

Workstream for the development of multi-vendor HVDC systems

and other power electronics interfaced devices



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ENTSO-E brings together the unique expertise of TSOs for the benefit of European citizens by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.



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EXECUTIVE SUMMARY

This paper outlines the joint perspectives of ENTSO-E, T&D Europe and WindEurope on research directions to solve the technical challenges caused by the integration of a large number of converter stations delivered by various technology providers. Focus is placed on the development, delivery and deployment of multi-terminal, multi-vendor high-voltage direct current (HVDC) systems providing the connection to offshore wind.

This document considers the current state of technology and research. Five interlinked workstreams are proposed and their performance detailed in a coordinated approach between different development stages (research and development [R&D] and industrial implementation) to achieve multi-terminal, multi-vendor HVDC systems:

- ▶ **Workstream 1:** Development of Standardised Interaction Study Processes and Interfaces
- ▶ **Workstream 2:** Assessment of Interoperability for Multi-Terminal, Multi-Vendor HVDC Systems

- ▶ **Workstream 3:** Multi-Terminal, Multi-Vendor Real Industrial-Scale Project
- ▶ **Workstream 4:** Cooperation Framework and Governance
- ▶ **Workstream 5:** Network Planning, Project Financing and Procurement

The steps proposed are essential for the development of future HVDC grids, and the real industrial-scale HVDC multi-terminal, multi-vendor project to meet this aim is critical to enable Europe's clean energy ecosystem to deliver future HVDC grids. In addition, this project can also address interoperability in the broader context of future power grids with multi-vendor power electronics interfaced devices (PEIDs), such as flexible alternating current transmission systems (FACTS), wind turbines, and solar panels.



CONTEXT

The EU has set for itself a target to become the first continent to achieve climate neutrality by 2050. This ambition flows from the EU's longstanding commitment to fight climate change and is supported by its climate and energy policy. The European energy sector is currently experiencing a major transition in order to achieve the objectives of the European Green Deal. A key element of this transition is the decarbonisation of the power system, which is to be finalised by the year 2050. Under such boundary conditions, a higher electrification of other sectors is expected, combined with a massive increase in electricity consumption¹.

Although the increase in electricity generation from variable renewable energy sources (RES) has been successfully achieved (to a certain degree) in many

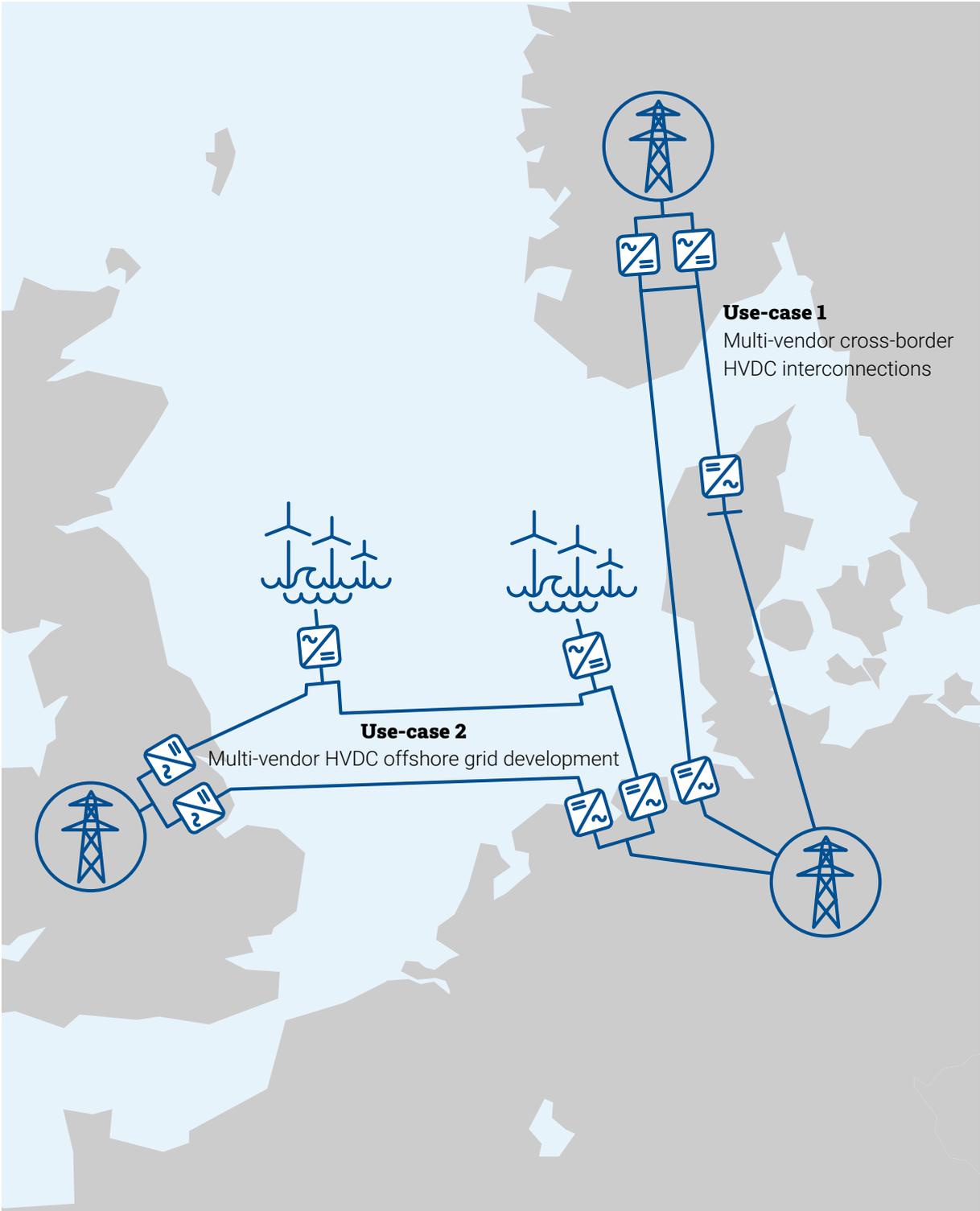
member states, further actions are required to achieve a carbon neutral power system. In this context, the massive deployment of offshore wind generation is expected to play a major role in the upcoming decades. Offshore wind development is advocated due to its higher availability rates and greater public acceptance compared to other renewable energy sources. In addition, on the demand side, new types of actors are appearing as increasingly attractive business cases, such as electrical mobility units (offering new, flexible options for the system operators) and data centres with a considerable amount of electricity consumption. Hence, AC/DC power converters² are increasingly being utilised in generation and on the demand side.

1 EC, EP, European Council et al.: 'A clean planet for all', November 2018.

2 AC/DC converters are equipment, based on power electronics, used to convert electricity from AC (alternating current) to DC (direct current), or vice-versa depending on the application.

Figure 1.

Illustrative use-cases for the development of multi-vendor HVDC systems and other peids



Moreover, the presence of large offshore wind power generation operations, in conjunction with increased decentralised and distributed generation and demand facilities as well as facilitation by a digital layer, would change the power flows across Europe. Such trends have a direct impact on the transmission infrastructure and observable cross-border power flows. Generally, more flexible products are expected to integrate those new types of connections in order to achieve cost-effective system operation. Meanwhile, the capability to control power flow across Europe is required. One of the key technologies to achieve power flow control (ensuring social acceptance and minimising the visual impact of the infrastructure) are HVDC transmission³ systems and other PEIDs, such as FACTS⁴ solutions. HVDC and FACTS technologies are already being deployed in larger numbers across various parts of the European transmission network. Therefore, following the EU strategy on offshore renewable energy⁵, it is clear that beyond 2030, offshore wind cannot grow without multi-terminal, multi-vendor HVDC systems to connect generation and loads.

The purpose of the initiative should be to enable extended HVDC grids to serve the European Green Deal. This means overcoming existing hurdles due to vendor-specific technical design and operation concepts, as well as architecture-related interfaces for control and protection and major power equipment between vendors. In short, Europe's future multi-terminal HVDC systems must be future-proof and extendable to multiple vendors.

Europe has a good starting point, but must work further to be able to approach the challenges posed by the ambition of climate neutrality with confidence. Most likely, Europe has the world's best and simultaneously most intricate electricity system. At the same time, Europe is home to world-leading technology providers for the electrical grid. Today, most HVDC systems are designed by European HVDC suppliers as point-to-point transmission systems and are pro-

vided by a single vendor. Recently, multi-terminal and 'multi-terminal ready' HVDC systems have been supplied. However, this does not yet represent multi-vendor delivery. Multi-vendor systems need standardised functional requirements for the HVDC converters and switching stations of several vendors, and standardised interfaces with the electrical grid to ensure interoperability. There are numerous examples of how this has been achieved in the past, such as the interoperability issues observed in the first HVDC Offshore Wind Connection system, which have been solved and which did not hinder the rapid development of the technology (>10 GW within 10 years). With a strong wind industry, close cooperation of all relevant stakeholders and the sufficient support of appropriate Member states, EU policy and a funding framework, Europe will be able to deliver an important solution.

This document proposes a coordinated approach between different development stages (R&D and industrial implementation) to achieve multi-terminal, multi-vendor HVDC systems. The first full industrial-sized HVDC multi-terminal, multi-vendor real industrial-scale project is critical to enable Europe's clean energy ecosystem to deliver future HVDC grids. Standardising the functional requirements and interfaces for such a project will contribute to the development of a competitive market environment. The project will preferably consist of three or more terminals connecting different countries, for which studies have already proven the long-term necessity (thereby expediting existing long-term plans), and will focus on multi-terminal, multi-vendor HVDC systems. Such an EU real industrial-scale project will have to be in line with European Commission (EC) objectives on the single electricity market and RES integration.

This proposal provides a joint perspective from ENTSO-E, T&D Europe and WindEurope on the research directions required to solve the technical challenges caused by the integration of a large number of converter stations delivered by various technology providers. Focus is placed on the development, deliv-

3 HVDC is a technology, based on AC/DC converters, to convert current from AC to DC, transmit it through a DC cable or overhead line, and convert it back to AC.

4 FACTs are power electronic devices used to enhance controllability and increase the power system transmission capacity of AC networks.

5 COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. COM/2020/741 final.

ery and deployment of multi-terminal, multi-vendor HVDC systems providing the connection to offshore wind. The steps proposed are essential for the development of future HVDC grids. Interoperability in the

broader context of future power grids with multi-vendor PEID systems, such as FACTS, wind turbines, and solar panels, can also be addressed with this project.

CHALLENGES

This section describes the main challenges expected due to the increasing share of PEIDs. Namely:

▶ **How can system stability be ensured under grid operation conditions with very high PEID penetration?**

In Europe, synchronous generators are being progressively replaced by converter-interfaced RES generation units (wind power plant modules and solar plants). Such a development will reveal power system stability challenges and bottlenecks which, so far, have not been observed due to the inherent physical response of conventional fossil fuel-driven power plants (inertial response and system strength). Among a number of technical issues, the reduction of total system inertia, which jeopardises frequency stability, is a concern, but not the only one. Most power converters connected to and operating in the system today utilise a grid-following control scheme as the grid connection interface which, according to recent studies, does not guarantee the same level of system stability, reliability, resilience, availability and quality in systems with an increasing penetration of PEIDs⁶.

▶ **How can the interoperability of converters provided by different vendors be ensured?**

Interoperability is the capability of HVDC converter stations, HVDC switching stations and power park modules to work together seamlessly with all other relevant parts of the transmission

system, allowing the transmission of electricity at the required power quality and level of security of supply. Interoperability is defined at the boundaries of the point of connection (PoC) of a converter station, switching station or power park module. Interoperability includes 'technological interoperability' and 'manufacturer interoperability'. Technological interoperability covers the operational compatibility of different technologies, for example, interoperability between 3-level voltage source converters (VSCs) and modular multi-level converters (MMCs). In this case, different technologies might also come from the same manufacturer. Manufacturer interoperability, however, describes the necessity of compatibility of the same technologies from different manufacturers⁷.

▶ **In power systems where AC/DC converters are installed increasingly densely, undamped adverse control interactions⁸ may occur**

between AC/DC converter connected equipment and other converters through the AC system (resonances, harmonic interactions, etc.). Similarly, in the engineering design and operation of more complex DC systems, such as multi-terminal HVDC systems, adverse interactions were observed in the Best Paths project⁹ using vendor electromagnetic transient (EMT) models and control replicas between converters connected on the same DC circuit and delivered

6 MIGRATE deliverable 3.1, 'Description of system needs and test cases', available from https://www.h2020-migrate.eu/_Resources/Persistent/85d17e132de9f44be3a67452723dfb585729cc5d/MIGRATE_D3-1_System%20needs%20and%20test%20cases_v01.pdf. ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources, 'High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters', Technical Report, 2019

7 ENTSO-E Position Paper on Offshore Development: Interoperability.

8 C. Buchhagen, C. Rauscher, A. Menze, et al. BorWin1 - First Experiences with harmonic interactions in converter dominated grids[C]/Int. ETG Congress 2015; Die Energiewende - Blueprints for the new energy age, Bonn, Germany: VDE, 2015, 1-7

9 Best Paths deliverable D4.3, 'Best Paths DEMO#2 First recommendations to enhance interoperability in HVDC-VSC multivendor schemes', available from <http://www.bestpaths-project.eu/en/publications>

by different suppliers¹⁰. In a multi-vendor context, where intellectual property and confidentiality concerns are of utmost importance, this raises new challenges and necessitates standardised functional requirements and procedures to achieve converter interoperability.

► **How can the way be paved for multi-terminal, multi-vendor and multi-purpose HVDC projects?**

HVDC systems are characterised by bulk transmission capacity, a non-negligible impact on the overall system stability and significant capital investment costs. Multi-terminal and multi-purpose projects combine the use of multiple (hybrid) grid elements for connection of wind power and as interconnectors. As such, a multi-purpose project may have terminal connections at generators (offshore wind, photovoltaics, and others), loads (oil and gas platforms), storage or P2X facilities and one or more AC grids. A hybrid asset is a legal term for the combined use of a single cable connection for connection of generation and as an interconnector. These two functions are regulated separately and thus, under law, need to be separated. Technically, the need to separate the functions is more of a control and interface issue. The realisation of a multi-terminal,

multi-vendor, multi-purpose HVDC real industrial-scale system does not come without risks and requires an enormous commitment from transmission system operators (TSOs); HVDC project owners, developers, and operators¹¹; HVDC vendors; and other stakeholders of HVDC systems. These risks can best be mitigated by a stepwise project definition and design process, including identification of a real HVDC project application, definition, and standardisation of HVDC functional units; definition and standardisation of functional requirements and standard interfaces¹² for these units; and computer simulations and testing of software-in-the-loop (SIL) and hardware-in-the-loop (HIL). In particular, performing dynamic stability and interaction studies will require an agreement on the minimum information that HVDC vendors should provide in the EMT models to be used for simulations, so that tuning and providing solutions to interaction issues is possible. In this dimension, the processes of a multi-terminal, multi-vendor approach based on functional specifications and a DC grid code (which is not defined yet) can be proven in the target environment and used as the best practise to improve the quality of the defined standard.

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- 10 Best Paths deliverable D4.3. EMT simulation on converter models designed by their suppliers to be as interoperable as possible resulted in 15% interoperability issues, witnessed in a wide variety of situations (from 2-terminal to 5-terminal structures). In comparison, real-time simulations with vendors' control cubicles were much more limited as they corresponded to an HVDC system extension where the new terminal was delivered by a different supplier; again, interoperability issues occurred, which required retuning the new control replica to fit into the original system.
- 11 In Europe, HVDC project owners, developers and operators might be TSO and non-TSO companies. For example, as enabled by the UK Energy Act, the upcoming offshore transmission system will be developed by non-TSO companies and ultimately owned and operated by Offshore Transmission Owner regimes typically owned by financial (non-TSO) investors.
- 12 For example, the ENTSO-E proposal for 'Standardized control interface for HVDC SIL/HIL conformity tests' [link] can serve as a starting point for development.

LESSONS LEARNED FROM FORMER R&D PROJECTS AND PRACTICAL EXPERIENCE IN EUROPE

With regard to the above challenges, there have been significant research outcomes from European R&D projects and from practical TSO experience, as reported below. In 2018, the Best Paths R&D project delivered several aspects regarding the interoperability of converters for multi-vendor DC systems, which supports some aspects of a real industrial project:

- ▶ **Interoperability issues** exist and **appeared in approximately 15% of the most plausible example grid configurations (with grid-following controls)**¹³.
- ▶ To date, **interoperability cannot be guaranteed from the specification or design stage of converters with the current technology.**
- ▶ A **methodology to fix interoperability issues was exhibited and demonstrated**, based on the vendor's control hardware, which protects the suppliers' intellectual property. EMT simulation is essential as it helps to screen for potential¹⁵.
- ▶ Best Paths considered an ambitiously large number of scenarios with a wide range of grid characteristics **rather than focusing on one well-defined scenario** and investigating that in full detail (e.g., regarding topology).
- ▶ The scope of Best Paths Demo #2 was focused on control and protection, whereas an optimised **multi-terminal, multi-vendor HVDC system design** should be further considered in a real industrial-scale project.
- ▶ The **interface specifications** were treated on a very basic level, but further projects should focus in more detail on standardisation.

- ▶ A small number of performance requirements, such as AC fault behaviour, were well-specified, but, for example, the **interaction of vendor-specific controller time constants was not anticipated.**
- ▶ A **resolution procedure for interoperability** was agreed upon, but the actual application was not fully implemented. Further agreements between stakeholders are required to be developed for application in a multi-vendor system.
- ▶ More **strong incentives were required** for the successful collaboration of all involved partners under a future commercial environment.

The ongoing **Johan Sverdrup project**¹⁴ (Norway) is the first real-world situation in which two parallel HVDC systems are delivered by different vendors. Interoperability risks identified during the design phase can jeopardise the entire system performance. Thus, both involved vendors, together with the third-party system integrator, are giving their full support to address all upcoming interactions and impacts. So far, all issues have been solved successfully.

Besides the aforementioned experience with HVDC interoperability, in 2019, the **MIGRATE** R&D project provided theoretical insights and a laboratory demonstration of major outcomes related to interoperability in a broader context¹⁵. In addition, more recently ENTSO-E has published the report 'High penetration of power electronic interfaced power sources and the potential contribution of grid forming converters'¹⁶. Multi-terminal, multi-vendor HVDC systems could play a role in providing grid-forming controls (GFCs) and an important role in system stability. However, this type of control is currently being investigated in known R&D projects without an HVDC real industrial-scale project.

13 Best Paths deliverable D9.3, 'Best Paths DEMO#2 Final Recommendations For Interoperability Of Multivendor HVDC System', available from <http://www.bestpaths-project.eu/en/publications>

14 K. Sharifabadi, 'Interaction assessment studies, challenges and solutions', workshop on interaction assessment of VSC-HVDC using EMT-type Tools, International Conference on Power System Transients (IPST 2019), June 2019, Perpignan, France.

15 RTE Webinar sessions on HVDC interaction studies with EMT simulation tools. May-June 2020. Link.

16 Technical Report 'High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid forming Converters'. Link.

OUTLOOK ON THE KEY FEATURES TOWARDS A FUTURE SYSTEM WITH HIGH PEID PENETRATION

From the previous lessons learned, several trends have been identified which will shape the infrastructure transition, for which Europe must prepare:

- ▶ **Interoperability** is becoming a major objective and must be solved. This requires standardised interfaces jointly developed by all stakeholders, including TSOs, HVDC project owners, developers and operators, HVDC vendors, and the simulation industry. Further steps, such as the standardisation of models and HIL simulation systems, will also contribute to this task. This will create a solid foundation for conducting interaction studies with multi-vendor solutions, resulting in implementation guidelines to minimise adverse interactions.

For HVDC systems, the first tests have already been made in standardisation (Best Paths project). However, **significant improvement must be made towards standardisation** (control and model interface, control HIL simulation system) **to support improving converter interoperability and validating the practical implementation of AC and DC grid codes** in a multi-vendor and multi-TSO framework.

- ▶ For multi-terminal, multi-vendor HVDC grids, in addition to the requirements at the AC connection point(s) provided in Network Code (NC) HVDC¹⁷, additional **requirements at DC connection point(s)** are necessary to ensure interoperability at the DC connection point(s) as well. Therefore, the requirements at the DC connection point(s) will be collected and justified in a new regulation (i.e., the DC Grid Code). Until now, it has been commonplace for TSOs, who define the Grid Codes, to simultaneously own the HVDC assets. However, as of recently, HVDC project owners, developers and operators in Europe can be both TSO and non-TSO companies. The involvement of

all stakeholders (owners, developers, operators, technology manufacturers and vendors) is essential to review the requirements. To avoid divergent requirements at the national level, it is of the utmost importance to have commonly agreed upon grid code requirements for an HVDC grid which, from the outset, spans many countries, avoiding as much as possible non-exhaustive and non-mandatory requirements. Therefore, experience collected from a demonstration project as well as coordination with the activities of other organisations, for example, the European Committee for Electrotechnical Standardization (CENELEC), is essential to avoid major changes in grid codes during the initial phase. It is worth mentioning that grid codes are essential for a future-proof design and to ensure non-discriminatory access to the grid for third parties.

- ▶ **A significant number of HVDC converters and large scale PEIDs for power generation must host grid-forming controls** to support power system stability. This applies to converters in point-to-point HVDC links but also in more complex HVDC structures (multi-terminal HVDC or DC grids) and large renewable parks connected through power electronics interfaces. Due to the importance of this topic, it has already been addressed and investigated in the work of CIGRE¹⁸. Grid-forming control is intended to enhance system stability under high level power electronic generation. Furthermore, interoperability between grid-forming HVDC converters is still subject to data exchange, models and interaction studies in the design phase of a project.
- ▶ **Parts of converter controls will require adaptation and assessment during their lifetime**, both to ensure their optimal performance and fit with new network topologies and system

17 Network Code on High Voltage Direct Current: COMMISSION REGULATION (EU) 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules.

18 B4.TF77: AC Fault response options for VSC HVDC Converters; B4.87: Voltage Source Converter (VSC) HVDC responses to disturbances and faults in AC systems which have low synchronous generation.

evolution steps in their vicinity as well as to support interoperability. At the same time, the high degree of dependency within converter power electronics and their control and protection must be considered. These dependencies are a key factor in technical optimisation and, consequently, economical effectiveness. The balance between the necessary adaptations and the freedom of technological developments can be found by identifying suitable interfaces between protected and open parts of the software. At the interfaces, exhaustive functional requirements must be defined. Based on the interface and functional requirement specifications, vendors can ensure that their equipment and controls can be adapted throughout their lifetime. In addition, the relevant system operator's obligations, which are to assess the compliance of an HVDC connection with the requirements of the NC HVDC throughout the lifetime of the connection, can be fulfilled.

- ▶ The **responsibilities in future HVDC systems for TSOs, non-TSO owners, developers, operators, and HVDC vendors need to change**. In an HVDC system, where all converters originate from the same vendor, all DC side functions are defined and coordinated by the vendor of the system. This is the normal delivery process today. However, multi-vendor HVDC systems need the TSOs to play a leading role in defining functions on both the AC and DC sides.
- ▶ Keeping **competition and innovation** (driving CAPEX and OPEX down continuously) within the **European HVDC market** will work best if the **future HVDC grid** is based on either a European or, even better, a worldwide **agreed upon**

technical standard and defined network code (which is yet to be developed). This standard should be developed step-by-step, reflecting within each iteration step the actual technological maturity. A good starting point for this process is the standardisation of functional requirements/specifications which, on the one hand, offers **high potential for competitive system innovation** but, on the other hand, requires coordinated action by several stakeholders in Europe's clean energy industrial eco-system. From what can be observed in other industries, this will unleash broad innovation potential and reduce the risk of stranded investments for investors and vendors. The immediate feedback on competitiveness and the economic benefits of these system innovations will force all HVDC system vendors to **fully follow market economy principles**. The resulting market-based risk sharing between HVDC system owners and vendors will be a **strong driver towards the high availability and maturity of technology**. However, the best boost for reducing system integration risks and providing **support for step-by-step DC grid development** can be given by using a **limited number of interfaces** between stations and **clearly defined conditions** for those interfaces.

Complex HVDC structures (such as multi-terminal, multi-vendor HVDC structures) are expected to be used in Europe soon, but the exact topology and required technical performance may differ from case to case. However, **the vision described above applies to all types of HVDC structures and topologies and benefits all kinds of configurations – both simple and more complex**.

MULTI-TERMINAL, MULTI-VENDOR HVDC INTEROPERABILITY WORKSTREAM

To overcome the challenges listed above, the research and industrial development and standardisation activities must go together, as defined below. Only if the close coordination of these activities is ensured can the gap between the current state-of-the-art knowledge and future infrastructure be bridged, resulting in an increased technology readiness level (TRL) of complex and multi-vendor HVDC structures. To steer all activities, five workstreams have been defined:

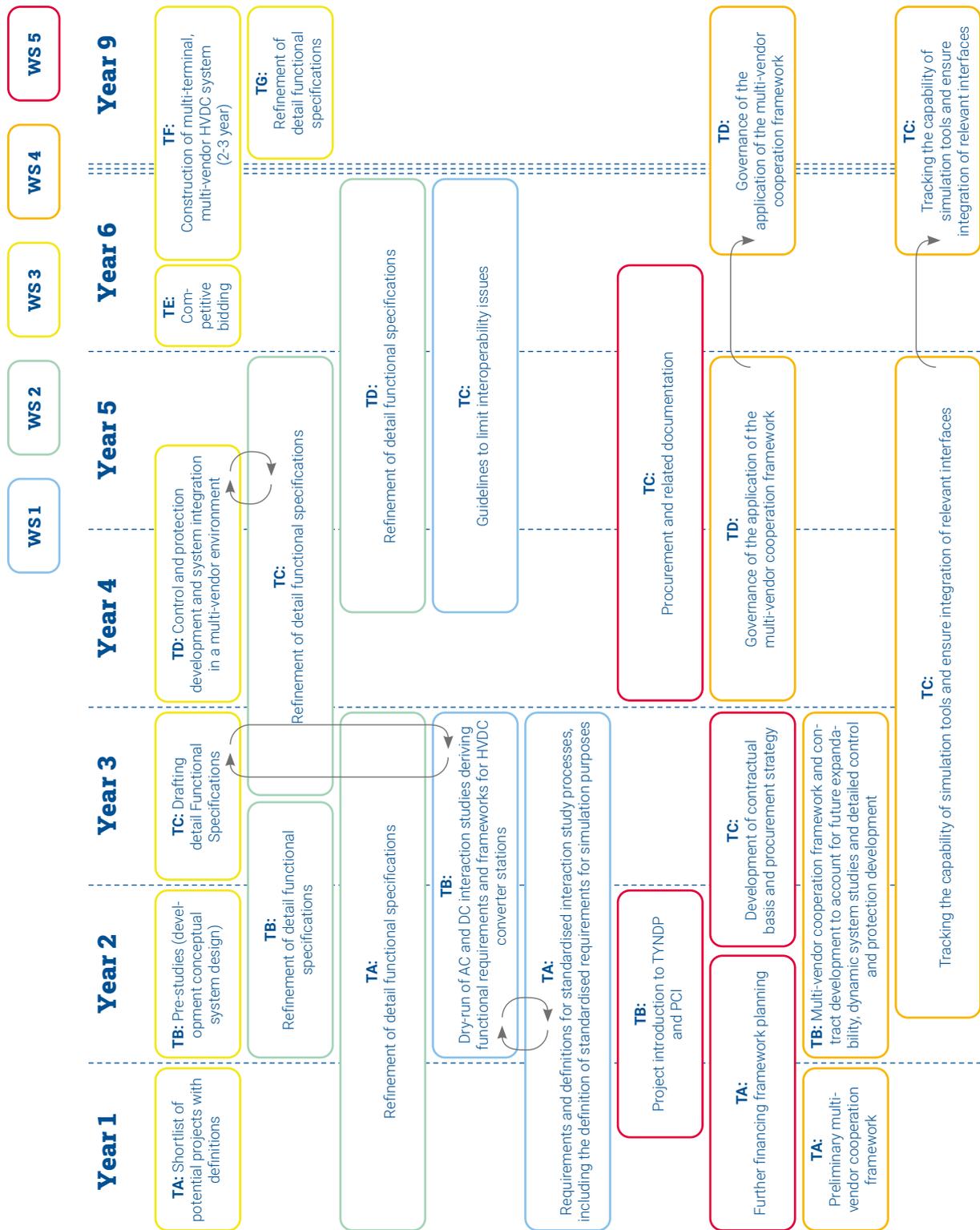
- ▶ **Workstream 1:** Development of Standardised Interaction Study Processes and Interfaces
- ▶ **Workstream 2:** Assessment of Interoperability for Multi-Terminal, Multi-Vendor HVDC Systems
- ▶ **Workstream 3:** Multi-Terminal, Multi-Vendor Real Industrial-Scale Project

- ▶ **Workstream 4:** Cooperation Framework and Governance
- ▶ **Workstream 5:** Network Planning, Project Financing and Procurement

Each workstream focuses on a specific development area but is also strongly dependent on the results of the other workstreams. Therefore, all the activities must be performed in close coordination and timely alignment. The lessons learned and recommendations from previous projects, such as Best Paths or Promotion, on the selection of one or more potential locations and evaluation of alternatives, integration into planning procedures performed by TSOs, regulation, operational and all other aspects have to be integrated. Thus, the Multi-Terminal, Multi-Vendor HVDC Interoperability Workstream Gantt chart is presented in Figure 2.

Figure 2.

Multi-terminal multi-vendor HVDC interoperability workstream



The project begins by shortlisting specific sites and applications for the multi-terminal, multi-vendor HVDC real industrial-scale project (WS3, TA) and discussing the most suitable financing framework (WS5, TA). In addition, the legal basis for sharing information will be implemented (WS4, TA), which is required for the later technical work. After the shortlist of potential projects is provided and the preliminary multi-vendor cooperation framework is set, the pre-studies for the development of a system design concept can begin (WS3, TB).

The first iterative part of the project then begins. This involves several tasks in WS1, WS2 and WS3 that exchange information. The first task of WS2 defines the functional requirements at the DC connection point, based on the needs of the system (WS2, TA). Once this is advanced and the development of the conceptual system design for potential locations is completed (WS3, TB), the drafting of the detailed functional specifications can begin (WS3, TC). This task will be executed in an iterative manner, with the development of functional requirements for GFCs (WS2, TB) and a definition of a generic framework for interaction studies (WS1, TB). Both will supplement the functional requirements for the multi-terminal, multi-vendor HVDC converter stations.

In parallel, the second iterative part of the project involves the aforementioned development of a generic framework (WS1, TA), together with the execution of interaction studies (WS1, TB). Once both iterations are complete, the detailed functional specifications will be available and the standardised interaction study process as well as the standardised interface will be defined.

Closely linked to all developments described in the first and second iterative parts, the tracking of appropriate simulation tools, compilers and interfaces will be initiated to tackle the increasing overall system complexity and develop recommendations for improvements (WS4, TC).

Parallel to the technical work so far, funding possibilities for the real industrial-scale project will be identified (WS5, TA). In addition, the project shortlist will be reviewed, and the necessary support will be provided

to ensure that the potential real industrial-scale project(s) are introduced in the Ten-Year Network Development Plan 2022 (TYNDP22) and the 6th Projects of Common Interest (PCI) list, in case Connecting Europe Facility Energy (CEF) funding is desired (WS5, TB). In addition, multi-vendor cooperation framework and contract development will be completed (WS4, TB), enabling future expandability, dynamic system studies and detailed control and protection development.

With the technical pre-work and multi-vendor cooperation framework in place, the control and protection development and system integration in a multi-vendor environment (WS3, TD) will begin. These developments will be performed in an iterative manner, with interaction studies for multi-vendor, multi-terminal HVDC systems at AC and DC connection points (WS2, TC). Thus, upon the conclusion of these tasks it will be clearly demonstrated that the multi-terminal, multi-vendor HVDC real industrial-scale project is feasible.

Once these work packages are advanced, the lessons learned regarding the application of the multi-vendor cooperation framework will be collected, and the necessary change requests for the deliverables of other tasks will be initiated (WS4, TD). In addition, the functional requirements for a DC grid code (WS2, TD) and a set of guidelines to limit interoperability issues (WS1, TC) will be defined.

In parallel, the TSOs will begin the procurement process and related documentation preparation (WS5 TD) for the implementation of the multi-terminal, multi-vendor real industrial-scale project. The conclusions of the above-mentioned tasks will provide strong technology readiness evidence from a technical and interoperability perspective and support the decision to open the competitive bidding (WS3, TE), thus beginning the commercial phase of the real industrial-scale project.

After the procurement phase is closed, the contractual relations will be in place and the actual implementation of the multi-terminal, multi-vendor HVDC real industrial scale project can begin (WS3, TF). Parallel to implementation, the lessons learned will be

used for the refinement of detailed functional specifications (WS3, TG) and a further review of modelling standards, duty definition and responsibility clarification to solve interoperability issues (WS4, TC and WS4, TD). Ultimately, these tasks are intended to set the foundation for industrial-scale, multi-terminal,

multi-vendor interoperability in future HVDC systems. Thus, results and knowledge will be shared with all relevant stakeholders to provide a starting point for future extensions or completely new multi-terminal, multi-vendor projects.

WORKSTREAM 1: DEVELOPMENT OF STANDARDISED INTERACTION STUDY PROCESSES AND INTERFACES

The aim of WS1 is to develop software model interfacing and the interaction study framework at the AC and DC PoC, relevant for real-time simulation – either Software In the Loop (SIL) or Hardware In the Loop (HIL) –, as well as offline EMT simulation. This workstream will focus on the development and testing of the standardised interface and the standardised interaction study process, including inputs and outputs required from each stakeholder for the assessment of interactions between the HVDC converters and wind power plants, but it will provide a baseline to study interactions between other PEID interfaces as well. Furthermore, it will define functional specifications for a standardized simulation platform to perform interaction studies. The proposed software model, which is connected via standardised interfaces, aims to host the actual control codes for the HVDC, FACTS and other PEIDs supplied by different vendors. In the long-term, it might reduce time and costs of HIL studies for TSOs and non-TSO HVDC system developers, as testing a specific HVDC or FACTS converter would simply consist of updating the control of the platform with the project-specific control software. The aims of this approach are to:

- ▶ **Facilitate practical interoperability studies for all concerned TSOs**, as studies would require very simple and limited means for real-time simulation.
- ▶ **Collect practical experience with simplified real time simulations** for the development of a commonly agreed upon simulation platform framework instead of vendor specific hardware, as is common practice today.
- ▶ **Reduce costs of interoperability studies**, especially for a DC grid, due to the limited marginal cost for each converter control.
- ▶ **Accelerate the realisation of insertion and interoperability studies**. A standard interface will be used to connect each vendor's control system to the simulator. Installation and validation tests will also be straightforward, reducing the overall delay.

The results of this workstream will be used to enable cost- and time-effective control and protection development and system integration in a multi-vendor environment. In addition, the recommendations for the AC Grid Code will be provided.

REQUIREMENTS AND DEFINITIONS FOR STANDARDISED INTERACTION STUDY PROCESSES, INCLUDING THE DEFINITION OF STANDARDISED REQUIREMENTS FOR SIMULATION PURPOSES

The purpose of this task is to prepare for interoperability and interaction studies at the AC PoC, as required in NC HVDC Art. 29, but also at the DC PoC. This task will define and justify the modelling requirements and the standard process for interaction studies, based on ongoing international efforts¹⁹ which address these issues. Clear technical processes for the real implementation of such studies will be set up. In the first step, these processes and studies will be defined either for offline and real-time simulation (in the latter case, using SIL and/or HIL), or within appropriate software platforms, both using the standardised interface considering the specific project defined in WS3 TA. As a second step, and considering the lessons learned, the standardised interface definition will be provided, which should be relevant for any type of power electronic converters. The task will also aim to develop standardised functional specifications for both hardware and software and the simulation platform itself, whereby exemplary studies will be performed with the involvement of the vendors of simulation tools.

Outcome of the task

- ▶ Requirements and definitions for the interaction studies
- ▶ Standardised interface definition report
- ▶ Definition of standardised interaction study process including inputs and outputs required from each stakeholder
- ▶ Standardised functional specifications for hardware and software

DRY-RUN OF AC AND DC INTERACTION STUDIES DERIVING FUNCTIONAL REQUIREMENTS AND FRAMEWORKS FOR HVDC CONVERTER STATIONS

This task focuses on verifying the methodology and dedicated type of studies defined in WS1 TA: the capability to build converter models and C&P cubicles with standard interfaces and a standardized simulation platform which complies with the requirements elaborated in WS1 TA will be assessed as well as their joint operation to validate the overall interaction studies process. Hence, the methodology capabilities to detect, investigate and limit adverse interactions for converter stations at the AC and DC connection point will be tested. The studies must be performed in close collaboration with the development of a detailed functional specification of the real industrial-scale project described in WS3 and must also contribute to defining the requirements and definitions for the standardised interaction study processes developed within WS1 TA. It is important to note that there will be iterative steps between these three tasks, as the results and experience from each of the tasks must be used to improve the dependant tasks. It is of utmost importance to develop a framework which is able to handle all the study activities within a multi-vendor situation. In addition, it is also advisable to collaborate with WS2 TA for the setup of interaction studies. Finally, functional requirements for converter stations (including control) are derived from the study cases.

Outcome of the task

- ▶ Recommendations for the improvement of standardised interface requirements
- ▶ Recommendations for the interaction studies' requirements and definitions
- ▶ Functional requirements derived from interaction studies
- ▶ Verification of methodology for the study process to mitigate AC side interactions
- ▶ Methodology for the interaction study process

¹⁹ As an example, CIGRE Working Group, N°B4.81 'Interaction between nearby VSC-HVDC converters, FACTS devices, HV power electronic devices and conventional AC equipment' focuses on methodologies to analyse and assess control interactions, required data and modelling recommendations, time schedules to perform such studies, simulation (offline and real-time) tools and models that can impact the study results, confidentiality issues and model exchange for multivendor systems, and risk assessment and solutions.

GUIDELINES TO LIMIT INTEROPERABILITY ISSUES

This task will further develop the processes and methods from WS1 TB and WS2 TC. Special attention will be given to addressing the areas of interoperability, interactions and related functionalities that would be generic and relevant to all types of projects. Thus, the interaction study aspects and related interoperability issues falling outside the scope of WS2 will be addressed in this task to ensure that the processes and platforms are further developed to cover the full scope of interoperability and interactions.

To achieve this, the task will build on continuous interaction with WS1 TA and WS2 TC to ensure that experiences from large-scale simulation related assessments (WS4 TD) and more detailed, project specific interaction and interoperability studies (WS2 TC) are taken into account when further developing and refining the processes, platforms and requirements.

This task will deliver recommendations for the AC Grid Code and standardisation activities regarding software model interfacing and the interaction study framework. To also include best practises, it is important to integrate the 'lessons learned' from WS3 TD.

Outcome of the task

- ▶ Recommendations for software model interfacing and the interaction study framework

WORKSTREAM 2: ASSESSMENT OF INTEROPERABILITY FOR MULTI-TERMINAL, MULTI-VENDOR HVDC SYSTEMS

The principal aim of WS2 is to analyse interoperability for a multi-terminal, multi-vendor HVDC system and support other workstreams to ensure safe and stable operation for specific projects. Consequently, several interactions with other workstreams are expected regarding this objective, mainly as follows:

- ▶ WS1 will define the relevant framework for interaction studies performed in WS2;
- ▶ WS3 will define the actual use case for the interaction studies performed in WS2;
- ▶ WS2 will elaborate the basic functional requirements required for the definition of detailed functional specifications in WS3;
- ▶ WS2 will support the implementation of

interoperable HVDC converters by the relevant manufacturers involved in WS3.

WS2 will also contribute to the roadmap by establishing basic functional requirements at the DC connection point ('DC grid code') and investigate the benefits of GFCs regarding interoperability and converter interactions. Moreover, WS2 will carry out the interaction studies of the control and protection demonstration test set up for the pilot project identified in WS3. The interaction studies will be performed using the platform framework developed in WS1, the standard control interfaces and procedures developed in WS1.

BASIC FUNCTIONAL REQUIREMENTS AT THE DC CONNECTION POINT FOR SYSTEM NEEDS

The purpose of this task is to prepare the first requirements at the DC connection point with the support of pre-studies and simulations (WS3, TB). Such functional specifications will be technology-agnostic and enable as many technology solutions as possible, including multi-vendor DC grids expansion. However, specifications are expected to be sufficiently precise to limit discrepancies in the behaviour of PEIDs connected to the DC bus in order to minimise the risk of interoperability issues.

The functional requirements are expected to comprise description of the expected ratings of the converters, earthing and layout, control modes, dynamic performance, signals exchanged, start-up and shutdown procedures, protection strategies, and fault-ride-through capability. This task will provide generic and structured functional framework visions for WS3. Key principles (state of the art) will be provided in order to ensure DC grid stability and DC-side converters interoperability. HVDC grid control and protection will be considered, in order to enable future expansion of the HVDC grid already in the basic design phase.

Outcome of the task

- ▶ Functional requirements at the DC connection point

FUNCTIONAL REQUIREMENTS FOR THE GFCs OF HVDC SYSTEMS

Advanced controls for AC/DC converters such as GFCs are necessary to enable an AC grid to be operated with a high penetration of PEIDs. This type of control is required to support the green transition, especially at the AC/DC interface of DC. Therefore, interoperability must be further examined in the presence of GFCs, and the functional definition of GFCs must be provided to the detailed functional specification developed in WS3.

The functional requirements of the GFC of HVDC systems will evaluate:

- ▶ Operation of a hybrid AC/DC system and coordination between the AC and DC sides to ensure power quality and provide GFC functionality.
- ▶ Requirements for ensuring interoperability for converters with GFCs.
- ▶ Dynamic performance during large disturbances.

The task will start from the results of ENTSO-E, MIGRATE, and OSMOSE. It is important to ensure that requirements for GFCs are in accordance with European functional requirements (e.g., CENELEC, CIGRE B4.87), and even with world-wide accepted requirements. Thus, close cooperation with CIGRE working group B4.87 is required.

Outcome of the task

- ▶ Functional requirements of GFCs of HVDC systems
- ▶ Recommendations of GFCs for DC grid codes

INTERACTION STUDIES FOR MULTI-TERMINAL, MULTI-VENDOR HVDC SYSTEMS AT AC AND DC CONNECTION POINTS

This task focuses on the interaction studies to be performed to investigate adverse interactions between converters and other assets (protection systems, cables, transformers, etc.) at the AC and DC connection points. Attention should be paid to the practicalities of handling such studies in a multi-vendor situation (e.g., setting up stakeholder responsibilities).

It is anticipated that the interaction studies will be based on EMT simulation with detailed models, as well as HIL simulation. This task will integrate the results of WS3 TD.

The interaction studies will demonstrate that the solution is validated and that risks during project execution are reduced to an absolute minimum following the multi-vendor cooperation framework (WS4, TD).

Thus, upon the conclusion of the interaction studies and HIL test, recommendations will be provided for the decision to move to the next construction phase from a technical and interoperability perspective.

Outcome of the task

- ▶ Report on the results of interaction studies
- ▶ Recommendations for the refinement of detailed functional specifications
- ▶ Initial SIL set-up
- ▶ Recommendations on the construction phase from a technical and interoperability perspective
- ▶ Factory Acceptance Test report
- ▶ Decision regarding whether construction is ready from a technical and interoperability perspective

INPUTS FOR DC GRID CODE DEVELOPMENT – FUNCTIONAL REQUIREMENTS FOR MULTI-VENDOR, MULTI-TERMINAL CAPABILITIES AT THE CONVERTER LEVEL FOR EACH OF THE CONVERTERS AT THE DC CONNECTION POINT

Requirements at the DC PoC should be defined for grid codes to complement the preliminary ones proposed in the Best Paths project. Furthermore, requirements, such as those for future DC ancillary services, will need to be defined to ensure the stable behaviour of the DC grid, as well as the proper AC/DC interface. It is important to ensure that the functional requirements for a DC grid code are at least in accordance with European ones and, if possible, with world-wide accepted requirements from independent institutions such as CENELEC or IEC, as well as ensuring that they do not prevent any technology or topology.

Outcome of the task

- ▶ Requirements at the DC PoC definition for grid codes
- ▶ Requirements for future DC ancillary services
- ▶ Initial DC grid code

WORKSTREAM 3. MULTI-TERMINAL, MULTI-VENDOR REAL INDUSTRIAL-SCALE PROJECT

To overcome the restrictions and limitations that accompany a typical R&D project (smaller scale, different surroundings, non-contract-equivalent hardware, limited scope, etc.) as experienced with R&D projects such as Best Paths, it is important to focus on a complete system view. This can usually best be achieved by adding commercial 'pressure for success', which means, in the context of developing a multi-terminal, multi-vendor HVDC grid, building a full

industrial-sized HVDC multi-terminal, multi-vendor real industrial-scale project.

This method enables all procedures and mechanisms to be investigated within their natural surroundings, and thus will not require any transfer between different eco-systems with technological limitations which might require fairly far-reaching adaptations at additional costs.

To support the EU Green Deal and drive the transition of the European Energy system, it is of the highest importance to develop and build a future-proof electrical infrastructure which directly addresses the

challenges potentially hampering the development of large complex structures as highlighted, for example, by PROMOTioN WP7.

SHORTLIST OF POTENTIAL PROJECTS WITH DEFINITIONS

The goal of this task is to define potential projects and to provide an overall understanding of the related HVDC Grid System by explaining the purposes and basic functions of the HVDC Grid System including all AC/DC converter stations (summarised in a basic specification).

To ensure the greatest benefit for Europe, the top-level review will kick-off from the PROMOTioN project, which identified a number of potential opportunities²⁰. The task will focus on a preliminary analysis and motivation to select and adapt only the few most promising projects (locations) for the purposes of this programme.

The shortlist (up to 3) decision criteria include, but may not be limited to, technical standards and requirements, technical complexity, build feasibility, and practicality (first projects may be onshore or offshore), and it is desirable to choose a matching project from ENTSO-E's TYNDP or one that is suitable to be introduced in the TYNDP. In addition, the task will deliver a basic feasibility analysis for each potential project. It will deepen the technical discussion and provide an initial evaluation of different technical options:

- ▶ Potential functional specification options
- ▶ Potential for future extendibility
- ▶ Preliminary technical studies (as inputs to WS1-5)
- ▶ Grid concept development (topology and potential operational configurations, control and protection strategies)
- ▶ Provide high level siting and routing (the spatial planning)
- ▶ Grid code compliance (high level, e.g., maximum loss of infeed)
- ▶ Losses and availability
- ▶ Preliminary non-technical aspects, including regulatory and legal considerations
- ▶ The cost-benefit analysis and (technical) risk analysis
- ▶ Where the project has multi-stakeholder ownership, cross-border cost allocation (CBCA) needs to be decided.

This process will (where possible) include a dialog with all project stakeholders regarding objectives, the description of existing infrastructure and technical specifications. Only in the event that these options turn out to be unachievable, and that there is no location where such a large-scale deployment can be installed, will a proposal for a completely new infrastructure, instead of an already required and planned asset, be developed.

The outcome of this task is the shortlist of potential projects (up to 3), which will be further developed in Task WS3, TB. For the shortlisted specific projects, the task will produce deliverables including a diagram showing the topology of the HVDC Grid System, including those of the individual installations and their connections. This diagram will contain information such as:

- ▶ AC networks showing the connection of each AC/DC converter station to the synchronous areas
- ▶ Main circuit data (DC voltage level and DC voltage band)
- ▶ HVDC Grid System topology, including converter station topology for each AC/DC converter station as well as each DC/DC converter station and cable system
- ▶ DC earthing impedances at each AC/DC converter station and DC/DC converter station
- ▶ Fault separation devices
- ▶ Energy absorbers, e.g., dynamic braking devices typically used for absorbing energy from wind farms or HV pole re-balancing after pole-to-earth DC faults

Outcome of the task

- ▶ Potential project definitions
- ▶ Topology diagram of HVDC Grid System for the shortlisted projects
- ▶ Shortlist of projects with supporting report

PRE-STUDIES (DEVELOPMENT OF CONCEPTUAL SYSTEM DESIGN)

The goal of this task is to provide a conceptual system design for potential locations as the joint work of all vendors. The conceptual system design will be based on a generic control and protection solution defined as part of the standardisation effort in WS1, TA. The studies will be conducted for a single generic location. As an input to this task, the functional requirements at the DC connection point from Task WS2, TA are required. It is essential to ensure that this task is limited to produce functional requirements and do not force or prevent any technical realisations such as hardware topologies or similar. This will allow and encourage vendors to innovate and respond to market needs, whereas TSOs and non-TSO HVDC project owners and developers will receive economic benefit based on technical innovation and competition between vendors.

In addition, the functionality of the DC grid controller (DC grid control layer) will be identified. As an input for this task, the functional requirements at the DC connection point from Task WS2, TA are required.

The output of this task will be the conceptual system designs for shortlisted projects, which, together with the functional requirements at the DC connection point, form the basis for the detailed functional specification.

Outcome of the task

- ▶ Pre-study report
- ▶ Generic SIL model set-up
- ▶ Conceptual system designs
- ▶ Selection of the project

DRAFTING DETAIL FUNCTIONAL SPECIFICATION

The goal of this task is to provide the detailed functional specification, comprising requirements and tests.

As in case of WS 3 Task B, it is essential to ensure that the specification is strictly limited to functional requirements.

The detailed functional specification will be the result of an iterative process of WS1 and WS2 and will be based on the pre-studies and conceptual system design developed in WS3 TB.

The functional specification must be a joint effort between all stakeholders (i.e., TSOs, HVDC system owners, developers and operators, and vendors). Therefore, interim workshops with WS1-2 and WS4-5 will be organised to cover different aspects, with a focus on the detailed functional specification. In addition, external stakeholder reviews of the detailed specification will be organised before closing the task.

The functional specification will, as far as possible, be compatible with the requirements defined in other European instances such as CENELEC and CIGRE.

Outcome of the task

- ▶ Detailed functional requirement specification
- ▶ Detailed functional test specification

CONTROL AND PROTECTION DEVELOPMENT AND SYSTEM INTEGRATION IN A MULTI-VENDOR ENVIRONMENT

The goal of this task is to develop the control and protection system as well as to integrate the solution in a multi-vendor environment.

This phase is used by vendors to develop their control and protection systems, including software and hardware, to match the previously defined functional requirements.

After finishing their individual studies, which will begin with system design work, vendors will adapt and develop their control and protection software. As part of this development process, the software is already integrated in a SIL test environment and compliance is checked for with the functional requirements. As soon as most of the identified issues are solved within the SIL environment, the software will be integrated and tested within a HIL setup. Checks regarding interoperability will be conducted by a vendor-independent system integrator who will have access to a set of control cubicles from each vendor. To allow the solution of possible detected interoperability issues, this system integrator must provide feedback and information to the different vendors to support their optimisation work.

Depending on the number and kinds of interaction phenomena, this system integration phase could run through several iteration steps. Ultimately, it is used to demonstrate that the control and protection system behaviour proceeds according to the functional specification, does not show any interoperability issues with other HVDC converters and also shows compliance with existing AC grid codes.

The entire integrated HVDC system, including the contributions from all vendors, will be simulated and tested based on proven system design as well as control and protection principles, such as state-of-the-art functional and dynamic performance testing.

A further output will be the creation of the necessary set-up for publicly accessible standards to be applied for future system developments.

At the end of this task, there should be consensus between all stakeholders regarding the suitability of the solution for the real project.

Outcome of the task

- ▶ Control and protection solution
- ▶ Consensus report

COMPETITIVE BIDDING

The goal of this task is to establish competitive bidding.

The competitive bidding phase is the beginning of the commercial phase of the real industrial-scale project. The competitive bidding process will follow the framework agreed upon in WS5 TC and the procurement rules of WS5 TD. Following the usual practice, the bidding will be done independently for the cable part of the project as well as for the HVDC converter station to secure competition within the market.

The scope of delivery for a single vendor is defined as one complete HVDC converter station, including hardware and control and protection systems.

Outcome of the task

- ▶ Contracts to vendors

CONSTRUCTION OF MULTI-TERMINAL, MULTI-VENDOR HVDC SYSTEM

The goal of this task is to construct the multi-terminal, multi-vendor real industrial-scale project.

After the contract award for the different converter stations, each vendor will start its procurement and production process. On-site construction and commissioning work will also be done according to the procedures of the vendor in charge. For the final acceptance tests, coordination work as well as review work from the above-mentioned vendor-independent system integrator is required to ensure all technical requirements are met. At the end of this task, the operation and service period can begin.

The output of this task is an extendable HVDC real industrial-scale installation in operation, where the interoperability of the systems built from multiple vendors is achieved. Ultimately, this task is intended to set the foundation of industrial-scale, multi-terminal, multi-vendor interoperability in future HVDC systems.

Outcome of the task

- ▶ Multi-terminal, multi-vendor HVDC installation in operation
- ▶ Lessons learned report on functional specifications and other interoperability aspects
- ▶ Project acceptance report and handover

REFINEMENT OF DETAILED FUNCTIONAL SPECIFICATION

The goal of this task is to refine the detailed functional specification previously developed in WS3 TC for future projects or future extensions. This work is not required as an input for the project being built and will be performed in cooperation with external stakeholders. Related workshops and stakeholder reviews on the detailed specification will be organised.

This task will make use of all the knowledge gathered during the project execution in WS3 TF, to provide an even better starting point for future extensions or completely new multi-terminal, multi-vendor projects.

Outcome of the task

- ▶ Enriched and revised functional specifications
- ▶ TRL 9 reached

WORKSTREAM 4: COOPERATION FRAMEWORK AND GOVERNANCE

In complex multi-stakeholder HVDC projects, specific attention must be paid to setting up a suitable coordination framework which ensures interoperability. Historically, both in other R&D-type projects and real-life projects where several stakeholders are involved, this has proven to be a major challenge because competing parties often need to share confidential data and simulation models in order to ensure a reliable and robust design.

The objective of WS4 is to ensure proper stakeholder involvement in order to develop the contractual and legal basis for the project, consolidate a common view of the relevant organization of the collaboration, facilitate a process of reaching the necessary common understanding between stakeholders, and

subsequently ensure appropriate simulation tool and data interface capabilities. Therefore, two main stakeholder groups are defined:

- ▶ Indirect stakeholders, meaning all potential stakeholders that could be involved in the development of the multi-terminal, multi-vendor HVDC projects and/or at a later stage are interested in the exploitation of the results of the real industrial-scale project.
- ▶ Direct stakeholders, meaning all stakeholders directly involved in the development of the multi-terminal, multi-vendor HVDC real industrial-scale project.

PRELIMINARY MULTI-VENDOR COOPERATION FRAMEWORK

In parallel to WS3 TA, a preliminary legal framework will be put in place to define the method of collaboration and share general information. This includes the sharing of generic models and technical parameters among directly involved TSOs, offshore developers, non-TSO HVDC asset owners, operators, integrators as well as vendors. The contract documents will cover the anticipated minimum requirements within the scope of this initial pre-study stage. Consequently, a preliminary multi-vendor cooperation framework will be prepared to kick-start and ensure the smooth progress of overall activities within the interoperability workstream.

Outcome of the task

- ▶ Contract for generic model sharing
- ▶ Definition of business contact guidelines, based on guidelines from standardisation bodies (IEC/CENELEC), preliminary role definition
- ▶ Collaboration agreement/NDAs
- ▶ Preliminary multi-vendor cooperation framework is set

MULTI-VENDOR COOPERATION FRAMEWORK AND CONTRACT DEVELOPMENT TO ACCOUNT FOR FUTURE EXPANDABILITY, DYNAMIC SYSTEM STUDIES AND DETAILED CONTROL AND PROTECTION DEVELOPMENT

Subsequent to WS4 TA and parallel to WS3 TB and WS3 TC, a generalised and universally applicable multi-vendor cooperation framework will be developed. This framework will enable both future expandability as well as dynamic system studies in the early planning stages and detailed control and protection development. Furthermore, roles, duties, responsibilities and a downstream amendment process will be defined.

Consequently, the derived contract documents will cover generic model sharing (e.g., in case an existing scheme is extended, and another stakeholder intends to connect, or for dynamic system studies in the early planning stages), and detailed model sharing (e.g., to perform high-quality de-risking and reliable system integration studies among involved stakeholders).

To achieve wide acceptance, the scope of these contracts will reflect connection requirements. Although those are already defined by the NC HVDC on the AC-side, a feasible approach for the DC-side will be adopted based on the results of WS2 TA.

This task will support WS3 TD, to build a framework for consensus between all stakeholders regarding the suitability of the solution for the real project.

Outcome of the task

- ▶ Contract information shared with indirect stakeholders: intermediate version at the end of year 1, final deliverable at the end of year 2
- ▶ Contract Information shared with direct stakeholders only (restricted use), final deliverable at the end of year 2
- ▶ Role, duty, and responsibility definition refinement as well as downstream amendment process, linked to experience made within WS3 TB, indirect stakeholders
- ▶ Compile generally applicable templates of all above-mentioned documents, indirect stakeholders
- ▶ Enable dynamic system studies at early stages of planning, based on generic models
- ▶ Enable detailed control and protection development
- ▶ Publish contractual framework to perform interaction studies

GOVERNANCE OF THE APPLICATION OF THE MULTI-VENDOR COOPERATION FRAMEWORK

Alongside the more detailed control and protection development within WS3 TD, and based on the major deliverables from WS1 TA, WS3 TC and WS4 TB, this task will provide a platform to monitor and discuss the issues that are critical in terms of overall project success and that require immediate action. Consequently, the established governance board will continuously evaluate and revise the multi-vendor cooperation framework as well as provide lessons learned for indirect stakeholders dealing with multi-terminal, multi-vendor HVDC projects. In case changes are required in the previously mentioned or interlinked deliverables (or tasks), this board will organise their implementation and approval.

Outcome of the task

- ▶ Lessons-learned report on the application of the multi-vendor cooperation framework
- ▶ Change requests for deliverables of other tasks to reflect lessons learned
- ▶ Organisation of change request implementation

TRACK THE CAPABILITY OF SIMULATION TOOLS AND ENSURE THE INTEGRATION OF RELEVANT INTERFACES

This task will ensure the availability and deployment of appropriate simulations tools, compilers and interfaces (grid data as well as standardised HVDC or PEID control interfaces) to tackle the increasing overall system complexity. In close collaboration with software companies, the development of appropriate technical solutions (e.g., improved parallelised computation, standardized EMT data and model data exchange formats for grids, such as Common Grid Model Exchange Standard [CGMES] formats for grids and standardised HVDC or PEID control interfaces) will be triggered and tracked to enable large-scale EMT simulation. In this context, 'large-scale' comprises extensive AC and DC grid structures. The main objective of this subtask is to facilitate the exchange of data for EMT simulations among all stakeholders involved in multi-terminal, multi-vendor HVDC systems.

Outcome of the task

- ▶ Recommendations for development of simulation tools and interfaces

WORKSTREAM 5: NETWORK PLANNING, PROJECT FINANCING AND PROCUREMENT

Multi-terminal, multi-vendor HVDC networks will combine several tasks in one technical solution, for example, connecting offshore wind power plants to the European transmission system and increasing the interconnection capacity between respective market areas. Workstream 5 is focused on the development of a framework for network planning and financing of multi-terminal, multi-vendor HVDC

systems. In a second step, the framework is applied to arrange the planning and financing of the multi-terminal, multi-vendor real industrial-scale project, including its construction. Following the agreements reached, this workstream will also take the lead in the procurement process and the development of related documentation for the realisation of the real industrial-scale project.

FURTHER FINANCING FRAMEWORK PLANNING

The funding scale of real industrial-scale projects is high. Therefore, this task will derive a proper financing framework for hybrid assets and multi-terminal HVDC systems and apply this to the projects on the shortlist (WS3, TA). The corresponding budgets for the next steps will be derived and possible funding schemes will be analysed. Based on this foundation, the task will produce initial project proposals for the targeted funding options. The process to achieve the funding will be defined as an update of this document and followed during further development stages.

Outcome of the task

- ▶ Funding scheme analyses and process for applications
- ▶ Initial project proposals
- ▶ Update of the Interoperability WS

PROJECTS' INTRODUCTION TO TYNDP AND PCI

In the event that the potential multi-terminal, multi-vendor real industrial-scale project(s) (WS3, TA) are not in the ENTSO-E's TYNDP and on the EC's PCI list, the funding for the CEF programme cannot be provided. The goal for this task is to ensure the potential real industrial-scale project(s) is(are) introduced in the TYNDP22 and PCI list #6, in the event that CEF funding is desired.

There may be country or TSO-specific application procedures, related, for example, to how detailed the project planning and the impact on other grid planning should be before any application for inclusion in the ENTSO-E's TYNDP and on the EC's PCI list can be submitted. In general, a CBA will be done before applying for a PCI list (or even TYNDP); therefore, WP5 TB will support the direct stakeholders regarding TYNDP and PCI related activities.

The TYNDP and PCI follow a strict sequence. Based on experiences from the TYNDP20 and PCI list #5, it is expected that project application for inclusion in the TYNDP22 will start in October 2021. The TYNDP22 is expected to be published for consultation in November 2022. In this same month, the project promoters are expected to be invited by the EC to submit their application for the EC's PCI list #6. The PCI list #6 is expected to be published one year later, in November 2023. After being in force, applications for CEF funding which respond to the EC's call for projects can be submitted.

Outcome of the task

- ▶ Project description for TYNDP22
- ▶ Project description for PCI list #6
- ▶ CBA and multi-terminal, multi-vendor real industrial-scale project selection

DEVELOPMENT OF CONTRACTUAL BASIS AND PROCUREMENT STRATEGY

The goal of this task is to establish the legal basis for the tendering/procurement procedure. The procurement strategy will ensure proper competition and optimise risk sharing between the parties. Based on the complexity of the project, several procurement procedures could be required for different components. Therefore, the procurement strategy will define, but not be limited to, the following aspects:

- ▶ HVDC converter tendering. It is expected that all the HVDC converter stations will be tendered as separate lots. Preferably, the HVDC converter stations will be delivered by three HVDC converter manufacturers that have participated in the workstreams.
- ▶ HVDC cables tendering. The HVDC cables can be of the mass impregnated or extruded cable type, and the procurement strategy will consider if it can be split into lots to increase competition. It is crucial that DC cable systems have already been considered in the previous stages, such as the selection of a suitable real industrial-scale project, to facilitate viable and cost-effective cable solutions. Splitting the cable systems into lots must be based on a reasonable compromise between cost-effectiveness and a balanced risk assessment.
- ▶ HVDC circuit breakers tendering. If HVDC circuit breakers are required for the real industrial-scale project, the procurement strategy will define whether they are ordered separately from the HVDC converter stations.

Due to the individual tendering of HVDC converter stations, HVDC cables, and other components, the main data and interfaces will be defined before tendering (WS5, TD).

The procurement strategy will also define the preferred contractual set-up. It is expected that all contracts will be Engineering, Procurement and Construction (EPC) contracts, and the conditions of the contracts will be based on international conditions, for example, the FIDIC Yellow Book. The procurement procedure will be led by TSOs that will subsequently own the infrastructure, or by non-TSO HVDC system owners and developers, following the EU Directives and National Regulation. The owners of the real industrial-scale project may decide if the contracts should include maintenance for a defined number of years after commissioning.

Outcome of the task

- ▶ Procurement strategy
- ▶ Terms and conditions for contracts

PROCUREMENT AND RELATED DOCUMENTATION

This task is focused on the implementation of a procurement strategy, defined in WS5 Task C. This includes the tendering and procurement procedures for all contracts for main components (HVDC converter stations, HVDC switching stations, HVDC cables, etc.) that are required for the construction of the multi-terminal, multi-vendor real industrial-scale project, as well as equipment to conduct corresponding interaction studies.

Therefore, in this task, the functional specification of all components will be developed. The technical specification for the HVDC converters will be based on the results from earlier tasks in WS2 and WS3.

The task will define the prequalification requirements and execute the procurement process. Moreover, it will provide the contractual set-up and define the scope of work for each contract as well as the interfaces between contracts.

In addition, the risk assessment for the multi-terminal, multi-vendor real industrial-scale project will be conducted, focusing on minimising major risks and risk sharing between direct stakeholders.

Thereby, the task will assist in providing the final investment decision to initiate the commercial phase of the real industrial scale project. Following the procurement procedure, the competitive bidding will be initiated, as described in WS3, TE. The owners of the real industrial-scale project will subsequently award contracts for all main components.

Outcome of the task

- ▶ Procurement rules, documentation and time schedule for procurement process
- ▶ Technical specification
- ▶ Risk assessment
- ▶ Final investment decision
- ▶ Award of contracts to vendors

ABBREVIATIONS

AC	Alternating Current
CBA	Cost–Benefit Analysis
CEF	Connecting Europe Facility
CENELEC	European Committee for Electrotechnical Standardization
CGMES	Common Grid Model Exchange Standard
CIGRE	International Council on Large Electric Systems
DC	Direct Current
EC	European Commission
EMT	Electromagnetic Transients
ENTSO-E	European Network of Transmission System Operators for Electricity
EP	European Parliament
EPC	Engineering, Procurement and Construction
FACTS	Flexible Alternating Current Transmission System
FAT	Factory Acceptance Test
GFCs	Grid Forming Controls
HIL	Hardware-In-the-Loop
HVDC	High-Voltage Direct Current
IEC	International Electrotechnical Commission
MIGRATE	Massive InteGRATion of power Electronic devices
MMCs	Modular Multi-Level Converters
NC	Network Code
NC HVDC	‘Network Code on High Voltage Direct Current’: COMMISSION REGULATION (EU) 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules
PCI	Projects of Common Interest
PEIDs	Power Electronics Interfaced Devices
PoC	Point of Connection
PROMOTioN	Progress on Meshed HVDC Offshore Transmission Networks
R&D	Research and Development
RES	Renewable Energy Sources
SIL	Software In the Loop
TA	Task A
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VSC	Voltage Source Converter
WS	Workstream

