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C1 POWER SYSTEM DEVELOPMENT AND ECONOMICS
PS3 Resilience as Pivotal Criterion for System Development

Reliability and Resilience Needs for Future Hybrid AC/DC Grids

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SUMMARY

The HVDC-WISE project aims to support further development of hybrid AC/DC transmission grids by developing new reliability and resilience (R&R) oriented planning and analysis tools and identifying HVDC-based grid architectures and technologies that can improve system performance and facilitate the integration of new renewable sources.

Power systems reliability is a well-known and established concept. There is less clarity or common understanding of the concept of resilience. The HVDC-WISE project has concluded that the definition provided by CIGRE WG C4.47 incorporates the key features of prior definitions and provides a suitable definition for use in the project. The definition should be read in terms of system outcomes rather than just the nature of the initiating disturbance. Whatever the root causes, an extreme event will mean the system is degraded beyond the outages normally considered in the assessment of adequacy and security.

The first step for the project was to review the R&R needs that are driving research and development. This paper presents the outcomes, identifying emerging trends in HVDC architectures and exploring TSO expectations with the deployment of HVDC solutions within their networks.

HVDC-WISE is focused on power system technical behaviour and its impact on R&R in future hybrid AC/DC systems, and on how HVDC architectures and technologies can enhance it. The project has defined an approach to characterizing HVDC architectures, including a topology analysis framework that provides a means of grouping and examining a wide variety of hybrid AC/DC grids.

A survey was conducted in late 2022 / early 2023 of existing and planned HVDC links. This revealed several trends in HVDC architectures with many links planned to be 525 kV, 2 GW, VSC bipoles and increasing use of multi-terminal designs. R&R implications include a range of opportunities to improve system performance as well as several perceived vulnerabilities.

The five TSOs in the HVDC-WISE consortium provide the basis for deriving wide-ranging and widely applicable needs and objectives for future hybrid AC/DC systems. The paper discusses common issues of concern as well as the events and disturbances that must be considered in the planning and operation of future hybrid AC/DC transmission systems. Issues of concern include the dominance of power electronics in future systems and cyber security risks. Events and disturbances are discussed in terms of root causes, responses, and system consequences that are considered of greatest relevance and importance to future hybrid AC/DC systems. This provides a high-level guide to what the TSOs need addressing and where improvements are required in HVDC grid architectures, technologies, and associated functionality.

KEYWORDS

HVDC – Reliability – Resilience – Architectures – Topology

1. INTRODUCTION

The power sector in Europe and globally is entering a transformative phase as conventional methods of generating electricity are being replaced by renewable sources, and transmission networks are being modernised. While these changes pose challenges to the reliability and resilience (R&R) of power supplies, they also bring opportunities for improvement through the adoption of modern HVDC technologies. It is crucial to address the new risks and capitalise on the opportunities available to enhance R&R beyond the current level.

This goal is being pursued in the HVDC-WISE project (hvdc-wise.eu), which is an EU Horizon project engaging 14 partners from 11 countries in the European Union and Great Britain including Transmission System Operator (TSO), academic and industrial organisations. The project is running from October 2022 to March 2026. The project aims to support further development of hybrid AC/DC transmission grids by developing new R&R oriented planning and analysis tools and identifying HVDC-based grid architectures and technologies that can improve system performance and facilitate the integration of new renewable sources.

The first step for the project was to review the R&R needs that are driving research and development. This paper presents the outcomes of that review, including:

- Reviewing emerging trends in HVDC architectures and technologies to identify opportunities and vulnerabilities for HVDC in delivering R&R benefits; and
- Exploring TSO expectations for R&R and issues of concern with the deployment of HVDC solutions within their networks.

Section 2 references definitions of power system R&R as explored in various other projects. Section 3 describes HVDC architectures and presents a topology analysis framework that was used in a survey of existing and planned HVDC projects (full details of the survey are available in a publicly available spreadsheet [1]). The section also contains a review of HVDC topology trends and implications for R&R. Section 4 sets out R&R needs and objectives in future hybrid AC/DC grids, especially from a TSO perspective. It discusses common issues of concern as well as the events and disturbances that must be considered in the planning and operation of future hybrid AC/DC transmission systems. This provides a high-level guide to what the TSOs need addressing and where improvements are required in HVDC grid architectures, technologies, and associated functionality. Conclusions are summarised in section 5.

2. DEFINING RELIABILITY AND RESILIENCE

A detailed review of the literature on the reliability and resilience concepts is presented in HVDC-WISE Deliverable 2.1 [2], to which the reader is referred for more information. This paper provides a summary of the most accepted definitions.

There is electricity industry consensus that reliability refers to the probability of satisfactory operation of the system in the long term. Reliability has been defined by several well-recognised institutions, such as CIGRE [3], [4], NERC [5], IEEE [6], [7], IEC [8], and ENTSO-E [9], [10], [11], in terms of adequacy and security.

A common theme is that **reliability** can be measured through the frequency, duration and intensity of situations of service degradation for customers and minimum standards are typically in place to benchmark performance and guide actions.

The concept of **adequacy** is the availability of resources and components, or system elements, which offer suitable capacity to meet demand without violating operating limits. All adequacy definitions include reference to unscheduled outages of system components, while some refer to “reasonably expected” unscheduled outages.

The **security** definitions concur that a system can be considered secure if it is in an acceptable operating condition after the occurrence of any single pre-determined credible contingency event.

Electrical power systems have for decades been designed and operated to withstand extreme conditions or recover from exceptional circumstances. However, the concept of **resilience** as a defined and analysed measure has emerged more recently. Many definitions of power system resilience have been offered, including IEEE [12], North American Transmission Forum (NATF) [13], UK Energy Research Centre (UKERC) [14], Power Systems Engineering Research Center (PSERC) [15], National Association of Regulatory Utility Commissioners (NAURC) [16], Sandia Lab [17], and CIGRE WG C4.47 [18].

The majority focus on the ability to anticipate, absorb, and rapidly recover from disturbances with a broad understanding that power system resilience addresses not only the more common single outage events but also how the system responds to rarer and more extreme disturbances that cause multiple outages directly or lead to cascading outages across large parts of the power system infrastructure. The most obvious of these are due to natural disasters or extreme weather, which cause “common mode” outages, i.e., multiple outages that are due to the same root cause. However, it is also possible for a seemingly “low impact” event to result in multiple outages and widescale disruption due to unexpected system responses.

The HVDC-WISE project has concluded that the definition provided by CIGRE WG C4.47 [18] incorporates the key features of prior definitions and provides a suitable definition for use in the project, where resilience is the:

ability to limit the extent, severity, and duration of system degradation following an extreme event.

The definition includes actionable measures to be taken before, during and after extreme events, namely: anticipation; preparation; absorption; sustainment of critical system operations; rapid recovery; and adaptation, including the application of lessons learnt. The C4.47 output makes clear that the definition should be read in terms of system outcomes rather than just the nature of the initiating disturbance. Whatever the root causes, an extreme event will mean the system is degraded beyond the outages normally considered in the assessment of adequacy and security.

Maintaining and improving R&R is a fundamental objective of all the various actors involved in generation, transmission, distribution, and related services. It is affected by many aspects of what these actors do and is a very large subject, covering issues such as logistics, asset management, workforce planning, stakeholder communication and interaction, definition and implementation of technical standards, design decisions, and procurement and commissioning actions. HVDC-WISE is focused on power system technical behaviour and its impact on R&R in future hybrid AC/DC systems, and on how HVDC architectures and technologies can enhance it. Threats to R&R that might result from contingencies, malfunctions, or interactions in large-scale HVDC systems will be analysed with the aim of identifying the appropriate design of architectures, controls, and protection to ensure that the integration of HVDC does not introduce any new risks.

3. HVDC ARCHITECTURES

Future hybrid AC/DC systems will feature the growing use of HVDC to expand transfer capability within and between countries, including subsea links and links between different synchronous areas, and the provision of connections for new, large renewable sources like offshore wind farms. It is anticipated that HVDC links will extend to all parts of Europe and play a critical role in overall system performance. This will involve various HVDC-based grid architectures, which may be defined in terms of:

1. The **purpose** of the HVDC link/network (e.g., international interconnection, connecting offshore wind, bulk power transfer within a TSO area), which should also consider the **dependency** of the TSO (or multiple TSOs) on the services and functions of the HVDC network, i.e., to what extent the AC network is impacted by the whole or partial loss of the HVDC network connected to it.
2. The **embedment level** (or connection) of the HVDC network within the AC system (i.e., all points of connection are in different synchronous areas, fully embedded within one synchronous area, or something in between).
3. The topology and configuration of the HVDC infrastructure, where

a. The **topology** refers to the way in which the AC and DC networks are interconnected.

b. The **configuration** refers to the way in which HVDC circuits are constructed to transfer power between nodes in the DC network, e.g., monopole and bipole configurations.

4. Its **technological components**, e.g., power electronics converters, breakers, storage devices, etc.

5. The **operational functions**, particularly those for control and protection, and accounting for flexibility and different operating modes that may form part of the design.

6. The **deployment plan**, specifying how to build such a grid in a stepwise manner and accounting for how all the above may change over time.

3.1. Topology Analysis Framework

The project has defined an analysis framework to categorise AC/DC topologies, which is introduced briefly here and described in detail in another HVDC-WISE paper [19] and in Deliverable 2.1 [2].

The framework is based on a 4x4 style classification of DC and AC grids. This is an evolution of previous work in several past projects (PROMOTioN [20], TWENTIES [21]). It provides a means of grouping and examining a wide variety of hybrid AC/DC grids based on their connection topologies (not considering market frameworks, line lengths or types, protection systems, etc.).

The four DC system topologies are described in Table I and represented graphically in Figure 1. The four AC system topologies are described in Table II. Figure 1 uses the AC1 topology only; the other topologies are not illustrated here but full details are available in Deliverable 2.1 [2]. The categories are not exclusive and there can be hybrids, e.g., as described in CIGRE TB804 [22].

In Figure 1, the black elements represent the DC grid components, and the green elements represent AC grids. The green graphics indicating wind farms or larger AC systems should be considered as interchangeable, with the option to connect a strong or weak AC network. The diagrams are illustrative only and should be interpreted in terms of the general topologies rather than as specific designs. It is not specified whether the DC-side configuration is monopole, bipole, rigid bipole, or a hybrid of those.

Table I: DC system topologies in the analysis framework

Abbreviation	Category	Description
DC1	Point-to-point links (P2P)	Converters connect to a single line that goes to one other converter station.
DC2	Radial links	Each converter is connected to a single line but that goes to a DC node (or "star point") that has lines to other converters. The DC node does not have any converters connected to it directly, it is a separate switching station.
DC3	Linear links	Each DC node is located at a converter station, such that some converters are connected to more than one line, and such that each switching station is part of a converter station.
DC4	Meshed links	There may be more than one path between terminals.

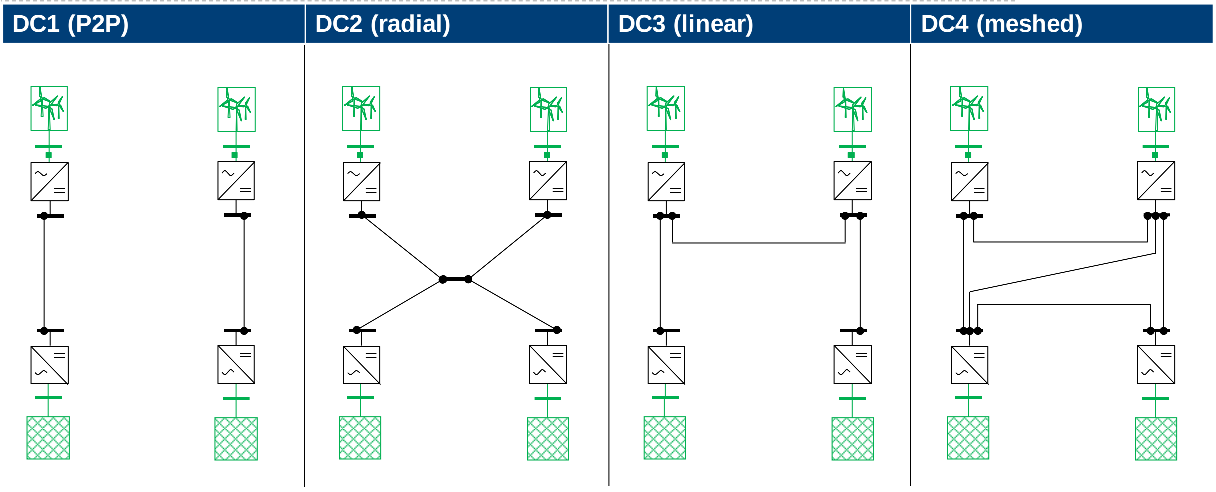

Figure 1: DC system topologies (single pole view)

Table II: AC system topologies in the analysis framework

Abbreviation	Category	Description
AC1	All separate	Every DC converter station is in a separate, asynchronous AC grid, some of which may be offshore wind farms or similar.
AC2a	One embedded + WPP/separate	At least two of the DC converter stations are in the same, synchronous AC grid and there are one or more separate, asynchronous AC grids that host other DC converter stations, some of which may be offshore wind or similar.
AC2b	Two separate embedded	The DC system connects two separate AC grids, each of which may host multiple DC converter stations. One example would be if there is an AC connection between two offshore wind farms that each have their own HVDC converter station.
AC3	Fully embedded	All converter stations of the DC system are connected to the same AC grid, so there are parallel AC and DC paths between all converter stations.

3.2. Trends in HVDC Architectures

A survey was conducted in late 2022 / early 2023 of existing and planned HVDC links. The results are publicly available [1] with some features summarised in Figure 2, Figure 3 and Figure 4. This revealed several trends in HVDC architectures:

- An increasing move towards development of VSC (green and blue) rather than LCC (yellow and red) based links.
- Use of bipole systems in preference to monopoles.
- Towards higher MW capacity, although most planned HVDC grids are in the 1-2 GW range.
- Some larger projects utilise very high voltages (up to 800 kV planned for VSC, and 1100 kV in existence for LCC) but there is a notable trend towards voltages of 320 kV and 525 kV.
- Some projects will use HVDC over very long distances, but most planned projects are for lengths of less than 750 km.

In the context of R&R, the increasing MW capacity of HVDC developments means that these HVDC links are often the single largest infeed/outfeed of the power system, meaning that the system operator must protect against increasingly large disturbances.

There is also a trend towards an increasing number of terminals for planned HVDC projects, with the associated flexibility these grids give on both AC and DC sides.

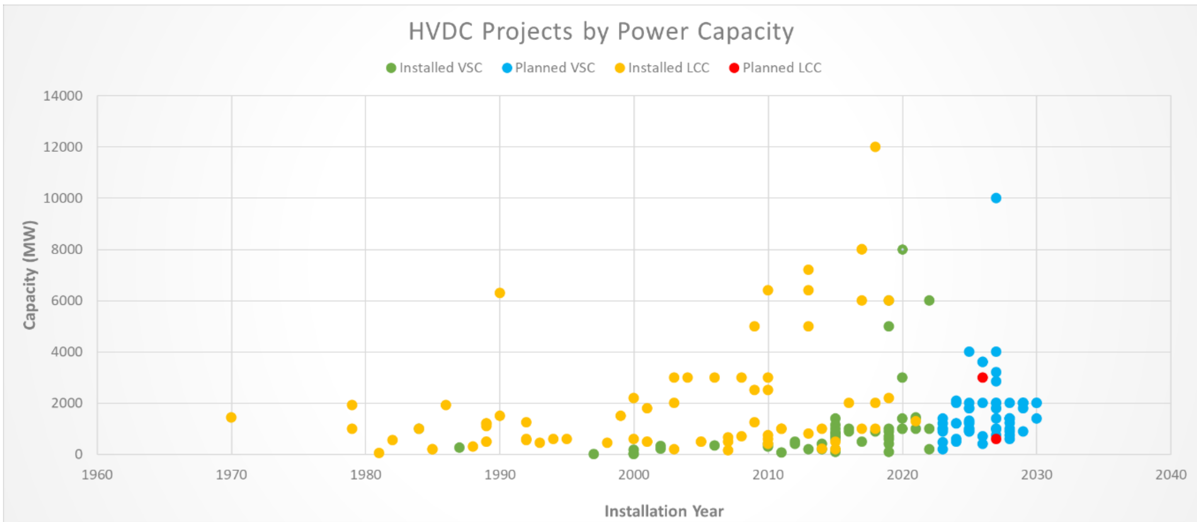

Figure 2: HVDC project power capacity over time

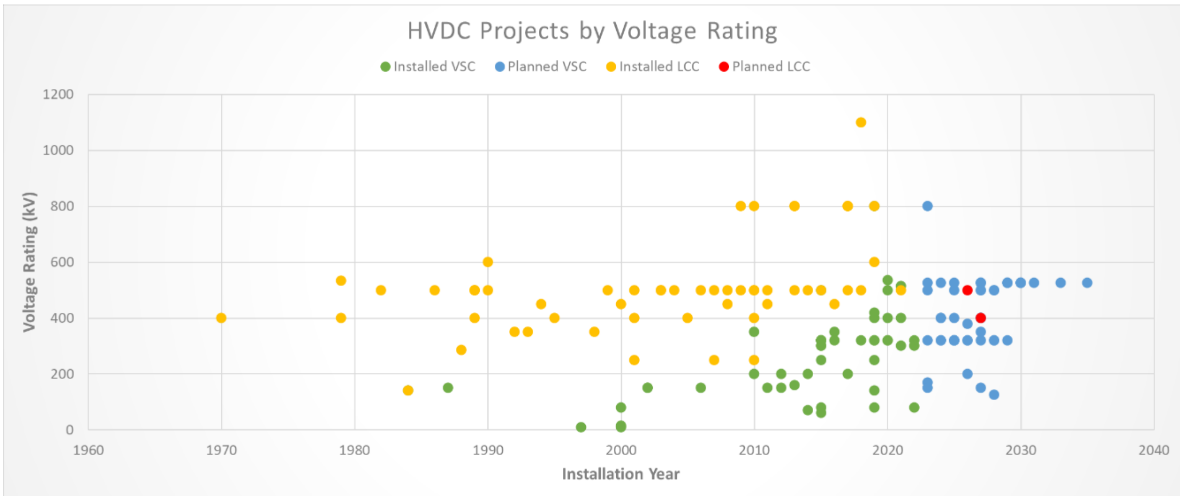

Figure 3: HVDC project voltage rating over time

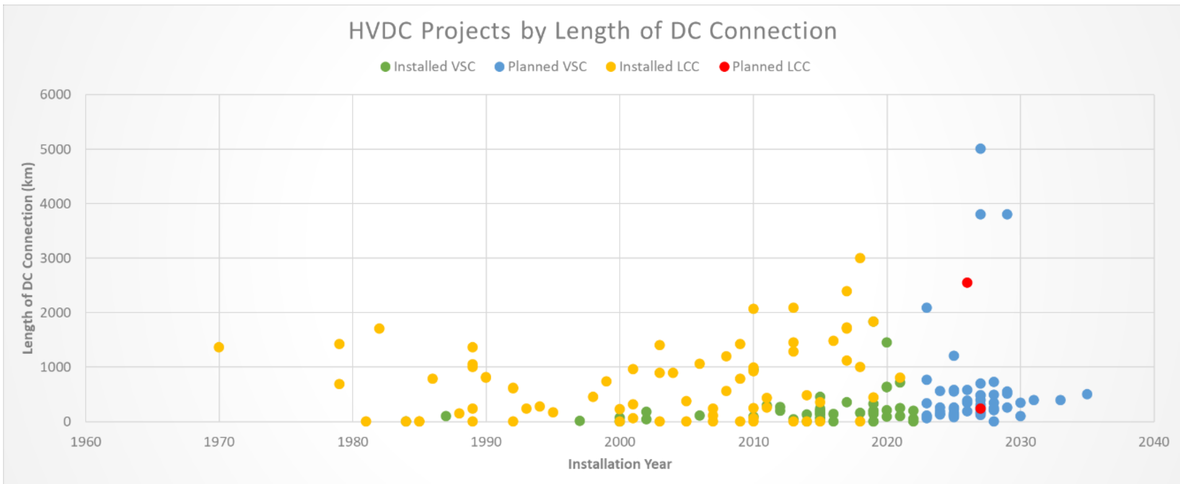

Figure 4: HVDC project DC connection length over time

The trends in HVDC architectures were reviewed in terms of R&R opportunities and vulnerabilities. The key outcomes are listed in Table III. HVDC-WISE Deliverable 2.1 [2] goes into more depth on the R&R related opportunities, and vulnerabilities for a range of HVDC control and protection functions.

Table III: Summary of R&R implications of trends in HVDC architectures

Opportunities	• Enables many AC grids to be interconnected through DC. • Improved asset utilization factor. • Increased system stability. • Increased resilience to faults regarding power transfer capability. • Increased potential for power from remote renewables to be transferred to load centres in a low-loss manner
Vulnerabilities	• Increases risk of contagion between multiple AC grids or connected devices. • More complex DC-side protection, with the associated risk of failure/unforeseen behaviours. • Potential multi-vendor interoperability issues. • Large capacity HVDC becomes the single largest infeed/outfeed in the network, meaning the system operator must provide for increasingly large N-1 contingencies. • Greater complexity requires more knowledgeable staff in all organisations.

4. TSO PERSPECTIVES

The five TSOs in the HVDC-WISE consortium represent three separate synchronous grid areas within Europe that are expected to share future multi-purpose HVDC interconnectors that will harness offshore wind in the North Sea and provide power transfer capability between areas. This provides the basis for deriving wide-ranging and widely applicable needs and objectives for future hybrid AC/DC systems.

Firstly, common issues of concern that have been identified by the five TSOs are summarised. Secondly, the events and disturbances that are of interest in relation to hybrid AC/DC system design are outlined. Together these provide a high-level guide to what the TSOs need to be addressed and where improvements are required in HVDC grid architectures, technologies, and associated functionality.

4.1. Common Issues of Concern

The following are issues of concern shared by the HVDC-WISE project TSOs:

- **Dominance of power electronics:** The main need is to ensure stability in a system dominated by power electronics (instead of synchronous generators). Experience in operating such systems is limited, although growing with the global transition to renewable technologies. New ancillary services are being designed, e.g. the GB Stability Pathfinder [23]. Codes and standards are being updated, e.g. proposals for changing the European Network Codes [24]. New approaches to modelling and testing are being developed, e.g. for studying sub-synchronous oscillations [25]. HVDC-WISE aims to inform these developments to consider R&R both in terms of what is possible and what is required.

- **Technology limitations:** HVDC converters are fully dependent on their software programming with fast acting control loops that need to respect both AC and DC network priorities. DC circuit breakers (DCCBs) are still an emerging technology for high voltages and powers. As technologies develop and new projects are delivered it is important to ensure R&R requirements are clearly defined to avoid unwanted behaviours and ensure compatibility across systems. Furthermore, real device behaviour must be simulated to verify its performance.

- **System stability:** Compared to synchronous generators or AC circuits, electronic devices have a limited overload capability, which impacts system balancing and provision of fault currents. HVDC links will be the largest electronic devices in future systems and will need to be specified to provide appropriate contributions to system stability and R&R.

- **Protection and control**: Testing and approval of HVDC control and protection may need to be refined, especially regarding the risk of interaction between controllers that are electrically close. DC protection needs to be much faster than AC, e.g. around 5 ms to ensure DCCBs can operate effectively, compared with 50 ms or more for AC protection. The post-fault recovery of the DC system also requires attention. Different ways for detecting faults in DC systems need to be investigated to bring the desired level of redundancy, with fall-back solutions in case of failure.

- **Power quality:** Even if modern converters generate less harmonics, power quality must be verified as resonances may arise due to the interaction of different HVDC links, other power electronic equipment, and passive network components. To ensure R&R is maintained, HVDC must be specified and tuned appropriately to manage and mitigate power quality impacts.

- **Cyber security:** Digital control and monitoring are critical and while the practicalities of implementation are in the hands of vendors, the cyber security requirements should come from the HVDC customers, e.g., TSOs, and governments. Digital R&R policies need to be developed to avoid unwanted interactions and cascading failures. Robust (local) fall-back solutions must be in place to deal with any failure or intrusion.

- **Readiness of tools and methods:** various new tools and methods for modelling, analysis, design, and decision making will be developed and adopted by TSOs and other stakeholders. To move from the research domain to application, new tools should be validated in real-world circumstances, plus training and ongoing support must be provided.

- **Inter-operability:** many of the above issues will be faced in DC systems that will involve technologies from multiple vendors. Achieving successful multi-vendor multi-terminal (MVMT) interoperability to maintain R&R will require new approaches to supervisory control, specification of interfaces and performance requirements, modelling, analysis, and testing.

- **Shared Responsibility:** HVDC links can introduce new risks in disturbance propagation and dependency on system conditions at each AC connection point. Further expansion of HVDC interconnection and growing levels of power transfer across large areas mean a greater degree of shared responsibility for R&R. This will require even more coordination between TSOs to ensure disturbances in one area receive the support needed from other areas without significant negative impact on those other areas.

4.2. Events and Disturbances

This section outlines some of the root causes, responses, and system consequences that are considered of greatest relevance and importance to future hybrid AC/DC systems is provided. The purpose is to identify the conditions of greatest interest as this helps to define the R&R needs and objectives.

Power systems must deal with relatively low-level events and disturbances all the time. These **high probability, low impact** events are dealt with through normal design and operation with the system expected to remain within its normal operating limits.

Power systems are also sometimes affected by extreme events and disturbances. These **low probability, high impact** events may push the system outside its normal operational range and prompt the use of emergency measures.

Root Causes

The root causes of events and disturbances are wide and varied with significant overlap that makes it difficult to characterise them completely. Those considered of greatest relevance to R&R in future hybrid AC/DC systems are:

- Routine faults that may affect any component in the AC or DC systems, including HVDC converter faults and loss of power infeed from HVDC systems.

- Natural events like extreme weather conditions, solar eclipses, geomagnetic storms, and earthquakes. Also, persistent conditions of low wind and solar irradiation, which lead to a prolonged deficit of renewable generation.

- Physical and cyber-attacks, with a particular focus on HVDC facilities that need numerous measurements and exchanges of information between the various controllers, which constitute potential entry points for malicious acts.

Responses

The impact of any event or disturbance very much depends on the responses from the multitude of devices connected to the power system. In future hybrid AC/DC systems, the overall system response will be strongly affected by the behaviour of HVDC schemes, particularly the converters at the interface between the AC and DC networks. The expansion of HVDC and its growing influence means the risks associated with unforeseen or adverse behaviour are significant threats. Even relatively minor, routine faults or changes in system state may trigger responses that could lead to the following:

- Undamped oscillations in local areas (especially weak areas) or at a larger scale.
- Sub-synchronous torsional interaction (SSTI) between electronic devices and torsional modes of the turbine-generator shaft of synchronous machines.
- Control interactions between HVDC converters, or between HVDC and other equipment.
- Converter blocking, due to conditions that exceed operating limits, and cause a sudden and potentially very large change in power flows and voltages on the AC and DC grids.
- Common mode protection or control behaviour, due to similar responses of several electronic devices facing the same disturbance.
- Triggering of system automatic controls, that may trigger erroneously due to unforeseen conditions compared to their design.
- Non-compliant behaviour compared to grid codes or connection agreements.

System Consequences

In terms of system consequences, those of greatest interest to TSOs were identified as:

- Impact on transmission system performance (availability, security, quality of service, and network constraints).
- Over-voltages in offshore energy hubs, for instance after a converter fault on an HVDC interconnection.
- System splits affecting the AC system and/or the DC system.
- System restoration, where there is room for new service types provided, for instance, by offshore wind farms and their connections to the grid.

HVDC-WISE aims to address TSO needs by developing new R&R oriented planning and analysis tools and demonstrating novel methods of control and protection. Advanced tools will be used to demonstrate and assess the power system performance benefits offered by different options. The project will make recommendations on how technical codes, standards, and industry tools and practices could be updated to support the adoption of new solutions and the improvement of R&R.

5. CONCLUSIONS

The HVDC-WISE project has reviewed definitions of power system resilience and concluded that the definition provided by CIGRE WG C4.47 is suitable for use in the project, where resilience is defined as “the ability to limit the extent, severity, and duration of system degradation following an extreme event.” An extreme event is determined by system outcomes rather than just the nature of the initiating disturbance but will mean the system is degraded beyond the outages normally considered in the assessment of adequacy and security.

The project has defined an approach to characterizing HVDC architectures, including a topology analysis framework that provides a means of grouping and examining a wide variety of hybrid AC/DC grids. The framework is based on a 4x4 style classification of DC and AC grids depending on connection topologies and on how DC links are embedded within AC grids.

In reviewing the R&R needs that are driving research and development, a survey was conducted of existing and planned HVDC links. This revealed several trends in HVDC architectures with many links planned to be 525 kV, 2 GW, VSC bipoles and increasing use of multi-terminal designs.

Based on the perspectives of the five TSOs in the project consortium, supplemented by input from all project partners, the discussion of common issues of concern together with events and disturbances that must be considered in the planning and operation of future hybrid AC/DC transmission systems provides a high-level guide to what the TSOs need addressing and where improvements are required in HVDC grid architectures, technologies, and associated functionality. Common issues of concern include:

- HVDC converters offer the potential to act as the foundation of stability in the future hybrid AC/DC system, but it is recognised that new solutions will be required to address issues of concern, deliver required performance, and maintain R&R.
- HVDC converters depend on programmable control software and do not have an inherent overload capability, leading to a risk of very fast changes in condition from acceptable operation to failure. These fast changes should be avoided by design where possible, or else the implications on the rest of the system must be understood.
- Future hybrid AC/DC systems need to be designed with similar levels of redundancy and dependability to AC systems. There must be fall-back cover for failure of any higher-level grid controller or communications and due account taken of cyber security risks.

Recognising the definition of extreme events by CIGRE WG C4.47, the events and disturbances of greatest interest in relation to hybrid AC/DC systems are discussed in terms of root causes, responses, and system consequences. Root causes include routine faults and operational conditions, natural events like extreme weather, and physical or cyber-attacks. In terms of system responses, we note that very complex combined AC and DC systems may react inappropriately to disturbances. The expansion of HVDC and its growing influence on the power system means the risks associated with unforeseen or adverse behaviour are a significant threat. Even relatively minor, routine faults or changes of system state may trigger undesired responses. System consequences could vary widely but the TSOs highlight energy dissipation in offshore hubs and wide-area system splits as being of interest, also noting the importance of understanding the role that HVDC schemes can play in system restoration in future hybrid AC/DC systems.

Based on the identification of R&R needs as described in this paper, the HVDC-WISE project is developing new R&R oriented planning and analysis tools and investigating novel methods of control and protection. Future publications will present project outcomes and recommendations that will support the adoption of new solutions and the improvement of R&R in future hybrid AC/DC systems.

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