A Way Forward to Achieve Interoperability in Multi-Vendor HVDC Systems

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Abstract

Interoperability for multi-vendor voltage source converter-based high voltage direct current (VSC-based HVDC) systems has been recognized as a new challenge. However, interoperability for multi-vendor power-converter-based islanded systems is not new. For example, well established practices and standards can be found in the areas of railway power supply and rolling stock. This paper provides a brief review of the challenges, and research completed in this area. Guidelines and standards developed to address these challenges will be summarized. A comparison between islanded systems with power converters for railway power supply and multi-terminal HVDC (MTDC) systems is presented. Finally, a way forward to achieve interoperability for multi-vendor VSC-based HVDC systems is described.

Introduction

The power system is undergoing a rapid transition, where power electronics interfaced devices are becoming the norm. This is driven by the ongoing transition towards a low-carbon society, where conventional synchronous generators are phased out and replaced by renewable energy sources that are connected via power converters. Power converters based on semiconductors with both turn-on/turn-off capability, e.g., insulated-gate bipolar transistors (IGBTs), have the advantages of flexible control and a fast response. However, interaction between power converters connected to the same network, especially where there are no other stronger sources, is a challenge. Interoperability is a well-known challenge in power converter domain AC and DC grids. The dynamic behavior and steady-state characteristics of power converters are very much dependent on the design of the controls. The converter control has been the core intellectual property (IP) of power converter manufactures from low voltage (e.g., photovoltaics and wind inverters), to medium voltage (e.g., traction applications), and up to high voltage (e.g., HVDC). It is expected that the industry will continue in this manner to maintain a competitive market and promote constant innovation, making it difficult to perform a thorough analysis of potential interactions. Nonetheless, there are not only analytic approaches to address the stability issues due to multiple converters coupling/interaction [1]-[3], but also mitigation methods [4].

An offshore windfarm is an islanded AC grid with “source” and “load” connected to it via power converters. Often the power converters may be provided by different manufacturers, thus it is a typical multi-vendor multi-converter system. References [2] and [3] present an overview, status, and outline of the CIGRE working group C4.49 on converter stability in power systems. Together with converter modelling assumptions, the following stability analysis methods were presented and evaluated using the proposed converter-based benchmark system:

- impedance-based stability analysis,

- passivity-based stability analysis,
- eigenvalue-based stability analysis,
- and time domain stability analysis.

In particular, a tutorial [3] was held to introduce procedures and guidelines to industry and academia on how to perform small-signal stability studies in modern power electronic based power systems. At the time of writing this paper, there are more than 10 offshore windfarms integrated by point-to-point VSC-based HVDC (from multiple vendors) that are operating with good operating experience indicating that converter interoperability can be realized in practice. Furthermore, there is rich experience in traction applications where guidelines and criteria have been established based on experiences and many years of research work [5]-[7]. This paves a path for realizing interoperability in multi-vendor systems without compromising the manufacturer's IP.

So far, there is no existing multi-vendor HVDC grid system. However, "Guidelines and Parameter Lists for Functional Specifications" featuring planning, specification, and execution of multi-vendor HVDC grid systems are published in [8]. This is a result of common efforts by a team of experts from leading vendors of HVDC technology, Transmission System Operators (TSOs), academia, and institutions. In general, [8] provides a common agreement for an open market of compatible equipment and solutions for HVDC grid systems. In relation to interoperability, the recommendation of [8] is that an assessment through electro-magnetic transient (EMT) simulations is necessary for ensuring HVDC grid system stability. Upon applying this recommendation, the research project, Best Path, identified potential instability due to interactions of converter control from different vendors [9]. As a result, challenges related to interoperability in multi-vendor HVDC grids have attracted a lot of attention from TSOs, academia, and industry. A multi-level sensitivity analysis approach has been developed in [1] to analyze the stability of multi-vendor MTDC systems. Although the approach is readily applicable for black-box systems, the analysis requires effort and it may only be necessary when the system is unstable, or close to instability with poor damping. DC impedances used for assessing DC dynamic interaction of a MTDC system is proposed in [10]. There are likely other ideas under investigation by researchers.

The purpose of this paper is to give a brief introduction to the experience in traction applications. The characteristics of a DC grid in comparison with traction electric systems is discussed. The established process, methodology and criteria in [7] can be readily applied in multi-vendor HVDC systems. This leads to the conclusion that interoperability in multi-vendor HVDC systems can be achieved.

Interoperability in Railway Systems

Historical Experience

Single-phase AC railway systems were introduced more than 100 years ago and have been in successful operation since then. In countries that electrified their railway system very early, a different frequency than the public grid frequency was introduced due to the technical capabilities at that time. For example, Switzerland, Germany, Austria, Sweden and Norway are using 16.7 Hz and parts of the USA are using 25 Hz. An impressive variety of technologies, systems and products are co-operating in such grids, such as dedicated single-phase generators, rotary frequency converters and many different kinds of static frequency converters. Examples of these static converters include:

- thyristor-based direct converters,
- VSC from several technology generations and/or vendors,
- locomotive and other traction vehicles ranging from old vehicles which are controlled by mechanically switched passive components (such as transformers, motors, resistors, capacitors and reactors) to thyristor-based converter locomotives,
- and VSC based vehicles of all technology generations and many vendors.

Traction vehicles represent highly varying loads to the system, both with respect to time and location. Furthermore, wire-based track safety systems of different functional principles, generations, and vendors are in operation. They communicate at a certain frequency or within a frequency band. They are part of the safety back-bone of the system since they report if a track section is occupied by a train or not.

Safe operation of the railway system has always been a key requirement and therefore, analysis of interoperability has played an important role from the very beginning. During the first couple of decades, when railway infrastructure and traction vehicle equipment were based on passive components, the system was sufficiently damped, and stability issues were not often observed.

Introducing a substantially large fleet of power-electronic-converter-based traction vehicles whilst decommissioning more and more old passive vehicles, increased interoperability challenges. An early and prominent example is from the Zurich main station area in 1995. After the introduction of a large fleet of VSC based locomotives, many legacy locomotives with traditional tap-changer-operated transformers were out of operation during a low-traffic period. In this situation, an instable situation tripped the complete railway system in the area. The root cause of this instability was not immediately understood, but a detailed analysis revealed that the modern VSC based locomotives were active in a certain frequency range and excited existing resonances. The resonances were sufficiently damped when old locomotives were in operation [11]. This experience made it clear that new processes were required to ensure interoperability among traction vehicles (both same and different types) and between traction vehicles and infrastructure.

Not only within the traction vehicles, but also on the infrastructure side, there has been an ongoing technology shift. For example, rotary frequency converters have increasingly been replaced by static frequency converters, to a point where expansion of the railway power systems has been almost exclusively done with static frequency converters.

Establishing EN 50388 standard

Following the experience in Zurich, the European research project ESCARV (Electrical System Compatibility for Advanced Rail Vehicles) was executed between 1998 and 2000. The experience gained [12] substantially influenced the elaboration of the EN 50388 standard by CENELEC (European Committee for Electromechanical Standardization) [5]-[7] to achieve interoperability. This standard has been available in a first release since 2012. It is under revision and will be split into two parts, EN 50388-1 [6] and EN 50388-2 [7].

EN 50388-1 will cover the general requirements, including a process of how to achieve interoperability. Apart from railway system specific topics, this standard covers important aspects relevant to other electrical systems. It can therefore be seen as a reference document describing how challenges derived from interoperability between very different assets in an electric grid can be managed. Such topics are discussed in Chapter 10 of the standard:

- Overvoltages caused by instability due to interaction between the controls of one or several active elements (converters) and passive elements. Normally, such instabilities occur in the frequency range of up to about 1 kHz, which is the bandwidth of the relevant controllers.
- Low frequency oscillations below and around supply frequency, which are the result of the nonlinear characteristics of modern converter systems.
- Overvoltages caused by harmonics and existing resonances.

The standard requires a compatibility study to be run when introducing a new element into the system. A process to check compatibility is laid out in the standard, defining roles and responsibilities of the involved stakeholders:

1. Characterization of the existing system and setting of acceptance criteria for the new element.
   Concerned parties: Organization in charge of the compatibility study, infrastructure manager, and operator/owner of rolling stock.
2. Design, characterization and testing of the new element.
   Concerned party: Supplier of the new element.
3. Perform compatibility tests.
   Concerned parties: Organization in charge of the compatibility study and infrastructure manager.

The "Organization in charge of the compatibility study" is not further specified, it could be a third-party consultant company or a dedicated expert team on the customer side. In any case, this organization collects all relevant data needed to perform the compatibility study.

EN 50388-2 establishes the acceptance criteria according to EN 50388-1 in relation to:

- co-ordination between controlled elements, and between controlled elements and resonances in the electrical infrastructure to achieve network system stability,
- and co-ordination of harmonic behavior with respect to excitation of electrical resonances.

Main phenomena identified and treated in this standard are:

- electrical resonance stability,
- low frequency stability,
- and overvoltages caused by harmonics.

Electrical resonance stability requirements

Electrical resonance stability concerns the excitation of electrical resonances in the power systems caused by feedback loop effects in the line converter controllers of rolling stock or static converters for power supply systems.

The following requirements shall be fulfilled:

- The lowest resonance in the power system shall not fall below the frequency limit (f_L). This limit is 87 Hz for a 16.7 Hz railway system or 300 Hz for a 50 Hz railway system.
- All components of the power system shall be included and considered. If resonances below f_L are unavoidable, sufficient damping shall be provided.
- All controlled elements shall be passive for all frequencies higher than f_L, which means that the phase for its frequency dependent input admittance lies between $\pm$ 90 degrees.

Low frequency stability requirements

Low frequency stability concerns oscillations at a frequency below the line frequency. These oscillations appear between rolling stock and power supply containing inductive and capacitive elements. They are initiated by feedback loops as well as limitations and protection functions within the system. Since low-frequency stability is multi-dimensional (coupled feedback loops for both magnitude and phase of voltage and current), no simple interface requirements for single components are defined so far. The system to be analyzed is a simplified case of a railway system which consists of:

- a constant or controlled voltage source (power supply system),
- a linear network (power supply system),
- and one or several vehicles or other new elements at a single location.

The investigation for small-signal stability shall be done:

- by time domain simulation,
- or according to the dq method (dq frequency response and multiple-input multiple-output (MIMO) Nyquist method) as detailed in Annex A.2 of the standard.

Interestingly, in the context of applications other than for railway, the standard includes the study case 'E' in which converters/compensators are to be tested against other converters/compensators.

Requirements related to overvoltages caused by harmonics

Specific overvoltage limits due to harmonics are given. Additionally, requirements specifically applicable to the railway application are provided, specifying how to handle the effect of multiple sources for harmonic current or voltage components. Other than that, the calculation of harmonics is straight forward and comparable to other standards.

Discussion

By far, not all aspects described in EN 50388 are applicable for other applications. However, even if the acceptance criteria will presumably have to be adapted, the described process on how to assess interoperability of a new asset in an existing grid seems to be applicable in general.

Comparison between electric traction system and multi-terminal HVDC system

There are three types of electric traction systems: DC, AC and composite electrification systems. A composite system includes both an AC and DC system, see Fig. 1. The most common is the AC electrification system, typically 16.7 Hz or 50-60 Hz single-phase. The AC system is among the most challenging systems from a stability and interaction point of view.

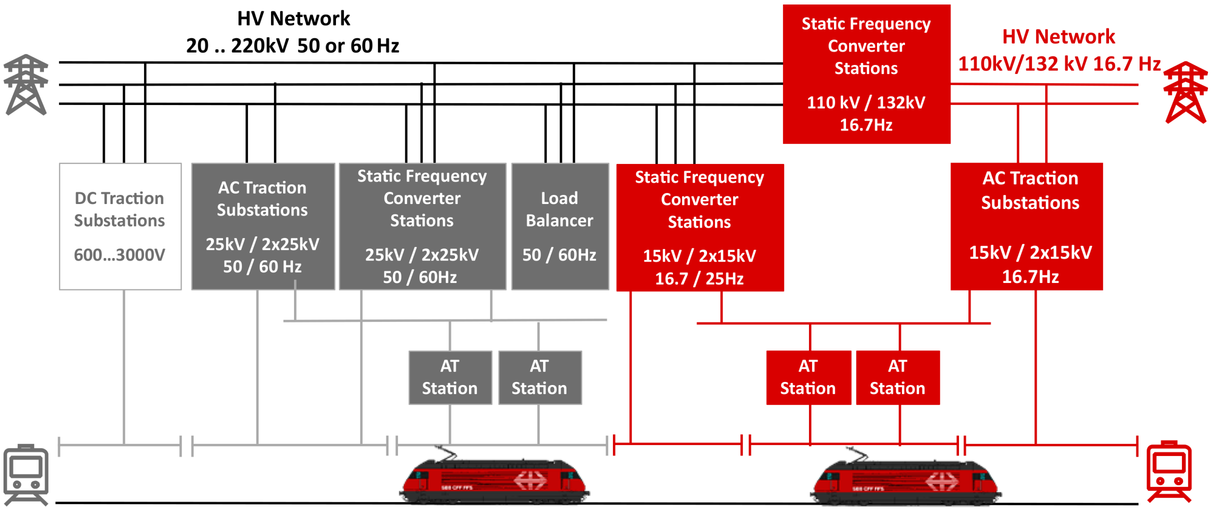

Fig. 1: A simplified overview of an electric traction system.

An example of an MTDC system is presented in Fig. 2. The terminals in grey are planned to be added to the existing Caithness–Moray HVDC link (between Spittal and Blackhillock).

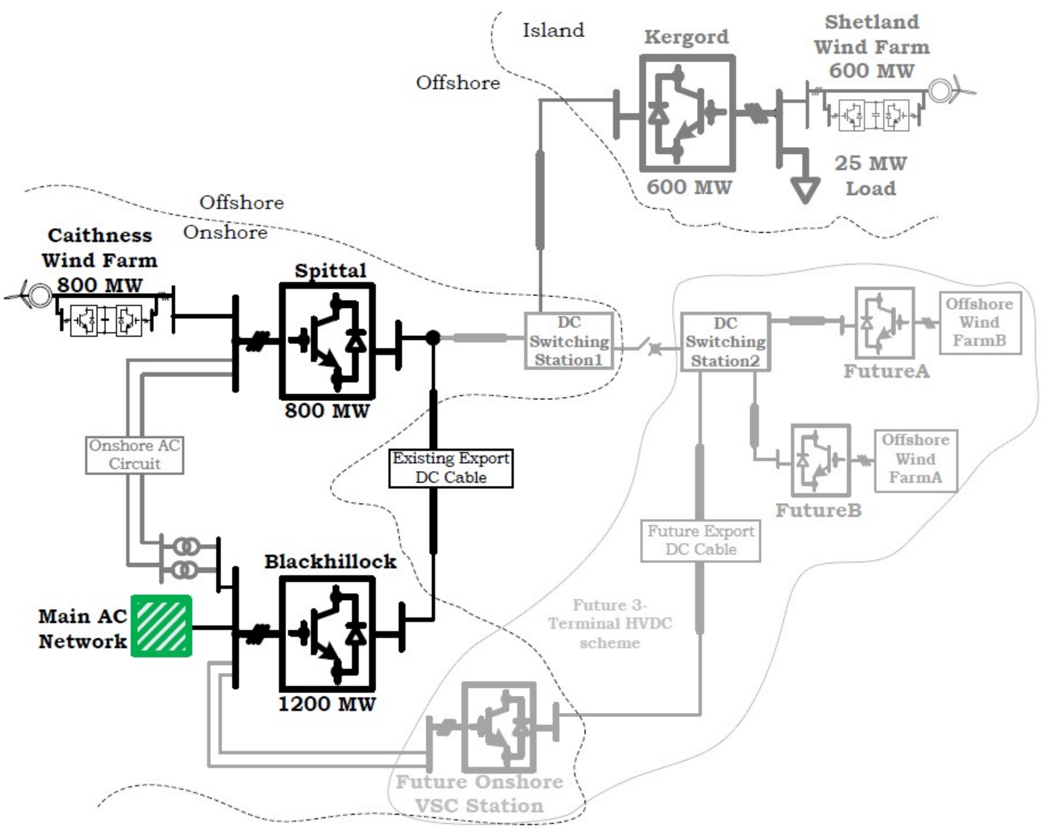

Fig. 2: A simplified overview of an MTDC system [13].

In the following comparison, the 16.7 Hz AC traction system will be used. The comparison will mainly cover three aspects: basic elements in the system, system configuration, and the potential stability aspects.

Basic elements

The basic building blocks may be categorized as “active elements” and “passive elements”. An active element may be defined as a control loop which is based on direct or indirect signals/variables sensed in the system of concern, i.e., 16.7 Hz single-phase for electric traction systems and DC network for MTDC. The active power sensed on the main grid side is an indirect variable since the power on either side of the converter is balanced (disregarding the minor converter losses). In a traction system, the line converter of rolling stock or a static converter for power supply systems are active elements. In an MTDC system, any converter which controls the DC voltage or active power is an active element. As shown in Fig. 3, the converter, including its control system, may be represented as a medium (blue box) which interconnects the concerned system and other systems. Other systems may be an AC main grid Fig. 3(**a**)-1/Fig. 3(**b**)-1, locomotive motor Fig. 3(**a**)-2 or an islanded grid Fig. 3(**b**)-2.

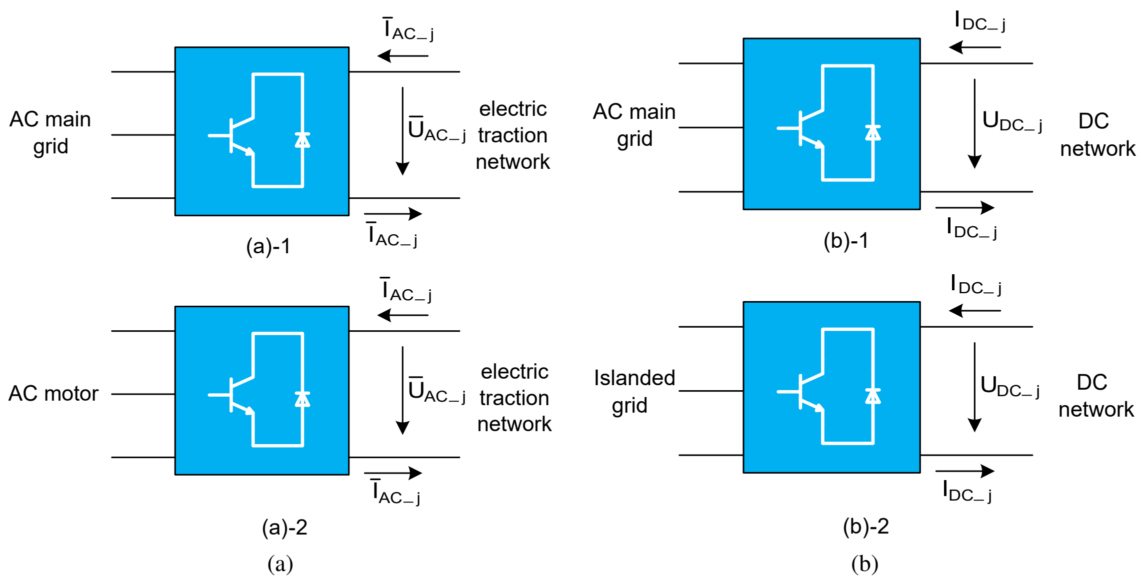

Fig. 3: Active element in (**a**) electric traction systems; (**b**) in MTDC.

In general, the active elements in both systems look similar. However, there may be some differences by looking at the details. As seen from the electric traction system, the voltage $\overline{U}_{AC\_j}$ and the current $\overline{I}_{AC\_j}$ are phasors having both a magnitude and an angle. This means that the coupling impedance between the voltage and current is a matrix related MIMO system. According to [7], it can be generalized as (1).

$$\begin{bmatrix} \Delta u_{d_j} \\ \Delta u_{q_j} \end{bmatrix} = \begin{bmatrix} Z_{dd_j} & Z_{dq_j} \\ Z_{qd_j} & Z_{qq_j} \end{bmatrix} \begin{bmatrix} \Delta i_{d_j} \\ \Delta i_{q_j} \end{bmatrix} \tag{1}$$

On the other hand, as seen from the DC network, the coupling impedance between voltage U_{DC_j} and current I_{DC_j} is a transfer function of a single-input single-output (SISO) system $\Delta u_{dc_j} = Z_{d_j} \Delta i_{dc_j}$ for one converter. The DC network may often be bipolar with a common neutral point connected to the ground to provide redundancy and to avoid significantly high voltages when there is a DC line fault. This means that at each terminal there are two converters: one connecting to the positive pole and the other connecting to the negative pole. Therefore, as seen from DC network at node j, the converter station may be described by (2).

$$\begin{bmatrix}\Delta u_{p_j}\\ \Delta u_{n_j}\end{bmatrix} = \begin{bmatrix}Z_{d_j} & Z_{pn_j}\\ Z_{pn_j} & Z_{d_j}\end{bmatrix}\begin{bmatrix}\Delta i_{p_j}\\ \Delta i_{n_j}\end{bmatrix} \tag{2}$$

where Z_{pn_j} irepresents the interaction between the positive and negative poles.

Furthermore, the active element is also a source of harmonics. In a traction system, the pulse width modulation (PWM) converter may generate harmonics in a wide range, from very low frequency (near fundamental frequency) to high frequency. In an MTDC system, the modular multilevel converter (MMC) may generate harmonics typically higher than N_c*50 Hz with a magnitude limited to below $1/N_c$, where N_c is the number of modules which is linearly related to the DC voltage level. For example, $N_c > 170$ for 500 kV DC. Thus, the active elements from a feedback control point of view are similar in both an electric traction system and an MTDC, but there is a difference from a harmonic source point of view.

The passive elements are similar in both electric traction and MTDC systems, which basically consist of distributed inductors and capacitors (in lines and cables) or inductance and capacitance from dedicated equipment such as auto-transformers, filters or current limiting reactors.

System configuration

In both electric traction and MTDC systems, the active elements are interconnected via the passive elements. The active elements are connected in parallel as seen from the concerned system point of view. Thus, the same equivalent can be used from system point of view as shown in Fig. 4.

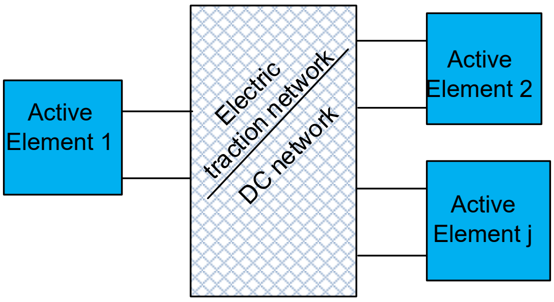

Fig. 4: Equivalent system configuration for electric traction and MTDC system.

Potential stability issues

As has been described earlier, the potential stability issues in electric traction systems for two types of instability (namely Electrical Resonance and Low Frequency Stability) are related to the control of a certain active element interacting with electric resonance frequency in the network. The interaction between the control of active elements is at low frequency.

Similarly, these two types of instability could occur in MTDC systems. This is firstly because the DC network could also have some resonances due to capacitive and inductive elements, and the resonance frequencies could be in the range of control bandwidth of active elements. Secondly, the converters are nonlinear devices, as voltage and current must be limited within the converters rating. Furthermore, the short circuit power ratio (SCR), which is defined as the short circuit power at the AC common coupling point divided by the converter rated active power, may be much lower for the HVDC converter. When the grid SCR is low i.e., the AC grid is weak, the HVDC function of supporting the AC grid has to be prioritized. In case of some severe events, it may even be necessary to transfer DC voltage control mode to other stations [14]. Overvoltages due to harmonics are unlikely in the MTDC system, mainly because the frequencies of generated harmonics are very high and losses in a DC network at high frequencies are often high due to the skin effect.

Proposal to achieve interoperability for a multi-vendor VSC-based HVDC system

It is the responsibility of each HVDC vendor to ensure a stable and robust performance when their converters are integrated into a multi-vendor MTDC system, but on the other hand vendors must also protect their IP. Accordingly, there should be a practical and simple approach to assess interoperability with sufficient accuracy whilst respecting IP rights.

Proven practice and guidelines [7] in electric traction systems may be used to achieve interoperability for a multi-vendor VSC-based HVDC system, whilst considering possible differences in pre-conditions related to VSC-based HVDC systems. Like electric traction systems, the challenges related to interoperability between HVDC terminals supplied from different vendors can be addressed in two aspects:

1. Stability related to interaction between HVDC control and resonance frequencies in the DC network.
2. Stability related to interaction between the control of different HVDC converter stations.

Both aspects could be assessed primarily by using the scanned impedance at the DC coupling point of the respective HVDC converter stations. Limited time domain simulations [8, 13] of defined cases may be used as a complementary assessment or verification.

The scanned impedance can be either provided by the vendor using the relevant pre-conditions provided by the DC network owner/TSO (such as the maximum and minimum short circuit power ratio at the point of common coupling at the converter station AC side). Alternatively, the impedance can be scanned by the DC network owner/TSO based on the black-box model of the HVDC link (with identical control as in the real system) provided by the vendor using the relevant AC network models. Note that for the DC network it is important to consider all elements and all possible configurations, from minimum three terminals to future expanding multi-terminals.

Interaction between HVDC control and resonance frequencies in the DC network

As for the interaction between HVDC control and resonance frequencies in the DC network, it can be avoided as long as the active control of HVDC converter remains passive at the resonance frequencies. This may be translated into a requirement on the impedance observed at the point of DC connection.

The following requirement shall be fulfilled:

- The phase of the scanned impedance (in case of matrix, element at the diagonal of matrix, refer to (2)) at the point of DC connection at resonance frequencies of a DC network shall lie between ± 90 degrees.

Interaction between the control of different HVDC converter stations

The interaction between the converter control at different terminals can also be examined by using the scanned impedance. The theory behind the detailed stability criterion [7] is based on the generalized Nyquist criteria. Using the equivalent system configuration for an MTDC system as shown in Fig. 4, the DC network may be described with an admittance matrix **Y**, arranged according to terminals, for example:

$$\begin{bmatrix} \Delta i_{p1} \\ \Delta i_{n1} \\ \Delta i_{p2} \\ \Delta i_{n2} \\ \Delta i_{p3} \\ \Delta i_{n3} \end{bmatrix} = \left[\quad \mathbf{Y} \quad \right] \begin{bmatrix} \Delta u_{p1} \\ \Delta u_{n1} \\ \Delta u_{p2} \\ \Delta u_{n2} \\ \Delta u_{p3} \\ \Delta u_{n3} \end{bmatrix} \tag{3}$$

A **Z** matrix collects the impedance of each terminal as seen from the respective connected DC point:

$$\begin{bmatrix}\Delta u_{p1}\\ \Delta u_{n1}\\ \Delta u_{p2}\\ \Delta u_{n2}\\ \Delta u_{p3}\\ \Delta u_{n3}\end{bmatrix} = \underbrace{\begin{bmatrix} 1 & & \\ & 2 & \\ & & 3 \end{bmatrix}}_{\mathbf{Z}} \begin{bmatrix}\Delta i_{p1}\\ \Delta i_{n1}\\ \Delta i_{p2}\\ \Delta i_{n2}\\ \Delta i_{p3}\\ \Delta i_{n3}\end{bmatrix} \tag{4}$$

where blocks 1, 2, and 3 are 2×2 matrices as shown in (2) for a bipolar HVDC system for terminal 1, 2, and 3. The other blocks are 2×2 matrices with 0 as elements.

The stability of the system is derived from the local minimum of the absolute value of:

$$N(j\omega) = \det(1 + \mathbf{Y}(j\omega)\,\mathbf{Z}(j\omega)) \tag{5}$$

As described in Section A.2.7 in [7], the system will be stable if the origin is on the left-hand side as seen from the trace of $N(j\omega)$ for all local minima of the absolute value. If the origin is on the right-hand side for at least one local minimum, the system will be unstable and oscillate at the corresponding frequencies as illustrated in Fig. 5.

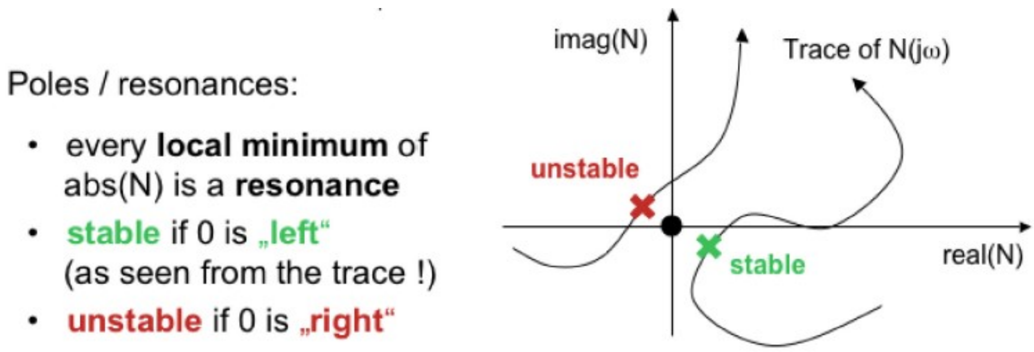

Fig. 5: Nyquist diagram for a stable and unstable system [7].

The control interaction may be also assessed via the impedance directly, as presented in [10], instead of plotting the trace of $N(j\omega)$.

Time domain simulation

Time domain simulations using EMT tools (PSCAD/EMTDC or alike) can be used for further verification. Black-box models would be sufficient for that purpose as suggested in [8]. The EMT verification can be done by TSOs, independent parties or HVDC vendors. Sometimes black-box models cannot be exchanged among different vendors due to proprietary reasons. In this case, the vendor can perform a verification using EMT software with co-simulation capabilities using separate computers (at the same or different physical locations) linked via fast telecommunication schemes [15]. In this case, simulations are run over a network where each vendor only gets access to a transmission line interface and the rest of model is running elsewhere (invisible to the user). This also requires an independent third-party that is organizing the setup. An example of such a verification can be found in [13] where a Dynamic Performance Study (DPS) verification was performed for the Caithness–Moray future MTDC. To speed up the simulation, parallel and high-performance computing, as proposed by PSCAD/EMTDC [16], can be utilized. Alternatively, a hardware-in-the-loop (or real time) simulation can be used [9, 17].

Conclusion

Interoperability for multi-vendor VSC-based HVDC systems has been recognized as a new challenge. However, interoperability for multi-vendor power-converter-based islanded systems is not new. A brief review of the challenges, and research completed in the areas of electric railway system have been presented. Guidelines and standards for addressing these challenges in this area have been presented. The comparison between the islanded system with power converters in a railway electric system with DC grids or multi-terminal HVDC systems shows that interoperability for multi-vendor VSC-based HVDC systems is not a new challenge. A way forward to achieve interoperability for multi-vendor VSC-based HVDC systems has been discussed. In summary, the interoperability in multi-vendor HVDC systems can be managed, through the process disclosed in the established standard [7] and the performance of time domain simulations [13], [15]-[17] without compromising the IP of vendors.

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