POSITION PAPER

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1. Background Material

LITERATURE USED:
• NPR-IEC/TR 61000-3-6 Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

2. Scope and Considerations

For the roadmap offshore wind 2030 (routekaart windenergie op zee 2030) TenneT is tasked with the connection of several offshore wind farms up to 2030. The wind farm zones 'Hollandse kust West' and 'Ten Noorden van de Waddeneilanden' will be connected with TenneT's previously established and consulted standardized 700 MW grid connection concept. Due to its size and distance to shore, a new grid connection concept has been established for the wind farm zone IJmuiden Ver. The figure below shows a schematic cross-section of this new grid connection concept. Wind turbines are connected through 66 kV “inter-array” cables (in orange) to an offshore (HVDC) converter station. Using 2 GW high voltage (525 kV) export cables (in green) the electricity is transported to shore. TenneT will be responsible for the offshore grid, from the onshore substation up to and including, the offshore substation. TenneT intends to create a new standard HVDC grid connection concept for both connections to IJmuiden Ver and potential future far shore wind farms.

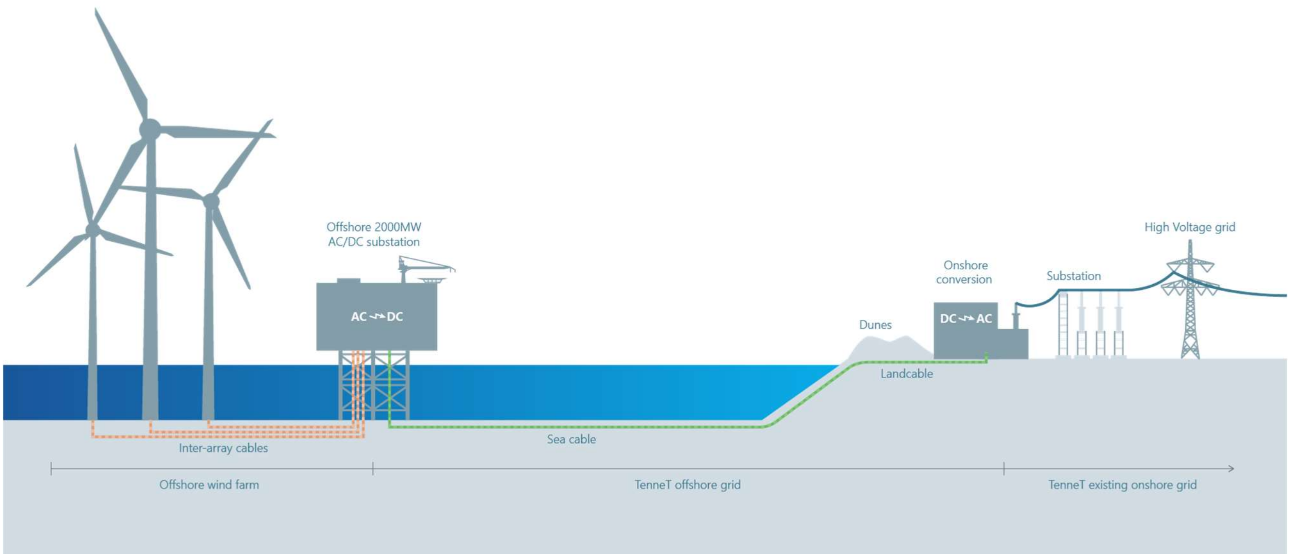

Figure 1 - HVDC grid connection concept

This paper describes how TenneT, as the offshore grid connection owner, proposes to deal with harmonics at the offshore grid.

3. Harmonics

3.1 Harmonic emission limits

Steady state harmonics got more and more attention in the past few years as power electronic based systems in combination with cables can cause high harmonic distortions in the network. Due to the fact that at this stage it is not possible to have detailed information of the offshore grid, the following engineering approach based on several steps is defined.

TenneT defines the planning levels of the harmonic emission limits at the 66 kV level, which will be further allocated to the individual connected parties based on the rated power of their installation. To meet the harmonic planning levels in the offshore grid, the planning levels for the high voltage grid given in IEC TR 61000-3-6 will be split between all PPMs of the OWFs and the offshore HVDC converter poles,. All connected parties shall plan for and take measures to fulfil the requirements.

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,8	1,4
7	4	2	9	1,2	1	4	1	0,8
11	3	1,5	15	0,3	0,3	6	0,5	0,4
13	2,5	1,5	21	0,2	0,2	8	0,5	0,4
$17 \leq h \leq 49$	$1{,}9 \cdot \frac{17}{h} - 0{,}2$	$1{,}2 \cdot \frac{17}{h}$	$21 < h \leq 45$	0,2	0,2	$10 \leq h \leq 50$	$0{,}25 \cdot \frac{10}{h} + 0{,}22$	$0{,}19 \cdot \frac{10}{h} + 0{,}16$

Table 1: Planning limits for harmonic voltages at 66 kV

At 66 kV level the defined offshore planning levels of the Total Harmonic Distortion (THD) are:

<u>Compatibility level:</u>
THD < 5 % for 95% of the ten minutes average measurements of one week;
THD < 6 % for 99,9% of the ten minutes average measurements of one week.

<u>Planning level:</u>
THD < 3 %, for 95% of the ten minutes average measurements of one week;
THD < 3,6 %, for 99,9% of the ten minutes average measurements of one week

As a starting point TenneT specifies the harmonic emission level E_{Uhi} per harmonic order and per PCC, for steady state operating conditions. The following remarks have to be made:

1) Harmonic compliance is determined at the 66 kV busbar (i.e. PCC) in order to cover the operational/contingency scenarios where switching re-configurations at the 66kV side have occurred (e.g. during monopole operation, transformer failure, etc.) resulting in different OWFs being

connected to the same bus (PCC). For example, the normal operational scenarios include topologies where all PPMs are connected to a single HVDC converter pole.

This means that the different OWFs shall exchange data (grid layout, impedances, etc,) to enable proper calculation. In case of the "other" OWF being unknown, the OWF shall base its calculations on a generic OWF (to be aligned with or provided by TenneT).

2) The harmonic emission limits will be allocated equally between the HVDC converter pole and the PPMs of the OWFs. This means that half of the planning limits will be allocated to the HVDC converter pole unit and the other half to all the PPMs. Due to the application of a bipole configuration with DMR cable in IJmuiden Ver, the two converter poles are electrically decoupled. However, due to the fact that one HVDC converter pole shall be designed to be connected to all PPMs during monopole operation, the PPMs need to share equally the remaining half of the planning limits at all times. Therefore, the following formula for emission limits per harmonic order for the OWF shall apply:

$$E_{Uhi} = \frac{L_{\mathrm{h66kV}}}{2} \times \frac{S_i}{S_t}$$

where,

L_{h66kV}: HV-EHV column according to table 2 of IEC 61000-3-6
S_i : Power capacity of an individual entity (including oil/gas field connections if applicable) connected at the PCC
S_t : Total power capacity connected to a single HVDC converter pole.

Any inter-harmonic emissions either from the HVDC converter poles or the PPMs shall be treated as part of the above mentioned harmonic emission limits, since in a solely power electronics based grid non-integer harmonics are equally likely to be present, if not more, as the integer harmonics. The inter-harmonic has any frequency which is not an integer multiple of the fundamental frequency.

As a second step, and as part of the detailed engineering phase during the construction part of the project, TenneT will ask the HVDC supplier to perform a harmonic analysis for the emissions levels of the HVDC converter units. This analysis will be based on fictional offshore grid and background noise data, as close as possible to reality (based on experience). During the harmonic analysis the HVDC supplier shall also cover the inter-harmonic and sub-harmonic emission levels of the HVDC converter units to demonstrate that no adverse effects are observed.

As a third step, TenneT will provide the applicable offshore grid impedance (frequency dependent) and background (HVDC converter) noise for each relevant HVDC-based transmission system to the OWF, once they become known. Based on such grid data, the OWF shall calculate their individual harmonic emissions, at the 66 kV busbar (PCC) as a percentage of the fundamental voltage (66kV). Each OWF shall prove through calculations that their installation complies with the harmonic emission limits set for each of the 66 kV busbars. The OWF shall consult TenneT when compliance cannot be achieved without the installation of filter equipment.

The fourth and final step is that TenneT will perform an overall harmonic study to verify that the planning levels at the PCCs on the HVDC platform are not exceeded during simultaneous operation of the OWF and HVDC station. All parties shall make the necessary information for these studies available to TenneT without restrictions, although always based on a non-disclosure agreement.

The step one up to and including four, based on several offshore grid configurations, is expected to be a part of the compliance verification process.

After completion of the construction phase, and as part of the operational preparedness activities, the amplitude of the harmonic voltage caused by the turbines' operation at each PCC will be measured. Performance shall be assessed by comparison of measured voltages against the values calculated/guaranteed by the OWF during the design stage.

3.2 Background amplification

In case of background amplification phenomena at the offshore PCCs, while the OWF being compliant with their individual harmonic limits at its 66 kV busbar, there will be a joint analysis between TenneT and OWF to determine the most efficient mitigation actions to remove the excessive distortion points.

In any case, TenneT will investigate in detail the effectiveness of harmonic damping controlling functions from the offshore HVDC station. Their duty will be to provide additional positive damping within a pre-defined frequency range to the best of the converters' capabilities.

It must be noted that the compliance and planning levels of the Total Harmonic Distortion (THD) at the 66 kV busbar should also be a design criterion for the PPMs of the OWFs. Therefore the OWF should take care of the withstand capability of their equipment against any amplification of background harmonics due to their inter array grid.

3.3 Control interactions – harmonic stability

Control interactions may happen if controllers, in this case of power electronic devices, get into resonance with the grid or other devices. In conventional power systems, this happens only at sub-synchronous frequencies. As power electronic devices also have control loops with a bandwidth higher than the nominal frequencies, this can happen at a wider range of frequencies and not necessarily in steady state operating conditions (e.g. during energisation, switchover procedures, etc.). If this phenomenon happens, higher order harmonics, not necessarily as integer multiples of the fundamental frequency, will be visible in the grid. These harmonics should not be mixed up with classical harmonics, which have a completely different root cause. In this case instability leads to harmonics which easily can reach several 10 % of the fundamental frequency voltage.

Additionally, special care needs to be taken so as no subharmonics are emitted by the HVDC converter poles and the PPM's to avoid problems of sub-synchronous control resonance. A subharmonic is an inter-harmonic with a frequency less than 50 Hz. In the absence of subharmonic emissions no consultations with the generator manufacturer are necessary to establish the specific limits for the HVDC converters and the PPM at specific frequencies.

It must be noted that the OWF developer is expected to deliver study results on this very topic; their exact description will be given in the grid compliance rules as part of the connection agreements. It is always the responsibility of the connecting party to do their utmost to ensure that their installation to the TenneT grid will not cause any stability problems to the overall performance of the system. If in the end stability problems do occur, all cost effective mitigation measures are compared and the most cost effective solution will be implemented (either HVDC converter or WTG).

In addition, TenneT also plans to analyse this topic based on a two-step approach. In the first step a screening study will be performed. TenneT prefers to use the impedance based stability criterion for the screening study. Within this approach the complete grid is divided into two parts, the generation unit and the rest of the grid. Within both parts frequency responses are calculated for different switching configurations. Afterwards all different combinations are evaluated using the Nyquist criterion and stability margins are calculated. If stability margins are low for certain switching configurations, these shall be analysed using electro-magnetic transients (EMT) simulations. These simulations shall show if results from the screening study are close to reality or too conservative. EMT-simulations should only be used after the screening study as they are very time consuming and not practical for screening the whole grid.

All in all, TenneT is responsible that the overall system operates correctly under all specified contingencies and operating conditions, without unacceptable adverse effects due to the interaction of the HVDC control system with physical resonances or with other controllers in the network. This may require all relevant information from the power park modules (PPMs) to become available.

4. Position TenneT

Above considerations lead TenneT to the following position:

TenneT specifies the total harmonic distortion, the harmonic emission levels per harmonic order (E_{Uhi}) and per 66 kV busbar (i.e. PCC) for the OWF for steady-state operating conditions.

The different OWFs shall exchange data (grid layout, impedances, etc,) to enable proper harmonic calculations. A detailed compliance procedure about harmonics will be prepared by TenneT in the coming years (prior to tender stage), where OWF developers will be further involved. TenneT is responsible to safeguard this procedure during the execution phase.

Harmonic studies will be performed by the OWF as part of the grid compliance procedure. Harmonic measurements will be made during system commissioning as part of the operational preparedness activities. In case of background amplification problems at the offshore PCCs, a joint analysis between TenneT and the OWF will be conducted to determine the most cost efficient mitigation actions.

TenneT will require harmonic damping controlling functions as part of the control and protection (C&P) system of the offshore HVDC station to effectively mitigate resonance problems during steady-state but also transient operating conditions.

Studies will be performed by both TenneT and OWF to analyse the offshore harmonic stability. TenneT remains responsible to prove that the overall offshore system operates correctly under all specified contingencies and operating conditions.