
Interactions between HVDC systems and other connections

ENTSO-E guidance document for national implementation for network codes on grid connection

05. March 2018

1 DESCRIPTION

1.1 LEGAL FRAME

Commission Regulation (EU) 2016/1447 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (NC HVDC), Art. 29 and Art. 31.

1.2 INTRODUCTION

This document addresses the increasing concern regarding potential interactions associated with HVDC systems. In addition, the document provides guidance on the analysis needed to be undertaken in order to identify possible interactions between HVDC systems and other grid connected equipment. The main areas to be analysed in details are namely:

- harmonic interactions between the network and the HVDC systems;
- resonances between other HVDC systems or synchronous generators and equipment (e.g., Closed-Cycle Gas Turbine, series compensation and wind turbine); and

sub synchronous oscillation or sub-synchronous torsional interactions between HVDC systems and generator shafts nearby as well as control interactions between different converter based modules. It is very important to keep in mind that the interaction between a HVDC system with the grid, should be analysed not only for the existing grid elements and planned projects, but also taking into account the long term plans that will take place in the life-time of the HVDC system [7].

The TSO has the task to specify the set of relevant studies required in Art. 29 (interactions between HVDC converter stations, or HVDC converter stations and other plants and equipment) and Art. 31 (sub-synchronous torsional interactions) of NC HVDC [2], relevant for the studies related to the equipment and relevant system conditions in the network system and securing exchange of all related information according to Art 51 (Information exchange and coordination).

The studies according to Art. 29 and 31 shall be provided by the HVDC system owner, unless Member States provide that the responsibility for the studies lies with the TSOs. In any case, the TSO shall assess the result of the studies based on their scope and extent, and may request additional studies if necessary. The TSOs may also review and replicate some part or all of the studies. In this case the HVDC system owner shall provide to the relevant TSO all necessary models and data that are adequate to perform the predefined studies. The study required by Art. 29 of NC HVDC shall identify the conditions, if any, where potential adverse interactions exists and propose possible necessary mitigation actions. Mitigating actions shall be reviewed by the TSO. It is understood that the TSO's review should cover completeness, robustness and adequacy of the mitigation action(s).

Finally, it is of high importance that the relevant TSO shall continuously monitor the performance of the HVDC system (Art. 53). This is vital to identify the upcoming interactions due to grid development and to reduce the risks of uncertainties.

Key definitions:

Sub-Synchronous Oscillations (SSO) are the phenomena which concern electro-mechanical interactions, either between a turbine-generator and passive system elements such as series capacitors, or between a turbine generator and active system elements such as HVDC transmission system equipment control and stative VAR system controls at frequencies below the nominal frequency of the system (i.e. < 50 Hz).

Sub-Synchronous Resonance (SSR) is the interaction between the mechanical/torsional masses in a generator (or Squirrel-cage Induction Generator (SCIG) type wind turbine also known as type 1 wind turbine) and the electrical resonance from series compensation (capacitor) at frequencies below the nominal frequency of the system (i.e. < 50 Hz).

Sub-Synchronous Torsional Interaction (SSTI) is the interaction between the mechanical/torsional masses in a generator (or type 1 wind turbine) and a Power Electronic (PE) device (such as an HVDC link, SVC, wind turbine etc...) at frequencies below the nominal frequency of the system (i.e. < 50 Hz).

Sub-Synchronous Control Instability (SSCI) is the adverse interaction between a PE device with other power object (such as Power Generating Module (PGMs), PE device or a series compensated system) at frequencies below the nominal frequency of the system (i.e. < 50 Hz).

Harmonic stability (i.e. harmonic resonance, Super-Synchronous instability/interaction or harmonic interaction) is the interaction between a PE device with another PE device or passive components of the system at frequencies higher than nominal frequency of the system (i.e. > 50Hz) leading to dynamic stability issues (this covers a wide range of frequencies from 100Hz to some kilohertz). One should not misunderstand the difference between harmonic stability and power quality issues. Although the nature of both are the harmonics, power quality is a steady state concern while harmonic stability reflects the transient and dynamic stability of the grid due to electromagnetic interaction of grid elements and PE control loops via high order frequencies.

1.3 FURTHER INFO

The latest NCs, the Guideline documents and further information documents are available here:

- [1] ENTSO-E Network Code for HVDC Connections and DC-connected Power Park Modules; Explanatory Note, 30 April 2014,
- [2] COMMISSION REGULATION (EU) 2016/1447 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules, 26. August 2016
- [3] CIGRE TB No 563. Modelling and Simulation Studies to be performed during the lifecycle of HVDC systems.

- 74 [4] CIGRE TB No 536. Influence of Embedded HVDC Transmission on System Security and
75 AC Network Performance.
- 76 [5] CLC/TR 50509 Technical Guidelines for Radial HVDC Networks
- 77 [6] IEC 62747 Ed 1.0:2014, Terminology for VSC Terminology for voltage-sourced converters
78 (VSC) for high-voltage direct current (HVDC) systems.
- 79 [7] ENTSO-E, IGD on High Penetration of Power Electronic Interfaced Power Sources
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- 81 [8] System strength considerations in a converter dominated power system, *IET Renewable*
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- 83 [9] Investigation of Subsynchronous Resonance With VSC-Based HVDC Transmission
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- 85 [10] Analysis of control interactions in multi-infeed VSC HVDC connections, *IET Generation,*
86 *Transmission & Distribution*
- 87 [11] General Methodology for Analysis of Sub-Synchronous Interaction in Wind Power Plants,
88 *IEEE Trans. on Power Systems*, Vol. 28, No. 2, May 2013
- 89 [12] Reader's Guide to Subsynchronous resonance, *IEEE Committee report, IEEE Trans. on*
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- 93 [14] Study Methods for SSCI: State-of-the-art, and the way forward, *IEEE PSE General Meeting,*
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- 101 [18] General methodology for analysis of sub-synchronous interaction in wind power plants, *IEEE*
102 *Trans. on Power Systems*, Vol. 28 No. 2
- 103 [19] Investigation of Subsynchronous Resonance With VSC-Based HVDC Transmission
104 Systems, *IEEE Trans. on Power Delivery*, Vol. 24, No. 1, 2009
- 105 [20] Interactions Investigations between Power Electronics Devices Embedded in HVAC
106 Network, *13th IET International Conference on AC and DC Power Transmission (ACDC*
107 *2017)*
- 108 [21] Frequency Domain Methods for Transmission Network Planning to Assess Subsynchronous
109 Torsional Interaction due to High Voltage Direct Current Transmission System, *Tuomas*
110 *Rauhala, Tampere University of Technology*
- 111 [22] Subsynchronous oscillations – aspects and experiences from Finland, *Tuomas Rauhala,*
112 *FINGRID*

2 INTERDEPENDENCIES

2.1 BETWEEN THE CNCs

Several aspects coincide in the three connection network codes (NC RfG¹, NC DCC² and NC HVDC, together CNCs), i.e. technical capabilities of the entities addressed by each of these CNCs have the same objective, for example maintaining frequency, voltage and rotor angle stability. In particular, the simulation models required in NC RfG and DCC (in some cases) must reflect the needs of the interactions studies.

Other more general areas will have an impact on the ability of HVDC system for example to damp power oscillations and therefore consistent strategies for frequency and active/reactive power control of generators and Demand-Side Response (DSR) must also be considered.

2.2 WITH OTHER NCs

There are interrelations with the Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SO GL, Art. 27 to 29 and Art. 156) notably regarding frequency management, system defence, and reserves. Grid conditions may exist where resonances and system strength are affected sufficiently to create possible risks with respect to the stable operation of the HVDC connections. Therefore various critical system conditions and scenarios shall be identified in the planning stage when the respective stability studies are created.

2.3 SYSTEM CHARACTERISTICS

Historically large synchronous generation facilities have formed the backbone of providing technical capabilities. In future, a growing amount of power electronics will lead to a transition of the system to a structure with very low level of synchronous generation, and at least in some specific areas system could be operated by inverter-based power generating modules (power park modules (PPM)) only. Hence, the increasing penetration of PE components in the HVAC transmission system would gradually change the way that TSOs operate it.

Complex interactions could occur between the different controllers of the PE devices or with the PGMs in electrical vicinity of HVDC converter stations resulting in, for instance, the propagation of frequency oscillations in the transmission and distribution grids. PE components can also induce harmonic currents that when interacting with grid resonance through their control loops can severely impact the delivered power quality and even cause tripping of PE based units. CNCs should be the means to guarantee that the users are capable to meet the system needs

¹ Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators

² Commission Regulation (EU) 2016/1388 of 17 August 2016 establishing a Network Code on Demand Connection

even in case of the expected increasing penetration of PE and the change in system characteristics from synchronous generator to converter dominated power systems.

Interactions between HVDC controllers and other connected devices, but moreover the adequate tuning of controllers with relevance to the phenomenon need to be studied in a methodological way, especially in cases where:

- several HVDC systems and/or PPMs are connected in the same area (risk of controllers interactions);
- HVDC links are connected in the electrical vicinity of synchronous Power Generating Module (SPGM) (risk of SSO);
- HVDC links or PPMs are connected in a region or corridor where modes of inter-area oscillations exist (need for power oscillations damping capability, controller tuning);
- HVDC links or PPMs are connected electrically close to series compensated lines (high risk of SSR); and
- HVDC links are used for the grid connection of large offshore islands where PE interfaced generation units are connected.

Grid characteristics shall be considered and adequately evaluated when planning the HVDC system and the point of grid connection. It is well known that special care has to be taken where the system strength is near or below the critical point, see [7]. This is especially relevant in case of line commutated converter (LCC) type of HVDC. With respect to harmonics stability assessment the system impedance curves for different harmonic levels may be needed for the HVDC accompanied by system performance analysis and equipment rating calculations. It should be noted that the size of HVDC systems in networks can be much more substantial than for example the largest generators. Hence, they could potentially have significant influence on system performance and should be carefully assessed considering various aspects.

2.4 TECHNOLOGY CHARACTERISTICS

It has been recognized that there are differences between the inherent functionalities of the two HVDC technologies, LCC and voltage source converter (VSC) HVDC transmission, but from the perspective of the NC HVDC they are both considered as a HVDC system connected to the network at a connection point. The requirements stated in the NC HVDC are based on system needs and consider the integrity of the power system, development trends in the future, and security of supply. The objective has been to define the minimum performance requirements needed to ensure reliable operation of connections. The performance requirements are defined in general for HVDC systems at the connection point. The approach is considered to be sufficiently flexible to guarantee technology neutrality and focus on the need for system performance. ENTSO-E has endeavoured to seek the views also of the wider industry (through the NC HVDC User Group) while drafting the draft NC HVDC as to ensure that the NC HVDC does not prevent future application of any HVDC technology.

From the power system perspective and considering the functionalities and performance of LCC and VSC it can be said that LCC is more sensitive to system strength and prone to create interactions with other HVDC systems controllers. For example, care has to be taken to mitigate the consequent effects due to the possibility of commutation failure with LCC.

In context of High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS), the performance expectations linked to the choice of converter control strategy are strong, see IGD on HPoPEIPS [7], to avoid excitation of system wide harmonic instability. Strategic performance expectations in context of stability (sub-synchronous and harmonic) are covered in the grid forming converter control strategy. A key element of avoiding instability is possible introduction of a bandwidth limit on the active controls of the converters. Studies referenced in [7] have shown that introducing a bandwidth limitation, similar to that imposed in some countries for excitation control systems of synchronous generators (e.g. 4-5Hz), has proven to be effective mitigation action.

3 COLLABORATION

The TSO is responsible to identify the parties (Art. 29(3) and 31(3)) that should contribute to the study and provide relevant data and models to meet the purposes of the study.

3.1 TSO – TSO

HVDC systems are mainly used for bulk power transmission over long distances or to link different synchronous areas. Even for an embedded HVDC transmission approach as in Germany or between Spain and France certain TSOs have at least one of the HVDC converters connected to their transmission system. A coordinated approach is necessary in order to avoid interactions between different control zones. Data exchange, including information on network components, PGMs, and network configuration, between different TSOs is crucial to guarantee secure operation of the HVDC system.

3.2 TSO – DSO

Cooperation between TSOs and DSOs for interaction studies, in particular within the TSO's control area is crucial. Often the necessary information needed to carry out the interaction studies are in the ownership of the neighbouring DSO, e.g. if a generator is connected to the distribution system but in close vicinity to the extra high voltage substation where the HVDC system is connected to. In this case, all the relevant distribution system data and as well the generator data (for the generator which is connected to the distribution system) has to be requested from the DSO.

3.3 RNO – GRID USER

Collaboration between the Relevant Network Operator (RNO) and Grid users for interaction studies is crucial. The studies shall be carried out by the connecting HVDC system owner with the participation of all other grid users identified by the TSOs. Such other parties shall contribute to the studies and shall provide their input as reasonably required to meet the purposes of the studies. The relevant TSO shall collect this input and pass it on to the party responsible for the studies.

3.4 METHODOLOGY

Interaction studies between PE based devices and the system are usually done during the planning stage of the new connections and will continue in the context of monitoring until the end of its lifetime. It is in TSOs interest to explore the risk of potential interactions and look for possible mitigation actions or new constraints on planning. Usually these are easier and significantly more cost effective to include at the earliest possible stage of the project.

Legal frame

Tasks for the TSO pursuant to Art. 29 and 31 NC HVDC:

1. For Art. 29, the relevant TSO shall specify that an interaction study is required, and the scope and extent of that study. For Art. 31, the relevant TSO shall specify the necessary extent of the SSTI studies, and provide input parameters related to the equipment and system conditions in its network;
2. The relevant TSO shall define and compose a list of required data to be collected for the purpose of the studies. The studies shall be performed by the HVDC system owner unless provided otherwise by the Member State, which may assign the responsibility for these studies to the TSOs. The studies are expected to cover both frequency and time domain calculations including well defined methodology and adequate modelling assumptions. The objective of these studies is to demonstrate the robustness of the HVDC operation for critical grid conditions and necessary mitigation actions when instabilities are detected. Adequate stability criteria shall be met for each HVDC connection under critical grid conditions;
3. The relevant TSO shall assess the result of the studies based on their scope and extent as specified. If necessary for the assessment, the relevant TSO may request the HVDC system owner to perform further studies in line with the scope and extent;
4. The relevant TSO may review or replicate the study using either offline or real time simulation studies. The HVDC system owner shall provide the relevant TSO all relevant data and adequate per study models that allow such study to be performed. The TSO may also need to extend the study to system wide super synchronous instability considerations, if the system is expected to be operated at HPoPEIPS within the expected life time of the HVDC plant [7].

Data collection

It is necessary that the entity in charge of the interaction studies has a good understanding of the relevant data and models which are essential to each specific study. Having identified the need and scope of the studies, the relevant TSO should collect all the relevant network data (lines, transformers, compensation devices, network impedance characteristics, etc.), power plant data, including electrical, mechanical (multi-mass model) and control data, and the relevant data for other HVDC links, FACTS devices, wind parks. In addition, control models of active components relevant to the studies are required. Hence, it is highly recommended to include, whether within the national codes or project-specific, additional requirements regarding details of the models from manufacturers necessary to the study.

It is also necessary to keep track of the updates and changes in the models from the planning stage through the implementation to the commissioning and to validate the relevant studies consequently, by the entity in charge.

In PE applications (HVDC, FACTS and converter interfaced power source modules) the control system (including both algorithms and their implementation) plays a significant role in determining the converter behaviour in very small time scales. The control impact ranges from the stress on individual components (e.g. transient over-voltages after a fault) to the steady-state grid interaction (e.g. reactive power support). The control generally consists of:

- the control algorithms; and
- the control hardware (incl. measurement).

Both have to be tested in view of the technical specifications and system interaction.

In reality collecting all these data for installed components can be challenging. There may also exist models in a black-box format. This is usually the case for wind turbine, HVDC and FACTS models. These models can be used but reservation has to be taken as the exact control logic is not directly known and in case of possible interactions deeper knowledge from the manufacturer is needed. This means that in order to perform studies multiple manufacturers may need to be involved and this could bring additional challenges.

Study conduction and analysis

The objective of these studies is to demonstrate that there are either no possible adverse interactions, or if there are, to identify and implement the mitigation measures. Relevant studies are as follow:

- inter-area and local power oscillation;
- SSR;
- SSTI;
- sub-synchronous control interactions between different converter based equipment; and
- harmonic stability.

For this purpose, Offline Simulation and Hardware in the Loop (HIL) - Real Time Simulation can be used. Offline Simulation and HIL are thus a means of quality assurance with the aim to:

- ensure compliance with technical specifications of projects;
- identify possible design errors (control algorithms, rating of components etc.) already in early phases of projects;
- support faults diagnostic;
- assess the interaction with other grid elements during the life time of projects; and
- replicate the studies of the manufacturers and give guidance to applications and settings with regards to the system needs.

Offline simulation

Nowadays, for most of projects, offline simulation has to be performed with approximate numerical models because the entities in charge of the studies are typically not granted access to controllers' source code by manufacturers and primarily because these codes are not easily portable on a standard PC system. These approximate numerical models are usually optimized for the specific tasks in hand and thus have to be fine-tuned regularly. Alternatively, SIL (software in the loop), i.e. real control source codes uploaded on simulators which are able to emulate specific architectures such as field-programmable gate array (FPGA) or digital signal

processor (DSP), could be used but it is too complex to implement (it would require highly refined skills as well as a close support from the manufacturer).

Compliance monitoring and validation

As required by Art. 70 of NC HVDC, the relevant TSO shall assess the compliance and behaviour of the HVDC system throughout its lifetime via monitoring and recordings (Art. 53) and simulation models (Art. 54). This would help the TSO to validate the behaviour of the HVDC system, address the uncertainties identified during the implementation and analyse the dynamic response to verify the nature of each phenomenon.

General guidance for studies

Since the nature of all relevant interactions is an oscillatory phenomenon but with different frequencies and between different elements (e.g. mechanical, electromagnetic and control systems), the following guidance can be used for all similar studies. Nonetheless, one should remember that the scope of the study, whether it is harmonic stability or SSTI, will define the set of relevant models required for the study, the relevant control functions to be included, how far from connection point is still relevant to include in the model and the depth of details and accuracy.

Furthermore, different types of simulations are appropriate for different purposes. Electromagnetic transient (EMT) simulations although very accurate and detailed, can be very time consuming if many variants and scenarios to be carried out. Therefore the study options that follow can be all considered but in different stages.

Time domain simulations

Time domain simulations using EMT type models are used for simulations of nonlinear HVDC systems and the surrounding grid. These models are very good for study asymmetrical transients associated with disturbances (e.g. single phase to ground fault) occurring in the power networks with HVDC. Time domain simulations can be performed either offline using desktop simulations software (EMT) or real time platforms. Detailed representation of the HVDC system (control modules) and the external grid is needed. Hence, the relevant large in size system with the small simulation time step required by the HVDC system increases the computation burden and thus the simulation time duration. Time domain EMT simulations provide an indication of possible interactions for a given operating point. Hence, it requires multiple simulation runs of different operating points and disturbances in order to define possible instabilities.

It shall be mentioned that only trial and error EMT type studies for a given operating point do not always reveal the hidden risks of harmonic instabilities in AC-DC systems. A trial and error approach considering a large number of operating points does not always provide confidence in robustness and stability. Hence, time domain studies shall be always accompanied with frequency domain studies as frequency dependent analysis is the most suitable methodology to be used for mitigating instabilities or improving the harmonic damping. Therefore EMT simulations are most suitable when the vulnerable scenarios and sensitivities are identified and the number of calculations is reduced to a manageable size.

Modal analysis

The modal analysis approach is the frequency domain methodology where the state space representation of the HVDC system and the AC grid model is defined in order to obtain the eigenvalues of the full order model of the studied system. The EMT type modelling assumptions shall be adopted for HVDC systems (full order model including all relevant control loops) and the AC grid (transformers, AC line and cables) covering the frequency phenomena. Modal analysis can be very effective to identify the controllability and observability of an eigenvalue and it is one of the main approach to support and lead the control design and mitigation measures.

Although modal analysis is an effective method for the design of HVDC controllers, it has the disadvantage that it requires for full order models of the HVDC station (including representation of all relevant control modules taking into account the time scales of the phenomenon being studied) as well as the detailed models of transmission network passive components and loads. In case of black-box models, it needs to be taken into account, that some tools only can perform modal analysis if the black-box has been developed by the same tool as the simulations.

Hence, it is in general regarded as a difficult task for large system stability studies. Additionally, the eigenvalues are strongly dependent on the switching state of elements and operation scenario, which can be tedious if this methodology is to be performed for all possible scenarios. Therefore, the interaction of field angular stability of the electric power system cannot be investigated using this method.

Impedance (admittance) based approach

The alternative approach to the analysis of interactions in AC-DC transmission systems is the impedance based method. It is also a frequency domain methodology but, in comparison to the modal analysis, the impedance based approach provides analysis locally predicting the interactions/resonance points of the connected HVDC converter with respect to the external grid frequency dependent impedance at the point of common coupling. Hence, the formulation of tedious state space matrices can be avoided and the contribution of each control module and system component to the interaction can be examined from the ratio of the HVDC output impedance and the grid frequency dependent impedance at the point of common coupling. It is worth mentioning that the output impedance of the HVDC station is assumed to be provided by vendors and be calculated based on the exact control modules and parameters of the relevant HVDC system. The impedance based approach utilizes in principle Nyquist criteria to define stability margins. The impedance method provides a straightforward and design oriented approach to the oscillatory interaction analysis.

Since this approach, together with frequency scan method do not require much calculation time and processing power, they are very helpful to define the operating scenarios and switching states with highest risks of instable oscillation (commonly known as screening process). Hence, it is recommended to simulate all the relevant and possible scenarios using these two approaches first, where they can identify the few worst cases and weak points of different system configurations. EMT simulations and modal analysis can be measures to validate the results and help to find solutions.

Frequency scan method

An alternative approach for the calculation of HVDC impedance is the frequency scan method. This approach is based on detailed EMT type models of the HVDC system (black box models from manufacturers) and the EMT model of grid at the connection point. With the HVDC system and the grid in steady state a small current with a wide range of frequencies (depending on the frequency spectrum studied) is injected to the bus bar where the HVDC system is connected. The grid impedance and the impedance seen from the grid to the HVDC station can be calculated from the measured voltage and current for each frequency (based on Fast Fourier Transformation). Important for the calculation of the grid and HVDC system frequency dependent impedance is the selection of the harmonic current amplitude to be injected. The latter should not be too small, in order to avoid being lost in noise and not too big in order to create instability.

The frequency dependent grid impedance and HVDC system impedance seen from the grid can be then defined from the measured voltages and currents for each harmonic. The derived results of grid and HVDC impedances can be used to identify potential risks or apply stability criteria (i.e. Nyquist stability criteria). In general, the frequency scanning method can result in adequate definition of the resonance conditions in AC-DC transmission systems and can provide an indication of possible risks. Ideally, the results obtained from frequency scan methods shall be validated with the results provided from manufacturers.

It is recommended to carry out the interaction studies with several test methods successively, taking into account the increasing details of models for subsequent stages of investment advancement. An example of the proposal is presented in table 1.

Table.1. Recommended studies methods for different investment development phase

Type of studies		Studies methods	Investment development phase
Offline simulation	Static studies of events in the power system	<ul style="list-style-type: none"> • modal analysis • impedance (admittance) based approach • frequency scan method 	<ul style="list-style-type: none"> • basic
	Studies sequence of events in the power system (electromagnetic transient)	<ul style="list-style-type: none"> • time domain simulation 	<ul style="list-style-type: none"> • advanced

Based on the study results and system performance assessment, if deemed necessary, new control functions may be necessary to be implemented within the new HVDC connection, or control settings for control functions e.g., Power Oscillation Damping (POD), Sub Synchronous Damping Controller (SSDC), frequency response, etc., may need to be updated.

Final definitions

Unit Interaction Factor: For sub-synchronous interactions (e.g. SSTI and SSR), the shaft model of generators nearby should be included in the simulations. To know which generator is considered nearby, one can use the Unit Interaction Factor (UIF). The method defines $UIF = 0.1$ as the threshold for one generator to be in the vicinity of a HVDC system, but this is not a final and exact measure.

$$UIF_i = \frac{MW_{HVDC}}{MVA_i} \left(1 - \frac{SC_i}{SC_{tot}}\right)^2$$

UIF_i : Unit interaction factor of the i:th unit (generator/machine)

MW_{HVDC} : MW rating of the HVDC system

MVA_i : MVA rating of the i:th unit

SC_i : Short circuit capacity at the HVDC connection point excluding the i:th unit

SC_{tot} : Short circuit capacity at the HVDC connection point including the i:th unit

Harmonic stability: Harmonic interactions are exhibited namely as high frequency voltage and current oscillations (typically from hundreds of hertz to several kilohertz). Such harmonic instabilities have been observed repeatedly in wind farms with long AC cables and recently in HVDC connected wind farms at the offshore AC island side where the wind turbines are connected to the HVDC station. Such phenomenon could be potentially observed in HVDC connections embedded in the system or being in the electrical vicinity of other power electronic based power plants (i.e. wind plants, STATCOM, SVC or other HVDC connections). In the case of using active filters, they should be included in the study as they might reduce the harmonics in a definite range, but they might introduce or amplify frequencies in higher ranges. It is the research to define the range of frequencies which the analysis should consider keeping in mind that the parameters and models for higher frequencies are more challenging to obtain even for passive elements.

Technology dependencies: Although each HVDC project should be carefully studied in respect of possible interactions, there should be more caution when HVDC system is of type LCC (also called “classical HVDC systems”). There are higher risks of unstable interaction between LCC HVDC systems and generators nearby. Unlike the LCC-based HVDC, the problem with VSC HVDC is minor except under constant power control of the inverter. However, the DC voltage control of the VSC (rectifier/inverter), close to generator units, actually provides small positive damping. Moreover, the operation of the LCC close to transmission lines with series compensation is a source of sub-synchronous frequency interactions.

Sub-synchronous Damping Controller: If there is a negative or very low damping of any critical frequency, a sub-synchronous damping controller (SSDC) is required. A damping controller is developed and integrated in the converter control system. It increases the damping at the critical frequencies by adding a small signal to the rectifier controller, which determines the firing instant. For classical applications, the magnitude of this signal is typically a fraction of a degree. The SSDC has to be adapted to each new project.