Offshore Grid Connection Requirements

Annex A_08:

Grid Forming Control Study

Area of application: DC-connected Offshore Windfarms

Revision history

Rev. Number	Date	Change	Author
1.0	28.07.2025	First edition	T. Neumann (AMP) T. Nguyen (50HzT)

1 Purpose and area of application

This document provides supplementary requirements to [1] and [2]. This annex to the grid code describes the minimum requirements for the grid forming control study to be performed by the connectee to demonstrate the compliance with the Offshore Grid Code Requierement [2] of TSO. The study comprises three parts:

1. A demonstration of performance at an early stage in the control design. The “preliminary GFM study”, compares the grid forming control performance of the DC connected offshore windfarm (OWF) with the preliminary requirements given in the grid code of TSO. It is not needed to fulfil all requirements when the study is conducted. Rather, it is the goal to clearly reveal the gaps between requirements and asset performance, to show the general feasibility and to define action items to close these gaps. Individual requirements for the study are defined in section 6.2 of this document.
2. An alignment with the HVDC system based on the preliminary study and definition of acceptance criteria (section 6.3), including the final definition of acceptance criteria on grid forming control by TSO.
3. A detailed study and compliance verification to be performed by the connectee (section 6.4).

This approach is coordinated with the requirements for the HVDC system on grid forming control.

The grid forming control study shall verify that the project specific acceptance criteria defined by TSO regarding instantaneous reserve and dynamic voltage control (see [1] and [2]) can be met. TSO’s requirements regarding instantaneous reserve and dynamic voltage control together form the framework for grid forming controls.

Providing instantaneous reserve to stabilize the onshore system is a new and complex functionality. However, as instantaneous reserve is urgently needed in the German and Continental European Syn-chronous Area, all involved parties need to collaborate to exploit the potential of OWF to help stabilize the onshore system.

2 Standards

If no explicit standards are specified, the following systems of standards shall be followed in the prioritized order:

i. German standards and regulations, including the grid codes of TSO
ii. Cenelec
iii. IEC
iv. Cigré recommendations
v. IEEE standards and recommendations.

If alternative standards will be used, they shall be approved by TSO. The latest edition including amendments of each standard and regulation shall apply.

SI units and the passive sign convention shall be used in all documents, if it is not otherwise specified by the TSO.

3 References

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs:

[1] VDE-AR-N 4131: 2019-03: Technische Anschlussbedingungen für HGÜ-Systeme und über HGÜ-Systeme angeschlossene Erzeugungsanlagen (TAR HGÜ).

[2] 50HzT, AMP: Offshore-Netzanschlussregeln

[3] FNN Guideline: Grid forming behaviour of HVDC systems and DC-connected PPMs, June 2020.

[4] DIN EN IEC 61400-21-1: Measurement and assessment of electrical characteristics –Wind turbines, Annex C: Measurement of active power, reactive power and voltage

[5] 50HzT, AMP: Offshore Grid Connection Requirements Annex A_01 General Requirements for Compliance Studies and Models

[6] 50HzT, AMP: Offshore Grid Connection Requirements Annex A_02 Main circuit parameter report

[7] 50HzT, AMP: Offshore Grid Connection Requirements Annex A_05 Requirements for EMT simulation models

[8] 50HzT, AMP: Offshore Grid Connection Requirements Annex A_07 Dynamic Performance study

[9] 50HzT, AMP: Offshore Grid Connection Requirements Annex_Grid Forming Control Study Test Scenarios

4 Definitions

OWF	Offshore Windfarm
WTG	Wind Turbine Generator
DBS	Dynamic braking system
DuT	Device under Test
EMT	Electromagnetic Transients

FSM	Frequency Sensitive Mode
LFSM-O	Limited Frequency Sensitive Mode – Overfrequency
LFSM-U	Limited Frequency Sensitive Mode – Underfrequency
GCP	Grid Connection Point
PPM	Power Park Module
GFM	Grid forming

5 General Requirements

The connectee shall develop an overall grid forming control concept including the provision of instantaneous reserve from the DC connected OWF.

For DC connected OWF, the connectee shall provide evidence of conformity for the behaviour of the instantaneous reserve and the dynamic voltage control in accordance with [3].

The connectee shall provide a study report (see [5]) which summarizes all study results for the grid forming controls.

The minimum requirement for all scenarios is to achieve a stable operating point, well-damped transition behaviour and to utilize the available energy capability of the system. If the response in individual scenarios is not stable, not well damped or does not reflect the expected grid forming behavior, the results need to be discussed in detail.

Project specific reference curves and envelopes may be used as acceptance criteria necessary for the conformity check. The TSO shall decide whether reference curves and envelopes are used in the Grid Forming study. The connectee shall provide the design parameters of the electrical components (main circuit parameters as given in [6]) to enable TSO to create and provide project specific reference curves, envelopes as acceptance criteria necessary for the conformity check.

The final and binding acceptance criteria necessary for the conformity check will be delivered by TSO, after the preliminary study defined in 6.2 with the process defined in 6.3.

As part of the Dynamic Conformity Study defined in [8], the connectee shall analyse with each revision all calculation cases as defined in chapter 7.

The connectee shall demonstrate that all acceptance criteria are fulfilled.

6 Requirements for DC connected offshore windfarm

Informative: The overall concept to provide instantaneous reserve from DC connected OWF consists of several iterative steps to be coordinated with all connectees in the offshore network.

Informative: Providing instantaneous reserve to stabilize the onshore system is a new and complex functionality. To establish this feature, additional requirements for coordinating OWF and HVDC system are defined in the following sections.

Informative: The approach and requirements for the HVDC system to transmit the instantaneous reserve exploited from the OWF to the onshore system is part of the HVDC engineering process. Coordinated with this concept, the requirements for the OWF are given in the following.

6.1 General requirements

The connectee shall contribute to a constructive collaboration ("partnership approach") between all involved parties in achieving the provision of instantaneous reserve to the onshore system and the dynamic voltage control.

The connectee shall participate in creating a coordinated overall plan including HVDC system and OWF, including time schedule and exchange of technical information, results, assumptions, and models.

During the commonly agreed concept development, the connectee shall allow for adjustments in the process, if technically necessary and agreed with all parties.

Informative: For instance, the exchange of models, partly repetition of study content, adjustable parameters in the models, etc. maybe necessary.

6.2 Preliminary study on grid forming control

Informative: This EMT study is intended to analyse the performance, limitations, and potential of the DC connected OWF for providing instantaneous reserve and dynamic voltage control without reactive current specification.

The connectee shall provide an overview of the control strategy for grid forming control, including

- Description of control concept
- Introduction on current and future developments in the control design for grid forming control (GFM)
- Explanations for inevitable limitations, dependencies, and uncertainties
- Potential for further re-tuning and re-designing of GFM relevant controls
- Possibilities to further tune the overall performance

The connectee shall request all relevant information from the HVDC system needed for the development and studies on GFM.

Vice versa, the connectee shall provide, under consideration of its intellectual property, the information requested by the HVDC system, to further refine the HVDC control design.

The connectee shall simulate all study cases given in section 7.

TSO may specify a small number of additional relevant cases, beyond those in section 7, based on the actual status of development.

Informative: These additional cases may include time functions of the voltage phasor, representing the offshore HVDC converter, to be applied to a controllable voltage source (i.e. the

Thevenin source in Figure 1).

For the cases given in section 7, the connectee shall compare it with the preliminary envelopes given in section 8, in one common plot.

The connectee shall explain how the characteristics of a wind turbine influence the performance compared to the ideal, non-wind-specific preliminary references of section 8.

The connectee shall investigate as a sensitivity analysis, how the characteristics of the events may change the performance of the OWF, e.g. frequency gradients with variable RoCoF, steps and gradients in voltage angle.

The connectee shall investigate how DC connected OWF can:

- utilize the energy stored in the rotor of the OWF and
- enable a power reduction of the OWF (e.g. DBS or pitch angle variation)

The connectee shall determine the inertia constant H (or the "Anlaufzeitkonstante" T_a) and the exploitable instantaneous reserve in MWs as a function of the active power operating point of the OWF.

For the preliminary study, the connectee shall use a) a single wind turbine model (abbreviation WTG) and b) a detailed cable string model (abbreviation PPM). See Figure 1.

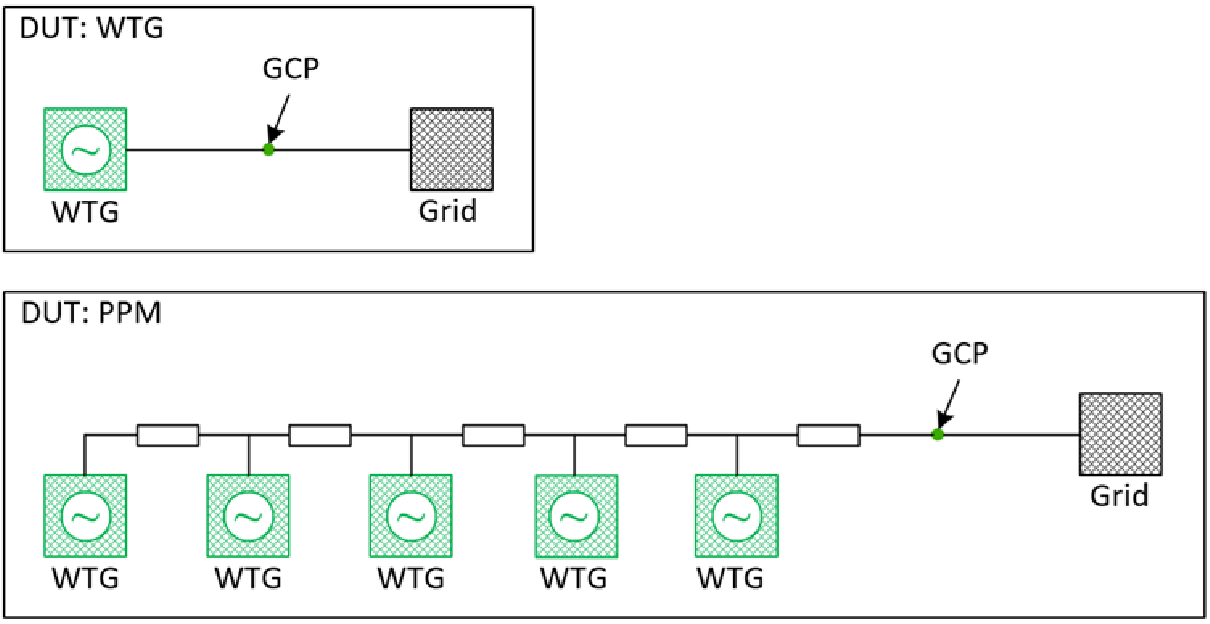

Figure 1: Model overview for preliminary grid forming control study

In any case, it shall contain the aerodynamics and the rotor dynamics of the wind turbines.

Together with TSO, the connectee may, as outcome of this study, specify requirements for the performance of the offshore HVDC converter.

Together with TSO, the connectee may, as outcome of this study, specify requirements for the information and model exchange with the offshore HVDC converter.

6.3 Alignment with HVDC system and definition of acceptance criteria

TSO will share the outcome of the preliminary grid forming control study, including results, models, reports, and findings with the supplier of the HVDC system.

Vice versa, TSO will provide the outcome of the feasibility studies of the HVDC system (as defined during the HVDC engineering) with the connectee.

Considering consultation with the connectee and the HVDC system, TSO will define the way forward based on the outcome of both studies, i.e. the feasibility study of the HVDC system and the preliminary GFM study of the OWF.

TSO will define the acceptance criteria for the DC connected OWF (e.g. in form of reference and envelope curves) based on the previous sentence.

Informative: TSO will consider the design limitations, as defined during the preliminary GFM study by the connectee.

Informative: Depending on the outcome of the studies, these requirements may differ from the formal definitions of grid forming control in [1] and [2].

Informative: TSO may also redefine the requirements for the offshore converter of the HVDC system.

6.4 Detailed study and compliance verification

Based on the alignment of 6.3, TSO defines the scope of a detailed study on grid forming control together with the connectee.

Informative: HVDC system will perform a detailed study including the GFM behavior of OWF. For the instantaneous reserve, it is the HVDC system to balance energy in the DC circuit and the offshore AC system, considering the relevant limitations and performance of the OWF.

The connectee shall consider the detailed EMT model of the HVDC system and the OWF, as defined in [7].

TSO will coordinate the detailed studies performed by the connectee and the supplier for the HVDC system.

The connectee shall verify all acceptance criteria for dynamic voltage control without reactive current specification for different operating points, operating modes, and other relevant factors, as defined in 6.3.

The connectee shall verify all acceptance criteria for instantaneous reserve, for different operating points, operating modes, and other relevant factors as defined in 6.3.

The connectee shall provide a gap analysis with respect to the acceptance criteria defined in 6.3.

For any violation, only TSO shall decide if this deviation is acceptable for justified exceptional cases.

7 Test scenarios

For the test scenarios for the preliminary study on grid forming control (compare 6.2) can be found in [9].

8 Procedure for evidence of system conformity for grid forming control

Informative:

1. This chapter specifies the verification procedure for the grid forming control in accordance with the process defined in the FNN reference paper [3].

2. For each of these tests, the test system and the quantities to be evaluated are described in this document.

3. In case reference curves and envelopes are used, the reference behaviour is obtained by EMT studies considering a generic converter model for the selected test scenarios.

4. In case reference curves and envelopes are used, additionally to the acceptance criteria a description of the curves is provided, mainly in order to indicate TSOs expectations on grid forming behaviour.

5. Saturation effects of the transformers as well as overvoltage arresters are not considered when creating the reference curves and envelopes for grid forming control.

6. If reactive or active power droop control functions are assumed for the reference behaviour, these will be specified for the respective calculation case.

8.1 Preliminary envelope curves

The preliminary reference behaviour and envelope curves will be provided project-spefically and shall serve as a general description of the qualitative behaviour required by TSO and shall illustrate the conformity process.

The preliminary tolerance band ("envelopes") of the reference curves shall be used in the preliminary GFM study, as defined in 6.2.

The preliminary tolerance band ("envelopes") of the reference curves shall not be used as the binding acceptance criteria for the verification of the grid forming behaviour.

8.2 Binding acceptance criteria

Following the approach defined in 6.3, TSO will hand over the acceptance criteria and the binding test scenarios to the connectee.

TSO will confirm system conformity, when the system behaviour demonstrated by the connectee complies with acceptance criteria.

For a violation of an acceptance criterion, only TSO shall decide if this deviation is acceptable for justified exceptional cases.

Applicability of sections 8.3 to 8.6 will be checked by TSO in the process of defining the final acceptance criteria (see 6.3).

8.3 Test system

The connectee shall use the test system shown in Figure 2 for all test scenarios in the conformity for grid forming control.

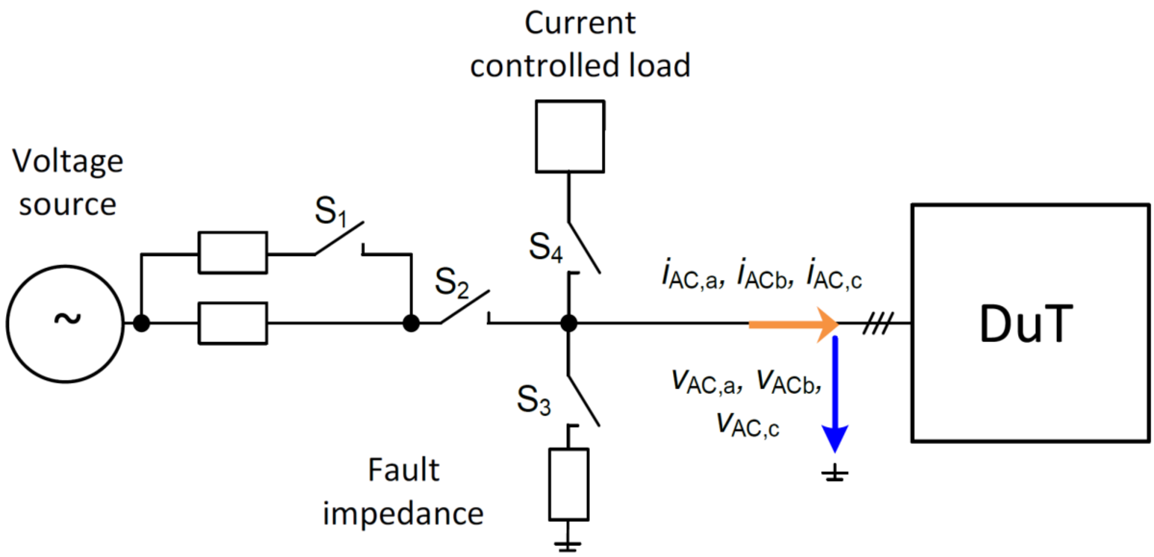

Figure 2: Simplified single line diagram of the test configuration for grid forming control

The connectee shall use an EMT model as specified in [7] to model the DC connected OWF.

The structure of the test network shall follow [3], consisting of an adjustable network impedance, a switchable, current controlled load, and a switchable fault impedance.

A change of the network impedance shall be done by switching S1.

The network equivalent shall be disconnected by switch S2.

Switches S3 and S4 shall be used to switch in a fault impedance and a current controlled load.

The current controlled load shall be implemented as defined by TSO during project execution.

8.4 Signal post-processing

The variable designation as well as their reference values shall be taken from Table 1.

Informative: For DC connected OWF, the rated power given in Table 1 is the rated active power depending on the used topology (compare Figure 1).

For the verification procedure, the connectee shall use the following calculation method in [4] for evaluating the electrical quantities at the GCP.

Additionally, for the detailed cable string model the individual measurement for each WTG shall be evaluated following calculation method in [4].

Informative: The method described below is used exclusively for ensuring a consistent post-processing signal calculation. It does not specify how PLL and signal evaluation in the control shall be implemented.

Based on the instantaneous values of the phase voltages and currents at the GCP the calculation method defined in [4] shall be used for getting the positive, negative and zero sequence quantities.

Active and reactive power (for positive and negative sequence), active and reactive current (for positive and negative sequence) and rms values of the phase-to-phase voltage (for positive, negative and zero sequence of the fundamental frequency) shall be calculated based on this method.

For the calculation of the Fourier coefficients in line with [4], a nominal window width of 20 ms and a sufficiently accurate nominal sampling time shall be assumed.

To be able to use the method according to [4] also for scenarios with time-variable grid frequency, a combination of a Digital Fourier Transformation (DFT) and a Phase Locked Loop (PLL) shall be used (compare [3]).

Informative: The combination of DFT and PLL ensures that the sampling time of the evaluation algorithm is adjusted as a function of the network frequency. This is illustrated in Figure 3.

The PLL shall be designed such, that the combination of DFT and PLL has a time constant of 200 ms for a frequency step (time until output signal reaches 63.2 % of the final value).

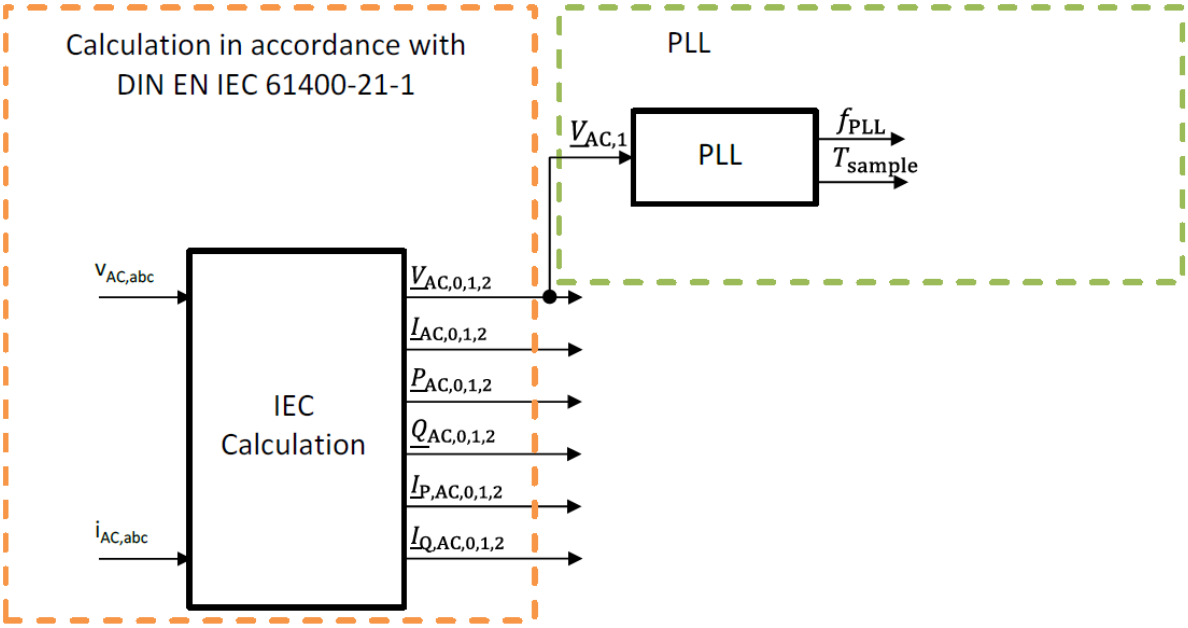

Figure 3: Principle of signal post processing in accordance with IEC (see [4])

Table 1: Signals and reference values for quantities at the GCP and at the WTG

Signal description	**Signal name**	**Reference value**
Three phase instantaneous quantities:		
Phase to ground voltage	$u_{AC,a}$, $u_{AC,b}$, $u_{AC,c}$	Phase to ground voltage
Currents	$i_{AC,a}$, $i_{AC,b}$, $i_{AC,c}$	Current at rated active power
Electrical quantities (calculated from the three phase instantaneous quantities):		
Positive sequence active power	$p_{AC,pos}$	Rated active power
Positive sequence reactive power	$q_{AC,pos}$	Rated active power
Positive sequence active current	$i_{p,AC,pos}$	Current at rated active power
Positive sequence reactive current	$i_{q,AC,pos}$	Current at rated active power
Positive sequence voltage	$u_{AC,pos}$	Nominal RMS line-to-line voltage
Negative sequence active power	$p_{AC,neg}$	Rated active power
Negative sequence reactive power	$q_{AC,neg}$	Rated active power
Negative sequence active current	$i_{p,AC,neg}$	Current at rated active power
Negative sequence reactive current	$i_{q,AC,neg}$	Current at rated active power
Negative sequence voltage	$u_{AC,neg}$	Nominal RMS line-to-line voltage
Zero sequence voltage	$u_{AC,zero}$	Nominal RMS line-to-line voltage
Output frequency of PLL	f_{PLL}	Nominal frequency
Phase angle of voltage phasor	φ_{AC}	-

8.5 Model of the DC connected OWF

All analyses performed in the verification procedure shall be performed with an EMT model as specified in [7].

Saturation effects of the transformers as well as surge arresters shall not be active for the verification procedure.

The connectee shall evaluate the saturation effects of the transformers as well as surge arresters for selected cases of the conformity check, as a variation to the standard tests without these effects.

All assumptions, model simplifications and settings shall be documented and described in detail.

The EMT model used for the verification procedure shall be delivered to TSO to ensure the reproducibility of the study results.

8.6 Evidence of system conformity

For the verification of the grid forming control, the connectee shall analyse all cases defined in chapter 7 with each revision of the Dynamic Conformity Study according to [8].

During project execution, the connectee shall comprehensively document the verification procedure and create a graphical comparison of the respective envelope curves and the associated curves from the connectee's DuT system behaviour, if required by the TSO.

All envelope curves will be handed over by TSO in csv format.

The connectee shall deliver in csv format all variables, which have been defined as acceptance criteria and which have been listed in table 1.