Offshore Grid Connection Requirements

Annex A_06: Requirements for harmonic simulation model

Area of application: DC-connected Offshore Windfarms

Revision history

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

1 General

This document provides supplementary requirements to [1] and [2]. This annex describes the minimum requirements of the TSO for the harmonic simulation model for DC-connected Offshore Windfarms (OWF) to demonstrate compliance with the grid code of TSO.

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

4 Definitions

TSO	Transmission System Operator
HVDC	High Voltage Direct Current
EMT	Electromagnetic Transients

5 Model deliverables

The connectee shall develop and provide to TSO detailed harmonic simulation model in the DIgSILENT PowerFactory software and machine-readable format (e.g., text files or Excel tables).

The model shall be provided with a detailed documentation, chosen damping or filter parameters with explanations and in a runnable file combined with the project specific HVDC model and with a Thevenin Source. The connectee shall validate the model and provide a validation report.

6 Model requirements - AC steady state harmonic model

The harmonic model shall be a Norton or Thevenin equivalent. The source in the Norton or Thevenin equivalent shall be frequency dependent.

The model shall be developed by considering measurements and/or calculation results.

The steady state harmonic model shall be provided in positive and negative sequence, if there are any differences between positive and negative sequence in either the harmonic emission or the frequency dependent impedance.

The harmonic model in integer multiples of 50 Hz as well as their phase angles shall be provided in a frequency range between 100 Hz and 9000 Hz for each power bin (e.g., 0,1 P_N, 0,2 P_N, …., 1 P_N)

The interharmonics shall be provided in a frequency range between 75 Hz and 8775 Hz in steps of 50 Hz for each power bin.

Informative: The connectee shall provide TSO with the steady state harmonic model of the system enabling TSO to assess the harmonic distortion levels.

The model shall include the 95 % and 100 % quantile harmonic voltage emission of the system for each power bin. The connectee shall provide the 99 % quantile of the 3 s average values of the harmonic emission additionally, if available.

The model shall include all worst case 95 % quantile harmonic emission in the range between 100 Hz and 9000 Hz in each power bin. The integer harmonics shall be grouped in harmonic subgroups.

The model shall include the phase angle of each integer harmonic (prevailing angle and prevailing angle ratio) for each power bin for frequencies between 100 Hz and 9000 Hz. The phase angle shall be given relative to the terminal fundamental voltage angle, i.e., relative to the zero-crossing of the fundamental voltage.

The model shall include all worst case 95 % quantile interharmonic emissions with a frequency step of 50 Hz for frequencies between 75 Hz and 8775 Hz. The interharmonics shall be grouped in interharmonic subgroups.

The impedance in the Norton or Thevenin equivalent shall be frequency dependent: The model shall contain the frequency dependent output impedances of the system considering influence of the control. The frequency dependent impedances shall be calculated separately in positive and negative sequence.

The frequency dependent impedance shall be provided for the unit at the transformer primary side (incl. frequency dependent impedance of all relevant equipment in the unit, e.g., transformer, converter reactor, filter based on supplier data and impacts from the auxiliary system, if applicable).

The connectee shall calculate and provide the frequency dependent impedance of the unit (real and imaginary part or magnitude and phase) for the frequency range from 0 Hz to 9000 Hz (or to a higher frequency if requested by TSO).

The connectee shall provide the converter impedance with a resolution of at least 0.1 Hz in the sub-synchronous range and at least 1 Hz in the super-synchronous range.

The connectee shall separately provide frequency dependent impedances of all relevant equipment (e.g. transformer, converter reactor, filter, cable, etc.) based on supplier data. The data shall be provided in figures and tables using a maximum frequency step of 1 Hz in the range between 0 Hz and 9000 Hz in a machine-readable format attached to the study report.

The frequency dependent impedance model shall be based on supplier data and not on generic models.

Informative: Steady-state harmonics affect the measurement of impedance at integer multiples of 50 Hz. Care should be taken to determine and then remove steady-state harmonics at the perturbation frequency when calculating the ratio of small-signal voltage to current to determine the impedance.

The frequency dependent output impedances shall be provided for every power bin if the real or imaginary part of the output impedance varies for more than 10 % or 5 Ohm in amplitude or 20° in phase (related to the reference impedance at 100 % $\boldsymbol{P}_{\mathbf{AV}}$ and 0 % $\boldsymbol{Q}_{\mathbf{ref}}$) considering the following influencing factors:

- Different steps of active power infeed with steps of 10 % $\boldsymbol{P_{AV}}$ between 0 % and 100 % $\boldsymbol{P_{AV}}$
- Different steps of reactive power infeed with steps of 10 % $\boldsymbol{Q_{ref}}$ between -$\boldsymbol{Q_{ref}}$ and +$\boldsymbol{Q_{ref}}$
- Different AC operating voltages (90 %, 100 % and 110 % U_r).
- Different control modes.
- Minimum, middle and maximum tap changer position of the wind turbine transformer, if applicable.

If the connectee states that a provision of separate output impedance is not necessary because the difference of the output impedance is below 10 % in amplitude or 20° in phase, the connectee shall justify this.

The connectee shall also provide a harmonic model with active damping or active filtering function as defined. For the impedance calculation, the connectee shall activate the active damping or active filtering in the specified frequency bandwidth starting with a target frequency from 0 Hz in 1 Hz increments. The connectee may keep bandwidth and virtual resistor of the active damping function at a constant value, to be agreed with TSO, for this calculation.

7 Model requirements – Harmonic stability model

Harmonic stability models of the system shall be developed by the connectee and provided to TSO.

Informative: The connectee shall provide TSO with the harmonic stability model of the system enabling TSO to detect any unsecure or inadmissible operational state in the onshore and/or offshore grid.

If the output impedance of the harmonic stability model is different from the output impedance delivered in the steady state model, the connectee shall justify this. The connectee shall name and justify simplifications which were made when calculating the output impedance of the system.

8 Validation

The documentation of the validation shall be provided together with the model.

Informative: Any harmonic stability analysis is based on reliable models of active elements. Therefore, TSO requests special attention to the model validation.

The frequency dependent impedance shall be validated by at least one of the following methods, excluding the method that was used to derive the impedance:

- EMT model,
- Real Time Simulation,
- Analytical model or
- Measurement during commissioning test

The validation shall be performed for all provided frequency dependent impedance curves. The validation shall be performed with a frequency step of 1 Hz from 0 Hz until 9000 Hz. TSO will consider the model as valid if the real and imaginary part of the unit frequency dependent impedance deviate less than 10 % or 5 Ohm in amplitude or 20° in phase.

The harmonic emission provided in the steady state harmonic model shall be validated by at least one of the following methods, excluding the method that was used to derive the impedance:

- EMT model,
- Real Time Simulation,
- Analytical model or
- Measurement during commissioning test.

The harmonic emission shall be validated for all given operating points in the model. The deviation between the harmonic model and the validation results shall not exceed 3%.

9 Documentation

The connectee shall document the models in line with general requirements on documentation as defined in this document and in [3]. The model user manual shall include a suitable description of the model: The documentation shall include a description of the method used to derive the frequency dependent impedance.

If the frequency dependent impedance was derived from the EMT-model, the documentation shall include the information needed to ensure reproducibility by TSO. The documentation shall include a description of the method used to derive the harmonic voltage source. In case the model is derived from measurements, the measurement report shall be provided.

The documentation shall include a description of the method used to validate the frequency dependent impedance. The connectee shall provide all necessary information for the interpretation of the converter impedance. The documentation shall include a description of the method used to validate the harmonic voltage source. In case the validation is done with measurements the measurement report shall be provided.