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ANNEX A – REQUIREMENTS FOR VOLTAGE QUALITY FOR THE CONNECTION OF HVDC SYSTEMS AND DIRECT CURRENT - REV 0

This specification of requirements presents Energinet's voltage quality requirements for the connection of HVDC facilities. The specification of requirements is included as background material in connection with the implementation of EU regulation 2016/1447 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (HVDC), and thus concerns requirements for HVDC facilities.

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	Original version for the Danish Utility Regulator	a	28-09-2018
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Please note that this is a translation of the original Danish text.
In case of inconsistencies, the Danish version applies.

Contents

Reading instructions

This specification of requirements includes all general and specific requirements for voltage quality for the connection of *HVDC facilities* to the *transmission grid*.

The specification of requirements is structured as follows: Section 1 contains terminology and definitions used in the specification of requirements. In the text, definitions are written in italics.

Section 2 contains objective, scope and regulatory provisions.

Sections 3 to 7 contain technical and functional requirements.

This specification of requirements is also published in Danish. If there are inconsistencies, the Danish version applies.

Present specification of requirements is published by Energinet and can be downloaded from Energinet's website, www.energinet.dk under Electricity - Rules and regulations.

1. Terminology and definitions

1.1 Definitions

This section contains the definitions used in this document.

1.1.1 Facility owner

The *facility owner* is the entity that legally owns the *HVDC facility*. The *facility owner* may hand over operational responsibility to a *facility operator*.

1.1.2 Facility component

A *facility component* is a component or subsystem which forms part of an overall *HVDC facility*.

1.1.3 Facility operator

The *facility operator* is the enterprise responsible for the operation of the *facility*, either through ownership or contractual obligations.

1.1.4 Harmonic background voltage distortion

The harmonic voltage distortion present in the point of connection before the HVDC facility is connected.

1.1.5 Electricity supply undertaking

The *electricity supply undertaking* is the enterprise to whose grid a *facility* is connected electrically. Responsibilities in the *public electricity supply grid* are distributed onto several *grid enterprises* and one *transmission enterprise*.

The *grid enterprise* is the company licensed to operate the *public electricity supply grid* up to and including 100 kV.

The *transmission enterprise* is the enterprise licensed to operate the *public electricity supply grid* above 100 kV.

1.1.6 Flicker

Flicker is rapid voltage fluctuations which for some types of light sources are identified by flicker being an irritant to the eye. *Flicker* is measured as described in DS/EN 61000-4-15 [1].

1.1.7 Flicker contribution

The *HVDC facility's* contribution of *flicker* to the transmission grid.

1.1.8 Threshold value for harmonic voltage distortion contribution (THD)

The threshold set for *harmonic voltage distortion contribution.*

1.1.9 Harmonic emission

The *HVDC facility*'s emission of harmonics, including the *harmonic voltage distortion* caused by harmonic voltages or currents from the *HVDC facility* (actively introduced distortion) and the amplification of existing *harmonic background voltage distortion* in *the point of connection* due to interaction between the facility's and the transmission grid's *harmonic grid impedance* (passively introduced distortion).

1.1.10 Harmonic grid impedance

The frequency-dependent grid impedance, determined as positive sequence, negative sequence and zero sequence impedances, expressed either as a real and imaginary value or as a magnitude and angle.

1.1.11 Harmonic planning margin

The part of the *available harmonic distortion headroom* that is reserved for future facilities while also used as a safety buffer in case of deviations.

1.1.12 Harmonic spectrum

An illustration of the Fourier coefficients (frequency components) resulting from a Fourier analysis of a given signal.

1.1.13 Harmonic voltage distortion

The distortion of grid voltage due to the presence of one or more higher order *harmonic voltage components*. The contribution may cover the full contribution in the form of *total harmonic voltage distortion* or be calculated per *harmonic voltage component*.

1.1.14 Harmonic voltage distortion contribution (HD)

The *HVDC facility's* contribution of *harmonic voltage distortion* to the transmission grid in *the point of connection*. The contribution may cover the full contribution in the form of *total harmonic voltage distortion* or be calculated per *harmonic voltage component*.

1.1.15 Harmonic voltage component

Fourier coefficients (frequency components) stemming from a Fourier analysis of a given voltage signal, wherein the frequency applicable to the Fourier coefficient is an integer multiple of the fundamental frequency.

1.1.16 HVDC facility

In this specification of requirements, an *HVDC facility* comprises both HVDC systems and DC-connected electricity-generating facilities (e.g. landing facilities) as well as remote HVDC inverters.

1.1.17 Interharmonics

Fourier coefficients (frequency components) stemming from a Fourier analysis of a given voltage signal, wherein the frequency applicable to the Fourier coefficient is not an integer multiple of the fundamental frequency.

1.1.18 Interharmonic voltage distortion contribution

The *HVDC facility's* contribution of *interharmonic voltage distortion* to the *transmission grid* in *the point of connection*. The contribution is set using *interharmonic subgroups.*

1.1.19 Interharmonic subgroup

Grouping of a series of *interharmonics*, executed as described in DS/EN 61000-4-7 [2].

1.1.20 Public electricity supply grid

Transmission and distribution grids that serve to transmit electricity for an indefinite group of electricity suppliers and consumers on terms laid down by public authorities.

The distribution grid is defined as the *public electricity supply grid* with a maximum rated voltage of 100 kV.

The transmission grid is defined as the *public electricity supply grid* with a rated voltage above 100 kV.

1.1.21 Grid impedance polygons

Method for describing the *transmission grid*'s frequency-dependent grid impedance in *the point of connection*.

1.1.22 Grid Connection Agreement

Terms and conditions entered into between the *electricity supply undertaking* and the *facility owner*, which includes relevant data and specific requirements and conditions.

1.1.23 Point of connection

The *point of connection (POC)* is the physical point in the *public electricity supply grid,* where the *HVDC facility* is or can be connected.

All requirements specified in this specification of requirements apply to the *point of connection*. The *electricity supply undertaking* determines the *point of connection*.

1.1.24 Planning level

The level of a specific *voltage quality parameter* according to which the transmission grid is coordinated.

1.1.25 Voltage quality parameters

The parameters that voltage quality is determined by. More specifically, *harmonic voltage distortion*, *interharmonics*, *flicker*, *voltage unbalance* and DC content are used.

1.1.26 Voltage unbalance

The negative sequence voltage content calculated as a percentage of the positive sequence voltage.

1.1.27 Voltage unbalance contribution

The *HVDC facility's* contribution of *voltage unbalance* to the *transmission grid* in *the point of connection.*

1.1.28 Voltage unbalance vector

Voltage unbalance vector is defined as the ratio of inverse sequence and synchronous sequence voltage, both expressed as vectors.

1.1.29 Transmission system operator (TSO)

Enterprise entrusted with the overall responsibility for maintaining security of supply and ensuring effective utilisation of an interconnected electricity supply system.

1.1.30 System model defined by impedance polygons

Limited simulation model of the *transmission grid* around a *point of connection*.

1.1.31 Available harmonic distortion headroom

The headroom available after *harmonic background voltage distortion* has been deducted from *planning levels*.

1.1.32 Total harmonic voltage distortion

Total harmonic voltage distortion is calculated as:

$$THD_U = \sqrt{\sum_{h=2}^{50} U_h^2}$$

where U_h is the root-mean-square (RMS) value of the h-th *harmonic voltage overtone* expressed as a percentage of the root-mean-square value of the fundamental voltage.

1.1.33 Transmission enterprise

The *transmission enterprise* is the enterprise licensed to operate the *public electricity supply grid* above 100 kV.

2. Objective, scope and statutory authority

This document is Annex A of the registered requirements which stipulate implementing measures under EU regulation 2016/1447 (HVDC); this document stipulates requirements for voltage quality.

3. Harmonic voltage distortion

Threshold values are set for the *HVDC facility's* maximum contribution *to harmonic voltage distortion* in the *point of connection*.

3.1 Planning level and definition of harmonic voltage distortion contribution

The *HVDC facility* is allocated threshold values in *the point of connection,* corresponding to the *facility's harmonic voltage distortion contribution*. Energinet uses *planning levels* for high-voltage systems, specified in IEC 61000-3-6 Table 2 [3], and will coordinate the individual *facility's* contribution according to these levels.

Threshold values for the *facility* are determined as the *threshold value for harmonic voltage distortion contribution (THD)* and defined as the maximum *harmonic voltage distortion contribution (HD)*, which the *HVDC facility* is permitted to introduce into the *transmission grid*.

The facility's *harmonic voltage distortion contribution* includes:

a) *harmonic voltage distortion* caused by *harmonic voltages* or currents from the facility (actively introduced distortion)
b) amplification of existing *harmonic background voltage distortion* in *the point of connection* due to interaction between the facility and the *transmission grid's harmonic grid impedance* (passively introduced distortion).

Contributions are illustrated graphically in Figure 1.

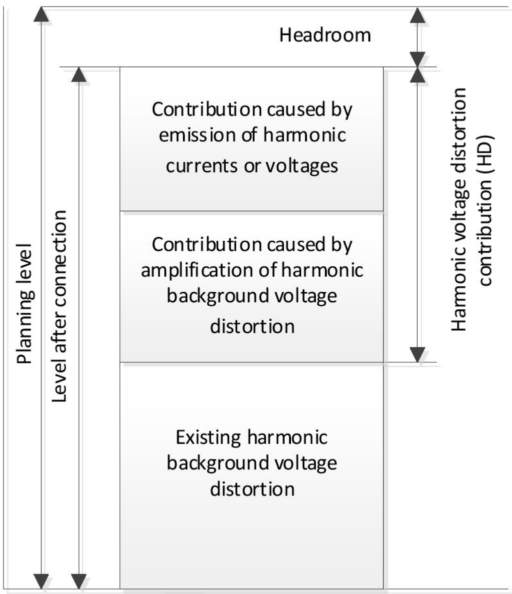

Figure 1 - Visual illustration of contributions to harmonic voltage distortion in the point of connection after commissioning of the facility.

Unique thresholds are defined per *harmonic voltage component* from the 2nd to the 50th order. These thresholds are determined as the root-mean-square (RMS) value of the individual *harmonic voltage overtone*, expressed as a percentage of the root-mean-square value of the fundamental voltage. In addition to the threshold value per *harmonic voltage component*, a threshold for the *total harmonic voltage distortion* is set (THD_U). *Total harmonic voltage distortion* is calculated as:

$$THD_U = \sqrt{\sum_{h=2}^{50} U_h^2}$$

where U_h is the root-mean-square (RMS) value of the h-th *harmonic voltage component* expressed as a percentage of the root-mean-square value of the fundamental voltage.

All these *harmonic voltage components* are defined as 95% percentile levels, calculated on the basis of 10-minute aggregated values measured over a week. Aggregation is carried out as specified in DS/EN 61000-4-30 [4].

3.2 Establishing requirements for harmonic voltage distortion contribution

The *threshold value of harmonic voltage distortion contribution* is set by the *transmission system operator*. The *threshold value* is set per *harmonic voltage component* based on the principle shown in Figure 2.

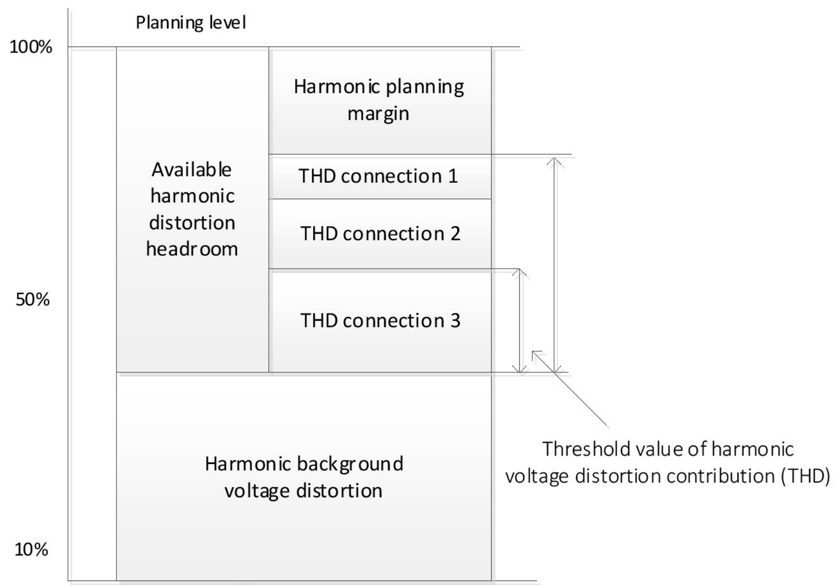

Figure 2 - Illustration of method used for determination of the threshold value for harmonic voltage distortion contribution.

The method for determining the threshold is based on the fact that the levels of *harmonic background voltage distortion* in the *point of connection* are known for all relevant *harmonic voltage components*. Based on this, the *available harmonic distortion headroom* is calculated. This is shared between the planned facilities that may connect in or near the *point of connection* of the *HVDC facility*. Part of the *available harmonic distortion headroom* is reserved for future facilities while also functioning as a safety buffer in the event of deviations. This reserved headroom is called the *harmonic planning margin.* The headroom is set by the *transmission system operator* and may vary from one connection point to another.

The *threshold value of the harmonic voltage distortion contribution* for facility number one is calculated by arithmetically subtracting the background level and the *harmonic planning margin* from the *planning level* of the relevant *harmonic voltage component*. In addition, thresholds allocated to other facilities that are not part of the harmonic background voltage distortion at the time of measurement are subtracted (see Figure 2):

$$U(h)_{GHF1} = U(h)_{PL} - U(h)_{bag} - U(h)_{PM} - U(h)_{GHF2} - \cdots - U(h)_{GHFn}$$

This means that the *facility owner* shall select an appropriate method for summation of the contributions from active *harmonic emission* and amplification of the existing *background distortion* (passive *harmonic emission*).

3.3 Verification of requirements

Sections 3.3.2 and 3.3.3 describe the respective calculation and measurement methods for verification of requirements for *harmonic distortion contribution*. Section 3.3.1 describes the data basis which the *transmission system operator* makes available to the *facility owner*.

3.3.1 Data basis for the verification of requirements for harmonic components

The *transmission system operator* makes the following data available for verification of the requirements for the *HVDC facility's harmonic distortion contribution*:

1. The level of *harmonic background voltage distortion*
2. *Grid impedance polygons* in the *facility*'s *point of connection* or *system model defined by impedance polygons*

3.3.1.1 Harmonic background voltage distortion

Harmonic background voltage distortion is stated as the 95% percentile of 10-minute values, aggregated as described in DS/EN [4] and measured over a week. Typically, measurements are recorded for 6-12 months prior to connection, and the highest *harmonic voltage components* for the three phases, of all recorded weeks, are stated.

Please note that the stated *harmonic background voltage distortion* is only to be used for the verification of operational requirements (THD). In respect of component design, design levels are determined by the component manufacturer, under the prerequisite that the individual *harmonic component* must be able to take on *the planning levels* in the *point of connection*.

3.3.1.2 Grid impedance polygons in the HVDC facility's point of connection or the system model delimited by grid impedance polygons

The transmission system operator decides whether the *transmission grid* behind the *point of connection* of the *facility* is described using *impedance polygons,* or whether a *system model delimited by impedance polygons* is used. This decision is made by the *transmission system operator* prior to the start-up of analyses for verification of requirements.

3.3.1.2.1 Grid impedance polygons in the HVDC facility's point of connection

The *transmission grid's grid impedance polygons* are defined in the R-X plane, seen from the *point of connection,* with the facility not connected. *The grid impedance polygons* are calculated using a number of grid and system configurations, including unfavourable, but planned, component outages. The *harmonic spectrum* from 50 Hz to 2500 Hz is divided into a number of frequency intervals, each represented by a six-point polygon. The polygon corner points are illustrated in Figure 3.

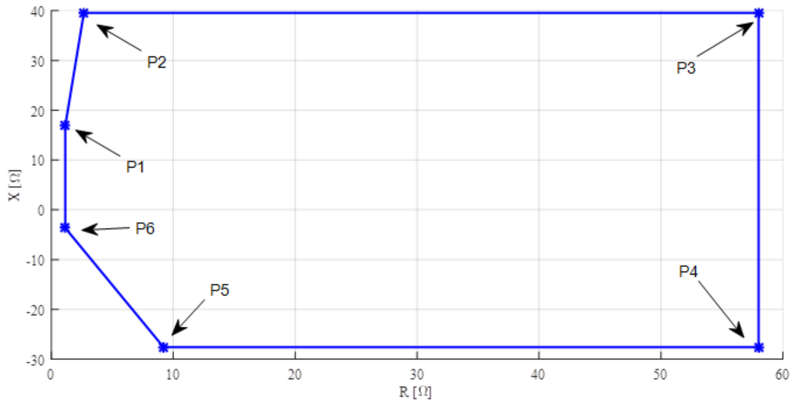

Figure 3 - Example of grid impedance polygon descriptive of grid impedance at the HVDC facility's point of connection.

The *facility owner* must verify that the *harmonic distortion contribution* does not exceed the allocated *threshold values for harmonic voltage distortion contribution* throughout the polygon area for each polygon stated. The calculation method using *grid impedance polygons* is determined by the *transmission system operator* in collaboration with the *facility owner*.

3.3.1.2.2 System model defined by grid impedance polygons

The *transmission system operator* may opt to provide a system model to verify threshold values for *harmonic voltage distortion contribution*. This option is relevant if the complexity of the system makes a system model either more representative due to mutual impact between parts of the system, or if it facilitates the *facility owner's* verification of requirements. If a system model option is selected, details of the process and method is agreed between the *transmission system operator* and the *facility owner* prior to the start-up of relevant studies.

3.3.2 Verification of requirements by calculation

To verify that the *HVDC facility* complies with the requirements for *harmonic voltage distortion* before energisation, the *facility owner* must complete a theoretical study that documents that the *facility*'s *harmonic distortion contribution* does not exceed the thresholds stated. This must be verified for all operating configurations to be used to operate the *facility*, making the 95% percentile threshold of one week's 10-minute values relevant. This includes any temporary configurations used when commissioning the facility.

The *facility owner* must determine and account for the method used to summarise *harmonic emissions* from several *facilities*. The *facility owner* must also determine and account for the method used to summarise contributions of actively and passively introduced distortion (points a and b in section 3.1).

The *transmission system operator* must approve the method used.

Sign-off on the requirements for the individual *voltage components* and THD_U is achieved when:

Verification criterion

Harmonic distortion contribution (HD) ≤ Threshold value of harmonic distortion contribution (THD)

In addition to stating the *HVDC facility*'s *harmonic voltage distortion contribution*, the theoretical study must include the extent of contributions from active emissions as well as the amplification of existing *harmonic background voltage distortion* (passive emission) before summation (points a and b in section 3.1). The exact scope of the study and the calculation method is agreed by the *facility owner* and the *transmission system operator* before the study is performed. The *facility owner* must submit descriptions of study scope and method before the study is performed.

3.3.3 Verification of requirements by measurement

The method for verification of requirements by measurement is determined jointly by the *transmission system operator* and the *facility owner*. The method is determined individually for each *HVDC facility* due to the complexity of measuring *harmonic voltage distortion contributions* at the high-voltage level.

4. Interharmonics

4.1 Planning level and definition of interharmonic voltage distortion contribution

The *interharmonic planning level* for the *transmission grid* is determined as described in IEC 61000-3-6 [3] and measured as defined in DS/EN 61000-4-7 [2].

4.2 Specification of requirements for interharmonic voltage distortion contributions

Threshold values for *interharmonic voltage distortion contributions* are set as requirements for the *interharmonic subgroups.* Each *interharmonic subgroup* must be evaluated as described in DS/EN 61000-4-30 [4] and DS/EN 61000-4-7 [2]. The threshold value is fixed at 0.36% in the frequency range from 50 Hz up to 2.5 kHz in accordance with IEC 61000-3-6 [4].

4.3 Verification of requirements

Documentation of compliance with requirements for *interharmonics* must be submitted to the *transmission system operator* no later than six months before commissioning of the *HVDC facility*. Verification is done using one of the following two methods:

1) By submitting a written technical report showing that the *interharmonic voltage distortion contribution* of the *HVDC facility* is negligible in the *point of connection*
2) By running a worst-case operating condition simulation using a simulation model that includes sources of interharmonics.

If the option to verify requirements using method 2 is selected, the *transmission system operator* will forward relevant data describing the *transmission grid* in the *point of connection*. The amount of data will depend on the simulation method selected for verification and is therefore determined following this selection.

The verification method and products must be approved by the *transmission system operator*.

Verification of requirements by measurement is carried out by the *transmission system operator*. This may be both immediately after commissioning before a final *grid connection agreement* is signed, and at any time during the *HVDC facility*'s service life. Should the facility fail to comply with requirements, the sanctions described in the regulation will be imposed.

5. Voltage unbalance

A threshold for *voltage unbalance* originating from the *HVDC facility* is set in the *point of connection*.

5.1 Planning level and definition of voltage unbalance contributions

The *planning level* for *voltage unbalance* for the *transmission grid* is determined as described in IEC 61000-3-13, Table 2 [5]. Part of this *planning level* is allocated to the *facility* in *the point of connection*.

The v*oltage unbalance vector* is generally defined as:

$$\vec{u}_2 = \frac{\vec{U}_2}{\vec{U}_1}$$

where $\vec{U}_2$ is the negative sequence voltage, and $\vec{U}_1$ is the positive sequence voltage, both set as voltage vectors (described by magnitude and angle) and determined in the *facility's point of connection*.

The *voltage unbalance contribution,* stemming from the connection of the *facility* to the *transmission grid*, is defined as the size of the *voltage unbalance contribution vector* $\vec{u}_{2,bidrag}$. The v*oltage unbalance contribution vector* is the difference between the *voltage unbalance vectors,* determined in the *facility's point of connection* after and before the *facility* is connected:

$$\vec{u}_{2,contribution} = \vec{u}_{2,after} - \vec{u}_{2,before}$$

where $\vec{u}_{2,before}$ is the *voltage unbalance vector* before the *facility* is connected, and $\vec{u}_{2,after}$ is the *voltage unbalance vector* after the *facility* is connected.

5.2 Setting requirements for voltage unbalance contributions

The *HVDC facility's voltage unbalance contribution* must not exceed 0.2% in the *point of connection*.

Connecting an *HVDC facility* may result in a reduced voltage unbalance in the *point of connection*. If this is the case, the *voltage unbalance contribution* is set equal to zero, and the requirement has been met.

Connecting a balanced *HVDC facility* may result in an increased unbalance level in *the point of connection* if the transmission grid is asymmetrical with a low short-circuit level. Such an increase is not the responsibility of the *facility owner*.

5.3 Verification of requirements

Documentation of compliance with requirements for *voltage unbalance* must be submitted to the *transmission system operator* no later than six months before commissioning of the *facility*. Verification is done using one of the following two methods:

1) By submitting a written technical report showing that the *voltage unbalance contribution* of the *HVDC facility* is negligible in the *point of connection.*

2) By running a worst-case operating condition simulation using a simulation model that includes sources of *voltage unbalance*.

If the option to verify requirements using method 2 is selected, the *transmission system operator* will forward relevant data describing the *transmission grid* in the *point of connection*. The amount of data will depend on the simulation method selected for verification and is therefore determined following this selection.

The verification method and products must be approved by the *transmission system operator*.

Verification of requirements by measurement is carried out by the *transmission system operator*. This may be both immediately after commissioning before a final *grid connection agreement* is signed, and at any time during the *HVDC facility*'s service life. Should the facility fail to comply with requirements, the sanctions described in the regulation will be imposed.

6. Flicker

A threshold for *flicker* originating from the *HVDC facility* is set in the *point of connection*.

6.1 Planning level and definition of flicker contribution

The p*lanning level* for *flicker* for the *transmission grid* is determined as described in IEC 61000-3-7 [6] and measured as defined in DS/EN 61000-4-15 [1].

6.2 Setting requirements for flicker

The requirements for *flicker contribution* for the *HVDC facility* in *the point of connection* are shown in Table 1. These are defined as the minimum thresholds recommended, see IEC 61000-3-7**Fejl! Henvisningskilde ikke fundet.**.

Parameters	Threshold
P_{st}	0.25
P_{lt}	0.35

Table 1 - Thresholds for flicker caused by the facility.

P_{st} is short-term *flicker* intensity, and P_{lt} is long-term *flicker* intensity, both defined as described in DS/EN 61000-4-15 [1].

6.3 Verification of requirements

Documentation of compliance with requirements for *flicker* must be submitted to the *transmission system operator* no later than six months before commissioning of the *HVDC facility*. Verification is done using one of the following two methods:

1) By submitting a written technical report showing that the *flicker contribution* of the *HVDC facility* is negligible in the *point of connection.*
2) By running a worst-case operating condition simulation using a simulation model that includes sources of *flicker*.

If the option to verify requirements using method 2 is selected, the *transmission system operator* will forward relevant data describing the *transmission grid* in the *point of connection*. The amount of data will depend on the simulation method selected for verification and is therefore determined following this selection.

The verification method and products must be approved by the *transmission system operator*.

Verification of requirements by measurement is carried out by the *transmission system operator*. This may be both immediately after commissioning before a final *grid connection agreement* is signed, and at any time during the *HVDC facility*'s service life. Should the facility fail to comply with requirements, the sanctions described in the regulation will be imposed.

7. DC content

A threshold for *DC content* in current supplied by the *HVDC facility* is set in the *point of connection*.

7.1 Setting requirements for DC content

DC content, measured in the AC current supplied by the *facility*, must not exceed 0.5% of the rated current in *the point of connection*.

7.2 Verification of requirements

Documentation of compliance with requirements for *DC content* must be submitted to the *transmission system operator* no later than six months before commissioning of the *HVDC facility*. Verification is done using one of the following two methods:

1) By submitting a written technical report showing that the *DC content* originating from the *HVDC facility* is negligible in the *point of connection.*
2) By running a worst-case operating condition simulation using a simulation model that includes sources of DC current or DC voltage.

If the option to verify requirements using method 2 is selected, the *transmission system operator* will forward relevant data describing the *transmission grid* in the *point of connection*. The amount of data will depend on the simulation method selected for verification and is therefore determined following this selection.

The verification method and products must be approved by the *transmission system operator*.

Verification of requirements by measurement is carried out by the *transmission system operator*. This may be both immediately after commissioning before a final *grid connection agreement* is signed, and at any time during the *HVDC facility*'s service life. Should the facility fail to comply with requirements, the sanctions described in the regulation will be imposed.

8. References

[1] DS/EN 61000-4-15:2011 Elektromagnetisk kompatibilitet (EMC) - Del 4-15: Prøvnings- og måleteknikker - Flickermeter - Funktions- og designspecifikationer, Dansk Standard, 2011.

[2] DS/EN 61000-4-7:2002 Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems ...; Corr.1:2004; A1:2009, Dansk Standard, 2002.

[3] IEC/TR 61000-3-6:2008 Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems, International Electrotechnical Commission, 2008.

[4] DS/EN 61000-4-30:2015 Elektromagnetisk kompatibilitet (EMC) - Del 4-30: Prøvnings- og måleteknikker - Metoder til måling af spændingskvaliteten; AC:2017, Dansk Standard, 2015.

[5] IEC/TR 61000-3-13:2008 Electromagnetic compatibility (EMC) - Part 3-13: Limits - Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems, International Electrotechnical Commission, 2008.

[6] IEC/TR 61000-3-7:2008 Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems, International Electrotechnical Commission, 2008.

The referenced international standards (IEC) and European standards (EN) must only be used within the topics mentioned in connection with the references in this specification of requirements.