Offshore Grid Connection Requirements

Annex A_09: Harmonic performance study

Area of application: DC-connected Offshore Windfarms

Revision history

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

1 General

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

The steady state harmonic study shall verify that the connectee-specific distortion levels defined by the TSO according to relevant standards for the emission and amplification of harmonics can be complied with. Any possible amplification of harmonics shall be determined and measures have to be investigated and implemented to prevent that the interaction of physical resonances with the harmonic sources results in unacceptable levels of harmonic distortion.

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] DIN EN 61000-4-7 VDE 0847: Electromagnetic compatibility (EMC)
[4] 50HzT, AMP: Offshore Grid Connection Requirements, Annex A_03 Grid Data Provided by the TSO

4 Definitions

TSO	Transmission System Operator
GAP	Grid Access Point
GCP	Grid Connection Point
PCC	Point of Common Coupling
OWF	Offshore Windfarm
WTG	Wind Turbine Generator
THD	Total Harmonic Distortion

5 Study requirements

For performing the harmonic studies, the TSO will hand over the frequency dependent grid impedances (impedance envelopes) at the GAP. The connectee shall prepare the steady state harmonic study at the node(s) GAP.

The connectee shall consider frequency steps of 50 Hz for all integer multiples of 50 Hz. A frequency range between 100 Hz and 2500 Hz shall be used.

> *Informative: If frequency bands of 200 Hz are given for frequencies above 2 kHz the connectee shall use them.*

The connectee shall consider all supraharmonics if the calculated harmonic distortion at that frequency at the GAP exceeds 0.1% of nominal fundamental frequency voltage. Those harmonics shall be grouped to bands of 200 Hz according to [3]. A frequency range between 2500 Hz and 9000 Hz shall be considered.

The connectee shall consider all interharmonics which cause a harmonic distortion at that frequency at the GAP above 0.1% of nominal fundamental frequency voltage. Those interharmonics shall be grouped to bands according to [3]. A frequency range between 75 Hz and 2475 Hz shall be considered.

The connectee shall use impedance envelopes handed over by the TSO for the respective grid. In special cases the TSO will hand over different sets of impedance envelopes.

> *Informative: In special cases, e.g. if some configurations exist with a rare likelihood but pronounced resonances, the TSO may provide more than one set of impedance envelopes. This will be done to ensure that very unlikely configurations will not lead to an exceedance of planning levels.*

If it is necessary to make further assumptions by the connectee for performing this study, the assumptions shall be accepted by the TSO before the study is done.

The connectee shall calculate the harmonic distortion at the node(s) GCP resulting from injected harmonics at the node(s) GAP. The harmonic model of the installation of the connectee according to the grid code shall be used.

The connectee shall use the worst case 95 % quantile of the harmonic emission over all operating points of the connectee's installation model according to the grid code.

If harmonic limits for 3 s are given, the connectee shall use in addition the 99 % quantile of the 3 s average values of the model according to the grid code.

> *Informative: In the following requirements the term output impedance is used. The output impedance of the connectee's installation is the frequency dependent impedance of the connectee's installation seen from the GAP.*
>
> *Output impedances change with operating point and operating modes. Different output impedances change the harmonic distortion at the $PCC_{AC,off}$. 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 according to the model defined in the grid code varies significantly (in this context, significant means more than 10 % in amplitude or 20° in phase) related to the impedance at 100 % $\boldsymbol{P_N}$ and 0 % $\boldsymbol{Q_N}$ of the connectee's installation, the following influencing factors shall be considered, if applicable. For installations of the connectee providing mainly reactive power, the output impedance curve based on 0 % $\boldsymbol{P_N}$ and 100 % $\boldsymbol{Q_N}$ shall be the reference.

> *Informative: $\boldsymbol{Q_N}$ refers to the nominal reactive power specified by the TSO in [4].*

- different infeed of active power
- different infeed of reactive power
- different AC continuous operating voltages
- control modes
- switching configurations

If an OWF consists of several distributed power generation units, 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 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 has to be assured that intermediate switching configurations can be operated safely.

The switching configurations are to be agreed in detail between the OWF and the TSO. The connectee shall provide and agree with the TSO a list of all relevant switching configurations.

If the 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 % $\boldsymbol{P_N}$ between 0 % and 100 % shall be considered. The connectee may use harmonic emission quantiles which correlate to the appropriate output impedance.

If the output impedance varies significantly due to variations in reactive power infeed, additional calculations shall be done. 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. The connectee may use harmonic emission quantiles which correlate to the appropriate output impedance. In this case the connectee shall provide the used harmonic emission in the steady state harmonic model.

If the output impedance varies significantly due to variations in continuous 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. The connectee may use harmonic emission quantiles which correlate to the appropriate output impedance. In this case the connectee shall provide the used harmonic emission in the steady state harmonic model.

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. The connectee may use harmonic emission quantiles which correlate to the appropriate output impedance. In this case the connectee shall provide the used harmonic emission in the steady state harmonic model.

If the output 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. The connectee may use harmonic emission quantiles which correlate to the appropriate output impedance. In this case the connectee shall provide the used harmonic emission in the steady state harmonic model.

The connectee shall consider minimum, middle and maximum tap changer positions of its grid connection transformers, if applicable.

If the TSO provides harmonic current planning limits, the connectee shall calculate the harmonic current injection caused by his installation. For its calculation, the connectee shall consider all the above requirements

If countermeasures are necessary to keep the harmonic distortion within harmonic planning limits provided by the TSO, then all calculation 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 fulfill harmonic requirements it shall be proven that these are lowering the harmonic distortion.*

The connectee shall attach the frequency dependent impedances of WTG transformers, loads, reactors and active elements in figures and tables using a maximum frequency step of 10 Hz in the range between 75 Hz and 9000 Hz in a machine-readable format to the study report.

Above 2 kHz the connectee may use frequency steps of 50 Hz.

> *Informative: The TSO will perform own harmonic calculations during the lifetime of the installation of the connectee. Therefore, it needs to know the frequency dependent behavior of all relevant assets.*

The connectee shall display all impedance loci together with the impedance of the OWF installation of the connectee within one figure for each harmonic frequency in the report. The size of the figure should be at least one third of a DIN A4 page.

> *Informative: The evaluation of the performed steady state harmonic study is only possible if relevant information like impedances is displayed in the study report.*

The connectee shall present all calculated amplification factors in a table.

The connectee shall compare the calculated harmonic distortion in a table and figure with the specified incremental limits.

The connectee shall compare the calculated harmonic currents with the harmonic current planning limits, if applicable.

6 Evaluation criteria

The TSO will compare individual harmonic planning levels and THD for harmonic voltage distortion (10 min. average values) with the planning levels.

The TSO will compare individual harmonic planning levels and THD for harmonic voltage distortion (3 sec. average values) with the planning levels, if applicable.

The TSO will compare individual harmonic planning levels for harmonic currents with the planning levels, if applicable.

The TSO will compare distortion levels for interharmonics and supraharmonics with the planning levels.

The TSO will evaluate on proposed countermeasures, if applicable.

7 Documentation

The connectee shall document which operating point lead to the highest harmonic distortion at the GAP if applicable.

The connectee shall mark within the impedance loci the area with the highest amplification fac-

tor.

The connectee shall use the following tables in the study report

Table: amplification factor for harmonic emission

Harmonic order h	Operational state of system resulting in highest amplification factor	Resistance at connection point of the distorting installation in Ohm	Reactance at connection point of the distorting installation in Ohm	Offshore Grid Resistance at connection point of the distorting installation in Ohm	Offshore Grid Reactance at connection point of the distorting installation in Ohm	Maximum amplification factor at connection point in p.u.
…						
…						

Table: harmonic distortion

Harmonic order h	Operational state resulting in highest harmonic distortion	Harmonic distortion due to emission in %	Harmonic distortion due to background amplification in %	Harmonic distortion due to emission and background amplification in %	Emission limit in %	Compliance with emission limit
…						Yes/No
…						Yes/No

Table: THD

Harmonic	Emission level in %	Emission limit in %	Compliance with emission limit
THD			Yes/No
			Yes/No

Table: interharmonics and supraharmonics

Harmonic	Emission level in %	Emission limit in %	Compliance with emission limit
Interharmonic			Yes/No
Supraharmonic			Yes/No

Table: harmonic current distortion

Harmonic order h	Operational state resulting in highest harmonic current	Harmonic distortion due to emission in %	Emission limit in %	Compliance with emission limit
…				Yes/No
…				Yes/No