European Network of
Transmission System Operators
for Electricity

# GRID FORMING CAPABILITY OF POWER PARK MODULES

## FIRST INTERIM REPORT ON TECHNICAL REQUIREMENTS

Final version | 3 May 2024

**ENTSO-E Mission Statement**

**Who we are**

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association for the cooperation of the European transmission system operators (TSOs). The 39 member TSOs, representing 35 countries, are responsible for the secure and coordinated operation of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E brings together the unique expertise of TSOs for the benefit of European citizens by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

**Our mission**

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the security of the inter-connected power system in all time frames at pan-European level and the optimal functioning and development of the European interconnected electricity markets, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

**Our vision**

ENTSO-E plays a central role in enabling Europe to become the first climate-neutral continent by 2050 by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires sector integration and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources. ENTSO-E acts to ensure that this energy system keeps consumers at its centre and is operated and developed with climate objectives and social welfare in mind.

ENTSO-E is committed to using its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

**Our values**

ENTSO-E acts in solidarity as a community of TSOs united by a shared responsibility.

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by optimising social welfare in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and innovative responses to prepare for the future and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with transparency and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

**Our contributions**

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its legally mandated tasks, ENTSO-E's key responsibilities include the following:

› Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;

› Assessment of the adequacy of the system in different timeframes;

› Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);

› Coordination of research, development and innovation activities of TSOs;

› Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the implementation and monitoring of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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# EXECUTIVE SUMMARY

In the context of grid forming capability for power park modules, this report proposes a first interim non-binding approach of detailing grid forming technical requirements for power park modules.

The report provides the basis for further discussions between the European TSOs and stakeholders to be consolidated in the phase II. Moreover, a range of parameters has been proposed accompanied with a proposal for compliance testing of grid forming capable power park modules.

To the best of the ENTSO-E view, and without prejudice of existing patents, the report adopts a technology-neutral stance, providing a patent-free framework for prescribing technical requirements on grid-forming capabilities for power park modules. This approach shall ensure independence from specific control implementations or manufacturer patents issued before the date of the report publication, fostering an environment conducive to innovation.

# 1 Introduction

## 1.1 Context and background

On 19 December, 2023, the Agency for the Cooperation of Energy Regulators (ACER) submitted its recommendations to the European Commission (EC) for amending the Network Connection Code (CNC) related to the requirements for generators (RfG Regulation)[1]. This proposal is based on inputs and feedback from different stakeholders gathered during an initial consultation process. Notably, it includes non-exhaustive Grid-Forming (GFM) requirements for Power Park Modules (PPM) based on the inputs from the EG on Advanced Capabilities for Grids with a High Share of PPM[2].

To facilitate its application and address stakeholders' concerns about harmonization, an Implementation Guidance Document (IGD) proposing exhaustive GFM requirements will be released after the publication of the updated regulation, expected in 2025, following a dedicated process.

It is worth noting that grid forming technical requirements have been recently adopted by system operators in Great Britain (GB) and Australia. The Electricity System Operator (ESO) published the GB GFM Best Practice Guide in April 2023[3] and the Guidance Notes in September 2023 following the inclusion of GFM requirements into the GB Grid Code (GC0137 - Minimum Specification Required for Provision of GB GFM Capability)[4], and Australian Energy Market Operator (AEMO) released a Core Requirements Test Framework in January 2024 to complement the Voluntary Specification for Grid-forming Inverters[5,6].

## 1.2 Objective and scope

The objective of this task force is to provide recommendations on the exhaustive technical reequipments of GFM requirements for PPM, while remaining independent of the specific controller implementation.

The technical requirements are intended to describe the GFM capabilities of PPM of type B, C and D. If not specified further, the term 'PPM' refers to PPMs of type B, C and D. Any potential extension to type A units may necessitate further analysis.

## 1.3 Report outline

The remainder of this report is organized as follows: Section 2 recalls the GFM requirements for PPM as proposed for inclusion in the RfG amendment proposal, submitted by ACER at EC for approval and

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[1] *ACER proposes amendments to the electricity grid connection network codes | www.acer.europa.eu*
[2] *GC-ESC EG ACPPM Report version 1.00 (windows.net)*
[3] *download (nationalgrideso.com)*
[4] *THE GRID CODE (nationalgrideso.com)*
[5] *https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan 2024.pdf?la=en*
[6] *https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf*

proposes their exhaustive formulation. To illustrate a possible method for verifying compliance, Section 3 first describes the recommended test cases while Section 4 discusses the verification of the compliance of the proposed exhaustive requirements. Finally, conclusions are drawn in Section 5.

The description of a droop-based control loop and an equivalent parametrization for a virtual synchronous machine implementation is included in Appendix A[7]. The physical concept to describe these needs and requirements including the physical response of an ideal system to disturbances is analysed in Appendix B. Appendix C includes a discussion on measurement considerations for selected key performance indicators (KPI). Finally, additional simulation results showing the response of a GFM inverter to different disturbances are included in Appendix D.

## 1.4 Nomenclature

Relevant definitions of the parameters[8] used are shown in Table 1. Table 2 presents those on the grid side.

Table 1 Unit parameters

| Parameter or value unit | Description | Comment |
|---|---|---|
| $\underline{u}_{\mathrm{DUT}}$ | Voltage of unit / device under test in pu | at LV or MV terminals |
| $\underline{u}_{\mathrm{Inv}}$ | Internal voltage at unit / device under test in pu | |
| $\underline{z}_{\mathrm{Tr}}$ | Unit LV/MV transformer impedance | |
| $\underline{z}_{\mathrm{Filt}}$ | Unit LV/MV filter impedance in pu | R and L only. |
| $\underline{z}_{\mathrm{Eff}}$ | Unit effective Impedance in pu | |
| $x_{\mathrm{Eff}}$ | Unit effective Reactance in pu | |
| $\underline{z}_{\mathrm{Control}}$ | Equivalent effective impedance of controller action | |

[7] *A comprehensive overview of GFM control implementations can be found at https://www.nrel.gov/docs/fy21osti/73476.pdf*

[8] *SI-values are in capital, pu-values in small letters, underline defines complex / phasor values consisting of magnitude and angle.*

Table 2 Grid parameters (related to Figure 8)

| Parameter or value grid | Description | Comment |
|---|---|---|
| $\underline{u}_{\mathrm{G}}$ | Voltage amplitude and voltage angle of grid equivalent | |
| $\underline{z}_{\mathrm{G}}$ | Impedance of grid equivalent | |
| $\underline{z}_{\mathrm{SC}}$ | Short circuit impedance | Activated by $S_{SC}$ |
| $\underline{z}_{\mathrm{Line}}$ | Additional impedance between fault location and unit. Also used to emulate changes of SCR and voltage angle changes | Activated by opening $S_{SCR}$ |
| $\underline{z}_{\mathrm{Load}}$ | Impedance for testing operation at very low SCR-values and for testing loss of last synchronous generator. | Load activated by opening $S_L$<br>Loss of last synchronous generator activated by opening $S_G$<br>while $S_L$ is closed |
| $\underline{z}_{\mathrm{L,SS}}$ | Additional load for testing small signal stability during normal operation and after loss of last synchronous generator | Activated by opening or closing $S_{L,SS}$ |

# 2 Grid forming Capability at the Point of Connection of PPMs

In accordance with the proposed RfG amendment, GFM capability is defined as follows[9], as in NC RfG 2.0 in chapter 3; Article Y (7):

*'Where grid forming capability is specified by the relevant TSO in coordination with the relevant system operator in accordance with NC RfG 2.0 proposal, Article Y. or defined in Articles 20, 21 and 22, a power park module shall be capable of providing grid forming capability **at the connection point**, considering the sub-cycle character of the physical quantities where appropriate.'*

Therefore, in NC RfG, all the connection requirements are evaluated for compliance (either by tests or simulations) at the Point of Connection (PoC) of the PPM with the grid. For the case of GFM capability and within the PPM's current and energy limits, the PPM shall be capable of behaving at the terminals of the individual unit(s) as a voltage source behind an internal impedance. Therefore, **technical requirements for the voltage source behaviour shall be defined at the terminal of the individual unit(s)**, while the compliance shall be proven at the connection point.

As illustrated in Figure 1, a PPM typically consists of individual units, referred to as the Device Under Test (DUT) in the remainder of this report (or else as generating units). It frequently includes an internal grid, also known as the Power Collection System (PCS). As the PCS is highly project-specific and may vary in design, defining general requirements for the voltage source behind an internal impedance at the PoC of the PPM poses challenges.

Consequently, technical requirements of the voltage source behind an internal impedance (Thevenin source) shall be specified by the relevant TSO, in coordination with the relevant system operators at the terminals of the DUT, and may or may not include connection transformer(s). The terminal voltage is then respectively denoted $\underline{u}_{\mathrm{DUT,MV}}$ and $\underline{u}_{\mathrm{DUT,LV}}$.(see Figure 1). The facility owner needs to ensure and prove that the PCS design maintains voltage source behaviour at the POC.

Section 2.1 first describes an equivalent circuit representation of the DUT. Subsequently, Section 2.2 elaborates on the expressions of the expected output currents. Finally, Section 2.3 proposes an exhaustive definition of the GFM requirements in terms of an upper bound of the DUT effective impedance.

[9] *ACER Recommendation 03-2023 Annex 1. .a NC RfG TC to original.pdf (europa.eu)*

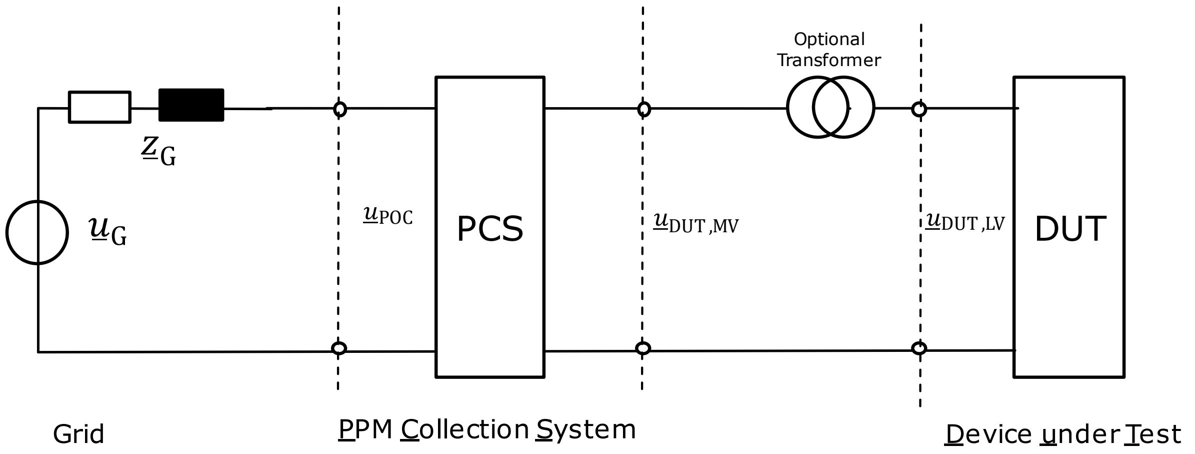


Figure 1: Definition of PPM PoC and unit terminals on medium and low voltage

## 2.1 DUT equivalent circuit representation

Figure 2 illustrates an equivalent circuit representation of a DUT connected to an infinite bus suitable to assess its response to grid events[10].

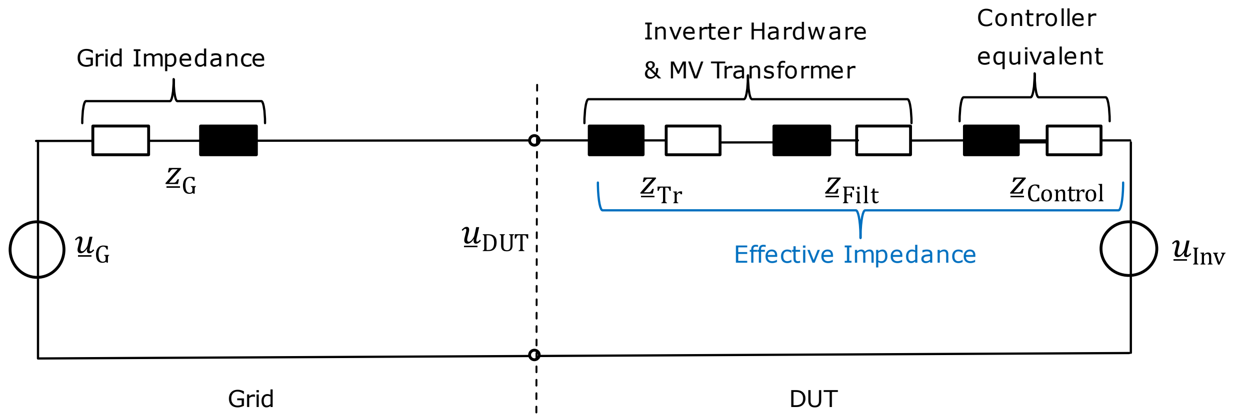


Figure 2: DUT positive sequence controller equivalent representation for evaluating the response to grid disturbances.

For the technical requirements regarding grid forming capability, the following are considered:

1. $\underline{u}_{inv}$ represents the internal voltage amplitude, voltage phase angle and frequency of the Thevenin source of a given DUT (known also as Generating Unit), as shown in Figure 2.
2. Converter physical parameters ($\underline{z}_{Tr}$, $\underline{z}_{Filt}$,…) are considered fixed for a given DUT.

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*[10] This makes no assumptions on the parameters of the grid impedance $\underline{z}_G$ which depends on local conditions and could include impedances of the PPM collector system (PCS).*

3. The impact of the control on the internal impedance can be represented by a controller impedance[11] $\underline{z}_{\mathrm{Control}}$. Its value can be defined at 50 Hz or in a wide band, up to 2.5 kHz, if requested by the relevant TSO, in coordination with the relevant system operator.
4. The internal impedance of the Thevenin source is given by the sum of physical and controller impedance ($\underline{z}_{\mathrm{Control}}$) and will be referred to as the effective impedance $\underline{z}_{\mathrm{Eff}}$. The effective impedance can be defined both at 50 Hz (synchronous frequency) but also in a wide frequency range, at least up to 2.5 kHz, if requested by the relevant TSO, in coordination with the relevant system operator.
5. The network is also represented by a Thevenin equivalent of voltage $\underline{u}_{\mathrm{G}}$ and impedance $\underline{z}_{\mathrm{G}}$.

For unbalanced conditions[12], Figure 3 illustrates an equivalent negative sequence circuit representation of a DUT connected to the grid.

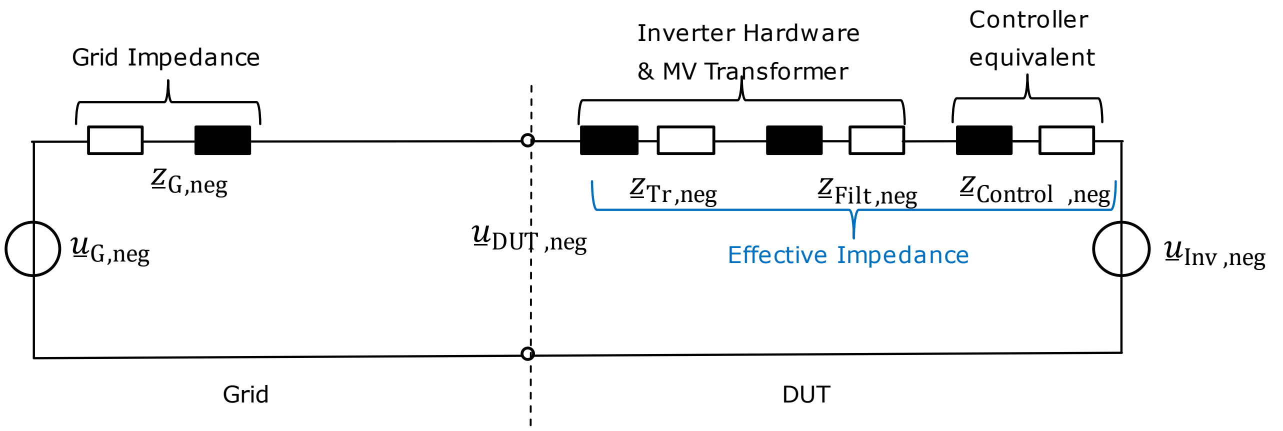



**Figure 3: DUT negative sequence controller equivalent representation for evaluating the response to grid disturbances.**

## 2.2 Analytical expressions of the expected initial output current

The active ($i_{\mathrm{P,DUT}}$) and reactive ($i_{\mathrm{Q,DUT}}$) components of the positive sequence (PS) current injected by the GFM DUT at the terminals can be approximated on the assumption of $r_{\mathrm{Eff}}$ << $x_{\mathrm{Eff}}$ (i.e $x_{\mathrm{Eff}} = z_{\mathrm{Eff}}$) by equations (1) and (2), respectively.

$$i_{\mathrm{P,DUT}} = \frac{p_{\mathrm{DUT}}}{u_{\mathrm{DUT}}} \approx -\frac{u_{Inv}}{x_{\mathrm{Eff}}} sin(\delta) \tag{1}$$

[11] $\underline{z}_{Control}$ *describes the impact of control response on the relation of voltage change at the DUT terminals to the change of current. It does not make any assumptions on the (physical) control implementation.*
[12] *NC RfG 2.0 describes requirements for positive sequence, as minimum requirements on the European level. For national implementations, if negative sequence requirements are needed to be detailed, this report provides a guidance on how this should be specified.*

$$i_{\mathrm{Q,DUT}} = \frac{q_{\mathrm{DUT}}}{u_{\mathrm{DUT}}} \approx \frac{1}{x_{\mathrm{Eff}}}\left(u_{\mathrm{DUT}} - u_{\mathrm{Inv}} \cdot cos(\delta)\right) \tag{2}$$

with $\delta = \varphi_{U_{\mathrm{DUT}}} - \varphi_{U_{\mathrm{Inv}}}$ denoting the phase difference between the terminal voltage angle $\varphi_{U_{\mathrm{DUT}}}$ and the internal voltage $\varphi_{U_{\mathrm{Inv}}}$ of the DUT.

Under unbalanced conditions, the negative sequence reactive current ($i_{\mathrm{Q,neg}}$) can be approximated by:

$$i_{\mathrm{Q,neg}} \approx \frac{1}{x_{\mathrm{Eff,neg}}}\left(u_{\mathrm{DUT,neg}} - u_{\mathrm{Inv,neg}} \cdot cos\left(\delta_{\mathrm{neg}}\right)\right) \tag{3}$$

with $u_{\mathrm{DUT,neg}}$ as the negative sequence voltage at the DUT terminal and $u_{\mathrm{Inv,neg}}$ as the negative sequence internal voltage. Typically, $cos\left(\delta_{\mathrm{neg}}\right)$ is assumed to be 1 under the assumption of no negative sequence active current.

When formulating those approximations, we assume that:

1. In accordance with the NC RfG proposal, both the inverter internal voltage $\underline{u}_{\mathrm{inv}}$ (in amplitude, phase, and frequency) and effective impedance $\underline{z}_{\mathrm{Eff}}$ are considered constant during grid events while current, energy or voltage limits are not reached.
2. The ratio $r_{\mathrm{Eff}}/x_{\mathrm{Eff}}$ of DUT impedance remains small[13], such that the impact of the resistive part of $\underline{z}_{\mathrm{Eff}}$ can be neglected for the description of the expected current response.

## 2.3 Proposed exhaustive requirements

Technical requirements for GFM capability specify the response of active and\or reactive current or power to voltage variations in amplitude, phase, frequency at the terminals of the DUT and they evaluated for compliance at the connection point (by test of simulations), typically in the form of *temporal parameters of the dynamic performance.*

In particular, technical requirements for the following quantities should be defined with respect to voltage amplitude or voltage phase angle changes:

1. The expected value of the active/reactive current or power output;
2. The response times[14] of the active/reactive current or power expected value;
3. The decay-rate or overshoot of the active/reactive current or power excursion (when relevant); and
4. The damping of the active/reactive current or power oscillation.

[13] *A ratio of $r_{Eff}/x_{Eff} < 0.1$ is recommended for implementation at national level.*
[14] *Assumed to be within one cycle for the instantaneous current response to voltage angle and magnitude changes.*

### 2.3.1 On the voltage source behaviour within capability limits

This section details the non-exhaustive requirement specified in Article Y(7) (a) - (c) of the NC RfG 2.0 amendment proposal:

*'(a) Within the power park module's current and energy limits, the power park module shall be capable of behaving at the terminals of the individual unit(s) as a voltage source behind an internal impedance (Thevenin source), during normal operating conditions (non-disturbed network conditions) and upon inception of a network disturbance (including voltage, frequency, and voltage phase angle disturbance). The Thevenin source is characterized by its internal voltage amplitude, voltage phase angle, frequency, and internal impedance.*

*(b) Upon inception of a network disturbance and while the power park module capabilities and current limits are not exceeded, the instantaneous AC voltage characteristics of the internal Thevenin source according to paragraph (a) shall be capable of not changing its amplitude and voltage phase angle while positive sequence voltage phase angle steps or voltage magnitude steps are occurring at the connection point. The current exchanged between the power park module and the network shall flow naturally according to the main generating plant and converter impedances and the voltage difference between the internal Thevenin source and the voltage at the connection point.*

*(c) After inception of a network disturbance in voltage magnitude, frequency or voltage phase angle, the following shall apply within the power park module's capability, including current limits and inherent energy storage capabilities of each individual unit.*

*(i) The relevant system operator in coordination with the TSO shall specify the temporal parameters of the dynamic performance regarding voltage stability.*

*(ii) Where current limitation is necessary, the relevant system operator in coordination with the relevant TSO may specify additional requirements regarding contribution of active and reactive power at the point of connection.*

*(iii) The power park module shall be capable of stable operation when reaching the power park module current limits, without interruption, in a continuous manner and returning to the behaviour described in paragraph (b) as soon as the limitations are no longer active. If reaching the current limit, the grid forming behaviour must be maintained for responses as specified in paragraph (b) for disturbances that require the current to vary in the opposite direction of the current limitation.'*

Note that, in accordance with NC RfG, Article Y, both the DUT (Generating Unit) internal voltage (in amplitude, phase, and frequency) and the effective impedance are considered constant *upon inception of a network disturbance at the connection point and while the PPM capabilities and current limits are not exceeded*. Moreover, according to equations (1) and (2) when the synchronisation mechanism[15] comes into play, the output current depends on the amplitude of the grid disturbance, namely *voltage phase angle steps and/or voltage magnitude steps*, which are external variables, and the effective impedance, the only design parameter at the hand of the OEM. For avoidance of doubt the internal Thevenin voltage source is allowed to slowly change to achieve desired performance in terms of synchronisation and damping.

**To ensure the generality of the requirement by making it independent of grid-side parameters, we propose defining it as a function of the effective reactance $x_{\mathbf{Eff}}$.** It is crucial to note that the technical requirement is at the generating unit (DUT) and is made by using **an equivalent circuit representation and does not imply anything about the specific control implementation leaving it technology and solution agnostic. The requirement shall be defined by the relevant TSO.** It should be noted, that although technical requirement at generating unit is imposed, the compliance shall be assessed by tests or simulations at the PoC, including the impact of the PPM collector system and internal cables design. This approach is illustrated in Figure 4, where a peak active current change ($\Delta\, i_{\mathrm{P,DUT}}$) of $\pm$ 0.25 pu is obtained for a δ of approximately $\pm$ 5° and is applied at the DUT terminals[16] using an $x_{\mathrm{Eff}}$ of 0.33 pu. In this example, the DUT terminal is defined at the MV side of the transformer. Manipulating equation (1) leads to a

$$i_{\mathrm{P,DUT,Peak}} \approx -\frac{1}{x_{\mathrm{Eff}}}\left(sin(\delta_1) - sin(\delta_2)\right) \qquad (4)$$

If we consider this active current output as the minimum requirement for such an event, the corresponding equivalent impedance can be established as an upper limit.

[15] *Understood as synchronising power or synchronising current according to (1) as the ability of the generating unit to inherently exchange power with the grid as result of the variation of the terminal voltage with respect to the internal inverter voltage.*
[16] *More details on the justification for this value are provided in Appendix B. 5° degrees has been chosen as an example only.*

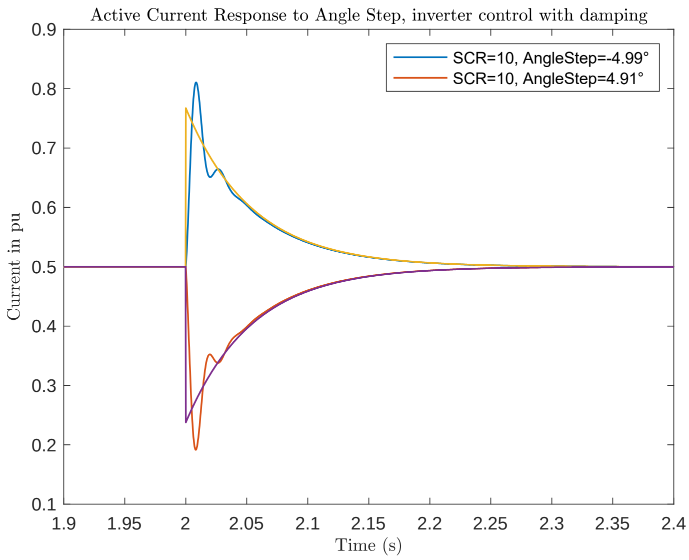



**Figure 4: Analytical calculation of phasor and instantaneous values of active current change with angle step by +- 5° at the grid voltage source. See also Annex B**

In practice, the variation in output current depends on the phase jump, but the proposed effective impedance serves as the proportionality coefficient between both magnitude and angle, and therefore, appears suitable for technical specification. It is worth noting that a similar approach was used to define the reactive current injection requirements applied to classical Grid-Following converter based generating units (GFL) as a function of the voltage drop.

Table 3 lists the recommended values depending on the definition of the DUT terminals to account for transformer physical impedance, considering typical values. For comparison, the range of reactive current gains 'k' currently used is included in the last column. It can be interpreted as equivalent to $1/x_{\mathrm{Eff}}$.

**Table 3: Proposed range of maximal values of the effective reactance $x_{Eff}$ (at 50 Hz) for different definitions of the DUT terminals or PPM connection point.**

| | $x_{\mathrm{Eff}}$ values (in pu) | | | Equivalent reactive current boosting gain k[17] |
|---|---|---|---|---|
| **Point of reference for evaluation** | **Min value** | **Default** | **Max value** | |
| Low voltage terminals (Unit level) | 0.17 | **0.25** | 0.27 | 5.9 .. 4 .. 3.7 |
| Medium voltage terminals (Unit or PPM level) | 0.25 | **0.33** | 0.35 | 4 .. **3** .. 2.8 |
| High voltage terminals (always at PPM level)[18] | 0.4 | **0.48** | 0.50 | 2.5 .. 2.1 .. 2 |

[17] *This column is added **for informative purposes** only to relate the xeff to requirement to existing connection codes. The reactive current gain k (di_Q/du_1) is equal to 1/x_eff.*
[18] *The internal controller reactance should not become negative. In the case of large collector systems, higher reactance values may be specified by the TSO.*

On the one hand, high effective impedance values may reduce the sensitivity of the active and reactive current injection regarding the voltage angle and amplitude variation provided by the GFM unit. On the other hand, too low effective impedance requirements may result in the high sensitivity of the PPM output to grid disturbances, especially in strong grid conditions, where this property is less essential. The objective of Table 3 is to propose a range of values that offer a reasonable trade-off between these two conflicting objectives: contribution to the system strength[19] and remaining in the linear domain of the control (within the unit capability limits).

Depending on local system needs, a higher contribution from the DUT may be required. In this case, *the relevant system operator in coordination with the TSO* could prescribe a lower threshold, typically in weak grid conditions. For instance, an effective impedance limited to 0.25 pu and an active current peak of 0.35 pu would be expected in the specific case considered in Figure 4 (a phase jump of -5° at the DUT).

Finally, the non-exhaustive requirement specified in Article Y(7)(b) can be expressed exhaustively as follows:

*Upon inception of voltage phase angle steps or voltage magnitude steps at the PoC and while the PPM capabilities and current limits are not exceeded, the instantaneous AC voltage characteristics of the internal Thevenin source of individual units shall remain constant and exhibit an effective impedance below the maximum values as define in Table 3*.

For the avoidance of doubt:

1. The use of a virtual (control) impedance in the control solution is neither prescribed nor forbidden as long as the performance-based requirements are achieved. The margin beyond physical impedances can be understood as a tolerance, a degree of freedom left to the OEM to optimise the overall performance of the solution.
2. This margin, in practice, also accounts for measurement processing and damping functions (see Appendix B).
3. According to equation (2), and as an indicative example, the same requirement defines the expected reactive current output following grid side voltage amplitude variations such that a voltage change of $\Delta u_{\mathrm{DUT}}$ = 5% at the DUT terminals would lead to a minimal reactive current of $\frac{\Delta u_{\mathrm{DUT}}}{x_{\mathrm{Eff}}} = 0.15$ pu for an effective reactance $x_{\mathrm{Eff}} = 0.33$.

Regarding the dynamic response for both voltage phase angle and voltage magnitude changes:

1. A peak active current change of between 50 and 70% of the (RMS-) value calculated based on (1) is expected as current response following a voltage angle step.
2. After a rise time (10% to 90%) of 10 ms, 90% of the expected <u>instantaneous</u> value of the active / reactive current or power variation shall be reached following a grid side disturbance.
3. The decay time constant of the active power following a grid side disturbance does depend on the effective reactance, the grid reactance and internal control settings. As demonstrated

[19] *Commonly referred to by the short circuit power as static definition*

in Appendix B, it can be estimated by equation (21) In the case illustrated in Figure 4, the decay time constant is estimated to 0.016 s. A 33% mismatch from the expected value may be deemed acceptable as error between measured and simulated data.

4. In the event a steady state value is expected (i.e., for voltage amplitude changes) following the disturbance, a settling time (defined as the last instant the measured value enters into a tolerance band of +-5 %[20] of the expected value) of 60 ms is expected.

A damping factor of at least 5% of the electromechanical (low frequency) active power oscillations is recommended.

The following diagram presents an indicative illustration of the definition of rise time as duration between 10% and 90% change from before the event to the new steady state value. The settling time is defined as the time when the signals enter a tolerance band around the steady state value for the last time without exiting any more.

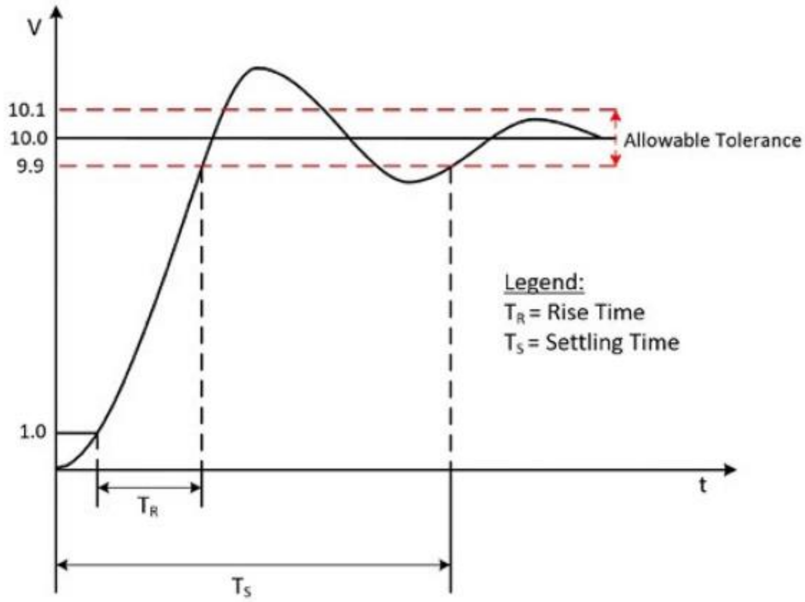



Figure 5: Definition of rise time and settling time

### 2.3.2 On the synthetic[21] inertia contribution within capability limits

This section details the non-exhaustive requirement as specified in Article 20 for type B:

*'5. With regard to grid forming capability type B power park modules shall fulfil the following additional requirements in relation to grid forming capability:*

[20] *Higher tolerances needed for DFIG (-10% + 20% in some national requirements)*

[21] *'synthetic inertia' means a prescribed electrical dynamic performance provided by a PPM or an HVDC system at its connection point with aim of emulating the equivalent dynamic effect of the inertia provided by a synchronous power-generating module (Article 2 RfG2)*

*(a) The relevant, TSO in coordination with the relevant system operator, shall specify the contribution to synthetic inertia. The power park module shall be capable of contributing to limiting the transient frequency deviation under high frequency conditions. Additionally, the electricity storage module shall be capable of contributing to limiting the transient frequency deviation under low frequency conditions.'*

**The non-exhaustive requirement specified in Article 21 for type C and D is:**

*'5. With regard to grid forming capability type C power park modules shall fulfil the following additional requirements in relation to grid forming capability:*

*(a) The relevant TSO, in coordination with the relevant system operator, shall specify the contribution to synthetic inertia. The power park module shall be capable of contributing to limiting the transient frequency deviation under high and low frequency conditions.*

*(b) The relevant TSO may require the provision of additional energy beyond the inherent energy storage in coordination with the relevant.'*

The change of active power due to a frequency change can be described by the ramp-up time $T_{\mathrm{R,PPM}}$.[22]

$$T_{\mathrm{R,PPM}} = \frac{\left(\frac{\Delta P}{P_{\mathrm{Rated}}}\right)}{\left(\frac{d(f/f_{\mathrm{Rated}}))}{dt}\right)} = \frac{\Delta p_{pu}}{\left(\frac{df_{pu}}{dt}\right)} \tag{5}$$

The ramp-up time $T_{\mathrm{R,PPM}}$ (in s), equivalent to 2H, can be used as a metric to describe the active power change regarding to frequency changes. It is used to relate the energy which is exchanged by the PPM at its connection points with the AC network to its rated power (Energy/Rated Power) while the grid frequency changes.

[22] *$T_{R,DUT}$ is equivalent to the ramp-up time constant $T_{R,SG}$ of a conventional power plant,  of the control of the DUTs, whose effect on the inertia of the internal voltage angle of the inverter-based GFM unit corresponds to the effect of the start-up time constant of a conventional power plant. $T_{R,SG}$ is the time required for a conventional power plant with the rated power $P_{rated}$ to accelerate the turbine set (turbine and synchronous machine, pole pair number p) having the moment of inertia $J_{SG}$ from standstill to rated speed or rated angular frequency $\omega_0$. The start-up time constant $T_{R,SG}$ is a measure of the inertia moment $J_{SG}$ of the generating unit relative to rated power and rated frequency and it is defined as $T_{R,SG} = \frac{J_{SG,}\cdot\omega_0^2}{P_{rated}\,p^2}$*

Table 4 lists recommended values for the ramp-up time $T_{\mathrm{R,PPM}}$

Table 4: Range of values of the ramp-up time $T_{R,PPM}$

| Values of ramp-up time $T_{\mathrm{R,PPM}}$ (in s) | | |
|---|---|---|
| Min value | Default | Max value |
| 0 | **10** | 25 |

While the frequency changes, a PPM is expected to provide an additional active power $\Delta P$ according to

$$\Delta P = T_{\mathrm{R,PPM}} \cdot \frac{df/f_{\mathrm{Rated}}}{dt} \cdot P_{\mathrm{Rated}} \tag{6}$$

**As example:** a 2 Hz/s df/dt and $T_{\mathrm{R,PPM}}$ of 25 leads to a 1 pu active power variation from steady state

$$\Delta P = 25 \cdot \frac{2\ Hz/s}{50\ Hz} \cdot 1 = 1$$

Assuming a constant df/dt, the energy needed can be calculated as

$$E = T_{\mathrm{R,PPM}} \cdot \frac{df/f_{\mathrm{Rated}}}{dt} \cdot P_{\mathrm{Rated}} \cdot \Delta t \tag{7}$$

with $\Delta t$ as time window of the RoCoF evaluation. Assuming frequency limits of **47.5 Hz or 52.5 Hz (given in NC RfG),** the term $\frac{df/f_{\mathrm{Rated}}}{dt} \cdot t$ is 0.05, independently of the rate of frequency change. The energy a PPM needs to provide is therefore:

$$E = T_{\mathrm{R,PPM}} \cdot 0.05 \cdot P_{\mathrm{Rated}} \tag{8}$$

Finally, the non-exhaustive requirement specified in Article 20(5)(a) and Article 21(5)(a) and (b) can be expressed exhaustively as follows:

*The PPM **shall** be capable of contributing to limiting the transient frequency deviation under high frequency conditions **by modulating active power / active current**. In addition, the electricity storage module shall be capable of contributing to limiting the transient frequency deviation under low frequency conditions.*

For the avoidance of doubt:

1. The relevant TSO, in coordination with the relevant system operator (RSO) may define expected, or maximum and minimum values of the ramp-up time $T_{\mathrm{R,PPM}}$ consistent with Table 4 specified range.
2. PPM without intrinsic storage are required to provide negative power changes only.

3. The active power change at the terminals of the PPM may be provided by all or a limited number of DUT, as long as the performance criteria at the terminals of the PPM are met.
4. If the concept of a distributed virtual power plant (DVPP[23]) is accepted by a TSO, in coordination with the relevant system operator, the location of the provision of the inertia contribution may differ from the location of the PPM terminals.

With regard to the dynamic response to frequency excursions:

1. After a rise time **(10% to 90%) of 100 ms,** 90% of the expected positive sequence active current or power variation shall be reached following a grid side disturbance.

### 2.3.3 When reaching current capability limit

This section details the non-exhaustive requirement as specified in Article Y(5)(ii):

*'(ii) Where current limitation is necessary, the relevant system operator in coordination with the relevant TSO may specify additional requirements regarding contribution of active and reactive power at the point of connection.'*

In the event the total current limits are reached, voltage source behaviour (increase of the share of active current if the grid voltage angle decreases and increase of the share of capacitive reactive current if the voltage magnitude decreases and vice versa) needs to be maintained.

**For the avoidance of doubt:**

- Active or reactive current prioritization is not fixed by the requirement. It is dictated by voltage angle and/or magnitude changes.
- The response to voltage angle and voltage amplitude changes is supposed to be equivalent to a voltage source (or a synchronous generator), with the difference that the current magnitude is limited.
- In the case of a voltage disturbance without relevant voltage angle changes a predominantly reactive current response is expected.

To achieve this goal, the current magnitude should be limited without imposing a hard limit on the underlying reactive and active current controllers. Consequently, in the event of a further voltage drop, the ratio of reactive to active current moves toward reactive currents (more reactive current on the expense of active current). If the voltage angle changes, the active current contribution is increased.

*[23] Distributed Virtual Power Plant. Describes locally distributed producers, storage and possibly consumers with centralised control, behaving like a single power plant.*

Using the equivalent DUT representation as shown in Figure 2, this can be achieved by increasing the value of $x_{\mathrm{Eff}}$ by modifying $\underline{z}_{\mathrm{Control}}$. while maintaining the internal voltage $\underline{u}_{\mathrm{Inv}}$constant to limit the currents within the hardware limits thereby modifying, positive sequence active ($i_{\mathrm{P,DUT}}$) and reactive ($i_{\mathrm{Q,DUT}}$) current and negative sequence reactive current $i_{\mathrm{Q,neg}}$ in a comparable manner (current magnitude limitation).

In the event current limits are reached, the total apparent current (consisting of active and reactive positive sequence and negative sequence reactive current shall be as close as possible to the rated current and shall not be less than 95% of the rated current.

1. The amplitude of the inverter internal voltage $\underline{u}_{\mathrm{Inv}}$ is assumed to be constant during grid events. The voltage angle $\varphi_{U_{\mathrm{Inv}}}$ is only to be modified to improve damping (see also Annex A) or in the case of voltage angle changes in the grid.
2. The negative sequence effective impedance should be equal to the positive sequence effective impedance $x_{\mathrm{Eff}}$ [24] ,but shall be within the range given by Table 3 while current limits are not reached. The negative sequence active current $i_{\mathrm{P,neg}}$ should be kept zero. If specified by the relevant TSO, in coordination with the RSO, and for the specific case of small unbalances with a negative sequence voltage amplitude of $u_{\mathrm{DUT,neg}} < 3\%$ the negative sequence reactive current $i_{\mathrm{Q,neg}}$ is allowed to be zero. The RSO may specify that no negative sequence reactive current is injected, which would be the equivalent to setting the negative sequence impedance to infinite. Wind turbines with a doubly fed generator system may have a different negative sequence impedance.
3. In the event the current limits of the generating unit (apparent current limit) are reached, the generating unit should still contribute to stabilising the grid while limiting the generating unit currents flowing to the grid. This can be achieved by increasing the effective impedance value $x_{\mathrm{Eff}}$ while keeping the inverter voltage $\underline{u}_{\mathrm{Inv}}$ of the equivalent DUT representation constant. The actual currents may deviate from this requirement, as specified by the relevant TSO but not more than 20 ms (one cycle) once a current limit is reached.
4. A DUT without storage may not be required to absorb active power. In the case of voltage angle jumps, the DUT is not required to reduce active power below the minimum power limit of the DUT.
5. For voltage variations within the range 0.85 – 1.1 pu (as defined in the NC RfG, and if the current limit of the DUT is not reached, the active current reference $i_{\mathrm{P_{Ref}}}$ is commonly calculated based on the voltage as

$$i_{\mathrm{P_{Ref}}} = \frac{p_{\mathrm{Ref}}}{u_{\mathrm{DUT}}} \tag{9}$$

[24] *For wind turbines with a doubly fed generator system (DFIG), the negative sequence effective reactance may be modified differently to form the effective positive sequence reactance if this can avoid additional hardware costs.*

Modifying of (1), the active current does not have to remain constant but may be increased until the unit current limit has been reached by modifying the inverter voltage angle.

6. After the fault clearance and both during and while leaving a current limitation mode, the DUT shall counteract any possible overvoltage at the connection point by providing inherently the relevant amount of reactive current.

The active and reactive currents using current magnitude limitation as a function of voltage are shown in Figure 6. The corresponding values of effective reactance $x_{\mathrm{Eff}}$ and inverter internal voltage angle are shown in Figure 7.

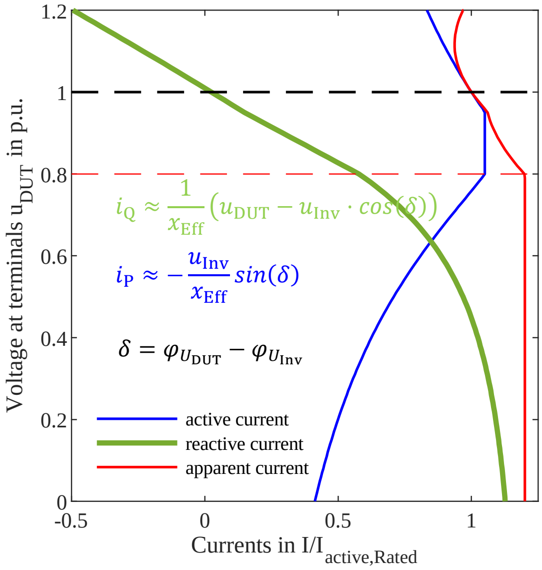



Figure 6: Active and reactive current of an inverter with current magnitude limitation.

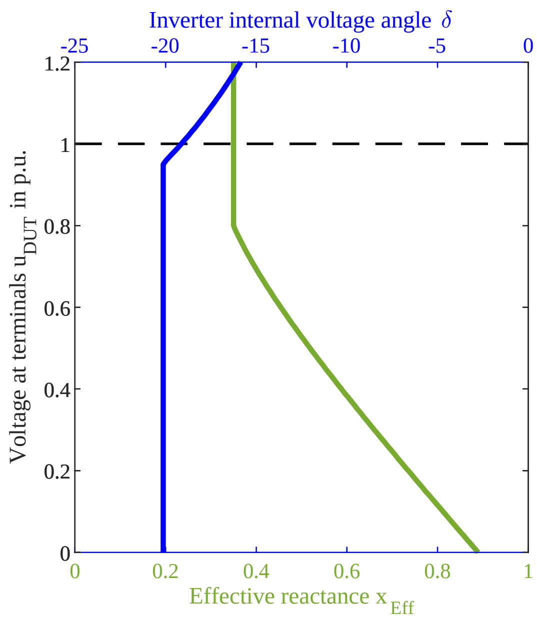



Figure 7: Corresponding values of voltage angle $\delta$ (green line), and effective impedance $x_{Eff}$ (blue line) for an inverter with current magnitude limitation. The internal voltage of the inverter remains constant.

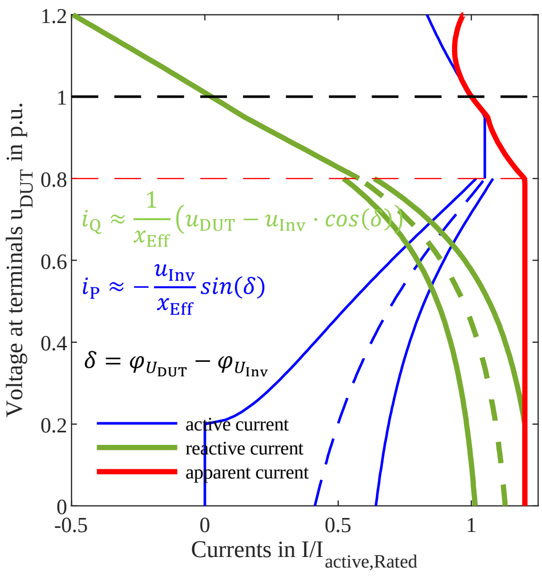



**Figure 8: Active and reactive current of an inverter with current magnitude limitation, including an allowed band for the current reference of 90% of the theoretical value.**

The requirements on current limitation (by limiting the current magnitude, not active or reactive currents separately) are discussed in Appendix B.

Regarding the dynamic response for both voltage phase angle and voltage magnitude changes when reaching the current capability limit:

1. The expected instantaneous reactive current in the case of a current limitation shall be within +-10% of the value calculated as shown in Figure 8.
2. After a rise time (10% to 90%) of which shall not be more than10ms, not less than 90% of the expected instantaneous value of the active / reactive current or power variation shall be reached following a grid side disturbance.
3. In the event a steady state value is expected following the disturbance, a settling time (defined as the last instant the measured or simulated value enters into a tolerance band of +-10 % of the expected value) of 60 ms is expected.

# 3 Description of the recommended test cases

First, Section 3.1 describes the proposed benchmark. Subsequently, Section 3.2 lists the considered events. Section 3.3 summarises the minimal cases necessary to verify GFM capability in the form of a test matrix.

## 3.1 Grid topologies

The proposed test bench is presented in Figure 9. As previously mentioned, the DUT terminals might be defined at the LV or MV side of the transformer. $u_G$ is a controllable voltage source with variable amplitude, phase and frequency. In addition, various switches allow for grid side topology modifications. In particular:

1. $S_{SCR}$ allows the grid connection series impedance to be changed.
2. $S_{L,SS}$ and $S_L$ introduce a load step at the connection point of the DUT.
3. Closing Ssc simulates a short-circuit at the connection point of the DUT.
4. Opening $S_G$ leads to islanding conditions.

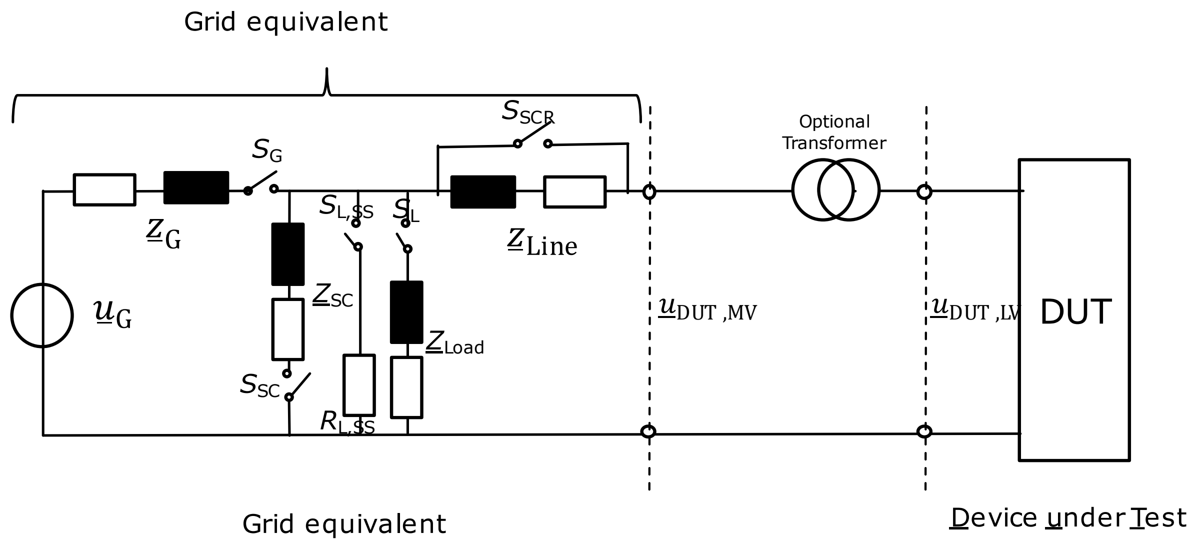



Figure 9. Test setup for evaluating the DUT performance.

## 3.2 Simulated events

More precisely, the test setup is intended to simulate the following events:

1. Voltage phase angle step by modifying $\underline{u}_G$;
2. Small symmetrical (three-phase) voltage magnitude step by modifying $\underline{u}_G$;

3. Short Circuit Ratio (SCR[25]) step by switching $S_{SCR}$;
4. Loss of last synchronous generator by opening $S_G$ while $S_L$ is closed;
5. RoCoF with increasing frequency up to 51 Hz triggered by modifying $\underline{u}_G$;
6. Large symmetrical (three-phase) voltage magnitude step by modifying $\underline{u}_G$ or closing $S_{L,SS}$[26];
7. Asymmetrical (phase to phase) voltage step;
8. Voltage phase angle step and a frequency drop down to 47,5 Hz with max RoCoF as it appears in NC RfG, triggered by modifying $\underline{u}_G$;
9. Voltage phase angle step and a max RoCoF an increasing frequency up to 52.5Hz with a max RoCoF as it appears in NC RfG, triggered by modifying $\underline{u}_G$.

For events 1 - 5 is assumed that no current limits are reached, while for 6 - 9 the DUT may operate at its current limit. The described test setup is supposed to reproduce the results of grid disturbances by activating the switches, except for the frequency variation and very large angle steps. In these cases, a variation of the grid voltage $\underline{u}_G$ is necessary.

## 3.3 Recommended test matrix

- Grid side parameters ($\underline{z}_G$) may vary to consider strong/weak/very weak grid scenarios.
- Grid side infinite bus voltage ($\underline{u}_G$) must be adapted according to the other system parameters to reach the desired OP at the DUT terminals.
- The disturbance applied at the connection point of the DUT must also be adapted to reach the desired disturbance at the DUT terminals.

A practical method of organising the data related to various test cases is presented in Table 5. For illustrative purposes it has been filled with the typical values used for compliance testing in grid connection processes which are considered relevant for assessing GFM capability.

Note: the objective of this table is to limit the number of simulations while simultaneously a broad range of operating conditions should be analysed to verify the performance and the compliance to requirements. Table 5 shall be considered as the starting point for describing these tests. Below the table, the motivation for each test case should be explained.

[25] *Ratio of grid short circuit power to PPM power. It can be calculated by using the reciprocal of the grid equivalent impedance in per unit (with respect to PPM power),* $(SCR = 1/z_G)$

[26] *It is recommended that this is followed by a change of network impedance (including phase angle jump) to account for breaker opening*

Table 5: Test cases

| ID | Benchmark | | Operating conditions/parameters | | |
|---|---|---|---|---|---|
| | Grid topology | Test | Operating Point | Event (at DUT MV terminals) | Comment |
| 1.1 | A | Phase jump, option (a), angle change at $\underline{u}_G$ | P=1, Q=0, U=1 pu | + 5° | Reducing active current should be possible at maximal power output |
| 1.2 | | | P=1, Q=0, U=1 pu | - 5° | At rated active power output, no active current response is expected if no inherent storage is available |
| 1.3 | | | P=1, Q=0, U=1 pu | +10° | |
| 1.3 | | | P=0.5, Q=0, U=1 pu | - 10° | Active current response is expected up to the inherent energy storage capability. Limitation should be justified. |
| 1.4 | | | P=1, Q=0, U=1 pu | | Withstand capability. Similar to FRT behaviour. Capability limits are probably reached. |

## Motivation:

- Test 1.1: The underlying assumption is the loss of XX% (25% used here) of either generation or load in the system. The initial response of the DUT should correspond to this active power change in the grid. See also Appendix B.
- Test 1.2: In the event of reaching the current limitation, stable functioning, and seamless transition back to voltage source mode is expected (see legal text proposal, c.iii).
- Test 1.3: In event of requested energy beyond intrinsic capabilities (asymmetrical response to phase jumps), stable functioning and disturbance rejection is expected.

# 4 Verifying compliance with the proposed exhaustive requirements

In this section, we detail a proposal[27] of the tests listed in Section 3.2, as a starting point. Each subsection should include the proposed formulation of the requirement (4.x.1), the compliance criteria applicable for the designed test (4.x.2), an illustration based on simulation results (4.x.3), and finally, a discussion paragraph highlighting the key aspects requiring careful consideration, notably how specific compliance criteria might depend on test settings.

Simulations are performed as an illustration example using a GFM controller described in Appendix A.

This is a proposal for how to verify the requirements at the terminals of the DUT based on simulations. The document will provide an illustration of compliance using a generic control.

## 4.1 Voltage phase angle step test

This section focuses on the DUT response following voltage phase variations on the grid. The expected grid forming DUT response to voltage phase angle changes is defined by the equivalent controller representation in Section 2.1. The relevance of the voltage phase jump test to capture the response of a voltage source to a load step is discussed in Appendix B, section 7.1.

For testing the compliance of the DUT response to voltage angle changes, a test setup as shown in Figure 9 is used.

The change in voltage phase angle can be induced by:

a) A change of the grid voltage phase angle of $\underline{u}_{\mathrm{G}}$ , or
b) By using a device that modifies grid impedance and/or voltage angle of $\underline{u}_{\mathrm{DUT}}$ as shown in Figure 9, or
c) By inserting a control signal that modifies the phase voltage angle of $\underline{u}_{\mathrm{Inv}}$.

As indicated in Section 3.3, we recommend the application of $\pm$5° at the DUT terminal considering a SCR of 10 (strong grid scenario) and two different OP. In practice, relevant TSOs may define compliance criteria on a project-specific basis, depending on the minimal and maximal short-circuit levels (SCL) at specific locations.

[27] *Disclaimer: The content of this chapter aims to give recommendations for the compliance schemes of generating units. For transmission connected PPMs a relevant discussion should take place separately*

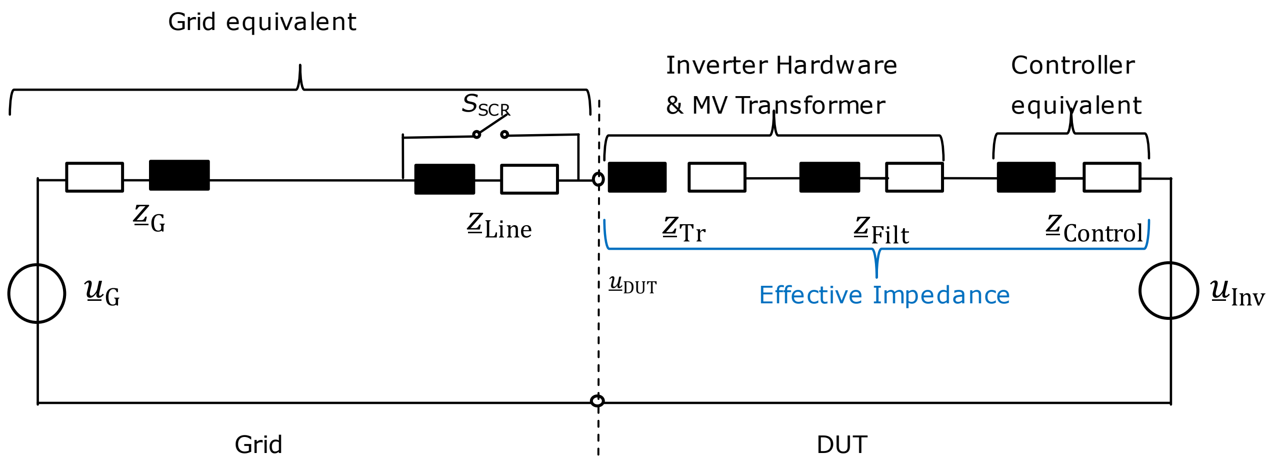



Figure 10. Simple grid equivalent consisting of a grid equivalent, unit MV transformer, inverter filter and control impedance for testing voltage angle steps.

## 4.2 Small symmetrical voltage magnitude step

This section focuses on the DUT response following voltage amplitude variations on the grid, which can be the result of load changes, switching operations or grid faults. A voltage amplitude change is considered to be small if no current limiting functions of the DUT become activated.

For testing the compliance of the DUT response to voltage amplitude changes, an equivalent representation as shown in Figure 11 is recommended. Without the impedance $\underline{Z}_{Line}$ the short circuit power during a fault increases significantly, which is unlikely in real grid faults.

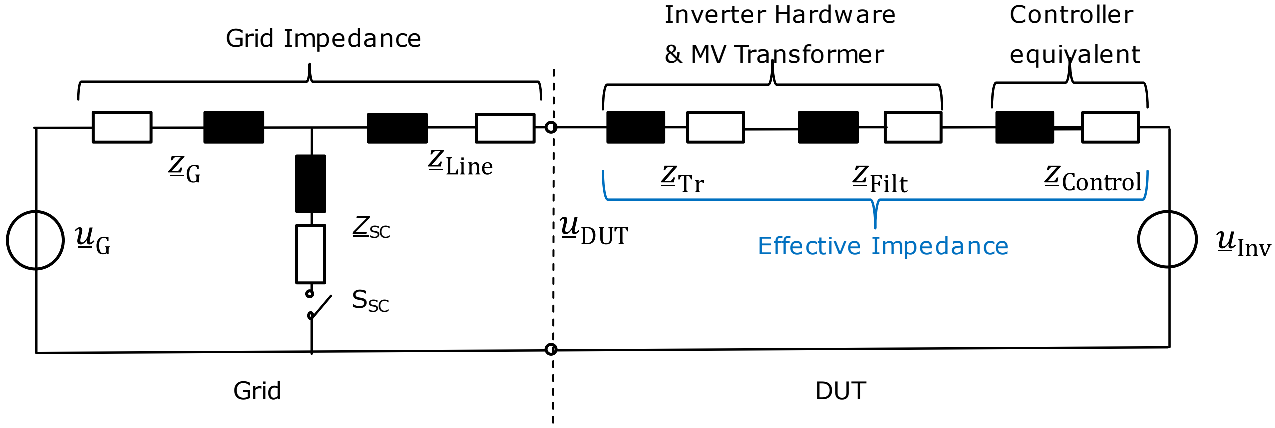



Figure 11: Simple grid equivalent consisting of a grid equivalent, unit MV transformer, inverter filter and control impedance for testing voltage amplitude steps in simulation or measurement.

The change in voltage amplitude can be induced by

a) A change of the grid voltage amplitude by $\Delta u_G$ , or
b) By a using device that modifies the voltage amplitude $\Delta u_{DUT}$ as shown in Figure 11, or

c) By inserting a bypass signal to the controller that changes the inverter voltage by $\Delta u_{Inv}$.

For compliance testing, the following quantities are evaluated and compared to calculated reference values:

1. The reactive current before and after the voltage change;
2. The damping of the reactive current oscillation following the voltage change.

## 4.3 Short circuit ratio step

For testing the compliance of the DUT to changes in the grid impedance (change of grid short circuit ratio), a test setup as shown in Figure 10 can be used.

The change in grid SCR can be induced by opening switch $S_{SCR}$.

For compliance testing, the following quantities are evaluated:

1. Damping of active and reactive power/ current oscillations;
2. Voltage excursion ;
3. Damping of voltage oscillations.

## 4.4 Loss of last synchronous generator

This section focuses on the DUT response following the loss of the last synchronous generator, which is one of the key tests for evaluating capability of a GFM DUT to operate a grid operated by inverter-based resources only.

For testing the compliance of the DUT response to the loss of the last synchronous generator, a test setup as shown in Figure 12 - or an active load with constant power or constant current - can be used.

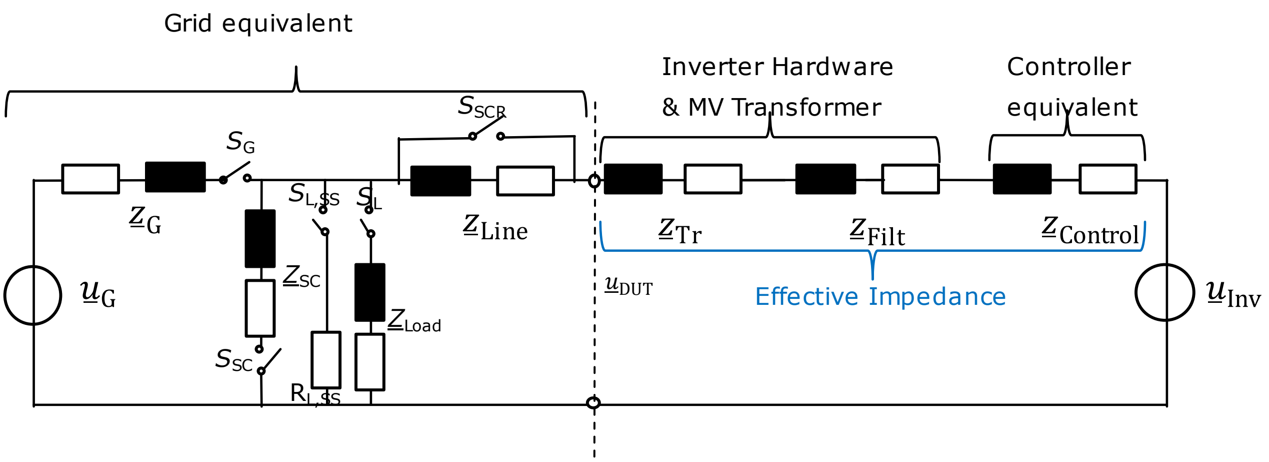



**Figure 12: Simulation of loss of last synchronous generator.**

The loss of the last synchronous generator requires the DUT to stabilise frequency and voltage.

The loss of the last synchronous generator can be induced by opening switch $S_G$ in Figure 12.

For compliance testing, the following quantities are evaluated:

1. Frequency;
2. Voltage.

The following test procedure is recommended:

1. Starting from a maximum active power injection of p = 0.75…1 pu the switch $S_G$ is opened while switch $S_L$ is closed, so the DUT exclusively supplies the adjustable load.
   The tests according to Table 5 are performed with an active power change of up to 50 % and reactive power values of -0.41, 0 and -0.41. The test is considered successful if:

   a) A steady state of frequency is achieved without protection tripping;
   b) The frequency transient settles to the steady-state value with a damping factor of D > 0.05;
   c) There are no transient undervoltages and overvoltages < 0.9 pu and > 1.1 pu.
2. Starting from a steady operation with $S_G$ open, the load (power factor = 1) is increased by closing switch $S_{L,SS}$ and re-opening it once a steady state operation has been reached.
   These tests are considered successful if the frequency transient settles to the steady-state value with a damping factor of D > 0.05.

3. By activating $S_{SC}$ for 150 ms and the appropriate parametrisation of $Z_{SC}$ or by using an active load, it should be evaluated if the DUT is capable of providing 60%, 80% and 100% $I_{Reactive}$ / $I_{Active,Rated}$.

## 4.5 RoCoF with increasing

This section focuses on the DUT response to a frequency increase, which is commonly the result of loss of load.

For testing the compliance of the DUT to frequency increase, a test setup as shown in Figure 2 can be used.

The change in grid frequency can be induced by:

a) A change of the grid frequency by modifying $\underline{u}_{\mathrm{G}}$, or
b) By inserting a bypass signal to the controller that changes the inverter frequency reference.

For compliance testing, the following quantities are evaluated and compared to calculated reference values:

1. The active power / current before and during the frequency change;
2. The rise time and damping of the active power following the frequency change.

The following tests are recommended:

a) Frequency increase by +2 Hz for 0.75 s;
b) Frequency increase by +0.5 Hz for 3 s.

## 4.6 Large symmetrical voltage amplitude step test

This section focuses on the DUT response following voltage amplitude variations on the grid, which can be the result of load changes, switching operations or grid faults. In this document a voltage amplitude change is considered to be large if the current limiting functions of the DUT become activated.

For testing the compliance of the DUT response to voltage amplitude changes, a test setup as shown in Figure 11 can be used.

The change in voltage amplitude can be induced by

a) A change of the grid voltage $\underline{u}_{\mathrm{G}}$ , or
b) By using device that modifies the voltage amplitude as shown in Figure 11.

For compliance testing, the following quantities are evaluated and compared to calculated reference values:

1. The reactive current before and during the voltage change / fault;
2. The damping of the reactive current oscillation following the voltage change;
3. The post-fault voltage excursion following voltage recovery.

## 4.7 Large asymmetrical (unbalanced) voltage amplitude step test

For testing the compliance of the DUT response to large asymmetrical voltage amplitude changes, an equivalent representation as shown in Figure 11 with the option to short-circuit 2 instead of three phases is recommended.

The unbalanced fault can be induced by

a) Adding a negative sequence voltage component to the grid voltage $\mathrm{u}_{G}$ , or
b) Using device that modifies the voltage amplitude $\Delta\mathrm{u}_{\mathrm{DUT}}$ by causing an unbalance fault.

For compliance testing, the following quantities are evaluated and compared to calculated reference values:

1. The positive sequence reactive current before and after the voltage change;
2. The negative sequence reactive current before and after the voltage change;
3. The post-fault voltage excursion following voltage recovery.

## 4.8 RoCof including voltage angle step changes

This section focuses on the DUT response to a voltage angle step followed by a frequency change, which is commonly the result of loss of load.

For testing the compliance of the DUT to a voltage angle step followed by a frequency change, a test setup as shown in Figure 2 can be used.

The voltage angle step followed by a frequency change can be induced by:

a) A change of the grid voltage phase angle and grid frequency by modifying $\underline{u}_{\mathrm{G}}$, or
b) By inserting bypass signals to the controller that changes the inverter voltage phase angle and frequency reference.

For compliance testing, the following quantities are evaluated and compared to calculated reference values:

1. The active power / current before and during the frequency change;
2. The rise time and damping of the active power following the frequency change.

The following tests are recommended with different parameters:

a) A voltage phase angle step followed by a frequency change. The parameters depend on the ramp-up time $T_{\mathrm{R,DUT}}$ of the inverter.

# 5 Conclusions

The goal of this report is to deliver comprehensive recommendations for defining GFM requirements for PPMs, with a focus on maintaining neutrality regarding any particular controller's implementation. A general concept for defining GFM capabilities based on a simple voltage source model has been used to derive exhaustive parameters for GFM capability requirements.

The results of the analytical solutions have been supported by time-domain simulations using a generic GFM model. The task force gives examples of how the requirement can fulfilled at the level of the DUT by using a concept of voltage source behind an effective impedance, but without requiring any specific controller design.

The document is intended to be amended by specific test cases for the different types of grid faults. The results of simulations based on these cases should be added to each section in section 4.

The document does not define how the performance may be assessed[28].

[28] The Relevant TSO, in coordination with the RSO, may decide for each test case, which of the following methods for assessing performance may be applied.

a) Field measurement of a single DUT (unit), if necessary including plant controller;
b) Test bench measurement of a single DUT (unit), if necessary, including plant controller;
c) Test bench measurement of DUT inverter;
d) Test bench measurement of DUT inverter controller;
e) Simulations with (relevant parts of the) original inverter controller software using 3 phase instantaneous values (‘EMT’);
f) Simulations with model from manufacturer using 3 phase instantaneous values (‘EMT’);
g) Simulations with (relevant parts of the) original inverter controller software using a phasor representation of positive and negative sequence (‘RMS’);
h) Simulations with model from manufacturer using a phasor representation of positive and negative sequence (‘RMS’);
i) Simulations with standardised (‘generic’) model and manufacturer-specific parametrisation using a phasor representation of positive and negative sequence (‘RMS’).

# 6 Appendix A: Grid forming control approach

## 6.1 General Structure

At present a large number of possible GFM control implementations are being discussed in the literature. Two relevant approaches are controls systems based on a virtual synchronous machine (VSM) model and control systems based on the description of droops. The implementation used here is based on droop control and is described in [Klaes et al., 2020][29] and [Klaes et al., 2024][30]. Parameters for an equivalent implementation as a VSM are also provided.

A relevant need of any GFM control is sufficient damping. The damping method used (phase feed-forward damping) is well known and assumed to be free of patents.

The basic control structure of the GFM control implementation used is shown in Figure 13.

The error signal between the active power set point and the actual measured filtered active power generates via the gain $k_f$ of the frequency droop an add-on frequency Δf, changing the voltage angle until the error is zero under stationary conditions. The calculated power is filtered with a first order low pass filter to give a good decoupling. To increase damping the basic frequency droop control in expanded by an additional direct path, that acts as a feed forward term from the power error Δp directly on the voltage phase Φinv (the circuit is highlighted in blue) via the phase feed forward damping coefficient k_φ. This is generally identical to a differential action of the power error onto the frequency.

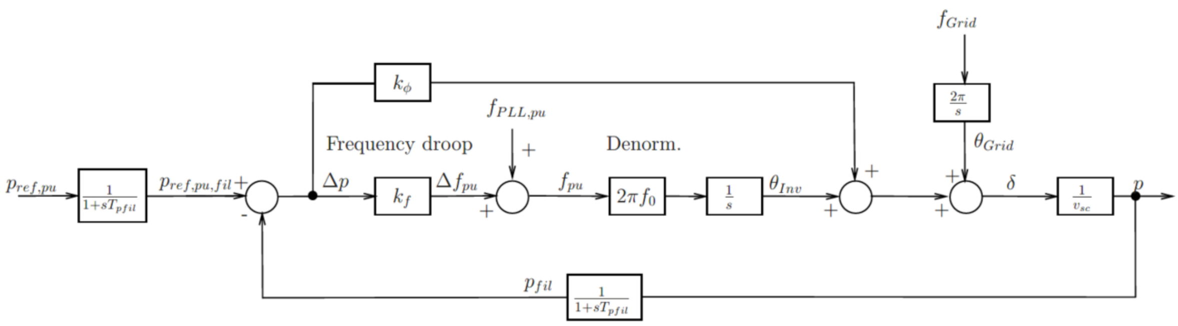



Figure 13 Reference implementation of a GFM active power control loop.

The correspondence between droop based and VSM-based GFM control is shown in Figure 14

[29] Klaes, Norbert, Nico Goldschmidt, and Jens Fortmann. 2020. "Voltage Fed Control of Distributed Power Generation Inverters with Inherent Service to Grid Stability" Energies 13, no. 10: 2579. https://doi.org/10.3390/en13102579

[30] Klaes, Norbert and Jens Fortmann. 2024. "Immunity of grid forming control without energy storage to transient changes of grid frequency and phase" IEEE Open Access Journal of Power and Energy - Manuscript ID OAJPE-00020-2024

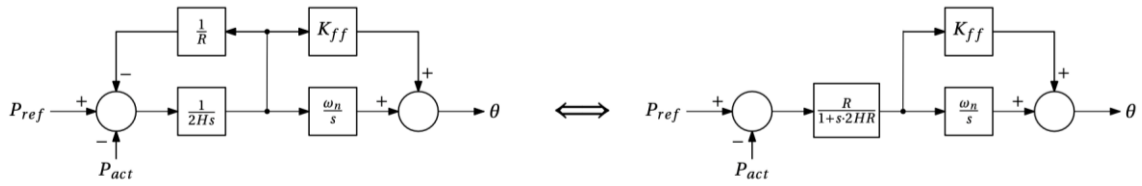


Figure 14 Corresponding VSM and droop based GFM control implementations.

The following correspondence exists between a VSM and a droop based implementation if phase feed forward damping is applied:

$$T_{\mathrm{pfil}} = 2H \cdot R \quad (10)$$

$$\mathrm{k_f} = R \quad (11)$$

$$k_{\Phi} = K_{\mathrm{ff}} \cdot R \quad (12)$$

with $k_{\Phi}$ as the phase feed forward damping coefficient, $K_{\mathrm{ff}}$ as the phase feed forward gain, $k_{\mathrm{f}}$ as frequency droop coefficient, $T_{\mathrm{pfil}}$ as active power filter time constant, $R$ as damping coefficient.

The resulting control structure provides good GFM performance under the assumptions, that there are no limitations in current and power capability. To prevent overloading and overcurrent some additions have to be used as shown in Figure 15.

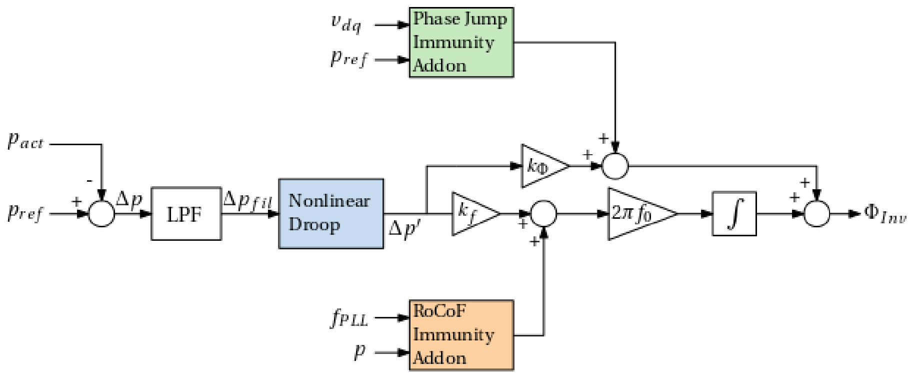



Figure 15 Additions to basic control structure for protection against overload conditions during grid.

## 6.2 Phase jump immunity add-on

GFM control requires a fast active power response of the unit to voltage angle changes. But some units (such as wind power of photovoltaic plants) may not be able to increase the active power output, because its primary power source operates at its optimal (maximum) power level. Another reason may be that an inverter is operating at its current limits already. In both cases, an active power increase must be prevented. An ideal grid following would avoid an active power increase by following the phase jump of the grid completely. If the control can keep the difference angle constant, then the active power remains constant. For this purpose, the quantities of the PLL can be used.

It is proposed to feed forward this detected angle change onto the phase of the inverter output voltage in the case of negative phase jumps to avoid an increase of active power. The details of proposed addition are shown in Figure 16.

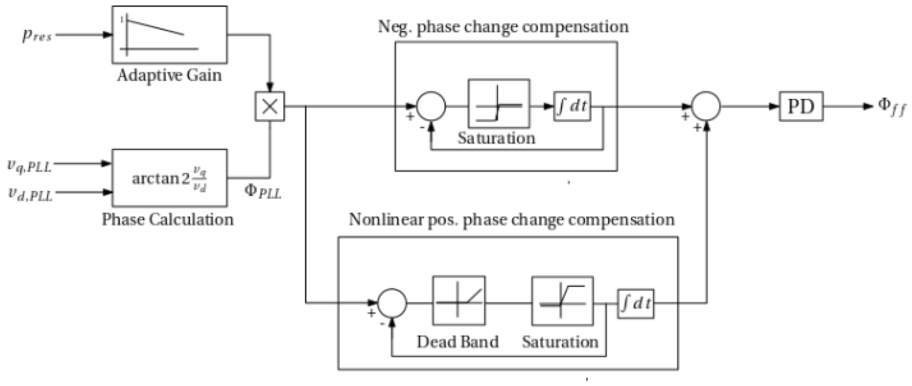



Figure 16 Phase jump immunity add-on.

An asymmetric ramp generator within the negative phase change compensation structure is used to allow for fast inverter phase changes in the case of negative phase changes but prohibit fast changes in the case of positive phase changes. The rates have been limited to -500rad/s and 0.01rad/s for negative and positive phase changes respectively. To counteract the reaction time of the PLL the phase change is further processed by a PD transfer element with unity d.c. gain.

In the event there is an active power reserve available, the phase change detected by the PLL is reduced by a regressive gain depending on the available active power reserve. In addition, a large positive phase changes the nonlinear negative phase change compensation structure, which will compensate partially for the positive angle jump to prevent excessive active power reduction and keep the active power positive.

## 6.3 RoCof immunity add-on

In the event of a quasi-stationary unbalance between the power consumption and the set-points of power generation a frequency deviation occurs according to the implemented p-f-characteristic. Especially when using small droop coefficients, such deviations of grid frequency could easily lead to excessive active power changes, even leading to negative power values.

To prevent this behaviour, it is proposed to make the p-f-curve nonlinear. In [Klaes et al., 2020][29], it has been shown that the optimal gain of the phase feed forward path is proportional to the droop. Therefore, the nonlinear behaviour has been realised by recalculating the power difference $\Delta$p by a nonlinear function to a new quantity $\Delta$p’, see Figure 15, that is progressively lower than the true difference $\Delta$p resulting in a lower frequency response especially at high power errors.

The non-linearity can ensure that the power corresponding to the frequency remains positive also at the maximum limit of grid frequency. At reduced reference active power, the factor K has to be adjusted to higher values to avoid negative power values. A suitable function K=f(p_{ref}) can be stored in a one-dimensional table.

Under-frequency events would lead to an increase of active power due to the p-f-curve. However, an increase of power is not available if the renewable power source is already operating at its maximum available active power, i.e., without any derating, and has no additional energy storage. The structure shownwill prevent overload using a fast feed forward control at negative rates of change of frequency (RoCoF), while the GFM behaviour is retained at positive RoCoF values or at negative values, if there is an active power reserve available.

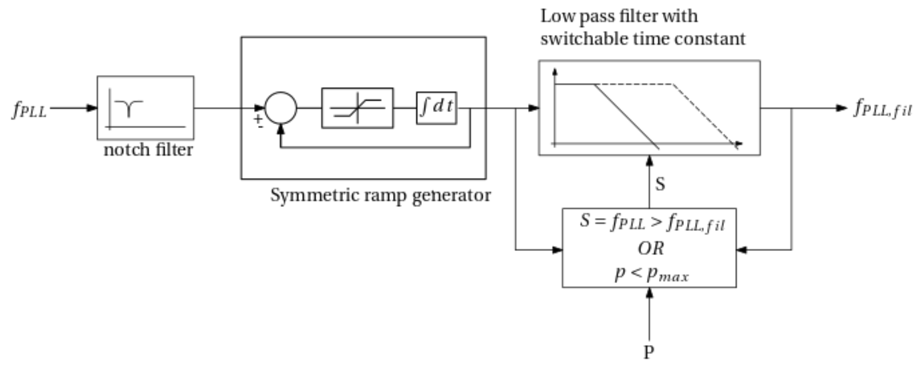



**Figure 17 RoCoF immunity add-on.**

The frequency detected by the PLL is first cleaned from line frequent components using a notch filter (Q=1). The notch filtered frequency is further processed via of a symmetric ramp generator, which cleans the frequency signal from transients during phase jumps by limiting the frequency change to a maximum absolute. The function of this ramp generator is like a nonlinear glitch filter. The result of the ramp generator is fed to a low pass filter with a switchable time constant. The long time-constant is used, if the input is higher than the output or the active power is less than the maximum available active power. In this case the influence on the inverter output frequency is fairly small and the GFM behaviour is retained. In the other cases the small time-constant is used, so that the detected frequency from the PLL is fed quiet directly onto the inverter frequency output, meaning that the active power remains almost constant and does not increase beyond it´s critical limit.

# 7 Appendix B: Physical model for the description of system disturbances

The following section intends to:

1. Describe an analytical approach to specifying performance requirements;
2. Provide a generic test network for simulating these requirements;
3. Derive specific performance criteria that a single unit should be capable of providing.

## 7.1 Voltage phase angle step

A phase angle step is commonly the result of a sudden change of power due to the loss of generation or of a load in the system (considered as a system-wide event) or a switching operation (considered as a local event). In the case of a system event, the remaining units in the system then need to compensate the power difference – they experience a change of the voltage angle. The relationship between power change and angle change can be approximated by:

$$p \approx -\frac{(u_{\mathrm{G}})^2}{x_{\mathrm{G}}} sin(\delta) \tag{13}$$

with $\delta$ as voltage angle difference between $V_{Grid}$ and the voltage at the load. For small angles, a proportional relationship between angle change and power change can be assumed (with $\delta \approx sin(\delta)$).

In a model representation shown in Figure 18, an opening of the switch $S_{L2}$ can emulate a loss of load and, a closing of $S_{L2}$ is equivalent to a loss of generation, increasing the load for the remaining generators.

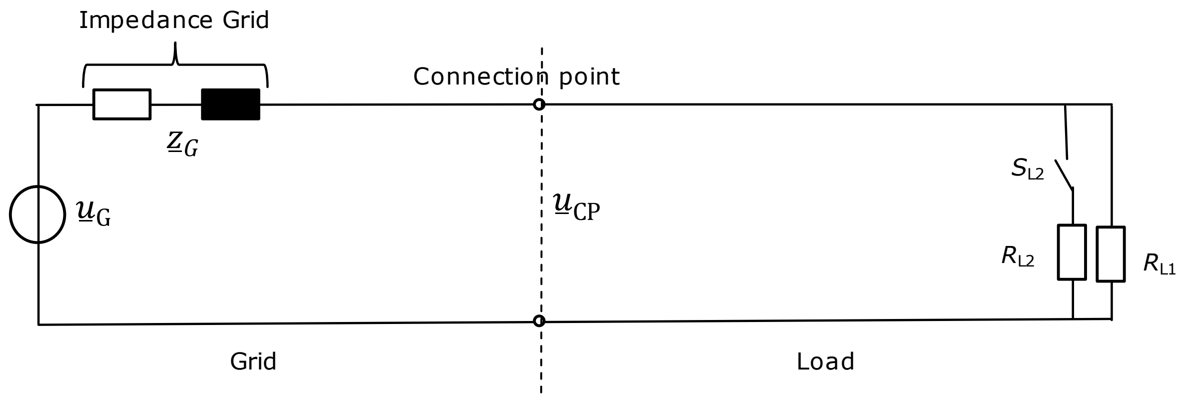



Figure 18: Simple grid and load equivalent for estimating a voltage angle change following a load change.

The resulting – average - voltage angle change for a given change of active power is a function of the system short circuit ratio (SCR) defined by the impedance $\underline{z}_G$ .The actual angle power change (in %) a specific unit experiences may be higher or lower than the average power difference experienced by the grid as a whole and depends on the impedance between the unit and the 'centre of gravity' of the grid.

Therefore, the angle changes experienced by an individual unit following a grid event depends on the location. DUT close to a grid event need to withstand higher voltage angle changes than more distant ones.

Note: In the distribution system, voltage angle changes frequently result from changes in the grid topology due to the connection or disconnection of lines and are not necessarily related to changes of the system load or generation. The following calculations focus on events that have an impact on the system frequency.

### 7.1.1 Phase angle step with grid impedance only

For a very simple grid equivalent consisting of a grid equivalent and an idealised Device Under Test (DUT) described by an ideal voltage source (with infinite inertia H) as shown in Figure 19, the steady state relationship between active current and voltage angle based on (1) can be approximated as

$$\delta \approx \arcsin\left(\frac{i_{\mathrm{P,DUT}} \cdot x_{\mathrm{G}}}{u_{\mathrm{Inv}}}\right) \tag{14}$$

The dynamic of the relationship between voltage angle change and power can be described as:

$$p_{Inv}(t) = p_{inv2,stat} - 3\frac{u_{\mathrm{Inv}}u_{\mathrm{G}}}{z_G} \cdot e^{-t/\tau} \cdot sin\left(\frac{\delta_2 - \delta_1}{2}\right) \cdot sin\left(\omega t + \frac{\delta_1 + \delta_2}{2} + \varphi_{\mathrm{sc}}\right) \tag{15}$$

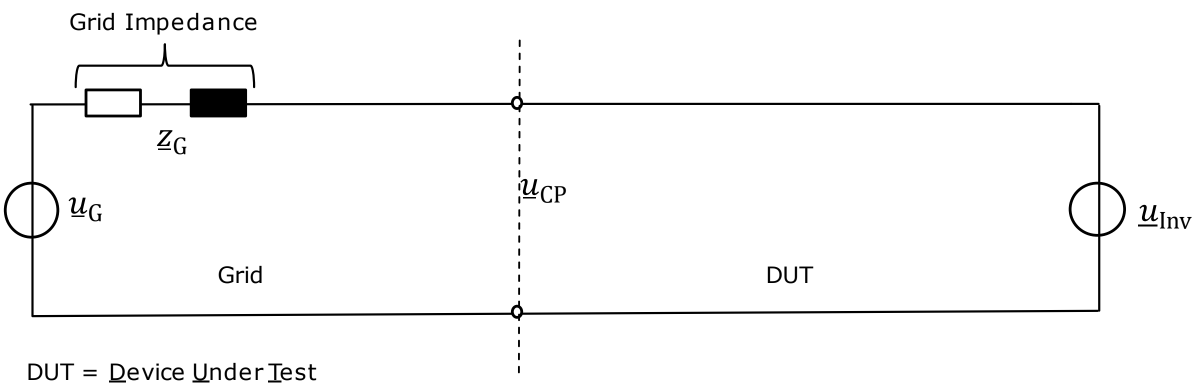



Figure 19:Simple grid equivalent consisting of a grid equivalent and an idealised DUT.

With $\delta_1$and $\delta_2$ as the voltage angle difference between grid and inverter voltage sources before and after the event. For a reference parametrisation with SCR = 10 and X/R = 30, the angle change resulting from a 25% change of active power in either positive direction (loss of load) or negative direction (loss of generation) can be calculated using (14) as 1.4°. The current change resulting from this change of power and voltage angle is shown in Figure 20.

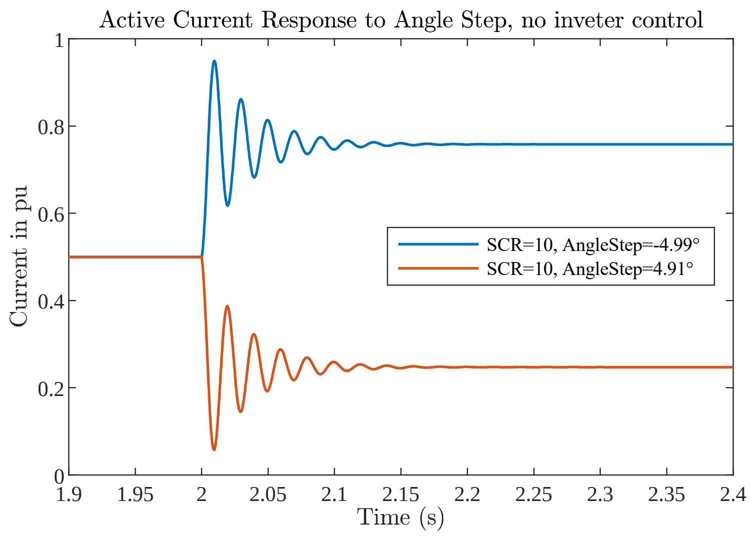



Figure 20: Active current change by ± 25% resulting from a change of grid voltage angle.

The current response can be described by (16)

$$i_{dinv}(t) = i_{\mathrm{dinv2,stat}} - 2\frac{u}{z} \cdot e^{-(t-t_0)/\tau} \cdot sin\left(\frac{\delta_2 - \delta_1}{2}\right) \cdot sin\left(\omega(t-t_0) + \frac{\delta_1 + \delta_2}{2} + \varphi_{sc}\right) \quad (16)$$

with a damping of

$$D = \frac{r}{x} \approx \frac{0.0033}{0.1} = 0.033 \quad (17)$$

### 7.1.2 Phase angle step with grid impedance and inverter hardware

An extended simple grid equivalent consisting of a grid equivalent and DUT described by an ideal voltage source and a unit hardware equivalent consisting of inverter filter and LV-MV transformer is shown in Figure 21.

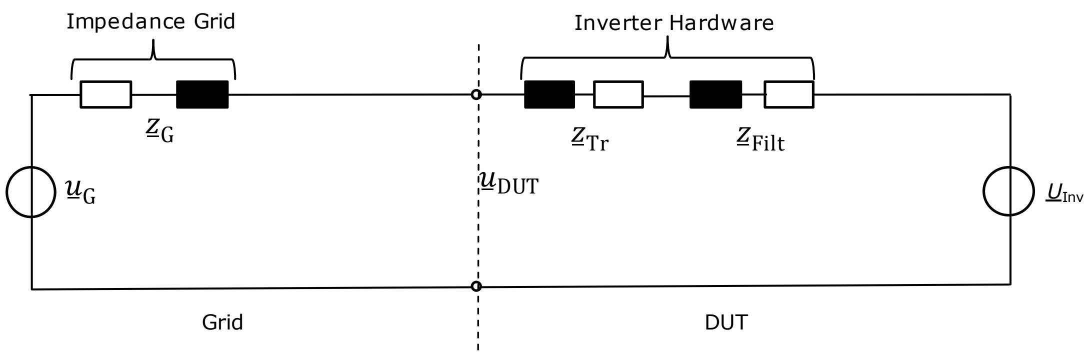



Figure 21: Simple grid equivalent consisting of a grid equivalent, unit MV transformer and inverter filter impedance.

If the unit MV to LV transformer and the filter impedance are added, a change by 25% active power results in an angle change between grid and inverter voltage sources using (14) and replacing $x_{\mathrm{G}}$ by $(x_{\mathrm{G}} + x_{\mathrm{Tr}} + x_{\mathrm{Filt}})$ of around 5° in either positive direction (loss of load) or negative direction (loss of generation) as shown in Figure 22.

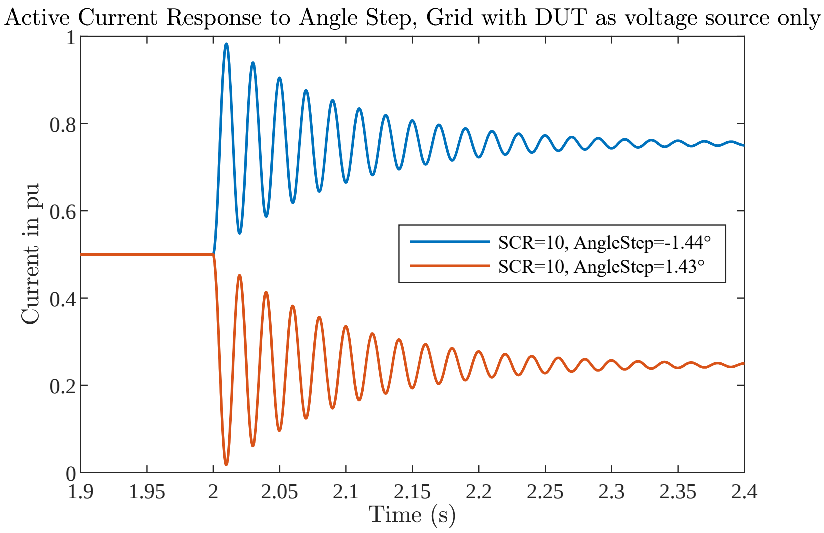



**Figure 22: Active current change by ± 25% resulting from a change of grid voltage angle with damping and without inverter control.**

The reference parametrisation is a SCR = 10 and X/R = 30 for the grid equivalent and a unit impedance (consisting of the inverter filter impedance $\underline{z}_{\mathrm{Filt}}$ and the LV/MV transformer impedance $\underline{z}_{\mathrm{Tr}}$) of $\underline{z}_{\mathrm{DUT}} = 0.24/8 + j0.24$, with a damping of the oscillations defined by the grid and DUT parameters as

$$D = \frac{r_{\mathrm{G}} + r_{\mathrm{Tr}} + r_{\mathrm{Filt}}}{x_{\mathrm{G}} + x_{\mathrm{Tr}} + x_{\mathrm{Filt}}} = \frac{0.033}{0.34} \approx 0.1 \qquad (18)$$

### 7.1.3 Phase angle step with grid forming control

The current response shown so far is based on an ideal system with infinite inertia. The response of a GFM-controlled unit to a voltage angle step can be described by an effective impedance $\underline{z}_{\mathrm{Eff}}$, by modelling the controller contribution using an additional impedance $\underline{z}_{\mathrm{Control}}$, as shown in Figure 23. $\underline{z}_{\mathrm{Eff}}$ defines the desired response of a GFM controlled DUT to a voltage angle step (and a voltage amplitude step as shown in the next section) in a method comparable to the response of a synchronous generator.

A grid following controller would not respond to a voltage angle change.

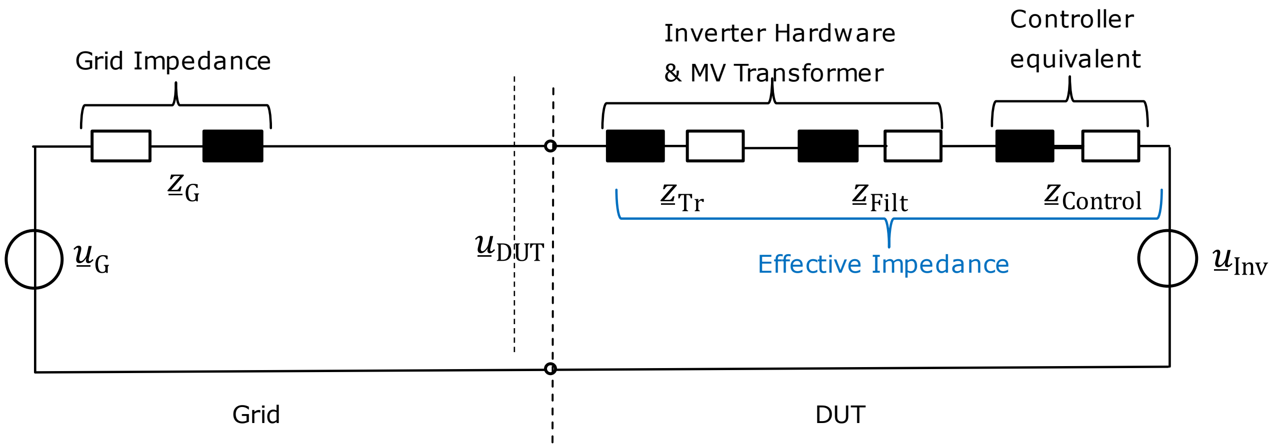



Figure 23: Simple grid equivalent consisting of a grid equivalent, unit MV transformer, inverter filter and control impedance.

Based on a GFM control implementation as described in Appendix A, the currents following a voltage angle change will decay as shown in Figure 24.

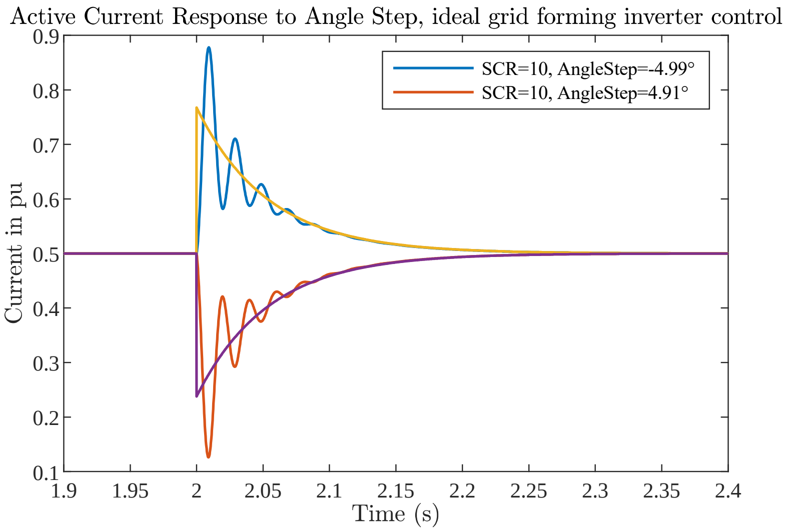



Figure 24: Active current change with angle step by ± 4.9° at the grid voltage source with simplified grid forming control according to Figure 14. The yellow and pink lines show the phasor based calculation.

The decay rate, as the ‘average current’ depends on the internal control implementation. For the control implementations shown in Figure 13 and Figure 14, the decay function (the pink and yellow line in Figure 24) can be calculated as phasor values. Assuming $u_G = u_{inv} = 1$, the active power change can be described as:

$$\Delta p = \Delta p_0 \cdot e^{-t/\tau} \qquad (19)$$

with

$$\Delta p_0 = -\frac{1}{x_{\mathrm{Eff}}} \cdot (\sin \delta_1 - \sin \delta_2) \tag{20}$$

and

$$\tau = \frac{x_{\mathrm{Eff}}}{k_{\mathrm{f}}\omega_0} \tag{21}$$

with $\tau$ as the time constant of the decay rate, $x_{\mathrm{Eff}}$ as the unit effective reactance, $k_f$ as the frequency droop (see Appendix B).

The equivalent active current response is:

$$\Delta i_P = \Delta i_{P0} \cdot e^{-t/\tau} \tag{22}$$

with

$$\Delta i_{P0} = -\frac{1}{x_{\mathrm{Eff}}} \cdot (\sin \delta_1 - \sin \delta_2) \tag{23}$$

Inverter based DUTs with GFM control can provide an additional damping independently from the value of $\underline{z}_{\mathrm{Eff}}$ by modifying the inverter voltage angle. Figure 25 shows the response of a unit with the same angle step and the same calculated power change of 25%, but an increased damping as described in (24).

$$D = \frac{r_{\mathrm{G}} + r_{\mathrm{Tr}} + r_{\mathrm{Filt}}}{x_{\mathrm{G}} + x_{\mathrm{Tr}} + x_{\mathrm{Filt}}} + D_{add} \approx \frac{0.033}{0.34} + 0.2 \approx 0.3 \tag{24}$$

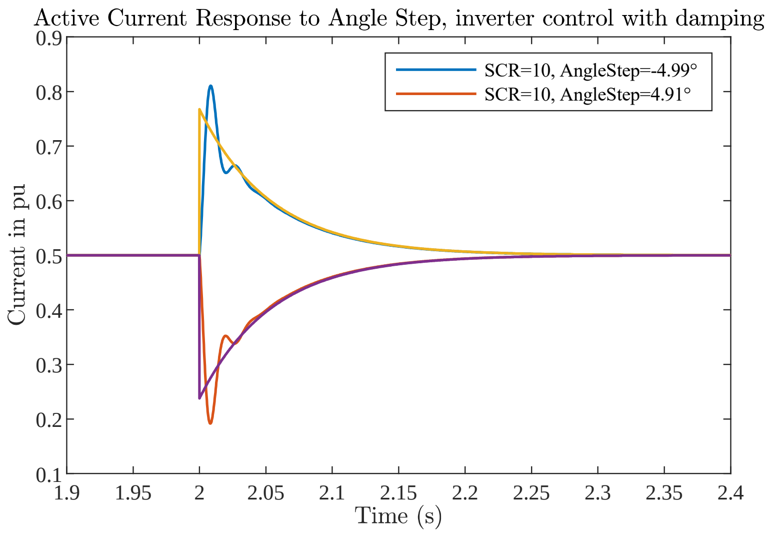



**Figure 25: Active current change with angle step by ± 4.9° at the grid voltage source with inverter control and additional damping.**

### 7.1.4 Performance criteria based on ideal and simulated response to voltage angle changes

A comparison of ideal and simulated response to voltage angle changes is shown in Figure 26. It shows a good correlation between the simulation results and the expected response. A close-up view directly following the angle step change is shown Figure 27 – 29.

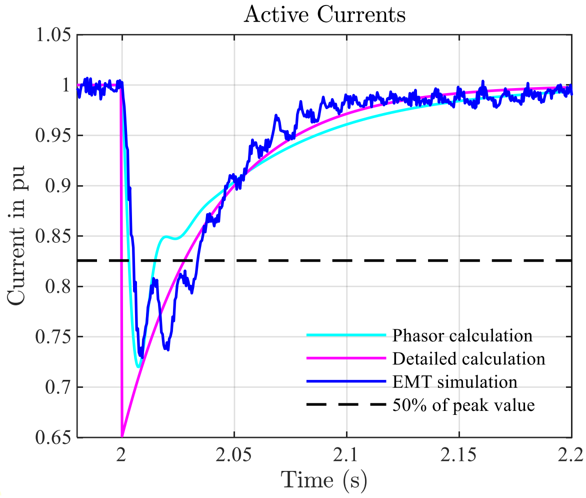



**Figure 26: Active current change following voltage angle change by 5° at the terminals of the unit at rated power. Comparison of ideal and simulated response to voltage angle change.**

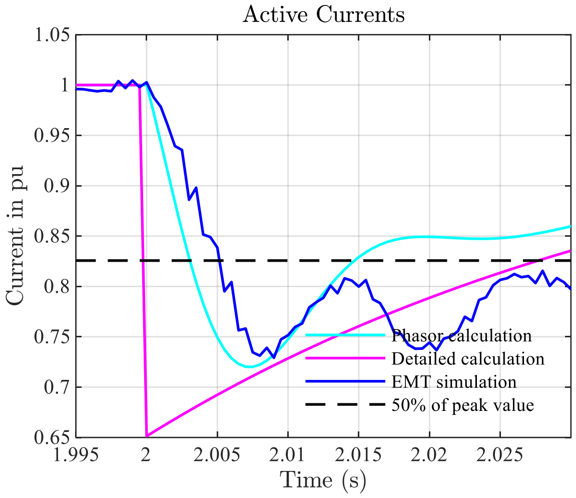



**Figure 27: Detailed view of active current change following voltage angle change by 5° at rated power**

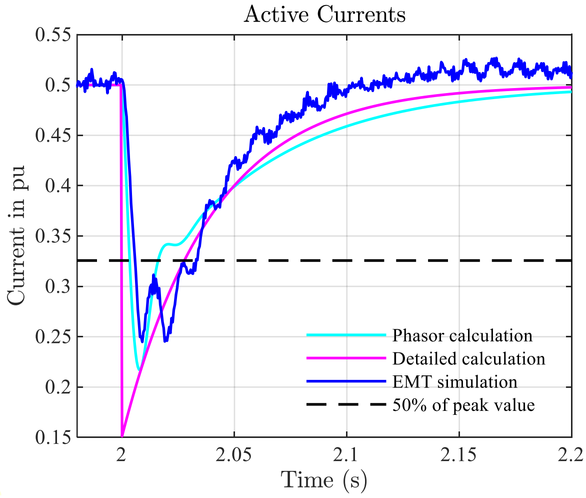



**Figure 28: Active current change following voltage angle change by 5° at the terminals of the unit at 50% rated power. Comparison of ideal and simulated response to voltage angle change.**

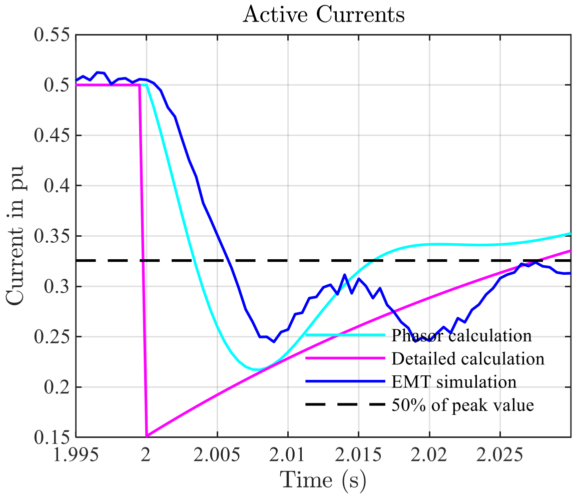



**Figure 29: Detailed view of active current change following voltage angle change by 5° at 50% rated power.**

The pink line shows the phasor calculation, the light blue the analytical solution-based instantaneous values. The black line shows the response of the EMT-Simulation based on the control structure shown in Appendix A.

There is a strong correlation between the peak value of the current on the damping. The EMT-simulation shows an additional time delay and a reduced peak compared to the analytical solution. The peak value of EMT-Simulation is at around 10 ms, which is comparable to the expected response of a voltage source.

**Recommendations**

Based on the phasor calculation, an expected response (depending on grid and test system impedance) to any given voltage angle change can be calculated.

Units without internal storage should only provide a reduction of power due to positive voltage angle changes.

## 7.2 Voltage amplitude step

A simplified test setup for evaluating small and large voltage amplitude steps is shown in Figure 30.

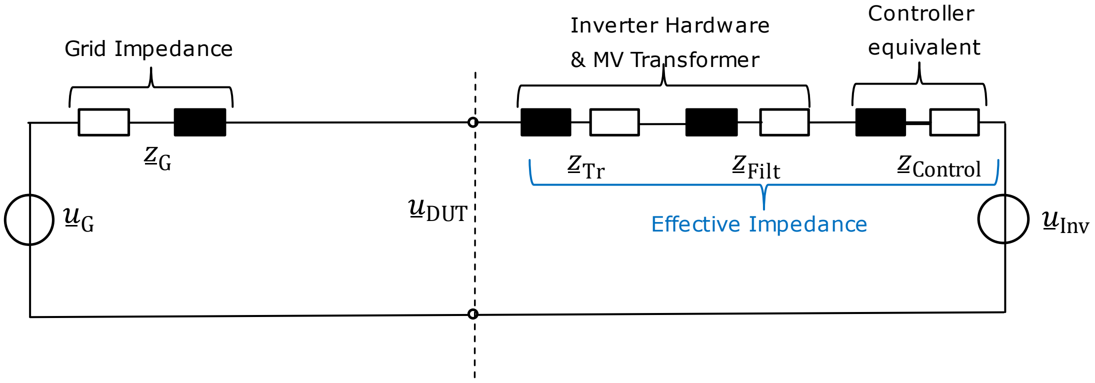



Figure 30: Simple representation of voltage amplitude changes

The response of a controlled voltage source to a voltage amplitude step change of $u_{\mathrm{G}}$ can be approximated by:

$$i_{\mathrm{P}} = \frac{p}{u} \approx -\frac{u_{Inv}}{(x_{\mathrm{G}} + x_{\mathrm{Eff}})} sin(\delta) \tag{25}$$

and

$$i_{\mathrm{Q}} = \frac{q}{u} \approx \frac{1}{(x_{\mathrm{G}} + x_{\mathrm{Eff}})} \left(u_{\mathrm{G}} - u_{\mathrm{Inv}} \cdot cos(\delta)\right) \tag{26}$$

for a change of the grid voltage $u_{\mathrm{G}}$.

f no current limits are reached (unconstrained operation**)**, the reactive current $i_{\mathrm{Q}}$ changes with voltage changes (26). The active current $i_{\mathrm{P}}$ does not change as a function of grid voltage (25). The apparent current becomes very high for low voltages.

Figure 31 shows the active and reactive current response as given by (25) and (26). The slight variation of active current above a voltage of 0.95 is the result of the active power control loop that modifies the active current depending on the grid voltage to maintain constant active power output (27). Some grid codes require that PPMs are capable of providing rated active power below 1 pu rated voltage.

$$i_{\mathrm{P_{Ref}}} = \frac{p_{\mathrm{Ref}}}{u_{\mathrm{DUT}}} \tag{27}$$

Figure 32 shows the corresponding voltage angle $\delta$ (green) that is modified (see (25)) to keep the active power constant for small voltage amplitude changes.

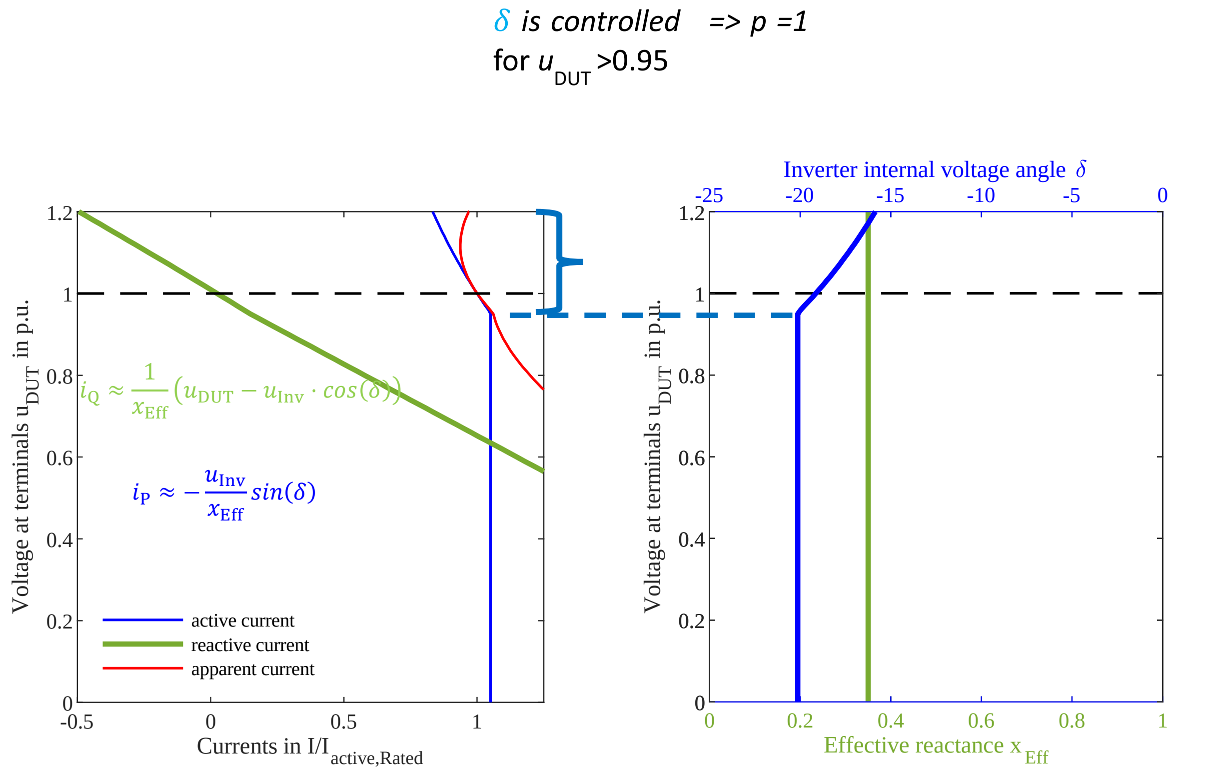



Figure 31: Active and reactive current of an inverter behaving as voltage source if no current limits apply.

Figure 32: Corresponding values of voltage angle $\delta$ (green line). This value is commonly adopted around rated voltage to ensure constant active power. The effective impedance $x_{Eff}$ (blue line) and the internal inverter voltage remain constant.

This is comparable to the behaviour of a synchronous generator. The internal voltage of the synchronous generator stays constant, the ratio between active and reactive current changes with a decrease of the grid voltage. In the event of a synchronous generator, the value of the impedance x would decrease during the fault due to saturation effects.

### 7.2.1 Current limitation using reactive power priority

If an effective reactance $x_{\mathrm{Eff}}$ value of 0.33 (in pu) is assumed, the typical current limit of an inverter (1.1 .. 1.2 pu) is exceeded once the voltage drops by more than 33% at the point of connection. For grid following inverters, it is common practice to limit active and reactive currents independently as a function of the remaining voltage. The resulting response to voltage drops can be highly nonlinear and possibly unstable.

Figure 33 shows active and reactive current in the event of reactive current priority in a typical configuration for wind turbines, the active current is not reduced to 0. Figure 34 shows the corresponding values of voltage angle δ and the effective impedance $\boldsymbol{x}_{\mathbf{Eff}}$ of an equivalent voltage source as shown in Figure 23. Figure 35 shows an equivalent current priority for solar parks, where no active current is needed during voltage drops, Figure 36 the corresponding values of voltage angle δ and the effective impedance $\boldsymbol{x}_{\mathbf{Eff}}$ respectively.

Both variants behave like a current source once the reactive current limit is reached. Any additional voltage change no longer leads to any change of reactive current. This is a typical implementation of grid following control today and does not meet the requirements of GFM behaviour.

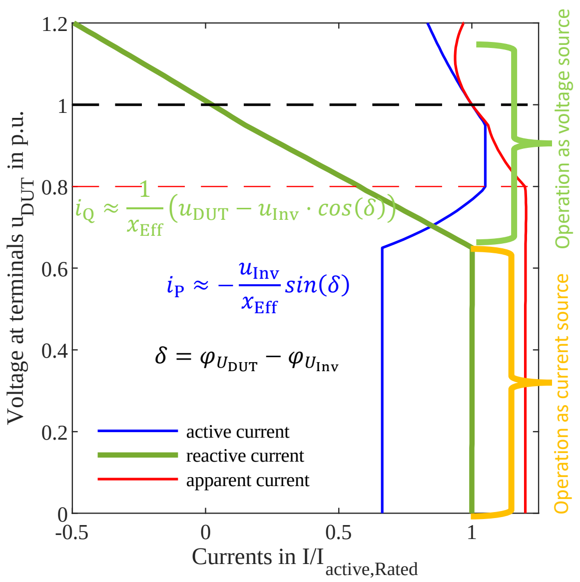



Figure 33: Active and reactive current of an inverter with voltage control and reactive current priority in a typical configuration for wind turbines

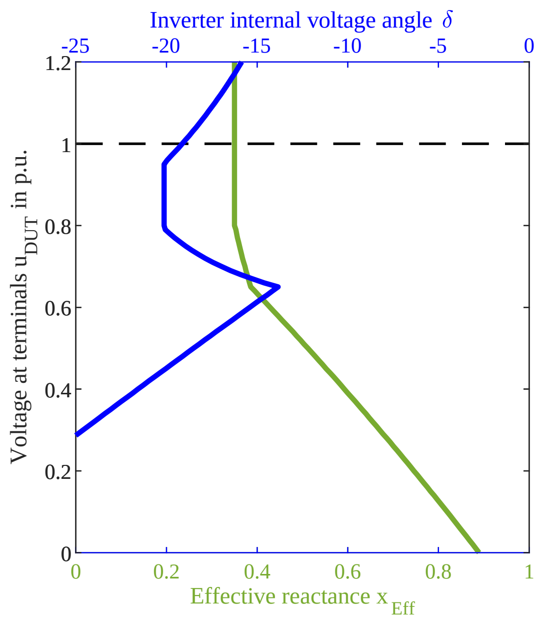
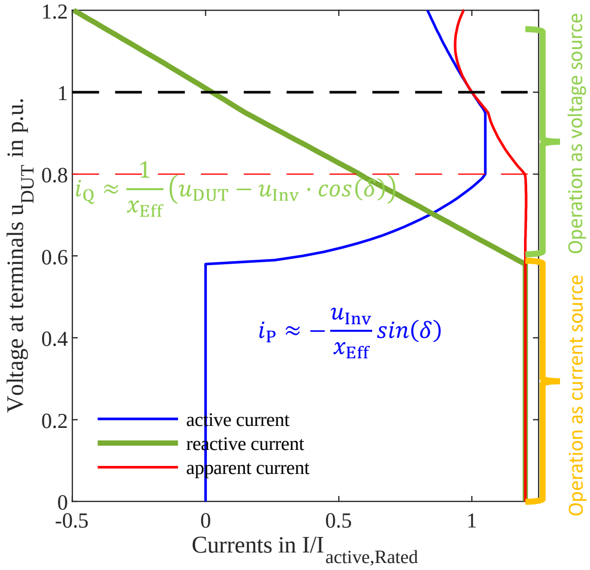



Figure 34: Corresponding values of voltage angle $\delta$ (green line), of an inverter with reactive current priority. The effective impedance $x_{\mathrm{Eff}}$ (blue line) and the internal inverter voltage remain constant.



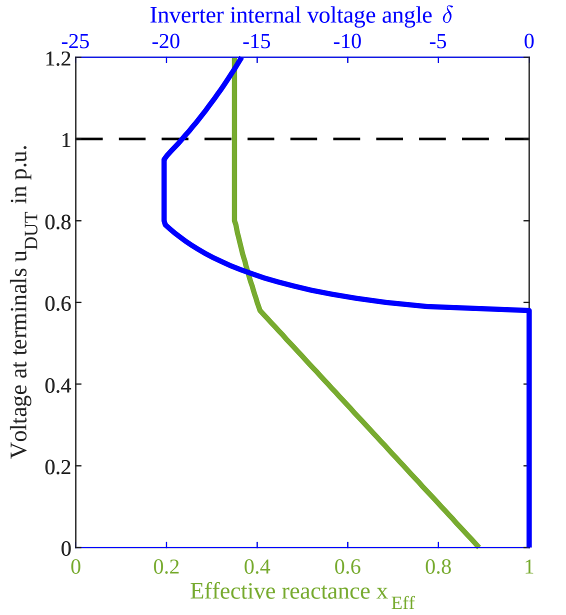




**Figure 35: Active and reactive current of an inverter with voltage control and reactive current priority in a typical configuration for solar plants.**

**Figure 36: Corresponding values of voltage angle $\delta$ (green line), of an inverter with reactive current priority. The effective impedance $x_{Eff}$ (blue line) and the internal inverter voltage remain constant.**

### 7.2.2 Grid forming implementation using magnitude limitation

The response of a controlled voltage source with current magnitude limitation to changes in voltage is shown in Figure 37 for 100% rated power. Figure 38 shows the corresponding values of the voltage angle and the effective impedance. The corresponding diagrams for 100% and 10% rated power are shown in Figure 39 and Figure 40. This can be achieved by dynamically increasing the value of $\underline{z}_{\text{Control}}$ in Figure 30, resulting in a dynamic increase of the effective reactance ($x_{\text{Eff}}$) in equations (25) and (26) respectively.

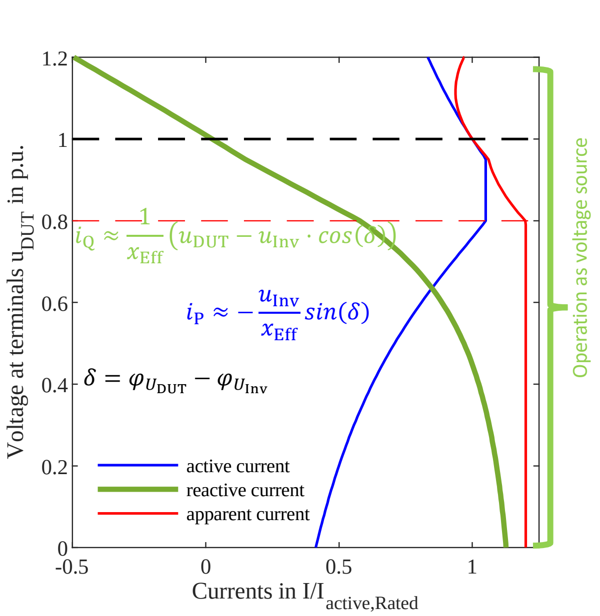



Figure 37: Active and reactive current of an inverter with current magnitude limitation.

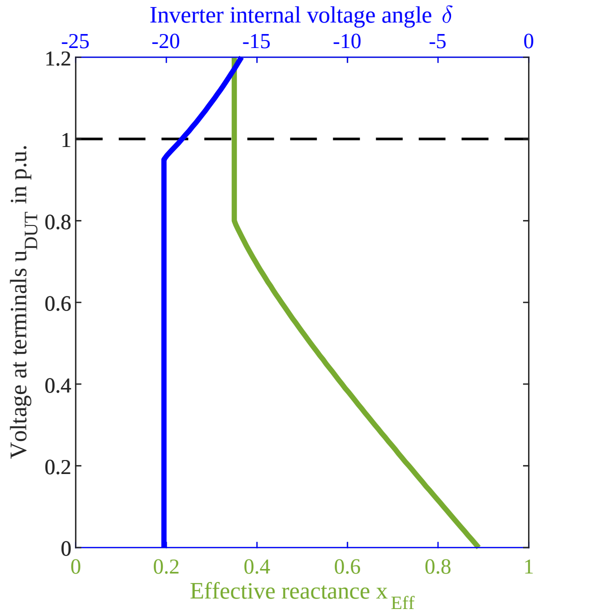



Figure 38: Corresponding values of voltage angle $\delta$ (green line), and effective impedance $x_{Eff}$ (blue line) for an inverter with current magnitude limitation.

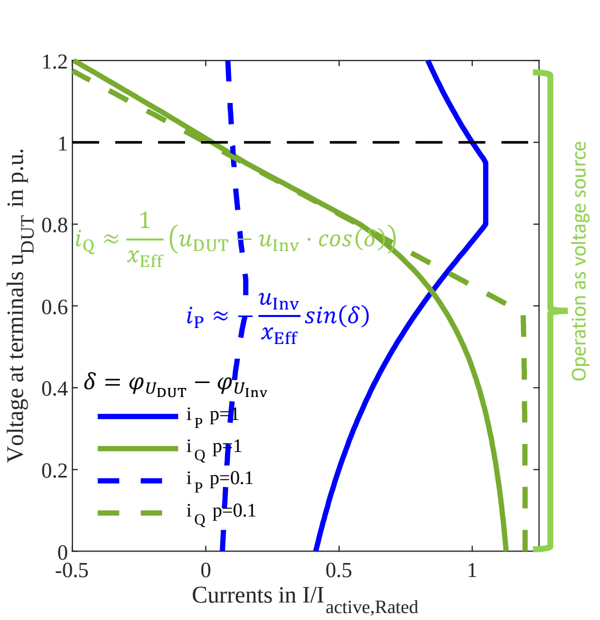



Figure 39: Active and reactive current of an inverter with current magnitude limitation at 100% and 10% active power.

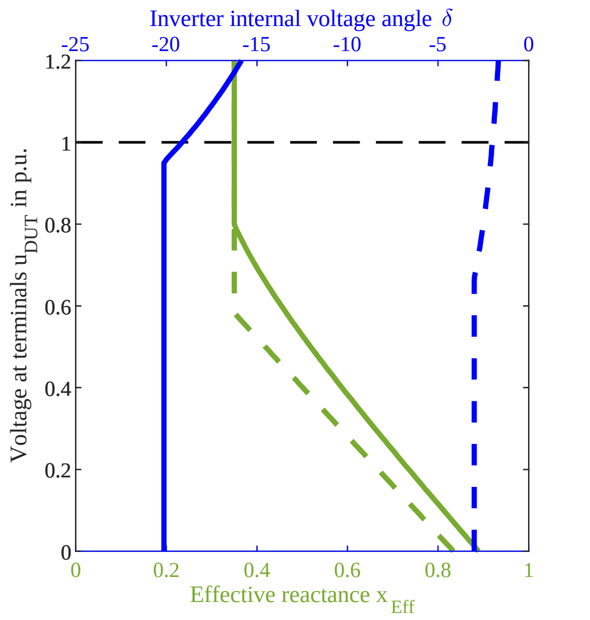



Figure 40: Corresponding values of voltage angle $\delta$ (green line), and effective impedance $x_{Eff}$ (blue line) for an inverter with current magnitude limitation.

### 7.2.3 Unbalanced voltage step

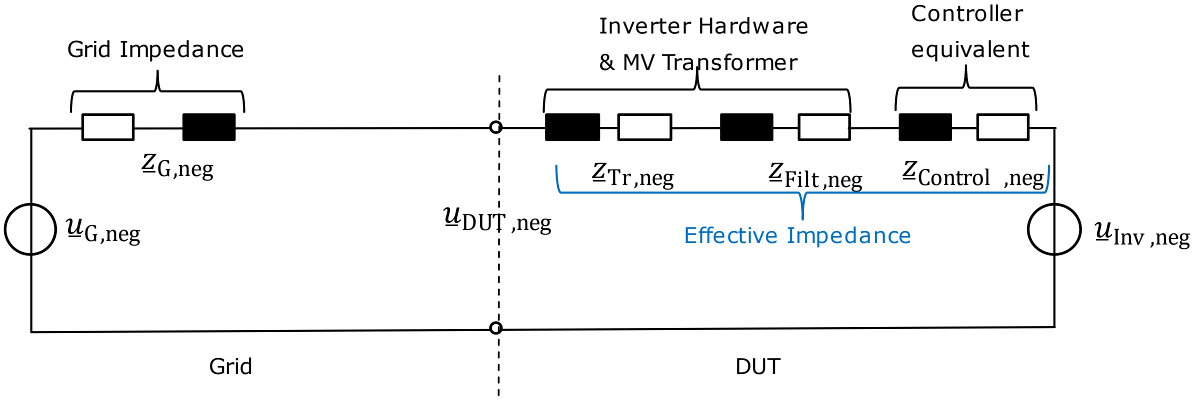



Figure 41. Test system for testing unbalanced voltage step.

Under unbalanced fault conditions, the negative sequence reactive current can be described as:

$$i_{\mathrm{Q,neg}} \approx \frac{1}{x_{\mathrm{Eff}}}\left(u_{\mathrm{DUT,neg}} - u_{\mathrm{Inv,neg}}\right) \tag{28}$$

with $u_{\mathrm{DUT,neg}}$ as the negative sequence voltage at the connection point and $u_{\mathrm{Inv,neg}}$ as the negative sequence inverter voltage (which is assumed to be zero). The negative sequence effective impedance should be equal to the positive sequence impedance $x_{\mathrm{Eff}}$.

In the event that current limits are reached, $x_{\mathrm{Eff}}$. shall be increased dynamically to limit active and reactive currents in the positive sequence and the reactive current in the negative sequence according to (1) - (3).

# 8 Appendix C: Measurement considerations

Evaluation of measurements and simulations:

1. For types B, C and D PPM with connection points at medium or high voltage level, it is expected that tests are performed at medium voltage level, while the unit is connected to the medium voltage grid by a unit transformer.
2. For types B, C and D PPM, the evaluation of results may be performed at the medium voltage connection point or at the low voltage connection point in Figure 8 at the choice of the manufacturer.
3. The diagrams usually refer to an evaluation at the MV terminals of a PPM. If an evaluation at the LV terminals is performed, a transformer as shown in Figure 8 upon needs to be included.
4. Results from field and test bench measurements need to be evaluated as positive and negative sequence values according to [IEC 61400-21-1].