Offshore Grid Connection Requirements

Annex A_07:

Dynamic Performance Study

Area of Application: DC-connected Offshore Windfarms

Revision history

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

1 General

This annex specifies the minimum requirements for the dynamic performance study to be delivered by the connectee to demonstrate the dynamic performance of the DC-connected offshore windfarm (OWF) and the **compliance** with [1] and [2].

The study can comprise of two parts:

- A pre-study of the Dynamic Performance at an early stage in the control design, called Dynamic Design Study. The **Dynamic Design Study** compares the dynamic performance of the DC-connected OWF with the requirements given in [1] and [2]. It is not needed to fulfil all requirements when the study is executed. Rather, the goal is to clearly reveal the gaps between requirements and asset performance, to show the general feasibility to close these gaps and to define action items.
- A dynamic performance study with a final control design in the **Dynamic Conformity Study**. At the end of this study, the DC-connected OWF shall show full compliance with the requirements given in the grid code of TTG.

All requirements from section **B.3 of [1]**, detailed by the requirements in this document, shall be fulfilled.

Unless indicated otherwise, the use of an **EMT model** in accordance with [6] is mandatory.

The report shall state for all p.u. and % values the respective base value.

The report shall be provided in the final version as soon as all data is available.

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] 50HzT, AMP: Offshore Grid Connection Requirements, Annex A_03 Grid Data provided by the TSO
[5] 50HzT, AMP: Offshore Grid Connection Requirements, Annex A_04 Requirements for RMS Simulation Model
[6] 50HzT, AMP: Offshore Grid Connection Requirements, Annex A_05 Requirements for EMT Simulation Model
[7] 50HzT, AMP: Offshore Grid Connection Requirements, Annex A_08 Grid Forming Control Study
[8] DIN EN IEC 61400: Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics –Wind turbines

4 Definitions

AC	Alternating Current
DC	Direct Current
EMT	Electromagnetic Transients
FSM	Frequency Sensitive Mode
GCP	Grid Connection Point
HVDC	High Voltage Direct Current
HVRT	High Voltage Ride Through
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LFSM	Limited Frequency Sensitive Mode
LVRT	Low Voltage Ride Through
OWF	Offshore Windfarm
ONAR	Offshore-Netzanschlussregel
p.u.	per Unit
RMS	Root Mean Square
TSO	Transmission System Operator
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e. V.
WTG	Wind Turbine Generator

5 Requirements for the Dynamic Design Study

In the Dynamic Design Study the connectee shall compare the dynamic performance of the DC-connected OWF with the requirements given in [1] and [2].

For this study, the TSO does not request fulfilling all requirements when the study is executed. The connectee will reveal and clearly describe the gaps, if any, between requirements and asset performance.

The connectee can use a preliminary EMT and RMS model of the DC-connected OWF. At the end of the study, the connectee shall deliver the complete EMT and RMS models as used in the Dynamic Design Study to the TSO to ensure the reproducibility of the study results. The provided model shall comply with the requirements stated in [5] and [6].

In order to allow the TSO to reproduce the results, the connectee shall provide all necessary tools and data with all calculation scenarios in the model implemented in form of study cases that were used in the study.

The connectee should use a Thevenin source equivalent considering the minimum and maximum short-circuit current of the offshore grid according [4].

Before commencing the detailed analyses, the connectee should provide a brief overview of the dynamic performance of the DC-connected OWF. For that purpose, the connectee should simulate the following cases:

- 3ph short circuit at the GCP with 0 p.u. residual voltage and 150 ms fault clearing time,
- 1ph short circuit at the GCP with 0 p.u. residual voltage and 150 ms fault clearing time,
- 3ph short circuit at the GCP with 0.7 p.u. residual voltage and 150 ms fault clearing time,
- Step in voltage angle of 30° at the GCP,
- Frequency gradient of +2 Hz/s from 50 Hz to 51.5 Hz at the GCP

The connectee should provide a detailed analysis for every simulation, including the description of the behavior with direct reference to plots, figures and measurements and possible flexibilities in the current control design to further improve the dynamic performance.

The connectee should include a detailed description of the relevant controllers and describe their impact on the dynamic performance of the DC-connected OWF in the study.

The detailed analysis and evaluation of dynamic design study shall include the following aspects:

- Active power control in accordance with section 7.
- Active power controls depending on frequency in accordance with section 8.

- Emergency power control activation and its impact on the system in accordance with section 9.
- Reactive power control in accordance with section 10.
- FRT capability of the DC-connected OWF covering LVRT and HVRT capability in accordance with section 11.
- Dynamic voltage support in accordance with section 12 and in accordance with [7].
- Active power recovery after a fault in accordance with section 13.
- Instantaneous reserve provision in accordance with section 14 and in accordance with [7].
- HVDC converter blocking behavior in accordance with section 15.
- Load shedding and asymmetrical longitudinal faults in accordance with section 16.
- Transient energization behavior in accordance with section 17.
- Active damping / active filtering function in accordance with section 18.

The connectee shall provide a study report summarizing all study results that is in line with the requirement for documentation stated in section 19 and in [3].

6 Requirements for the Dynamic Conformity Study

The connectee shall demonstrate the dynamic conformity of the DC-connected OWF according to [1] and [2] with the final control design in the Dynamic Conformity Study.

Before commencing the detailed analyses, the connectee shall provide a brief overview of the dynamic performance of the DC-connected OWF by simulating the dynamic event cases defined in Section 5.

The connectee should compare the Dynamic Conformity Study results with the results from the Dynamic Design Study within a common diagram for all cases.

The connectee shall provide a detailed analysis for every simulation, including the description of the behavior with direct reference to the simulation results.

The connectee should include a detailed description of the changes in the relevant controllers after the Dynamic Design Study and describe their impact on the dynamic performance of the DC-connected OWF in the study, if applicable.

At the end of the study, the DC-connected OWF shall show full compliance with all requirements given in [1] and [2].

If changes in the hardware of controls, measurement or protection systems occur during the commissioning, trial or operation phase that may affect the dynamic behavior, the connectee shall repeat the affected parts of the dynamic conformity study. If the connectee with agreement of the TSO can verify that the changes do not influence the dynamic behavior, a repetition may not be necessary.

The connectee shall use the detailed EMT and RMS model of the DC-connected OWF following the requirement stated in [5] and [6]. The connectee shall use for the proof of slow control functions a RMS simulation. For fast control functions a EMT simulation shall be used.

Depending on the project-specific progress and the availability of models, the connectee shall perform the Dynamic Conformity Study with the project-specific HVDC model. If usage of a project-specific HVDC model is not possible due to unavailability, the TSO shall specify for each project whether the connectee shall use a project-specific HVDC model or a Thevenin source equivalent considering min. and max. short-circuit level provided by the TSO in [4].

The connectee shall deliver the full EMT and RMS models, as used for the Dynamic Conformity Study to the TSO to ensure the reproducibility of the study results in accordance with [3]. The provided model shall comply with the requirements stated in [5] and [6].

In order to allow the TSO to reproduce the results, the connectee shall provide all necessary tools and data with all calculation scenarios in the model implemented in form of study cases that were used in the study.

The detailed analysis and evaluation of dynamic conformity shall include the following aspects:

- Active power control in accordance with section 7.
- Active power controls depending on frequency in accordance with section 8.
- Emergency power control activation and its impact on the system in accordance with section 9.
- Reactive power control in accordance with section 10.
- FRT capability of the DC-connected OWF covering LVRT and HVRT capability in accordance with section 11.
- Dynamic voltage support in accordance with section 12 and in accordance with [7].
- Active power recovery after a fault in accordance with section 13.
- Instantaneous reserve provision in accordance with section 14 and in accordance with [7].
- HVDC converter blocking behavior in accordance with section 15.
- Load shedding and asymmetrical longitudinal faults in accordance with section 16.
- Transient energization behavior in accordance with section 17.
- Active damping / active filtering function in accordance with section 18.

The connectee shall prepare, present the study outline, and provide a study outline report.

Before commencing the study, the connectee shall wait for the TSO to approve the study outline.

The connectee shall prepare a test matrix in the outline that lists all simulation cases of the Dynamic Conformity Study to be considered. The test matrix shall be further developed jointly by the connectee and the TSO and shall be approved by the TSO before the start of the Dynamic Conformity Study.

If additional critical or relevant scenarios or fault cases are discovered during the study or during the evaluation of the results, the connectee shall investigate and add them to the initial test matrix.

The connectee shall provide a study report summarizing all study results that is in line with the requirement for documentation stated in section 19 and in [3].

7 Active Power Control Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding active power control in in [1] and [2].

The connectee shall provide evidence of conformity providing simulations (RMS) or overshoot measurement report (EMT or RMS) to be agreed between connectee and the TSO.

The DC-connected OWF shall demonstrate their capability to operate below a setpoint specified by the TSO.

The DC-connected OWF shall demonstrate that the setpoint is reachable with a ramp rate according to [1], [2] and [4].

The connectee shall demonstrate the dynamic behavior of the DC-connected OWF and the compliance with the technical requirements stated in 10.2.3.2 of [1] in terms of settings and accuracy of controls.

The active power of the OWF shall be within the tolerance area.

Dynamic power oscillations occurring during normal operation (e.g. due to wind gusts) and during or after network faults shall also be considered.

8 Requirements applying to Active Power Controls depending on Frequency

The connectee shall demonstrate the operation of the active power controls depending on frequency in accordance with [1] and [2].

The connectee shall use a RMS simulation.

The connectee shall perform the following simulation cases for different initial operating points in active power:

Table 8-1: Simulation cases for frequency-dependent active power control

	Operating points in active power in p.u. of contractual

	agreed active power P_{AV}:	
Overfrequency (f > 50.2 Hz) in the offshore network (dead band of the FSM mode = 200 mHz)	1 p.u.	0.4 p.u.
Underfrequency (f < 49.8 Hz) in the offshore network (dead band of the FSM mode = 200 mHz)	0.7 p.u.	0.4 p.u.
Overfrequency (f > 50 Hz) in the offshore network (dead band of the FSM mode = 0 mHz)	1 p.u.	0.4 p.u.
Underfrequency (f < 50 Hz) in the offshore network (dead band of the FSM mode = 0 mHz)	0.7 p.u.	0.4 p.u.

The connectee shall consider frequency steps and ramps big enough to activate a change in the active power by at least 10 % of the nominal power for all above simulation cases.

The connectee shall verify and provide a table for the steady-state parameters of the active power control depending on frequency for the FSM mode including droop, deadband and active power range in relation to the instantaneously available active power.

The connectee shall verify and provide a table for the steady-state parameters of the active power control depending on frequency for the LFSM mode including droop and frequency threshold value.

The connectee shall verify the dynamic parameters of the active power control depending on frequency, including step response time and settling time.

The connectee shall provide a table for the step response time and settling time according to Figure C.1 from [1] for a settling tolerance band of +/-5% of the steady state final value.

The connectee shall consider the delays caused by frequency measurement and communication. This shall be described in detail in the study report.

9 Emergency Power Control (EPC) Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding Emergency Power Control as given in [2].

The connectee shall simulate all EPC functions in accordance with [2].

The connectee shall provide evidence of conformity providing simulations (RMS) or measurement report to be agreed between connectee and the TSO.

The connectee shall describe the implementation details of the EPC function in the study report. The response time to the EPC signals shall be clearly described in terms of processing and transferring of the signal.

10 Reactive Power Control Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding reactive power control as given in [1] and [2].

The connectee shall use RMS simulation.

The connectee may use a Thevenin equivalent with min short circuit power to model the offshore grid. The modelling of the offshore grid shall be agreed with the TSO.

The connectee shall demonstrate the dynamics of all reactive power control modes, as defined in [1] and [2].

The connectee shall provide Bode plots of all reactive power control modes.

The connectee shall demonstrate the behavior of the DC-connected OWF when reaching the reactive power limits for all reactive power control modes.

The connectee shall demonstrate a smooth transition between the reactive power control modes as defined in [1] and [2].

The connectee shall demonstrate how the reactive power control modes may contribute to stabilizing the voltage magnitude in the offshore AC grid.

The connectee shall analyse how reactive power control modes and their controller parameters influence fault ride through (FRT) performance in accordance with section 5.11 and dynamic voltage support in accordance with section 6.6 of [2]as well as voltage stability during and after FRT.

The connectee shall analyse how different reactive power control modes support stabilizing the voltage magnitude during different events in the offshore grid, which increase or decrease the voltage magnitude, such as load shedding or energization of further DC-connected OWF in addition to the operational ones.

The connectee shall recommend and document in the study report a most suitable parameter set for the reactive power control modes.

The connectee shall simulate for active power of 1 p.u. of contractual agreed active power P_{AV} and reactive power control mode (Q = const.) the following transition: maximum inductive reactive power and grid voltage of 1.1 p.u. of nominal AC voltage $U_{AC,n}$ → maximum capacitive reactive power and grid voltage 0.9 p.u. of nominal AC voltage $U_{AC,n}$

The connectee shall show the dynamic reaction of the **reactive power control mode (Q = const.)** for the following step responses and evaluate the parameters:

- Step response in the reactive power set value of 5 % of $Q_{max,cap}$
- Step response in the reactive power set value from $Q_{max,ind}$ to $Q_{max,cap}$
- Step response in the reactive power set value from $Q_{max,cap}$ to $Q_{max,ind}$
- Step response of U_{GCP} of 5% of the nominal AC voltage $U_{AC,n}$.

The connectee shall evaluate and provide a table for the rise time, overshoot, and settling time for the settling tolerance according to [1] and [2] considering the variations in the operation of the DC-connected OWF.

The connectee shall show the dynamic reaction of the **power factor control mode** for the following step responses and evaluate the parameters rise time, overshoot, settling time.

- Step response in the power factor set value of 0.01 (capacitive)
- Step response in the power factor set value from cos $\varphi_{max,ind}$ to cos $\varphi_{max,cap}$
- Step response in the power factor set value from cos $\varphi_{max,cap}$ to cos $\varphi_{max,in}$

The connectee shall evaluate and provide a table for the rise time, overshoot, and settling time for the settling tolerance according to [1] and [2] considering the variations in the operation of the DC-connected OWF.

The connectee shall consider the variations in the operation of the DC-connected OWF considering the parameters shown below. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in bold.

Table 10-1: Variation in operation condition to be considered for reactive power and power factor control

Grid voltage in p.u. of nominal AC voltage $U_{AC,n}$ at the GCP	0.9 p.u.	**1.0 p.u.**	1.1 p.u.

Operating points in active power in p.u. of contractual agreed active power P_{AV}	0 p.u.	**1 p.u.**	

The connectee shall perform the following simulations regarding **voltage control mode with reactive power droop**: U_{set} step response test (p.u. base is nominal AC voltage $U_{AC,n}$)

- U_{GCP} = 1 p.u., U_{set} 1 p.u. → 1.01 p.u.
- U_{GCP} = 1 p.u., U_{set} 1.01 p.u. → 1.04 p.u.
- U_{GCP} = 1 p.u., U_{set} 1.04 p.u. → 1.08 p.u.
- U_{GCP} = 1 p.u., U_{set} 1 p.u. → 0.99 p.u.
- U_{GCP} = 1 p.u., U_{set} 0.99 p.u. → 0.95 p.u.
- U_{GCP} = 1 p.u., U_{set} 0.95 p.u. → 0.92 p.u.

The connectee shall evaluate and provide a table for the step response time, overshoot, droop, and settling time for the settling tolerance according to [1] and [2] for U_{set} steps as given in above.

The connectee shall consider the variations in the operation of the DC-connected OWF considering the parameters shown below. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in **bold**.

Table 10-2: Additional variation in operation to be considered for Q(U) control mode

Short circuit power without blocking of the HVDC as defined in [4]	**Minimum**	Maximum
Operating points in active power in p.u. of contractual agreed active power P_{AV}	0 p.u.	**1 p.u.**
Droop k minimum and maximum as defined in [1]	2%	**7%**

11 Fault-Ride-Through (FRT) Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF for the system need “FRT capability and fault behavior” in accordance with [1] and [2].

The connectee shall determine in agreement with the TSO if the FRT Simulation will be performed in RMS or EMT mode.

If the simulation shall be performed in RMS mode, the connectee shall ensure and document the applicability of RMS simulations based on EMT simulations (e.g., for behavior during asymmetrical faults).

The connectee shall verify the low voltage ride through (LVRT) capability of the DC-connected OWF. The connectee may use a controllable voltage source to apply different voltage drops and fault duration according to the LVRT profile within the specified boundary conditions given in [1] at the GCP.

The connectee shall simulate the following symmetrical and asymmetrical faults as well as remaining voltages and fault durations. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case

Table 11-1: List of faults for FRT simulation

		Fault type			
		Three phase	Two phase to earth	Two phase to phase	One phase
Remaining voltages in p.u. of nominal AC voltage $U_{AC,n}$ (fault duration according to Figure 15 of [1])	0				
	0.15				
	0.5				
	0.8				

The applied remaining voltage according to Figure 15 of [1] shall be the lowest voltage (phase to ground or phase to phase according to the fault type).

After the voltage drop the voltage shall be back to the pre fault value.

The simulation duration shall also cover a period of at least 1.5 s following voltage recovery.

The connectee shall verify the LVRT capability considering the variations in the operation of the DC-connected OWF as defined in the table below. The connectee shall provide time diagrams for the voltage drop and active and reactive current contribution.

The connectee shall verify the high voltage ride through (HVRT) capability of the DC-connected OWF. The connectee may use a controllable voltage source to apply different voltage steps and fault duration according to the HVRT profile within the specified boundary conditions given in Figure 15 of [1] at the GCP.

The connectee shall simulate the following voltage steps and fault durations: 1.25, 1.2 and 1.118 p.u. of nominal AC voltage $U_{AC,n}$ (overvoltage duration according to Figure 15 of [1].

The applied voltage steps according to Figure 15 of [1] shall be the highest voltage (phase to ground or phase to phase).

After the overvoltage period the voltage shall be back to the pre fault value.

The simulation duration shall also cover a period of at least 1.5 s following voltage recovery.

The connectee shall verify the HVRT capability, considering the variations in the operation of the DC-connected OWF as defined in the table below.

The connectee shall provide time diagrams for the voltage step and active and reactive current contributions.

The connectee shall consider the variations in the operation of the DC-connected OWF. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in **bold**.

Table 11-2: Variation of operation to be considered for FRT simulation

Grid voltage before the fault in p.u. of nominal AC voltage $U_{AC,n}$ at the GCP	0.9	**1.0**	1.1
Reactive power control mode as defined in [1] and [2]	Reactive power/voltage Q(U) characteristic with maximum droop	**Reactive power control**	Power Factor Control
Operating points in active power in p.u. of contractual agreed active power P_{AV}	0	0,5	**1**
Operating points in reactive power	full capacitive	**zero**	full inductive
Different switching configurations (e.g. grid connection transformers, shunt reactors or filter systems), if applicable.	**Two transformer per pole**	One Transformer per Pole	
Transformer tap positions, if	minimum	**neutral**	maximum

applicable			
Short circuit power without blocking of the HVDC provided by the TSO	**minimum**	maximum	

12 Dynamic Voltage Support Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding the system function “dynamic voltage control” as given in section 6.6 of [2].

The connectee shall provide a description of the control system relevant for the simulation results.

The connectee shall determine in agreement with the TSO if the simulation will be performed in RMS or EMT mode.

If the simulation is performed in RMS, the connectee shall ensure applicability of RMS simulations based on EMT simulations.

The simulations in dynamic voltage support with detailed HVDC model shall be performed in EMT mode.

The connectee shall provide time diagrams for the voltage step and active and reactive current contributions during the following voltage steps at the GCP:

1. Three phase voltage steps of ± 0.02 p.u. of nominal AC voltage $U_{AC,n}$
2. Three phase voltage steps of ± 0.05 p.u. of nominal AC voltage $U_{AC,n}$
3. The connectee shall consider the base cases of operation as specified in the table Table 12-1.

The connectee shall provide diagrams that shows maximum transient and settled positive and negative sequence active and reactive current contributions for each individual fault scenario (3p, 2pp, 2pe and 1p faults) in steps of 0.05 p.u. to the maximum voltage drop up to 1 p.u. at the grid connection point (only contribution of windfarm).

The applied voltage drop shall be the lowest voltage (phase to ground or phase to phase according to the fault type). The connectee shall investigate the impact on the settled active and reactive currents for all variation of operating scenario as shown in the table below. The connectee shall determine the settled active and reactive currents contribution for the positive and negative sequence.

The connectee shall provide a table for the step response time and settling time of the active and reactive currents according to Figure C.1 of [1] for a settling tolerance band of +/-5% of the steady state final value. The connectee shall identify the cases with the longest step response and settling time individually for every single variation of operation scenario. Based on the results of the variation in operation scenario, the connectee shall prepare one over-all worst-case scenario for the longest step response and settling time.

The connectee shall provide a table for the k-factor for positive, negative and zero sequences, if applicable.

The connectee shall consider the following variations in the operation of the DC-connected OWF. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in **bold**.

Table 12-1: Variation of pre-fault operation condition to be considered for dynamic voltage support simulation

Grid voltage before the fault in p.u. of nominal AC voltage $U_{AC,n}$ at the GCP	0.9	**1.0**	1.1
Reactive power control mode as defined in [1] and [2]	Reactive power/voltage Q(U) characteristic with maximum droop	**Reactive power control**	Power Factor Control
Operating points in active power in p.u. of contractual agreed active power P_{AV}	0	0,5	**1**
Operating points in reactive power	full capacitive	**zero**	full inductive
Different switching configurations (e.g. grid connection transformers, shunt reactors or filter systems), if applicable.	**Two transformer per pole**	One Transformer per Pole	
Transformer tap positions	minimum	**neutral**	maximum
Short circuit power without blocking of the HVDC provided by the TSO	**minimum**	maximum	

The connectee shall add a systematic analysis evaluating the impact of the variations of operation scenario on the settled active and reactive current contributions, maximum transient active and reactive currents, as well as on the response time and settling time of the active and reactive currents.

Additionally, the connectee shall provide evidence of conformity of the of the DC-connected OWF with the requirements regarding the system function “dynamic voltage support” as part of [7].

For the analysis of dynamic voltage support, the connectee shall perform the following cases in EMT mode considering the HVDC model. The connectee shall perform the simulation with the manufacturer HVDC model, if available. Otherwise, the HVDC system modelling shall be agreed between connectee and the TSO. The connectee shall consider the following fault cases:

Table 12-2: List of faults for dynamic voltage support simulation

		Fault type			
		Three phase	Two phase to earth	Two phase to phase	One phase
Remaining voltages in p.u. of nominal AC voltage $U_{AC,n}$ (fault duration according to Figure 15 of [1])	0				
	0.15				
	0.5				
	0.8				

The connectee shall consider various conditions for the DC-connected OWF according Table 12-1.

The connectee shall provide time diagrams according to the study report requirements stated in this document and [3].

The connectee shall evaluate the following for each case:

- settled active and reactive current contributions,
- maximum transient active and reactive currents,
- step response time and settling time of the active and reactive currents according to Figure C.1 of [1] for a settling tolerance band of +/-5% of the steady state final value.

13 Recovery of Active Power after a Fault

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding the system function “Power recovery after grid faults” as given in section 6.7 of [2].

The connectee shall use the simulations in dynamic voltage support to demonstrate the post-fault active power recovery.

14 Instantaneous Reserve Requirement

The connectee shall provide evidence of conformity of the DC-connected OWF with the requirements regarding the system function “instantaneous reserve” as given in [2].

The connectee shall perform the study in accordance with the grid forming control study as defined in [7].

15 Behavior during HVDC Converter Blocking

The connectee shall provide evidence of conformity and demonstrate the behavior of the DC-connected OWF in EMT simulation in case of blocking of the semiconductor valves in the HVDC converter, to which the OWF are connected, as given in [2].

The connectee shall provide a description of the control system relevant for the simulation results.

The connectee shall provide a description of the test grid and the method to apply the HVDC converter blocking. The current interruption shall be considered without delay and shall not expire at the next zero crossing (e.g. by simulating a simultaneous AC switching operation within the maximum current of a line).

The connectee shall test the behavior of the DC-connected OWF for the blocking of the semiconductor valves in the HVDC converter for 150 ms.

The connectee shall provide time diagrams for the voltage and active and reactive current contributions at the GCP and relevant nodes in the offshore grid for the base case of operation.

The connectee shall describe the method for the determination of the fundamental frequency overvoltage at the GCP.

The connectee shall evaluate and provide a table for the fundamental frequency overvoltage at the GCP considering the variations in the operation of the DC-connected OWF in the table below.

The connectee shall identify the cases with the highest fundamental frequency overvoltage at

GCP individually for every single variation, while keeping all other variations constant at the base case as shown in Table 15-1.

Based on the results of the variation the connectee shall prepare one overall worst-case scenario for the highest fundamental frequency overvoltage at GCP.

The connectee shall consider the following variations in the operation of the DC-connected OWF. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in bold.

Table 15-1: Variation of operation condition for HVDC blocking simulation

Grid voltage before the fault in p.u. of nominal AC voltage $U_{AC,n}$ at the GCP	0.9	**1.0**	1.1
Reactive power control mode as defined in [2]	Reactive power/voltage characteristic with maximum droop	**Reactive power control**	Power Factor Control
Operating points in active power in p.u. of contractual agreed active power P_{AV}	0 p.u.	0.5 p.u.	**1 p.u.**
Operating points in reactive power	full capacitive	**zero**	full inductive

The connectee shall evaluate the impact of the transformer saturation on the behavior of the DC-connected OWF in case of blocking of the semiconductor valves in the HVDC converter by comparing selected cases with and without transformer saturation activated in the EMT model, if applicable.

16 Load Shedding and Longitudinal Faults

The connectee shall demonstrate in EMT simulation the behavior of the DC-connected OWF for the following load shedding cases:

1. load shedding of 100% of contractual agreed active power P_{AV}
2. load shedding of 50% of contractual agreed active power P_{AV}
3. load shedding of one string

The load shedding is foreseen for unexpected circuit breaker opening events.

The connectee shall simulate the load shedding cases and define the worst case, considering the variations in the operation of the DC-connected OWF.

The connectee shall consider the variations in the operation of the DC-connected OWF. The connectee may reduce the number of simulation cases by varying only the respective parameter while keeping the other parameters fixed at the base case. The base case is highlighted in bold:

Table 16-1: Variation in operation to be considered

Grid voltage before the load shedding in p.u. of nominal AC voltage $U_{AC,n}$ at the GCP	0.9	**1.0**	1.1
Reactive power control mode as defined in [1]	Reactive power/voltage characteristic with maximum droop	**Reactive power control**	Power Factor Control
Different operating points in active power in p.u. of contractual agreed active power P_{AV}	**1.0**	0.5	
Different operating points in reactive power	full capacitive	**zero**	full inductive
Short circuit power without blocking of the HVDC as defined in [4]	**minimum**	maximum	

The connectee shall demonstrate the behavior of the DC-connected OWF for the following longitudinal fault cases:

1. Three-Phase interruption of one string
2. Two-phase interruption (L2-L3) of one string, if possible, with the applied switching devices.

3. Single-phase interruption (L1) of one string, if possible, with the applied switching devices.

The connectee shall simulate the longitudinal fault cases and define the worst case, considering the variations in the operation of the DC-connected OWF. The basic operations to be considered are full active power production with maximum capacitive, zero and maximum inductive reactive power operation.

The connectee shall provide as results for all fault cases time diagrams for the voltage, active and reactive power as well as active and reactive current contributions at the GCP for the base case and worst case.

17 Transient Energization Behavior

The connectee shall demonstrate in EMT simulation the stepwise start-up of the DC-connected OWF to verify energization without impermissible system perturbations. The sequence shall correspond to the realistic network set-up, usually as follows:

1. Energization of the submarine cables of the OWF
2. Energization of the generator transformers of the WTG.

The energization times shall be selected according to the system behavior planned or, implemented by the connectee.

Demonstrated shall be that:

- the voltage variation stays within the max 2% voltage drop
- the transient harmonics have to disappear in coordination with HVDC harmonic protection function and system design specification
- the transient harmonics shall not lead to an excitation in the system
- Additionally, a worst-case analysis shall also be conducted.

18 Active Damping / Active Filtering Function

The connectee shall investigate how the functionalities of active damping/ active filtering, as given in [2] may influence the dynamic performance of the DC-connected OWF.

In particular, the connectee shall analyse how the functionalities of instantaneous reserve, dynamic voltage support may be compromised by active damping or active filtering.

The connectee shall compare dynamic events for both activated and deactivated active damping/ active filtering function.

19 Documentation

The connectee shall ensure that the reports for the Dynamic Design Study and for the Dynamic Conformity Study comply with the minimum requirements for study report specified in [3].

The connectee shall describe all plots, measurement signals and measuring points covered in the simulations. Plots and measurement signals verifying the same system requirement may be described together.

The connectee shall prepare the study report including the following aspects:

1. The report shall include a list of simulation cases at the beginning of the report.
2. The report shall contain a summary of the results of all system requirements.
3. At each simulation case, a hyperlink shall be included, which leads directly to the plots of this simulation case. The plots may be attached to the report or may be in external files. Plots that do contain the most relevant information shall be marked.
4. The report shall include a list of assumptions, simplifications and restrictions, if applicable.
5. The connectee shall provide the version of simulation software, compiler and visual studio used for the study.
6. The connectee shall provide at least the following signals for all simulation cases:
    a. **AC voltage (magnitude and phase angle) and frequency** at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    b. **Active and reactive power and current** of the DC-connected OWF at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    c. **Active positive and negative sequence currents** of the DC-connected OWF at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    d. **Reactive positive and negative sequence currents** of the DC-connected OWF at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    e. **Positive and negative sequence voltages** of the DC-connected OWF at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    f. **Phase angle** for the positive sequence voltages of the DC-connected OWF at the connected $PCC_{ACoff,X}$ (with X = A,B,C,D,…) and GCPs as well as at the WTG terminal for the first and last WTG of a string
    g. **State of the chopper (energy/ thermal capacity)**, if applicable
7. The connectee shall provide a table containing all signals.
    a. The connectee shall uniquely name the signals in the table.
    b. The connectee shall enter the units for the signals in the table.
    c. The connectee shall enter the base reference in case of per unitized signals.
8. The figures shall include, besides the recorded signals, the acceptance criteria, if applicable. For example, if the FRT profile is verified, the profile should be drawn within the figures to easily evaluate if criteria are met.
9. For the calculation of RMS values used in the EMT simulation, the connectee shall use the calculation method as in [8].

10. Together with the study report, the connectee shall submit all plots to the TSO as high-resolution graphical files and machine-readable data files (e.g. Comtrade and PDF). The format shall be agreed with the TSO. Graphs shall be fully labelled (units, axes, relevant value points, etc.) and presented with sufficient resolution, if necessary, with color representation

The connectee shall provide the EMT and RMS simulation model together with the study. If the simulation software provides this feature, the connectee shall deliver snapshot files for all simulations together with the model. The model shall be fully initialized at the beginning of the snapshot.

In addition to the general requirement for the model documentation stated in [5] and [6], the following information shall be specified as minimum requirement in the study report as used input data:

- Magnetization characteristics of all relevant transformers;
- Information on the use of controlled switching (strategy, trigger values, devices used);
- If applicable, relevant technical data and application strategy of any existing pre-insertion resistors;
- If applicable, relevant technical data and deployment strategy for the use of choppers in the generating units;
- If necessary, supplementary information with regard to the dynamic control of both the individual generating units and the entire generating plant (e.g. setting values, control speed, supplementary block diagrams).

If changes in the hardware of controls, measurement or protection systems occur during the commissioning, trial or operation phase that may affect the dynamic behaviour, the Contractor shall repeat the affected parts of the conformity study.