machine	☐ Inertia	
	☐ Synchronous machine (coupled directly)	☐ Phase shifter operation	
	☐ Network connection with full converter * (no storage)	☐ Inertia	
	☐ Storage	☐ Inertia	
	Others		
Operating mode	☐ Peak load coverage / Optimisation of houseload consumption ☐ Balancing energy market / Ancillary services ☐ Island operation ☐ Inertia ☐ Other		
Unit manufacturer:	....	Type:	
Power data	Rated apparent power S_{rE} *		.... kVA
	Maximum active power (10-minute average) P_{Emax} **		.... kW
	$P_{\mathrm{min,dyn}}$: minimum dynamic active power available for the provision of negative inertia		.... kW
	$P_{\mathrm{max,dyn}}$: maximum dynamic active power available for the provision of the maximum inertia		.... kW
	$P_{\mathrm{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia		.... kW
	$P_{\mathrm{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia		.... kW
	Temporary 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): where applicable, at high-voltage level: 0.50 p.u.		 ....p.u. ....p.u. ....p.u.
	Contribution to the initial short-circuit current I_{K} “........ kA ***		at V
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance .... % ☐ 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 (check list for the information to be submitted to the system operator by the connection owner; to be completed by the connection owner)	4 (4)
Single-phase overview circuit diagram of the customer installation (minimum requirements): • 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)) ○ 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 system operator serve as the basis for issuing the plant certificate. Changes of any kind shall be immediately indicated in writing to the relevant system operator. These data sheets will only be processed if fully completed.	
.... Place, Date	.... Signature of the connection owner

C.I.4. (E.9) System operator questionnaire – 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 rule)

System operator questionnaire for new plants Connection/modification of a power-generating module or storage					1 (7)
Designation of power-generating module					
Maximum generation active power, cumulated $\sum P_{\text{Amax}}$ Agreed active connection power $P_{\text{AV,E}}$ Agreed apparent connection power $S_{\text{AV,E}}$		Existing unit		New plant	Complete (existing + new plant)
	$\sum P_{\text{Amax}}$	kW		kW	kW
		Current (actual)		Total (new)	
	$P_{\text{AV,E}}$		kW		kW
	$S_{\text{AV,E}}$		kVA		kVA
$P_{\text{AV,E}}$ – Monitoring		☐ yes		☐ no	
Information from the system operator	Date of the TCC MV		Contact details (e.g. email or telephone)		
Registration number of the system operator					
Designation of the transfer station					
Designation of the network connection point[26]					
Demand facility at the same network connection point (except for houseload of the power-generating module)	Demand facility provided ☐ yes (mixed customer site in accordance with VDE-AR-N 4110) ☐ no		Agreed active connection power $P_{\text{AV, B}}$		
			$P_{\text{AV, B}}$		kW
Other comments:					

---

[26] Line designation when connected to a line or designation of the neighbouring station(s) or designation of the lowvoltage output switch panel when directly connected to the busbar of a system operator's own substation.

System operator questionnaire for new plants Connection/change of a power-generating module	2 (7)

1. Set values for the protection equipment at the network connection point

1.1 Short-circuit protection equipment (select where appropriate)

☐ Take-away circuit

☐ Distance protection:

Setting values		**Default settings from the system operator**		☐ 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 shall always be attached			
Zero sequence starter	$I_E >$ [A]			
	$U_{NE} >$ [kV]			

☐ Overcurrent protection ☐ HH-fuse with maximum……………....A

Setting values	Default setting system operator		☐ 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

Setting values	Default setting system operator		☐ Integrated into the distance and overcurrent protection ☐ 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]			

System operator questionnaire for new plants **Connection/change of a power-generating module**	3 (7)

1.2 Primary loss of mains protection

Function	Setting values	Recommendation in accordance with VDE-AR-N 4110	Default settings from thesystem operator	
Voltage surge protection	$U >>$	1.20 U_c		U_c ☐ kV
	$t_U >>$	300 ms		ms
Voltage surge protection	$U >$	1.10 U_c		U_c ☐ kV
	$t_U >$	180 s		s
Undervoltage protection	$U <$	0.8 U_c and at least 0.1 I_N		U_c ☐ kV
	$t_U <$	2.7 s		s
$P_{AV,E}$ – Protection device	$P >>$	See FNN Guideline $P_{AV,E}$ – Monitoring [Table 5]		kW
	$t >>$			s
	$P >$			kW
	$t >$			s
	$P <$			kW
	$t <$			s

1.3 Mixed customer sites (if demand facility available)

Primary loss of mains protection	Medium-voltage measurement location	Trigger location
	☐ Transfer station ☐ 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.

System operator questionnaire for new plants **Connection/change of a power-generating module**	4 (7)

2. Default settings for power-generating units (e.g. PGU or temporarily stored loss of mains protection)

2.1 Loss of mains protection

Function	Setting values	Recommendation in accordance with VDE-AR-N 4110 MV-SS	Recommendation in accordance with VDE-AR-N 4110 MV network	Default settings[27] system operator	
Voltage surge protection	U >>	1.25 U_{LV} [28]	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 Voltage source control (for Type 2 plants only)

Function	Default setting system operator
Suspend power supply below 0.7 U_c	☐ enable
Droop k of the voltage source control	☐ k = 2 ☐ k = ... ☐ *no specification (grid-forming)*

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[27] 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.

ULV is the voltage on the lowvoltage side of the generator transformer. It results from ULV = Uc/ü.

<table>
<tr><td colspan="11">System operator questionnaire for new plants
Connection/change of a power-generating module</td><td>5 (7)</td></tr>
<tr><td colspan="12">3. Static voltage support</td></tr>
<tr><td>Reactive power adjustment range</td><td colspan="11">☐ 0.33 $Q/P_{\text{b inst}}$ underexcited to 0.33 $Q/P_{\text{b inst}}$ overexcited in accordance with VDE-AR-N 4110
☐…….. underexcited to ……….. overexcited (separate closed-loop control)</td></tr>
<tr><td>☐ Reactive power/voltage characteristic Q(U)[29]</td><td colspan="11">☐ Standard characteristic in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110
☐ individual values
Gradient of the characteristic curve:
Upper voltage limit $U_{\text{MAX}}/U_{\text{C}}$ = …….. (e.g. 1.04)
Lower voltage limit $U_{\text{MIN}}/U_{\text{C}}$ = …….. (e.g. 0.96)
Maximum reactive power QMAX-underexcited/Pb inst = ……… (e.g. 0.33)
Voltage deadband = ± ………..% % U_{c} (e.g. ± 1.0 % U_{c})
Reference voltage:
☐ $U_{\text{Q0,ref}}/U_{\text{C}}$ = ……… (e.g. 1.00) ☐ Reference voltage variable through a telecontrol system[30]</td></tr>
<tr><td rowspan="3">☐ Characteristic $Q(P)$[31]</td><td colspan="11">☐ Standard pairs of values in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110
☐ Individual values</td></tr>
<tr><td>$P/P_{\text{b inst}}$ [%]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$Q/P_{\text{b inst}}$ [%]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>☐ Reactive power Q with voltage limitation function</td><td colspan="11">☐ Standard pairs of values in the MV-network in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110
☐ Standard pairs of values UW-Direkt/SS in accordance with Clause 10.2.2.4.1 in VDE-AR-N 4110
☐ Individual values
Characteristic P1 ($U_{\text{P1}}/U_{\text{c}}$; $Q_{\text{P1}}/P_{\text{b inst}}$) = …………..... (z. B.0.94; -0.33)
P2 ($U_{\text{P2}}/U_{\text{c}}$; $Q_{\text{ref}}/P_{\text{b inst}}$) = …………… (z. B.0.96; 0)
P3 ($U_{\text{P3}}/U_{\text{c}}$; $Q_{\text{ref}}/P_{\text{b inst}}$) = …………… (z. B.1.04(1.06); 0)
P4 ($U_{\text{P4}}/U_{\text{c}}$; $Q_{\text{P4}}/P_{\text{b inst}}$) = …………..... (z. B.1.06(1.08); +0.33)
☐Variable by means of a telecontrol system[10] ☐ Schedule[32]</td></tr>
<tr><td>☐ Displacement factor cos φ</td><td colspan="11">☐ cos φ = …….. ☐ overexcited ☐ underexcited
☐ variable via a telecontrol system[10] ☐ Schedule[12]</td></tr>
<tr><td>Control behaviour for setpoint step changes</td><td colspan="11">For $Q(U)$, $Q(P)$, Q, cos(phi)
Time constant 3 Tau = ………. s (setting range 10 s to 60 s (for Type 1), 6 s to 60 s (for Type 2))</td></tr>
<tr><td>Response in the event of a telecontrol system failure[11]</td><td colspan="11">☐ continue operation with the last received value
☐ $U_{\text{Q0}}/U_{\text{C}}$ = …..; Q = …... kvar; cos φ = … (depending on the chosen method)
☐ switch-over to ☐ $Q(U)$, ☐ $Q(P)$, ☐ Q, ☐ cos φ[13]</td></tr>
<tr><td>Response to a failure of either the PGM controller or the associated measurement or the connection between PGM controller and PGU</td><td colspan="11">☐ Continue operation of all PGUs with the value received last
☐ Continue operation of all PGUs with P = ………. (aggregate value for the PGM)
☐ Continue operation of all PGUs with Q = ………. (aggregate value for the PGM)
☐ Continue operation of all PGUs with cos φ = ……….</td></tr>
<tr><td>Requirements for the reactive power behaviour of the existing units in mixed customer sites of different PGMs[33,34]</td><td colspan="11">☐ Integration into the reactive power control system of the new plant
☐ cos φ = ………… at the NCP ☐ overexcited ☐ underexcited
☐ cos φ = ………… at the PGU ☐ overexcited ☐ underexcited
☐………....underexcited to ……….. overexcited
☐ maintain existing operation (unless otherwise specified
, a cos(phi) value of 1 may be assumed in the verification process)</td></tr>
<tr><td></td><td colspan="11">MV measurement of the reference variable U: ☐ at the transfer station ☐ at the PGM</td></tr>
<tr><td colspan="12">Other comments</td></tr>
</table>

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[29] Recommendations can be found in Clause 10.2.2.4, Section a).

[30] If setpoints are provided by a telecontrol system. Specifications of the telecontrol system shall be provided by the system operator or can be found in the TCC of the system operator.

[31] Up to 10 pairs of values may be predefined.

[32] If schedules are required, they shall be provided as a separate sheet or under other comments.

[13] Specifications are handed over by the system operator or can be found in the system operators. In the case of several existing power-generating modules with differing reactive power behaviours or agreements with the system 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)).

In the case of several existing power generating plants with differing reactive power behaviours or agreements with the system operator, please attach detailed information for each of the existing power generating plants on a separate page (e.g. in the form of this page 5 (7)).

[34] In addition to the mode of operation agreed for the existing power-generating modules, their actual behaviour shall be taken into account. The calculation method is described in FGW TR 8.

System operator questionnaire for new plants Connection/change of a power-generating module	6 (7)

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 (für T_k = 1 s)[35]	≥	kA
Minimum network short-circuit power at the point of common coupling[36] 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[37] 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 system operator's MV network connected upstream	
Type of neutral-point treatment	☐ Resonant neutral earthing (earth fault compensation) ☐ Neutral earthing with low impedance ☐ Solid neutral earthing ☐ No neutral-point treatment (free, isolated neutral point)

* For the normal network switching state.

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[35] For dimensioning of the transfer station regarding the short-circuit current capability.

[36] In order to allow for the plant certificate to be prepared, the system 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 in accordance with the relevant rules.

[37] 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.

System operator questionnaire for new plants Connection/change of a power-generating module	7 (7)

6. Neutral-point treatment of the system operator’s HV network connected upstream

Type of neutral-point treatment	☐ Resonant neutral earthing (earth fault compensation) ☐ Neutral earthing with short-time low impedance .... Ω ☐ Neutral earthing with low impedance .... Ω ☐ Solid neutral earthing ☐ No neutral-point treatment (free, isolated neutral point)

7. PGM model

☐ The system operator has a model of the power-generating module at its disposal for performing network calculations:

☐ Set of parameters in accordance with Appendix C.5 ☐ with optional additional information

☐ Set of parameters in accordance with the specifications of the system operator

☐ Set of parameters in accordance with the specifications of the system operator

☐ Computable dynamic model in accordance with system operator specifications

Other comments

______________________________ Place, Date	____ Signature of the system operator The questionnaire for the system 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 rule.)

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: .... ☐ Gauss-Krüger coordinates Reference ellipsoid: .... ☐ UTM coordinates Zone: .... Easting: .... Northing: ....
Point of connection to the network of the system operator	Designation: .... Metering point for billing purposes: ....
Official approval	Type: ☐ Construction permit ☐ Approval as required by the BImschV ☐ Authorization under the water law ☐ .... File number: .... Date: ....
Compliance with legal provisions (EEG/KWK-G)	☐ The requirements of § 9(1) or (2) EEG are fulfilled (network protection and network management in compliance with statutory power limits) ☐ The requirements of § 9(5) No. 1 EEG are fulfilled (hydraulic retention time, applies to biogas plants only) ☐ The requirements of § 9(5) No. 2 EEG are fulfilled (including gas consumption devices for preventing biogas release, applies only to biogas plants) ☐ The prerequisites for a compensation installation summary in accordance with § 24 Abs. 2 EEG are not met (applies to ground PV plants only)
	Index number for the Market Master Data Register .... Award number in accordance with § 35 EEG: ....
	☐ 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) ☐ Notification of the CHP plant as per § 10 Abs. 6 KWK-G (attach the notification filed with BAFA) ☐ 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: .... Plant certificate number: .... Date of issue: ....
Power data	Maximum active power: .... kW (power installed as per § 3 No. 31 EEG; for PV plants the module power on the negative-sequence side) 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 (to be completed by the plant operator; also applies to storage)			2 (2)
Documentation	☐ Loss of mains protection successfully tested (please attach the protection test reports) ☐ Voltage source control of the PGU is in accordance with the plant certificate ☐ limited voltage source control ☐ All other parameters influencing the electrical properties are set in accordance with the plant certificate ☐ Power-generating unit integrated into the network security management ☐ Proportion of nominal effective power for inertia market m =........... ☐ Start-up time constant T_A = ...		
Commissioning	The power-generating unit was commissioned on:	Date:	Time: ....
	The power-generating unit has started feeding energy into the network of the system operator (in the case of mixed customer sites has started generating energy):	Date:	Time: ....

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.

The power-generating unit was installed in accordance with the conditions specified in VDE-AR-N 4110 and the Technical Connection Conditions of the system 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.

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 system 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
	Temporary minimum power		kW
Registration number of the system 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 plant certificate	Certification body		
	Street, number		
	Postcode, town		
	Plant 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)	2 (7)

Commissioning of all power-generating units (existing and new plants)

Manufacturer	Type	Firmware version	Serial number	Rated active power P_{rE}	Commissioning date
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	

Commissioning of additional components (intermediate storage protection devices, compensation systems if required)

Component	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, where applicable, reactive power control by the control centre of the system operator (protocol to be provided by the system operator);	Verification of the system operator	☐
Alternative 1: Test of the entire chain of action by simulating the interface to the telecontrol system of the system operator (if agreed with the system operator)	Verification	☐
Alternative 2: Test of the entire chain of action with the system operator to be agreed at a later date. Including confirmation from the system operator (not part of the commissioning declaration)	Confirmation from the system operator	☐
Functional test of the telecontrol system up to the transfer station (if required by the system operator), to be performed by the system operator (request test, process data scope)	Verification of the system operator	☐
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	☐
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	☐
Function test of the reactive power characteristic curve or the reactive power fixed values in accordance with specifications from the system 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 (using simulated reference variable U or P). After the test, the original characteristic has again been set.	Test protocol	☐
Protection test report for the protection equipment at the network connection point	Protection test report(s)	☐
Protection test reports for protection equipment on the individual power-generating units or, where applicable, the intermediate storage protection devices	Protection test report(s)	☐

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		4 (7)
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: - Manufacturer, type, serial numbers and, where 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 where 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 Where applicable, for plant control exclusively via the PGU: - See the PGM controller setting records for details.	Settings record(s)	☐
Setting records of the PGM controller including designation, parameters used in VDE-AR-N 4110; minimum information: - Manufacturer, type, serial numbers and, where 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, where 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	☐
Arc fault qualification certificate for the switchgear or risk assessment for existing systems	Verification	☐
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)		☐
- Type plates of the MV switchgear		☐
- 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)		☐

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		5 (7)
- Type plates of transformers with tap changers		☐
- Type plates of switchgear (e.g. circuit breakers) assigned to the protection devices		☐
- Protection settings that are set directly on the switchgear (e.g. rotary switches/dip switches)		☐
- Type plates of network analysis devices (if used for protection/PGM controllers)		☐
- Type plates of PGM controller (with serial number)		☐
- Type plates of mains-independent auxiliary power supplies/UPS (with recognisable capacity of the connected battery) of the transfer station and, where applicable, the temporarily stored protection devices		☐
- Fuse outlets with type and size		☐
- Nameplates for all stations		☐
Comments:		
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.		
Confirmation		
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’. 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’. 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. The signatory confirms the accuracy of the information provided in the commissioning declaration, including the required attachments.		

.... 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

Protection test report for the protection equipment at the network connection point

Minimum information, see Appendix *1:

- System designation, plant 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 plant 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 increases 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 system operator (does not apply if the system 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 overvoltage and undervoltage protection thresholds
- Specification of whether automatic reconnection was deactivated in the protection device or, where applicable, by external circuitry
- Checking the tripping of the switchgear in the event of:
    - Failure of the auxiliary power supply
    - where 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 applicable, in case of physical separation between protective and switching devices: failure of the connection between protective and switching devices

The system operator may specify different requirements and request further tests.

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, where applicable, the intermediate storage protection devices

Minimum information:

- System designation, plant 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 plant 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)
- 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.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 system operator (does not apply if the system 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 overvoltage and undervoltage 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
  - where applicable, in the event of physical separation between the protective device and the switching device: failure of the connection between protective and switching devices

The system operator may specify different requirements and request further tests.

C.I.7. (E.12) Statement of compliance for power-generating modules or storage – Highvoltage

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 rule.)

Name of the certification body…………………………………….….. **Accredited in accordance with DIN EN ISO/IEC 17065 for VDE-VDE-AR-N 4110**	LOGO 1 (2)
Statement of compliance **for power-generating modules or storage**	Number: ………..……………….........…. Signed copy number: ………........................

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
Creator of the plant certificate	First name, Surname	____________________
	Street, number	____________________
	Number of verifications for the plant	____________________
	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 plant certificate and the provisions of the system operator.

☐ 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 plant certificate.

☐ 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 system operator.

☐ Passed

NOTE____

____

2 (2)

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 system operator’s TCC

and was installed in compliance with the plant 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 system 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 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 - Highvoltage

C.II.1. (E.1) Application - Highvoltage

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 rule)

Application for network connection (highvoltage) (to be completed by the connection owner)			1 (4)
Designation of the construction project		____________________	
Location of the plant	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	☐ Connection owner is the property owner ☐ Authority the property owner is supplied with the application		
Plant installer (if known)	Company, postcode, town Phone, email	____________________ ____________________	
Plant type	☐ Demand facility ☐ Power-generating module ☐ Mixed customer site	☐ Charging system for electric vehicles ☐ Storage ☐ Temporary connection (e.g. power for a construction site) ☐ Emergency power generator	
Allocation of network connection	☐ New plant	☐ Extension or modification	☐ 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 customer sites the location of the power-generation units shall be clearly indicated.	☐ yes ☐ no

Anticipated active connection power $P_{\text{AV, B}}$ and $P_{\text{AV, E}}$ [kW]

	previously	total value required hereafter (in final stage after measure)
Consumption active power $P_{\text{AV, B}}$		
Feed-in active power $P_{\text{AV, E}}^*$		

For power-generating modules, mixed customer sites 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: ☐ basic MPOs ☐ other MPOs________

Power expected to be consumed on site	☐ no	If yes: Power _____ kW	Starting date _____

Is a data sheet for assessing system perturbations (Form E.2) for the connection of a demand facility attached?	☐ yes ☐ no
Time schedule for the construction works attached?	☐ yes ☐ 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 (highvoltage) (to be completed by the connection owner of power-generating modules, mixed customer sites or storage)				2 (4)
Type of the power-generating module (multiple choice possible for energy mix)	☐ Wind energy	☐ Hydropower		☐ ………………..............
	☐ Photovoltaics	☐ Ground area	☐ Roof area	☐ Other
	☐ CHP plant	Fuel type used (e.g. natural gas, biogas, biomass) …………………………………………………........................…		
	☐ Thermal power plant			
	☐ Storage			
Operating mode	☐ Peak load coverage / Optimisation of houseload consumption ☐ Balancing energy market / Ancillary services ☐ Island operation ☐ Inertia ☐ Other:______________________________			
	☐ Stand-by generator with > 100 ms parallel network operation ☐ Stand-by generator with ≤ 100 ms parallel network operation	Operating mode: ☐ Trial operation in accordance with DIN 6280-13 or VDE 0100-560 (VDE 0100 560) ☐ Peak consumption coverage ☐ Balancing energy market ☐ ______________________________		
Measure for a power-generating module	☐ New plant	☐ Extension or modification		☐ Dismantling

Power data	Available (existing)	New plant / extension / dismantling	in final configuration (new planned total value)
Maximum generation active power, cumulated $\sum P_{\text{Amax}}$ *	………………….kW	……………...kW	…………….kW
Maximum generation apparent power, cumulated $\sum S_{\text{Amax}}$ *	………………..kVA	… ……..kVA	… ……..kVA
For PV: module power [kWp]			
Houseload of the power-generating module ………kW			

All energy fed into the network of the system operator?	☐ yes	☐ no
Is feed-in monitoring (PAV, E – monitoring) planned at the network connection point?	☐ yes	☐ no
Notes on the power-generating module:		

* Resulting from the sum of the maximum 10-minute average values of all installed PGUs and storage according to information from the unit certificates at the NCP. 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 output power (P_{max}) under standard test conditions (STC conditions) in accordance with DIN EN 50380 (0126-390).

Application for network connection (highvoltage)
(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 ☐ yes ☐ no. When no: ☐ Prototype ☐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	☐ Double-fed asynchronous machine	☐ Inertia
	☐ Synchronous machine (coupled directly)	☐ Phase shifter operation
	☐ Network connection with full converter (no storage)*	☐ Inertia
	☐ Storage	☐ 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_{Emax} **	.... kW
	$P_{\mathrm{min,dyn}}$: minimum dynamic active power available for the provision of negative inertia	.................MW
	$P_{\mathrm{max,dyn}}$: maximum dynamic active power available for the provision of the maximum inertia	.... MW
	$P_{\mathrm{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia	.... MW
	$P_{\mathrm{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia	.... MW
	Temporary 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): including a unit transformer (or on the medium-voltage side of the unit): where applicable, at high-voltage level: 0.50 p.u.	................p.u. ....p.u. ....p.u.
	Contribution to the initial short-circuit AC current I_{K} “....... kA ***	at V
	☐ Cover sheet of the unit certificate 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 .... %
☐ Manufacturer data sheet attached

Additional data for storage

Connection of storage		☐ via its own inverter ☐ via the inverter of another power-generating unit (in a PGSU) ☐ direct connection to the AC-network or three-phase network
Operation of storage	☐ Consumption and feed-in from and into the network of the system operator	Feed-in from the storage into the network of the system operator planned simultaneously with PGUs ☐ yes ☐ no
	☐ No consumption, but feed-in into the network of the system operator	
	☐ No consumption and no feed-in from/into the network of the system operator	
	☐ Consumption, but no feed-in into the network of the system 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 (highvoltage) (to be completed by the connection owner for charging equipment for electric vehicles)			4 (4)
General information of the charging device	☐ public ☐ 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*	☐ yes ☐ no	
Information of each identically constructed charging device	Number of charging devices	Maximum charging capacity of the charging device	Charging technology
		.... kW	☐ AC ☐ DC** ☐ Bidirectional*** ZEREZ ID:
			☐ AC ☐ DC**
			☐ AC ☐ DC**
Metering	Is a separate metering of the charging devices requested by the responsible party or a third-party metering point operator?		☐ yes*** ☐ no

* The system operator may require a device to control the active power.
** The reactive power specifications of the system 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 - Highvoltage

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 rule)

Commissioning report (highvoltage)
(to be completed by the plant operator of the transfer station)

1 (1)

Postal address of the plant
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 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 agreement):
....

Station data
☐ Stub ☐ Double stub ☐ Looping-in
☐ Demand facility ☐ Feeder ☐ Mixed customer site/storage

TF blocks (blocker for audio-frequency ripple control)
Required in the connection offer: ☐ yes ☐ no
Installed: ☐ yes ☐ no
Test protocol available: ☐ yes ☐ no

Documentation: Updated project documents handed over to the system operator at least 2 weeks prior to commissioning of the transfer station: ☐ yes ☐ no

☐ Network control agreement available
☐ Network operation prerequisites fulfilled
☐ Schematic circuit diagram, wiring diagrams for secondary equipment, if any
☐ Test protocol of the transfer protection and for power-generating modules of the primary loss of mains protection
☐ Joint commissioning (with the system operator)
☐ Protection checked by switch tripping

☐ Calibration certificates for the transducers
☐ Protocol of the earth connection measurement
☐ Confirmation in accordance with DGUV Regulation 3
☐ Measurement value transmission checked
☐ Reports checked
☐ Remote control checked (including emergency-stop circuit breaker)

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 4120, and the Technical Connection Conditions of the system operator. The results of the tests were documented. During handover of the plant, 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.

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 qualified electricians or persons trained in electrical engineering. 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

The customer installation was connected to the high-voltage network on:
Date: ....Time: ....

....	....
Place, Date	System operator

C.II.3. (E.6) Data sheet for power-generating modules or storage - Highvoltage

This form replaces Appendix E.6 of VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE Application rule)

Data sheet for power-generating modules – Highvoltage (to be completed by the connection owner, also applies to mixed customer sites and storage)	1 (4)
Feeder number of the connection owner ________________	
Location of the plant	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 system operator, a new network compatibility assessment by the system operator may be required.	☐ yes, Date E.1_____________ ☐ no
Are existing power-generating modules or storage connected to the network connection point? ☐ yes ☐ no Final plant certificate number: ________________________________ Date: ________________ NOTE If no plant 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?	☐ yes, …………………..kW ☐ no
Island operation intended?	☐ yes ☐ no
Black start capability provided?	☐ yes ☐ no

Data sheet for power-generating modules – Highvoltage (the following information shall be shown in the overview diagram of the power-generating module	2 (4)
Details on the HV/MLV transformer	• 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_{bUV} in kV • Short-circuit voltage u_{k} in % • Switching group • Control range of the tap changer ± in % • Number of steps
Generator transformer	• Rated apparent power S_{r} in kVA • Short-circuit voltage u_{k} in % • Switching group • Control range of the tap changer ± 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	• 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)	• 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 – Highvoltage (to be completed by the connection owner; use one data sheet for every structurally different existing power-generating unit or storage without a plant certificate)		3 (4)
Number of identically constructed power-generating units or storage: .... units		
Unit type	☐ Double-fed asynchronous machine	☐ Inertia
	☐ Synchronous machine (coupled directly)	☐ Phase shifter operation
	☐ Network coupling with full converter*	☐ Inertia
	☐ Storage	☐ Inertia
	Other	
Operating mode	☐ Peak load coverage / Optimisation of houseload consumption ☐ Balancing energy market / Ancillary services ☐ Island operation ☐ Inertia ☐ Other	
Unit manufacturer:	....	Type: ....
Power data	Rated apparent power S_{rE} *	.... kVA
	Maximum active power (10-minute average) P_{Emax} **	.... 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
	Temporary 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): including a unit transformer (or on the medium-voltage side of the unit): where applicable, at high-voltage level: 0.50 p.u.	................p.u. ....p.u. ....p.u.
	Contribution to the initial short-circuit current I_K “........ kA ***	at V
For directly coupled synchronous generators: saturated direct-axis sub-transient reactance .... % ☐ 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 – Highvoltage
(check list for the information to be submitted to the system operator by the connection owner; to be completed by the connection owner)

4 (4)

Single-phase overview circuit diagram of the customer installation (minimum requirements): ☐

- 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))
    - 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 system operator serve as the basis for issuing the plant certificate. Changes of any kind shall be immediately indicated in writing to the relevant system operator. These data sheets will only be processed if fully completed.

....
Place, Date

....
Signature of the connection owner

C.II.4. (E.7) System operator questionnaire – Highvoltage

This form replaces Appendix E.7 of VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE Application rule)

System operator questionnaire for new plants Connection/modification of a power-generating module or storage									1 (6)
Designation of power-generating module									
Maximum generation active power, cumulated $\sum P_{\text{Amax}}$ Agreed active connection power $P_{\text{AV,E}}$ Agreed apparent connection power $S_{\text{AV,E}}$		Existing unit				New plant		Complete (existing + new plant)	
	$\sum P_{\text{Amax}}$		MW				MW		MW
		Current (actual)				Total (new)			
	$P_{\text{AV,E}}$			MW				MW	
	$S_{\text{AV,E}}$			MVA				MVA	
$P_{\text{AV,E}}$ – Monitoring		☐ yes				☐ no			
Information from the system operator	Date of the TCC HV			Contact details (e.g. email or telephone)					
Registration number of the system operator									
Designation of the transfer station									
Designation of the network connection point[38]									
Demand facility at the same network connection point (except for houseload of the power-generating module)	Demand facility provided ☐ yes (mixed customer site in accordance with VDE-AR-N 4120) ☐ no				Agreed active connection power PAV, B				
					$P_{\text{AV, B}}$			MW	
Other comments:									

---

[38] 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 system operator.

System operator questionnaire for new plants
Connection/change of a power-generating module

2 (6)

1. Set values for the protection equipment at the network connection point

1.1 Short-circuit protection equipment (select where appropriate)

☐ Take-away circuit

☐ Distance protection:

Setting values		**Default setting system operator**		☐ 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 shall always be attached			
Zero sequence starter	I_E > [A]			
	U_{NE} > [kV]			

☐ Overcurrent protection

Setting values	Default setting system operator		☐ Separate settings sheet attached Comments: ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………
	Old (actual)	New (setpoint)	
I >> [A]			
t_I >> [ms]			
I > [A]			
t_I > [ms]			

☐ Earth fault protection ………………………………………………

Setting values	Default setting system operator		☐ Integrated in the distance or overcurrent protection ☐ 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]			

System operator questionnaire for new plants Connection/modification of a power-generating module or storage	3 (6)

1.2 Loss of mains protection

Function	**Setting values**	Recommendation in accordance with VDE-AR-N 4120	**Default setting system operator**	
High-voltage side				
Voltage surge protection	$U >$	1.25 U_n		
	$t_\text{U} >$	500 ms		
Undervoltage protection	$U <$	0.8 U_n		
	$t_\text{U} <$	5.0 s		
Overfrequency protection	$f >$	51.5 Hz		
	$t_\text{f} >$	5.4 s		
Underfrequency protection	f	47.5 Hz		
	$t_\text{f} <$	$\leq$ 400 ms		
Low-voltage side				
Voltage surge protection	$U >>$	1.20 U_MV		valid for U_MV = ….. kV[39]
	$t_\text{U} >>$	300 ms		
	$U >$	1.10 U_MV		
	$t_\text{U} >$	180 s		
$P_\text{AV,E}$ protection device	$P>>$	See FNN Guideline $P_\text{AV,E}$ monitoring (Table 5)		
	$t>>$			
	$P>$			
	$t>$			

1.3 Mixed customer sites (if demand facility available)

	Point of measurement	**Trigger location**
Primary loss of mains protection	☐ Transfer station ☐ Power-generating module	☐ Transfer station ☐ Power-generating module

NOTE For existing systems, Q-U-protection may be deactivated during the repeated test in accordance with Clause 11.5.5.

---

[39] 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-involtage protection shall be converted correspondingly. The controller setpoint voltage set shall be given in the statement of compliance.

System operator questionnaire for new plants Connection/modification of a power-generating module or storage	4 (6)

2. Default settings for power-generating units (e.g. PGU or temporarily stored loss of mains protection)

2.1 Loss of mains protection

Function	Setting values	Recommendation in accordance with VDE-AR-N 4120 HV network	Default settings[40] system operator	
Voltage surge 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 Voltage source control (for Type 2 plants only)

Function	Default setting system operator
Droop *k* of the voltage source control	☐ *k* = 2 ☐ *k* = ... ☐ *no specification (grid-forming)*

---

[40] 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.

System operator questionnaire for new plants Connection/modification of a power-generating module or storage		5 (6)
3. Static voltage support		
Reactive power adjustment range	☐ Option 1 in accordance with Clause 10.2.2 ☐ Option 2 in accordance with Clause 10.2.2 ☐ Option 3 in accordance with Clause 10.2.2 ☐........ underexcited to .... overexcited (separate closed-loop control)	
Desired reactive power value and method	☐ to be found in the TCC	
	☐ Reactive power/voltage characteristic $Q(U)$41))	Gradient of the characteristic curve: Upper voltage limit U_{MAX}/U_n = ... (e.g. 1.04) Maximum reactive power $Q_{MAX\text{-}underexcited}/P_{b\ inst}$ = ... (e.g. 0.33) Voltage deadband = ± .... % U_n (e.g. ± 1.0 % U_n) Reference voltage: $U_{Q0,ref}/U_n$ = ... (e.g. 1.00) ☐ U_{Q0}/U_n variable by means of a telecontrol system42)
	☐ 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) ☐ Q = ... Mvar ☐ variable by means of a telecontrol system43)) ☐ Schedule44))
	☐ Displacement factor cos φ	☐ cos φ = ... ☐ overexcited ☐ underexcited ☐ variable by means of a telecontrol system12 ☐ Schedule13
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 failure45))	☐ continue operation with the value received last ☐ U_0 = ...kV; Q_{ref} = ... Mvar; cos φ = ... (depending on the chosen method) ☐ switch-over to46) ☐ $Q(U)$ ☐ Q ☐ cos φ	
Response to a failure of either the PGM controller or the associated measurement or the connection between PGM controller and PGU	☐ Continue operation of all PGUs with the value received last ☐ Continue operation of all PGUs with P = ... (aggregate value for the PGM) ☐ Continue operation of all PGUs with Q = ... (aggregate value for the PGM) ☐ Continue operation of all PGUs with cos φ = ...	
Requirements for the reactive power behaviour of the existing units for mixed customer sites 47), 48)	☐ Integration into the reactive power control system of the new plant ☐ cos φ = ... at the NCP ☐ overexcited ☐ underexcited ☐ cos φ = ... at the PGU ☐ overexcited ☐ underexcited ☐.............underexcited to .... overexcited ☐ maintain existing operation behaviour (unless otherwise specified, a cos(phi) value of 1 may be assumed for verification purposes)	

* For the normal network switching state.

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41) Recommendations can be found in Section 10.2.2.4.

41)If setpoints are provided by means of a telecontrol system. The telecontrol system specifications shall be enclosed by the system operator or they can be found in the system operator's TCC.

43)The telecontrol system specifications shall be enclosed by the system operator or they can be found in the system operator's TCC.

44) If schedules are required, they shall be provided as a separate sheet or under other comments.

44)If setpoints are provided by means of a telecontrol system.

45)Specifications are provided by the system operator or to be found in the system operator's TCC.

46)If several old plants with different reactive power responses or different reactive power Agreements with the system operator exist, provide detailed information on a separate sheet.

48) In addition to the mode of operation agreed for the existing plants, their actual behaviour shall be taken into account. The calculation method is described in FGW TR 8 [10].

System operator questionnaire for new plants Connection/modification of a power-generating module or storage	6 (6)

4. Network data		
Nominal voltage of the high-voltage network U_n	………………	kV
Rated short-time current I_k (for T_k = 1 s)[49]	………………	kA
Minimum network short-circuit power at the point of common coupling[50] S_{kV}*	………………	MVA
Network impedance angle at the network connection point ψ_k*	………………	°
Cabling proportion of the network	………………	% of the system length
Reference power[51] S_0	………………	MVA
Centralized ripple-control frequency	………………	Hz
Effective network capacity	………………	µF

5. Neutral-point treatment		
Type of neutral-point treatment	☐	Resonant neutral earthing (earth fault compensation)
	☐	Neutral earthing with low impedance
	☐	Solid neutral earthing
	☐	No neutral-point treatment (free, isolated neutral point)

6. PGM model

☐ The system operator has a model of the power-generating module at its disposal for performing network calculations:

☐ Set of parameters in accordance with Appendix C.4 ☐ with optional additional information

☐ Set of parameters in accordance with the specifications of the system operator

☐ Set of parameters in accordance with the specifications of the system operator

☐ Computable dynamic model in accordance with system operator specifications

Other comments ……………………………………………………………………………………………………

……

……

…………………………………………………………… .. Place, Date	……………………………………………………………………………… Signature of the system operator The questionnaire for the system operator (E.7) is valid until:

---

[49] For dimensioning of the highvoltage transfer station regarding the short-circuit current capability.

[50] In order to allow for the plant certificate/ qualified plant report to be prepared, the system 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 in accordance with the relevant rules.

[51] 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 - Highvoltage

This form replaces Appendix E.8 of VDE-AR-N 4120.

(This form is intended to be replicated by the user of this VDE Application rule.)

<table>
<tr><td colspan="5">**Commissioning report for power-generating units – HV**
(to be completed by the plant operator; also applies to storage)</td><td>1 (2)</td></tr>
<tr><td>Plant designation</td><td colspan="5">..</td></tr>
<tr><td>Number of PGUs:</td><td>.............
..</td><td>Manufacturer of PGUs:</td><td>.......................</td><td>Type of PGUs:</td><td>...............</td></tr>
<tr><td>Registration number of the DSO</td><td colspan="5">..</td></tr>
<tr><td>Postal address of the power-generating unit</td><td colspan="5">Postcode: .... Town: ....Street, number: ....</td></tr>
<tr><td rowspan="2">Location of the power-generating unit (when no address available)</td><td colspan="5">Local sub-district: .... Cadastral section: .... Plot: ....</td></tr>
<tr><td colspan="5">☐ Gauss-Krüger coordinates Reference ellipsoid:
....
☐ UTM coordinates Zone: ....
Easting: .... Northing: ....</td></tr>
<tr><td>Point of connection to the network of the system operator</td><td>Designation:
Metering point for billing purposes:</td><td colspan="4">..
....</td></tr>
<tr><td>Official approval</td><td colspan="5">Type: ☐ Construction permit ☐ Approval as required by the BImschV
☐ Authorization under the water law ☐ ....
File number: .... Date: ....</td></tr>
<tr><td rowspan="3">Compliance with legal provisions (EEG/KWK-G)</td><td colspan="5">☐ The requirements of § 9(1) or (2) EEG are complied with (network protection and network management in compliance with statutory power limits)
☐ The requirements of § 9(5) No. 1 EEG are complied with (hydraulic retention time, applies to biogas plants only)
☐ The requirements of § 9(5) No. 2 EEG are fulfilled (including gas consumption devices for preventing biogas release, applies only to biogas plants)
☐ The prerequisites for a compensation side plant summary in accordance with § 24 Abs. 2 EEG are not satisfied (applies to ground PV plants only)</td></tr>
<tr><td colspan="5">Index number for the Market Master Data Register .... Award number in accordance with § 35 EEG: ....</td></tr>
<tr><td colspan="5">☐ 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)
☐ Notification of the CHP plant as per § 10 Abs. 6 KWK-G (please attach the notification filed with BAFA)
☐ Approval as a CHP plant as per § 10 KWK-G (please attach the BAFA approval)</td></tr>
<tr><td>Certification body for the power-generating unit</td><td>Name:
Postal address:
Unit certificate number:</td><td colspan="4">..
....
.... Date of issue: ....</td></tr>
<tr><td>Certification body for power-generating modules</td><td>Name:
Postal address:
Plant certificate number:</td><td colspan="4">..
....
.... Date of issue: ....</td></tr>
<tr><td>Power data</td><td colspan="5">Maximum active power: .... kW (power installed as per § 3 No. 31 EEG; for PV plants the module power on the negative-sequence side)
Maximum apparent power: .... kVA (for PV plants use the inverter output power on the network side)
Storage capacity .... kWh (in storage)</td></tr>
</table>

Commissioning report for power-generating units – HV (to be completed by the plant operator; also applies to storage)			2 (2)
Documentation	☐ Loss of mains protection successfully tested (please attach the protection test reports) ☐ voltage source control of the PGU implemented according to the plant certificate ☐ all other parameters influencing the electrical properties are set in accordance with the plant certificate ☐ The power-generating unit is integrated into the network security management ☐ Proportion of nominal effective power for inertia market m =........... ☐ Start-up time constant T_A = ...		
Commissioning	The power-generating unit was commissioned on:	Date: ………..	Time: ………..
	The power-generating unit has started feeding energy into the network of the system operator (in the case of mixed customer sites has started generating energy):	Date: ………..	Time: ………..

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 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.

The power-generating unit was installed in accordance with the conditions specified in VDE-AR-N 4120 and the Technical Connection Conditions of the system operator. During handover of the plant, 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.

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 system 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.II.6. (E.9) Commissioning statement for power-generating modules or storage - Highvoltage

This form replaces Appendix E.9 of VDE-AR-N 4120.
(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 $P_{\mathrm{AV,\,E}}$			MW
	Agreed apparent connection power for feed-in $S_{\mathrm{AV,\,E}}$			MVA
	Agreed active connection power for consumption $P_{\mathrm{AV,\,B}}$			MW
	Installed active power P_{inst}			MW
	$P_{\mathrm{min,dyn}}$: minimum dynamic active power available for the provision of negative inertia			MW
	$P_{\mathrm{max,dyn}}$: maximum dynamic active power available for the provision of the maximum inertia			MW
	$P_{\mathrm{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia			MW
	$P_{\mathrm{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia			MW
	Temporary minimum power			MW
Registration number of the system 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 plant certificate	Certification body			
	Street, number			
	Postcode, town			
	Plant 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)	2 (7)

Commissioning of all power-generating units (existing and new plants)

Manufacturer	Type	Firmware version	Serial number	Rated active power P_{rE}	Commissioning date
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	
				kW	

Commissioning of additional components (intermediate storage protection devices, compensation systems if required)

Component	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, where applicable, reactive power control by the control centre of the system operator (protocol to be provided by the system operator);	Verification of the system operator	☐
Alternative 1: Test of the entire chain of action by simulating the interface to the telecontrol system of the system operator (if agreed with the system operator)	Verification	☐
Alternative 2: Test of the entire chain of action with the system operator to be agreed at a later date. Including confirmation from the system operator (not part of the commissioning declaration)	Confirmation from the system operator	☐
Functional test of the telecontrol system up to the transfer station (if required by the system operator), to be performed by the system operator (request test, process data scope)	Verification of the system operator	☐
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	☐
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	☐
Function test of the reactive power characteristic curve or the reactive power fixed values in accordance with specifications from the system 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 cosϕ(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	☐
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)	☐
Protection test reports for protection equipment on the individual power-generating units or, where applicable, the intermediate storage protection devices Minimum information, see Appendix on page 6 of 7	Protection test report(s)	☐

<table>
<tr><td colspan="2">Commissioning statement for power-generating modules or storage
(to be completed by the plant operator; also applies to storage)</td><td>4 (7)</td></tr>
<tr><td>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:
- Manufacturer, type, serial numbers and, where 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 where 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
Where applicable, for plant control exclusively via the PGU:
- See the PGM controller setting records for details.</td><td>Settings record(s)</td><td>☐</td></tr>
<tr><td>Setting records of the PGM controller including designation, parameters used in VDE-AR-N 4120; minimum information:
- Manufacturer, type, serial numbers and, where 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, where 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 (<i>P</i>(<i>f</i>) characteristic curve), switch-on parameters in undisturbed network operation</td><td>Settings record</td><td>☐</td></tr>
<tr><td>Arc fault qualification certificate for the switchgear or risk assessment for existing systems</td><td>Verification</td><td>☐</td></tr>
<tr><td>Photographic documentation (the assignment to operating equipment shall be recognisable). The certification body may accept alternative verifications.
Minimum information:</td><td>Photos</td><td></td></tr>
<tr><td>- 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)</td><td></td><td>☐</td></tr>
<tr><td>- Type plates of the HV switchgear</td><td></td><td>☐</td></tr>
<tr><td>- 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)</td><td></td><td>☐</td></tr>
</table>

Commissioning statement for power-generating modules or storage (to be completed by the plant operator; also applies to storage)		5 (7)
- Type plates of transformers with tap changers		☐
- Type plates of switchgear (e.g. circuit breakers) assigned to the protection devices		☐
- Protection settings that are set directly on the switchgear (e.g. rotary switches/dip switches)		☐
- Type plates of network analysis devices (if used for protection/PGM controllers)		☐
- Type plates of PGM controller (with serial number)		☐
- Type plates of mains-independent auxiliary power supplies/UPS (with recognisable capacity of the connected battery) of the transfer station and, where applicable, the temporarily stored protection devices		☐
- Fuse outlets with type and size		☐
- Nameplates for all stations		☐
Comments:		
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.		
Confirmation		
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'. 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'. 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. The signatory confirms the accuracy of the information provided in the commissioning declaration, including the required attachments.		

Date	Signature of the person who prepared the declaration of commissioning

Commissioning statement for power-generating modules or storage

6 (7)

(to be completed by the plant operator; also applies to storage)

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

Protection test report for the protection equipment at the network connection point

Minimum information, see Appendix *1:

System designation, plant 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 plant 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 increases 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 system operator (does not apply if the system 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 overvoltage and undervoltage protection thresholds

Specification of whether automatic reconnection was deactivated in the protection device or, where applicable, by external circuitry

Checking the tripping of the switchgear in the event of:

- Failure of the auxiliary power supply
- where 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
- where applicable, in the event of physical separation between the protective device and the switching device: failure of the connection between protective and switching devices

The system operator may specify different requirements and request further tests.

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, where applicable, the intermediate storage protection devices

Minimum information:

- System designation, plant 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 plant 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 system operator (does not apply if the system 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 overvoltage and undervoltage 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 system operator may specify different requirements and request further tests.

C.II.7. (E.10) Statement of compliance for power-generating modules or storage – Highvoltage

This form replaces Appendix E.10 of VDE-AR-N 4120.
(This form is intended to be replicated by the user of this VDE Application rule)

Name of the certification body…………………………………….. **Accredited in accordance with DIN EN ISO/IEC 17065 for VDE-VDE-AR-N 4120**	LOGO 1 (2)
Statement of compliance **for power-generating modules or storage**	Number: ………….……………….........… Signed copy number: ……….......................

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 plant certificate	First name, Surname	__________________
	Street, number	__________________
	Number of verifications for the plant	__________________
	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 plant certificate and the provisions of the system operator.

☐ 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 plant certificate.

☐ 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 system operator.

☐ Passed

NOTE____

____

2 (2)

The power-generating module or storage described above

☐ meets the requirements of VDE-AR-N 4120 “TCR Highvoltage”

☐ meets the requirements of the FNN Guideline “Technical requirements for grid-forming capabilities including the provision of inertia”

☐ meets the requirements of the system operator’s TCC

and was installed in compliance with the plant 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 system 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 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-highvoltage

C.III.1. (E.6) Data sheet of power-generating modules or storage - Extra-highvoltage

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 rule.)

Data sheet of power-generating modules or storage – Extra-highvoltage (to be completed by the connection owner)		1 (5)
Postal address of the plant	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)	☐ Wind energy ☐ Hydro-power ☐ …………………	
	☐ PV plant ☐ Free area ☐ Roof area ☐ Façade	
	☐ CCGT ☐ Thermal power plant	Fuel type used (e.g. natural gas, biogas, biomass) ……………………………………………………
	☐ Storage	
Plant type	☐ New plant ☐ Extension ☐ Dismantling	
Power data	Available active connection power $P_{\text{AV, E}}$	…………… MW
	New active connection power $P_{\text{AV, E}}$	………… MW
	Rated active power of modules in PV plants for this purpose*	………… MWp
	Rated active power of inverters $P_{\text{r,WE}}$ (PV plants)	………… MW
	Total active connection power $P_{\text{AV, E}}$	………… MW
	Technical minimum power	………… MW
	Houseload of the power-generating module (including consumption power of storage)	…………… MW
	$P_{\mathrm{min,dyn}}$: minimum dynamic active power available for the provision of negative inertia	…………… MW
	$P_{\mathrm{max,dyn}}$: maximum dynamic active power available for the provision of the maximum inertia	…………… MW
	$P_{\mathrm{limitneg,max}}$: maximum dynamic active power for the provision of negative inertia	…………… MW
	$P_{\mathrm{limitpos,min}}$: minimum dynamic active power for the provision of positive inertia	…………… MW
	Temporary minimum power	…………… MW
	T_{A}: start-up time constant	…………… s

* Sum of existing and new 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-highvoltage (to be completed by the connection owner)	**2 (5)**
All energy fed into the network of the system operator?	☐ yes ☐ no
Island operation intended?	☐ yes ☐ no
Black start capability provided?	☐ yes ☐ no
Carrier-frequency utilization of the customer network intended?	☐ yes ☐ no
Brief description:...	
EHV/HV(MV) transformer	Upper rated voltage U_{rOV}............. kV
	Lower rated voltage U_{rUV}............. kV
	Rated apparent power S_{r} .... MVA
	Short-circuit voltage u_{k} …….…... %
	Vector group: .... Tap changer: .... Control range: ± .... % 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: ☐ deleted ☐ isolated ☐ low-impedance earthing
	☐ Schematic overview diagram of the network attached with details on the lengths and cross-sections of all cables used
Reactive power compensation system	☐ not provided ☐ provided ……….….. kvar
	Degree of choking/resonance frequency: .... Hz
	Assigned: ☐ to the power-generating module ☐ to the power-generating units
	☐ Schematic overview diagram and manufacturer data sheet attached

Data sheet of power-generating modules or storage – Extra-highvoltage (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 ☐ prototype

☐ Existing unit with capability to provide ancillary services: ☐ as old plant ☐ as temporary/new plant

Number of last valid qualified plant report/certificate: ______________________ Date: ....

NOTE 2 Where a qualified plant report/certificate is available for the existing unit, this sheet 3 (5) may be omitted for this existing unit.

Unit type	☐ Double-fed asynchronous machine	☐ Inertia
	☐ Synchronous machine (coupled directly)	☐ Phase shifter operation
	☐ Network coupling with full converter*	☐ 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
	☐ 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 .... %

☐ 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: ± .... %; .... 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.

**** Where applicable, data for other relevant transformers shall be indicated.

Data sheet of power-generating modules or storage – Extra-highvoltage (to be completed by the connection owner; please, use one data sheet each for every structurally different storage)		**4 (5)**
Operating mode	☐ Houseload increase of the customer demand facility (load optimising)	
	☐ Provision of ancillary services	
	☐ Provision of control energy	
	☐ Maintaining island operation of the customer installation	
	☐ Miscellaneous	
Connection of storage	☐ via own inverter	
	☐ via the inverter of the PGU	
	☐ direct connection to the three-phase network	
	Maximum power P_{Emax} (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_{Emax}:	.... kVA
	Active power of inverter P_{Emax}:	.... 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):	☐
	Primary energy sources used (e.g. solar, wind, gas):	....
	Different primary energy sources are registered separately:	☐
	Different feed-in tariffs are accurately registered:	☐
	Energy of storage is not consumed from the network and fed in as supported energy:	☐
Verifications	For the inverter of storage, the extract from the test report for network compatibility in accordance with FGW/TR 3 [5] was submitted	☐
	Unit certificates in accordance with VDE-AR-N 4130 were submitted:	☐
Comments	....	

Data sheet of power-generating modules or storage – Extra-highvoltage (check list for the information to be submitted to the system operator by the connection owner; to be completed by the connection owner)	**5 (5)**
Site map showing the location relative to places and roads, cadastral and plot designations, designation and limits of the property, and the plant 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?	☐
Building permit for the power-generating module attached?	☐
Preliminary building permit attached? (not required for PV plants on approved structures)?	☐
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)?	☐
Project schedule available? (please attach)	☐
Planned transition to continuous operation	…………….....

This data sheet is part of the network compatibility check and possibly the network connection offer. Together with the questionnaire E.7 to be completed by the system operator, it also serves as a basis for the preparation of the plant certificate. Changes of any kind shall be immediately indicated in writing to the relevant system operator. These data sheets will only be processed if fully completed.

.... Place, Date	.... Signature of the connection owner