# Offshore Grid Connection Requirements

# Annex A_10: Harmonic Stability Study

Area of application: DC-connected Offshore Windfarms

**Revision history**

| Rev. Number | Date | Change | Author |
|---|---|---|---|
| 1.0 | 28.07.2025 | First edition | O. Kerfin (AMP)<br>T. Nguyen (50HzT) |
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# 1 General

This document provides supplementary requirements for [1] and [2]. This annex describes the minimum requirements for the harmonic stability study to be performed by the connectee to demonstrate compliance with the grid code of TSO.

Harmonic stability refers to unintended control interactions at frequencies below and above the nominal frequency. It can lead to significant unwanted interactions and therefore needs to be prevented. The connectee shall prove that the overall system operates correctly under normal operation and all defined contingencies, without unacceptable adverse effects due to the interaction of the control system with physical resonances or with other controllers in the grid.

The study may not need to be performed if the installation of the connectee does not have controllers with a bandwidth above nominal frequency. In such a case the connectee shall provide frequency scans of the machine controllers to justify the assumption.

# 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] J. Sun, „Impedance-Based Stability Criterion for Grid-Connected Inverters", IEEE Transactions on Power Electronics, vol. 26, no. 11, November 2011

# 4 Definitions

| | |
|---|---|
| TSO | Transmission System Operator |
| GCP | Grid Connection Point |
| PCC | Point of Common Coupling |
| OWF | Offshore Windfarm |
| WTG | Wind Turbine Generator |

# 5 Requirements for Harmonic Stability Study

*Informative: The assessment of control interactions is split into a screening study, which is performed in the frequency domain, and a detailed study, which shall be performed in the time domain. Performing the detailed study is necessary if stability margins are below the values defined within this document.*

If the installation of the connectee has control loops with bandwidths above nominal frequency and all data is available and delivered by the TSO, the connectee shall perform the harmonic stability study.

*Informative: To perform a control interaction study, vendor models and detailed grid information must be available. Otherwise, results may not reflect reality.*

The connectee shall use the method "impedance-based stability criterion" as described in [3].

The connectee shall consider a frequency range between 1 Hz and 2500 Hz with a stepwidth of 1 Hz.

The connectee shall calculate the phase and gain margins at all GCPs of the installation of the connectee.

If the impedance-based stability criterion cannot be applied to the entire frequency range, the connectee shall determine the applicable frequency range. If applicable, the connectee shall propose and agree with the TSO on an alternative method outside the frequency range for which the impedance-based stability criterion can be applied.

The connectee shall consider data of neighbouring power-electronic-based systems (e.g. other OWFs) provided by the TSO.

If a DC-connected OWF consists of several distributed WTGs, all relevant switching configurations of its internal grid shall be considered.

The connectee shall determine the relevant switching configurations of the internal grid of the DC-connected OWF considering

- operation philosophy,
- energisation sequence.

*Informative: Intermediate switching configurations during energisation which are needed to reach the final switching configuration may be instable. Thus, it must be ensured that intermediate switching configurations can be operated safely.*

The connectee shall provide and agree with the TSO a list of all relevant switching configurations.

The connectee shall consider all frequency responses provided by the TSO.

The connectee shall consider all operating scenarios provided by the TSO.

The connectee shall consider all extension variants provided by the TSO.

*Informative: In the following requirements, the term output impedance is used. The output impedance of the installation of the connectee is the frequency dependent impedance of the installation of the connectee seen from the GCP.*

*Informative: Output impedances change the stability margins at the GCP. Therefore, it is necessary to consider their variation. To limit additional work, it is only necessary to perform further studies if the changes of the output impedance exceed 10 % in amplitude or 20° in phase.*

If the output impedance varies significantly (in this context, significant means more than 10 % in amplitude or 20° in phase) related to the impedance at 100 % $P_{AV}$ and 0 % $Q_{max}$ for the installation of the connectee, additional calculations shall be done. For installations of the connectee providing mainly reactive power, the impedance curve based on 0 % $P_{AV}$ and 100 % $Q_{max,ind}$ shall be the reference. The following influencing factors shall be considered, if applicable:

- If the output impedance varies significantly due to **variations in active power infeed** (if applicable), additional calculations shall be done at least for the impedance values

with significant deviations. Impedance curves with different steps of active power infeed with a step size of 10 % $P_{AV}$ between 0 % and 100 % shall be considered.

- If the output impedance varies significantly due to **variations in reactive power infeed**, additional calculations shall be done for:
  - **Installations providing mainly active power:**
    At least for the impedance values with significant deviations impedance curves with minimum, maximum and zero reactive power shall be considered.
  - **Installations providing mainly reactive power:**
    At least for the impedance values with significant deviations impedance curves with different steps of reactive power infeed with a step size of 50 % $Q_{max}/P_{AV}$ between $Q_{max,inductive}$ and $Q_{max,capacitive}$ including Q = 0 MVar shall be considered.
- If the output impedance varies significantly due to **variations in AC operating voltages**, additional calculations shall be done. At least for the impedance values with significant deviations impedance curves with 90 %, 100 % and 110 % of the nominal voltage shall be considered.
- If the output impedance varies significantly due **to different control modes**, additional calculations shall be done. At least for the impedance values with significant deviations impedance curves with all available control modes shall be considered.
- If the impedance varies significantly due to **variations in switching configurations**, additional calculations shall be done. At least for the impedance values with significant deviations, impedance curves with all possible switching configurations shall be considered. If the installation of the connectee uses several parallel grid connection transformers then all calculations shall be performed using one and two, etc. grid connection transformers.

  *Informative: The different output impedances change the phase and gain margin at the PCC. Therefore, it is necessary to consider its variation. To limit additional work it is only necessary to perform further studies if the changes of the output impedance exceed 10 %.*

If countermeasures are necessary to ensure a stable operation, then all calculations shall be repeated with implemented countermeasures. Calculated results shall be compared with calculation results where no countermeasures were implemented.

*Informative: If countermeasures are necessary to ensure a stable operation it shall be proven that the countermeasures are sufficient to enable a stable operation.*

If the phase margin is smaller than 35° or the gain margin is below 15 dB, the connectee shall perform a detailed EMT study for the corresponding variant.

# 6 Requirements for Follow-Up Detailed EMT Study

The connectee shall prepare a study outline report which needs to be approved by the TSO.

The connectee shall build up all models in his simulation tool for conventional assets (e.g. lines, cables, transformers, loads, power plants, ….) by himself. If the TSO delivers models for special assets, the connectee shall use them. The connectee shall perform switching configuration changes, control mode changes, etc. to create the instable scenario.

The connectee shall identify the elements which are causing the instability.

If the TSO does not deliver models for special assets, the connectee shall consider the frequency dependent impedance(s) which led to a violation of the phase and/or gain margin in a detailed EMT study by fitting them to an equivalent RLC model.

If countermeasures are necessary to ensure a stable operation, then all calculations shall be repeated with implemented countermeasures. Calculated results shall be compared with calculation results where no countermeasures were implemented.

*Informative: If countermeasures are necessary to ensure a stable operation it shall be proven that the countermeasures are sufficient to enable a stable operation.*

# 7 Evaluation Criteria

The TSO will check stability margins of provided scenarios, variations, grid extension variants, etc.

The TSO will check modelling of the detailed study, if applicable.

The TSO will check and evaluate simulation results of the detailed study, if applicable.

The TSO will evaluate on proposed countermeasures, if applicable.

# 8 Documentation

The connectee shall display all frequency dependent output impedance curves of the installation of the connectee.

The connectee must provide all impedance curves in a machine-readable format.

The connectee shall display all calculated stability margins including the switching configurations within the following Tables 1 and 2.

Table 1: Phase margin

| Grid scenario | Switching configuration new installation of the connectee | Operating point new installation of the connectee | Phase margin in ° |
|---|---|---|---|
| … | | | |
| … | | | |

Table 2: Gain margin

| Grid scenario | Switching configuration new installation of the connectee | Operating point new installation of the connectee | Gain margin in dB |
|---|---|---|---|
| … | | | |
| … | | | |