Deliverable 2.1

Resilience Needs and Objectives

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Executive Summary

The goal of HVDC-WISE is 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 be readily deployed to improve system performance and facilitate the integration of new renewable sources.

The project seeks to provide new evidence to update thinking on power system reliability and resilience, reflecting the changing nature of the power system – especially the large-scale integration of HVDC systems – and new and emerging threats to system integrity. We will concentrate on technical aspects of R&R in future hybrid AC/DC systems, and on how HVDC architectures and technologies can enhance it and reduce the likelihood of interruptions to supply, or make it easier for the impact of events and disturbances to be contained and any interrupted supply to be restored. Advanced tools will be used to demonstrate and assess the power system performance benefits offered by different options and guide the high-level specification of HVDC-based solutions. We will also make recommendations on how technical codes, standards, and industry tools and practices could be updated to support the adoption of new solutions and improvement of R&R.

Work Package 2 of the project is concerned with identifying requirements, opportunities, and demonstration needs for R&R in future AC/DC systems. This Deliverable 2.1 presents the outcomes of our work in the first six months on:

- TSO expectations for R&R with the deployment of HVDC solutions within their networks
- Identifying opportunities, risks and barriers for HVDC in delivering R&R benefits
- Initial views on codes, standards and regulatory framework issues

Firstly, to provide a basis for the research being done in HVDC-WISE, we present definitions of power system reliability and resilience, as explored in other projects by various organisations around the world. Power systems reliability is a well-known and established concept. There is less clarity or common understanding on the concept of resilience, but the project shall build on the outcomes of CIGRE Working Group C4.47, which defines power system resilience as the “ability to limit the extent, severity, and duration of system degradation following an extreme event”. The definition is in terms of system outcomes rather than in relation to the nature of the initiating disturbance, so any event that has an adverse impact, beyond specified performance targets, on system performance, component integrity, operational capabilities and unsupplied customers is defined as an “extreme event”. The Working Group also identifies key actionable measures to be taken before, during and after extreme events. This includes taking action in terms of anticipation and preparation for events, having measures in place for absorption of impacts and the sustainment of critical system operations, then facilitating rapid recovery from a disruptive event and learning lessons on what adaptations can be made to improve resilience in future.

There are five TSOs in the project consortium representing three separate synchronous grid areas within Europe. This provides the basis for deriving wide-ranging and widely applicable needs and objectives for future hybrid AC/DC transmission systems. We discuss common issues of concern as well as the events and disturbance that must be considered in planning and operation. This provides a high-level guide to what the TSOs need addressed and where improvements are required in HVDC grid architectures, technologies, and associated functionality. Key issues identified by the TSOs and other project partners include:

- HVDC control, dynamics, behaviours, and vulnerabilities are likely to dominate system behaviour, in the same way as synchronous generators do now. 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.
- HVDC converters depend on programmable control software and protective limits applied to the technology, need to respect both AC and DC network control simultaneously, and do not have an inherent overload capability. There is a risk of very fast changes in condition from acceptable operation to failure.
- HVDC control systems are more like existing AC network protection than AC generator control, as they act very quickly and can result in very sudden and significant changes of state. 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.
- Multiple issues relating to system stability and power quality in hybrid AC/DC systems must be addressed. This includes current limitation and non-linearity in HVDC converter response to disturbances, DC fault propagation and interaction with all connected AC systems, risk of inter-area oscillations or control system interaction, and ensuring voltage stability on the AC and DC systems after a loss of multiple HVDC converters.
- Dependence on digital information for the functioning of the entire system is increasing, which raises concerns around cyber resiliency.
- It is important that new tools are made ready for proper use by TSOs. Training and ongoing support will be required as tools and methods are trialled and applied to real-world circumstances.

The events and disturbances that are of interest with relation to hybrid AC/DC system design are discussed in terms 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 contingencies. The expansion of HVDC and its growing influence on the power system means the risks associated with unforeseen or adverse behaviour is 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, noting also the importance of understanding the role that HVDC schemes can play in system restoration in future hybrid AC/DC systems.

The parallel activities in work packages 3, 4 and 5 are summarised in this report, with further details available in other project deliverables. To help meet the WP2 objective to identify opportunities, risks and barriers, we present a topology analysis framework developed in WP3 and use it in a survey of existing and planned HVDC projects, with commentary on trends relevant to R&R and emerging common designs. We present an initial review of different HVDC topologies and of the control and protection functions of greatest interest. We list the HVDC technologies that have been identified and subject to preliminary investigation in WP4, and summarise the work done in WP5 on reviewing existing methods and tools and starting to identify how they must be improved and developed.

This report presents an initial review of codes and standards across the TSOs involved in this project. This will be further explored and recommendations will be made over the next six months.

Together with the first version of Deliverable 2.2 (“Requirements and demonstration targets of the use cases”), this report satisfies Milestone 1 of the project, which is that resilience and demonstration needs are available. While this report presents the high-level R&R needs and objectives, Deliverable 2.2 complements this by identifying Key Performance Indicators (KPIs) and indicating how they can be demonstrated through different types of analysis. Deliverables 3.1 and 5.1 present further detail on the calculation and application of KPIs for R&R.

In the next six months, WP2 will help to define and inform the real-world use cases where new R&R capabilities will be demonstrated and evaluated in later stages of the project.

1 Introduction

The goal of HVDC-WISE is 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 be readily deployed to improve system performance and facilitate the integration of new renewable sources.

To achieve this general goal, the HVDC-WISE project targets the following five ambitious objectives:

- To develop new R&R-oriented planning toolsets (metrics, methodology, and tools) with appropriate representation of different HVDC-based grid architecture concepts aiming to fulfil TSO reliability and resilience needs defined during the project.
- To identify, propose and compare different HVDC-based grid architecture concepts aiming to address TSO reliability and resilience needs for widespread AC/DC systems.
- To identify, assess, and model emerging technologies for HVDC-based grid architecture concepts needed for the deployment of widespread AC/DC transmission grids.
- To validate in an industrially relevant environment the resilience-oriented planning toolset and the HVDC-based grid architecture concepts on three realistic use cases.
- To prepare for the adoption and deployment of the proposed solutions by the industry.

The power industry in Europe, and around the world, is at the beginning of a period of massive change as new renewable sources replace conventional generation and transmission networks are adapted and upgraded. For many in the industry, these massive changes present a threat to R&R but new HVDC technologies also offer opportunities for improvement. In HVDC-WISE we seek to mitigate the new risks and also exploit the opportunities so that R&R is not just maintained at the high levels currently achieved but improved where possible.

Work Package 2 is concerned with identifying requirements, opportunities, and demonstration needs for R&R in future AC/DC systems. Its objectives are:

1. Provide clarity on TSO expectations for R&R as applies to the deployment of HVDC solutions within their networks
2. Identify opportunities where HVDC capabilities may deliver additional R&R benefits, and also identify risks and barriers
3. Provide definitions and guidance for the real-world use cases where R&R capabilities will be demonstrated, tested, and evaluated
4. Identify codes, standards and regulatory framework issues

This Deliverable 2.1 presents the outcomes of our work in the first six months of the project addressing the first two objectives, and presents initial views on objective four. Over the next six months, WP2 will help to define and inform the real-world use cases where these R&R capabilities will be demonstrated and evaluated in later stages of the project.

The first version of Deliverable 2.2 ("Requirements and demonstration targets of the use cases") [1] is also issued at this time; a second version will be issued at the end of the project's first year. Together these reports satisfy Milestone 1 of the project, which is that resilience and demonstration needs are available. While this report presents the high-level R&R needs and objectives, Deliverable 2.2 complements this by identifying Key Performance Indicators (KPIs) and indicating how they can be demonstrated through different types of analysis.

The project has produced several other deliverables at this time:

- Deliverable 3.1 defines different AC/DC grid architectures with associated control and protection concepts, and presents an early qualitative assessment of their pros and cons.
- Deliverable 4.1 identifies key technologies, potential benefits and restrictions, providing the basis for further work later in the project.
- Deliverable 5.1 outlines the functionalities to be added to existing simulation and planning tools, plus possible needs for additional models, interfaces and data sharing to successfully carry out R&R-oriented studies with AC/DC architectures.
- Deliverable 5.2 provides representative but simplified test systems that will be used to test tools and models later in the project.

Chapter 2 of the report provides the basis for our research by presenting the definitions of R&R being used in the project, highlighting the key features of power system reliability and resilience.

Chapter 3 sets out our view on R&R needs and objectives in future hybrid AC/DC grids, especially from a TSO perspective. It discusses a number of common issues of concern as well as the events and disturbance that must be considered in planning and operation of future hybrid AC/DC transmission systems. This first deliverable provides a high-level guide to what the TSOs need addressed and where improvements are required in HVDC grid architectures, technologies, and associated functionality. These high-level requirements are reflected in the KPIs reported in Deliverables 2.2 and 3.1 [1] [2], which go into much greater detail on how to evaluate specific reliability and resilience metrics.

Chapter 4 describes HVDC architectures, reflecting the parallel work done in WP3. We present a topology analysis framework (see also D3.1) that has been used in our survey of existing and planned HVDC projects (full details of the survey are available in an accompanying spreadsheet). To meet our objective to identify opportunities, risks and barriers, there is a review of the HVDC topologies and of the control and protection functions of greatest interest.

Chapter 5 summarises the HVDC technologies that have been identified and subject to preliminary investigation in WP4, while chapter 6 reflects the work done in WP5 on reviewing existing methods and tools and starting to identify how they must be improved and developed.

Chapter 7 presents our initial review of codes and standards across the TSOs involved in this project. This will be further explored and recommendations will be made over the next six months.

Chapter 8 offers some early conclusions from the project, discusses next steps and summarises the research objectives for the remaining three years.

The Appendices provide additional information on HVDC grid architectures featured in literature and real-life examples of extreme weather events, and the accompanying spreadsheet provides full details of our review of existing and planned DC projects. A comprehensive list of references is included at the end of the report.

2 R&R Definitions

Electrical power systems are the backbone of any modern society, supporting several other critical infrastructures, such as transportation, communication, water, etc. A disruption in the continuous electricity supply can have catastrophic consequences, as experienced during numerous blackouts in the last decades. However, ensuring an uninterrupted electricity supply is challenging, as power systems are exposed to a variety of threats and disturbances. Disturbances, which may result from a variety of factors including interactions with the natural environment or the failure of systems or components, typically manifest as equipment outages. Power systems, particularly transmission systems, are typically designed to maintain reliable operation in the event of any single commonly expected outage event. Power systems reliability is a well-known and established concept, commonly defined in two aspects, adequacy and security, which are discussed further in Section 2.1.

In contrast, there is less clarity or common understanding on the concept of resilience. A broad understanding of power system resilience is that it 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. Considering and quantifying these severe disturbances in spatial and temporal cascading models would provide important insights on the resilience performance and enhancement of the system. Definitions of resilience are explored further in Section 2.2.

2.1 Reliability in Power Systems

The concept of ***reliability*** was introduced to assess the performance of the power system in providing energy to users even in the case of disturbances. Reliability has been defined by several well-recognised institutions, such as CIGRE, IEEE, IEC, NERC, and ENTSO-E, in terms of ***adequacy*** and ***security***. Table 1 summarizes the definitions from these different entities.

A common theme across the reported definitions is that ***reliability*** refers to how successful a power system is in supplying the desired levels of power to customers. The degree of 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.

As far as ***adequacy*** is concerned, the key concept is the availability of resources and components, or system elements, which offer suitable capacity to meet demand without violating operating limits. To be adequate, a power system must be endowed with resources for generation, storage, demand flexibility, as well as transmission capacity sufficient to cover the expected demand plus reserves for contingencies, at all times. Adequacy must therefore be considered in terms of long-term planning horizons to ensure a suitable development of the above resources, within the mechanisms defined by the applicable regulatory frameworks.

All adequacy definitions include explicit reference to “*unscheduled outages of system components*”, i.e., contingencies. In particular, NERC, IEEE and ENTSO-E refer to reasonably expected unscheduled outages, thus also including an application criterion (i.e., the credibility criterion) in the definition.

TABLE 1: DEFINITIONS OF RELIABILITY, ADEQUACY AND SECURITY

	Reliability	Adequacy	Security
CIGRE [3], [4]	A measure of the ability of a power system to deliver electricity to all points of consumption and receive electricity from all points of supply within accepted standards and in the amount desired.	A measure of the ability of a power system to meet the electric power and energy requirements of its customers within acceptable technical limits, taking into account scheduled and unscheduled outages of system components, where: Power system includes all elements of the generation, transmission and distribution systems, and customer facilities that supply or use power and energy, or provide ancillary services; Customers include all parties that supply power and energy or ancillary services, as well as those who consume them; Requirements of customers include their basic power and energy needs, and agreed use of customers' ability to vary power supply, adjust demand and provide ancillary services; Acceptable technical limits and scheduled and unscheduled outages are those specified in the applicable planning criteria and standards; and System components include all elements of the supply, delivery and utilization systems regardless of ownership or control.	The ability of the power system to withstand disturbances, where: Power system includes all elements of the generation, transmission and distribution systems, and customer facilities that supply or use power and energy, or provide ancillary services; Ability to withstand will vary depending on specific disturbances and applicable criteria or standards, and includes agreed use of customers' ability to vary power supply, adjust demand and provide ancillary services; Disturbances include electric short circuits, unanticipated loss of system facilities, or other rapid changes such as in wind or solar generation.
NERC [5]	The degree to which the performance of the elements of that system results in power being delivered to consumers within accepted standards and in the amount desired.	The ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.	The ability of the bulk power system to withstand sudden, unexpected disturbances, such as short circuits or unanticipated loss of system elements.
IEEE [6], [7]	Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.	The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outage of system elements.	Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.
IEC [8]	The ability of a power system to meet its supply function under stated conditions for a specified period of time.	The ability of an electric power system to supply the aggregate electric power and energy required by the customers, under steady-state conditions, with system component ratings not exceeded, bus voltages and system frequency maintained within tolerances, taking into account planned and unplanned system component outages.	The ability to tolerate a credible event without loss of load, over-stress of system components, or deviation from specified voltage and frequency tolerances.
ENTSO-E [9], [10], [11]	The degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired.	The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.	The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

As for ***security***, CIGRE [3], NERC [5], and ENTSO-E [9], [10] [11] definitions are perfectly coherent in recognizing security as “the ability to withstand sudden disturbances”. IEC definition [8] includes the requirement of “integrity of demand supply” (i.e., “without loss of load”) in case of an event which satisfies a credibility criterion. IEEE [6] [7] similarly specifies “without interruption of customer service”.

In view of that, all 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. In this context, security analyses and quantifies the transition of the system performance between the pre- and post-outage state.

The adequacy aspects and planning of investment are often informed by quantified probabilistic modelling to compute different metrics such as loss of load expectation (LOLE) or expected energy not served (EENS) and the system can be designed to meet certain agreed minimum standards. While operational performance is often similarly quantified, probabilistic modelling to inform decision making in operational timescales is much less common.

The level of security that a system operator should provide is typically defined via “security standards” that specify events to be secured against (contingencies) and potential consequences of those events that are to be avoided, such as overloads of lines, voltages or frequency too high or too low, poor damping following a disturbance, or interruptions of supply to end users of electricity [12]. A system is therefore either secure or not secure. To the extent that any metric is computed by a TSO, it is the cost of system operator actions (or, in the longer term, TSO investment actions) to comply with the security standard.

Various approaches have been proposed to quantify the level of reliability implied by a particular security standard, compliance with it or different ways of complying (see, for example [13]). The GARPUR project [14] proposed a framework that could be used to inform decision making in system and operational planning, based more on explicit consideration of quantified risk than is usually the case today. It recognised that disturbances of many kinds can occur and lead not just to those outages that are typically included in contingency lists, but also to other outages or combinations of outages. It outlined the concept of residual risk to represent the risk associated with outages that are not secured against, and offered the system operator a way of judging what to secure against and what not to secure against. It also offered a way of comparing preventive (pre-outage) actions with corrective (post-outage) actions. However, the main barrier to the adoption of the approach is the lack of data on the probabilities of different events.

2.2 Definitions of Resilience

Electrical power systems, recognised as amongst the most critical of infrastructure, 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 in itself has emerged more recently. There have been several attempts by organizations worldwide in the power and energy engineering communities to define resilience and distinguish it from the concept of reliability. A pioneer definition comes from the Multidisciplinary Center for Earthquake Engineering Research[1], where a generic resilience framework was developed that is applicable to any critical infrastructure, including power systems, based on the “4Rs” of robustness, redundancy, resourcefulness, and rapidity.

[1] https://www.buffalo.edu/mceer/about.html

Many definitions of power system resilience have been offered, but the majority focus on the ability to anticipate, absorb, and rapidly recover from disturbances. Although even quite common and simple disturbances might lead to interruptions to supply that need to be contained and recovered from, many power systems publications focus on resilience against an external, high-impact, low-probability shock. Table 2 provides an overview of existing definitions of power system resilience in the literature.

TABLE 2: EXISTING DEFINITIONS OF RESILIENCE IN THE POWER SECTOR

Source	Definition
UKERC, UK Energy Research Center (UKERC), "Building a Resilient UK Energy System", 2009 [15]	The ability of a power system to withstand extraordinary and high-impact, low-probability events such as due to extreme weather, rapidly recover from such disruptive events and absorb lessons for adapting its operation and structure to prevent or mitigate the impact of similar events in the future.
Haimes [16]	The ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.
NIAC [17]	The ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.
UK Cabinet Office [18]	The ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event.
PSERC [19]	Ability of a system to gradually degrade under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed.
NAURC [20]	Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event.
Presidential Policy Directive 21: Critical Infrastructure Security and Resilience, 2013 [21]	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.
Sandia Lab 2011 [22]	Given a **disruptive event** (or set of events), the resilience of a system to that event (or events) is the ability to reduce **efficiently** both the magnitude and duration of the deviation from targeted **system performance** levels. The **bold words** of this definition are key components of resilience: • **Disruptive event**: Different disruptions may affect a system in different ways and thus necessitate different recovery processes. Hence, a system may have different levels of resilience to different disruptions. This definition considers resilience of a system to a specific disruption. • **Efficiently**: Efficiently means using the lowest possible amount of resources during recovery processes; depending on the domain, these resources could be dollars, repair man-hours, infrastructure replacement assets, or time. • **System performance**: Given the flexibility of many systems to adjust and reconfigure to a disruptive event, maintaining system structure is not as important as maintaining system performance. Hence, measurement of resilience should evaluate how a disruption affects system performance and causes productivity to decrease relative to targeted system performance levels: that is, how the system should behave during and after disruptive events.
Italian Ministries of Economic Development and of Environment and Land and Sea Protection, Strategia Energetica Nazionale (SEN 2017), 10 November, 2017 [23]	The ability of a system not only to resist to stresses which have overcome the withstanding limits of the system itself, but also to come back fast to a normal state of operation. The effectiveness of the resilient system depends on its capability to anticipate, to absorb, to adapt to and/or recover itself from an extreme event.
IEEE Task Force on Definition and Quantification of Resilience, April 2018 [24]	The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.
National Security Policy for Critical Infrastructures, Brazilian government, November 2018 [25]	The capacity of the critical infrastructures to be recovered after the occurrence of an adverse situation.
NATF (North American Transmission Forum) [26]	The ability of the system and its components (i.e. both the equipment and human components) to minimize damage and improve recovery from non-routine disruptions, including high-impact, low-frequency (HILF) events, in a reasonable amount of time. Resiliency includes a diverse range of topics, such as flexibility, hardening, security and recovery.

US National Academies of Science [27]	The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.
CIGRE WG C4.47, Sept 2019 [28]	The ability to limit the extent, severity, and duration of system degradation following an extreme event. As an integral part of the definition, it includes the following key actionable measures to be taken before, during and after extreme events: anticipation, preparation, absorption, sustainment of critical system operations, rapid recovery, and adaptation, including the application of lessons learnt.

2.2.1 Key Features of Power System Resilience

Although resilience is a relatively new term in relation to power systems, the concept of managing extreme events is long established. Figure 1, taken from CIGRE Working Group C1.17 in 2010, outlines a three-layered approach to the "management of major unreliability events". This provides an overview of the measures that power system operators have historically taken to prevent, contain and recover from major events and, despite not explicitly using the term resilience, it maps closely with many of the updated definitions of power system resilience outlined in Table 2.

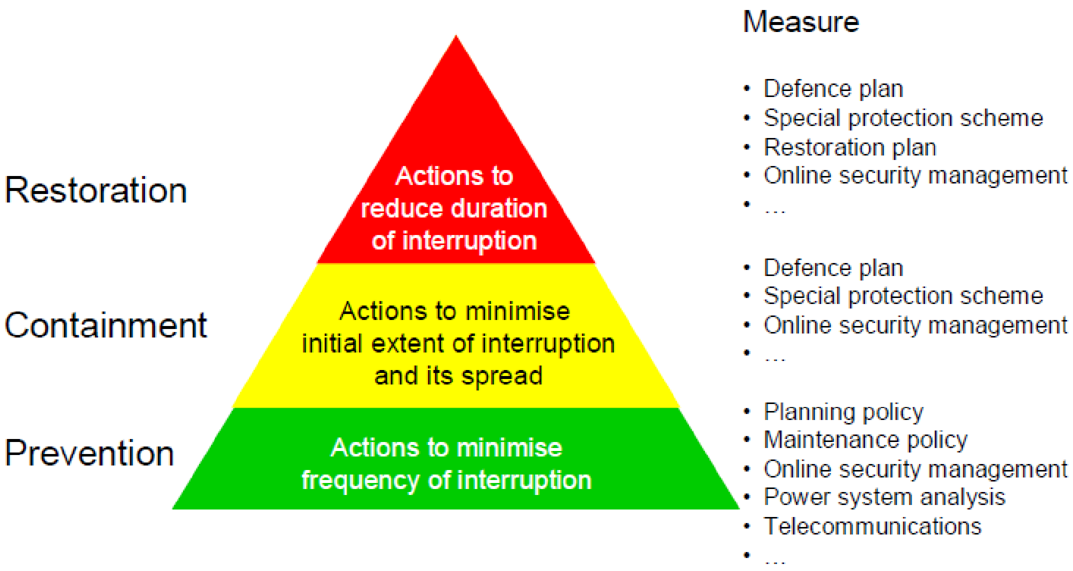


FIGURE 1: PYRAMID APPROACH TO MANAGING MAJOR UNRELIABILITY EVENTS [12]

Many of the highlighted resilience definitions focus on "extreme events" (an expanded definition on what that encompasses is offered later in Section 2.2.2 with reference to [28]), while a number refer more broadly to "disruptive events". The former gives an obvious point of differentiation between reliability (focused on a defined set of credible events) and resilience (focused on extreme events, assumed to not be contained with the defined set of credible events). Many considerations about the actual relationship between reliability and resilience properties have been carried out in different international working groups (such as in CIGRE Study Committees C1, C2 and C4). However, there is still not a prevalent view on this point.

It can be argued a resilient power system is one with the ability to recover from *any* system event that leads to interruption to supply. Reference [29] presents a conceptual model that highlights the interactions between the environment and the power system. It notes how natural or human-related threats may, due to vulnerabilities in the system, lead to contingencies, which may in turn affect other vulnerabilities, starting a cascading process that leads to significant impact. Reference [30] depicts resilience as the overarching aim for the power system and identifies some of the actions and processes needed to deliver that, including the design of, and investment in, key elements of the power system and the development of appropriate structures and policies to plan for and guide resilience.

A conceptual model relating to the operational resilience of a power system in response to a specific disturbance event is given in Figure 2. The resilience trapezoid [31] recognises that a power system might reside in different states or phases when exposed to an external shock and seeks to characterise these to enable a systematic resilience assessment and enhanced preparedness. The concept outlines three phases associated with the progression of an external disturbance highlighting the scale and speed of progression of system degradation, the length of time in the degraded state and scale and speed of the restoration process. The resilience level reflects the system performance during the event, which can be any system performance indicator (e.g., load connected during the event). The types of actions that can be taken in each of these phases and before and after the onset of the disturbance to maximise resilience are also highlighted. It is also worth noting that the post-disturbance state may have a higher or lower resilience level than the pre-disturbance state, depending on the actions taken by the system operator.

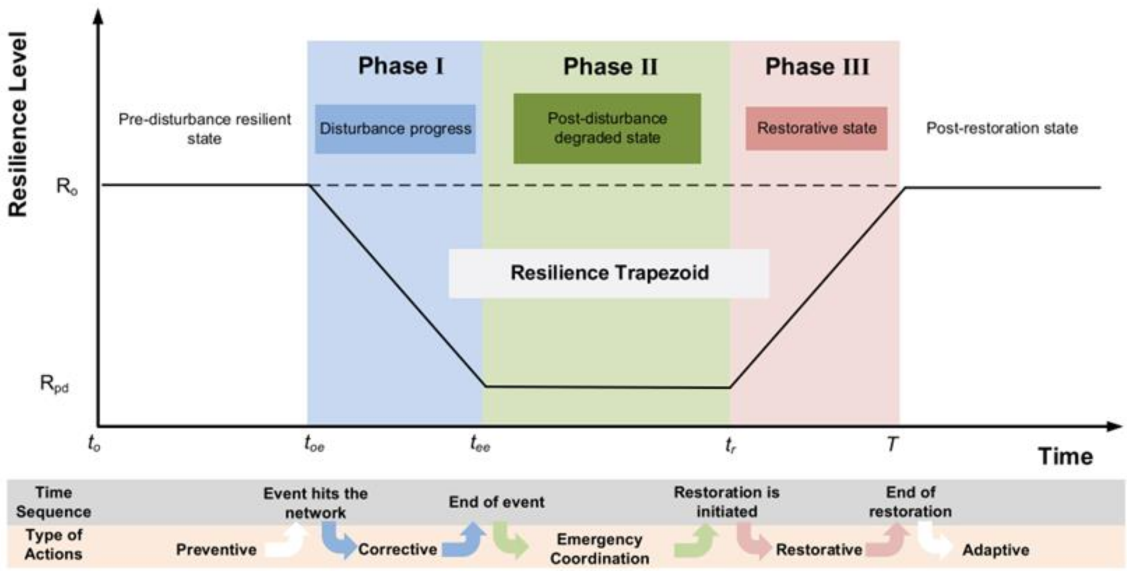


FIGURE 2: RESILIENCE TRAPEZOID: CONCEPTUAL PHASES RELATED TO RESILIENCE OF A POWER SYSTEM [31]

According to [31], a power system that is resilient to disturbances should possess the following key features at each stage of the trapezoid concept.

- Pre-disturbance resilient state: A sufficient estimation of the event’s location and severity would enable the application of preventive actions and the network configuration in a state that would help the system operator to deal effectively with the upcoming event. It would also enable the prepositioning of the resources possibly required following the event, e.g., repair and recovery crews, mobile generators, etc. Therefore, preventive operational flexibility is critically important. The extent to which preventive actions can be taken will depend on the level of foresight or prior warning associated with the particular event.

- Phase I (disturbance progress): High robustness / resistance and redundancy would help boost the resilience to the initial impacts of the external shock and reduce the level of resilience degradation (i.e., Ro-Rpd in Figure 2). Further, resourcefulness (supported by smart grid technologies, e.g., advanced monitoring and distributed energy systems) is particularly important as it provides the corrective operational flexibility required for dealing with the prevailing conditions and reducing the slope / speed of the resilience degradation. Also, advanced information systems would help develop high situational awareness allowing the system operators to remain adequately informed on the evolving conditions.

- Phase II (post-disturbance degraded state): Disaster assessment, priority setting, and proper emergency preparedness and coordination would help the system operator to assess the damage caused by the event, identify the critical components for the recovery of the system to a resilient state, and initiate as fast as possible the procedures for restoring the damaged infrastructure. This reduces the duration of Phase II, i.e., between times t_{ee} and t_r in Figure 2.
- Phase III (restorative state): Following the actions in Phase II, a resilient system should demonstrate high restorative capabilities to first restore the disconnected customers (i.e., operational resilience) and then restore the collapsed infrastructure (i.e., infrastructure resilience). Several actions should take place in this phase, such as re-energizing transmission and distribution lines, restoration of damaged components, unit restarting, resynchronization of areas, load restoration, etc. The aim of these actions should be to reduce the duration of Phase III, i.e., between times T and t_r in Figure 2.
- Post restoration state: Following the event and the restoration of the infrastructure, the impact of the event and the performance of the network should be thoroughly analysed to identify weaknesses or limitations of the system, which could be improved to be better prepared for future (similar or unforeseen) events. Therefore, being adaptive to and reflective of the experiences gained through the different events and threats is a key feature of a resilient infrastructure.

If a power system possesses the key resilience features mentioned throughout the different phases of an event, then it should be capable of effectively anticipating the impacts of the upcoming event, rapidly recovering from the degraded to a resilient state, and adapting its operation and structure to reduce the effects of future events.

2.2.2 Adopting a Reference Definition for Power System Resilience

CIGRE established Working Group (WG) C4.47 “Power System Resilience” in 2019 with the aim of formulating a reference standard definition and approach to resilience for power systems. This working group performed an international survey with over 100 respondents from around the globe including industrial, consultancy, governmental and academic organizations. The survey exposed the participants to wider interpretations of power system resilience and invited participants to comment and provide their views on these definitions. It is therefore believed that the definition provided by the WG incorporates the key features of prior definitions and provides a well-suited definition to be adopted by the electricity sector. CIGRE WG C4.47 defined power system resilience as:

the “***ability to limit the extent, severity, and duration of system degradation following an extreme event***” [28].

As an integral part of the definition, it includes the following key actionable measures to be taken before, during and after extreme events:

1. anticipation
2. preparation

3. absorption
4. sustainment of critical system operations
5. rapid recovery; and
6. adaptation, including the application of lessons learnt.

An extended explanation of the properties of the resilience definition and of the actionable measures that WG C4.47 outlined is available in [28]. This makes clear that the definition should be read in terms of system outcomes rather than in relation to the nature of the initiating disturbance. **Extent, severity** and **duration** are therefore linked to the geographical extent, intensity of adverse impact (to the system and for its users), and period of time for which system degradation occurs. **Degradation** is measured in relation to deviation from specified performance targets, while an **extreme event** is defined in relation to impact on system performance, operational capabilities, and unsupplied customers as well as damage to components. That is, any event that has an adverse impact, beyond specified performance targets, on system performance, component integrity, operational capabilities and unsupplied customers is defined as an "extreme event".

The first two actionable measures reflect measures to be taken in advance, i.e., in both long-term planning and shorter-term operational planning for resilience. The process of **Anticipation** relates to the evaluation of foreseeable scenarios that could lead to severe system outcomes including emergent threats and enumeration of the plausible disaster scenarios and proposed mitigation plans. **Preparation** relates to how learning from the anticipation process is used in the implementation of resilience strategies and objectives to guide the deployment of resilience measures.

During extreme events, there is an expectation that resilience measures should be in place to absorb impacts, enable critical operation to be sustained and facilitate rapid recovery. **Absorption** is the ability to minimise or avoid consequences from extreme events and is measured in relation to the slope and level of degradation. The **sustainment of critical system operations** gives emphasis to the maintenance of critical loads and a minimum system load level to sustain an acceptable functioning of everyday life and orderly functioning of a modern society. This also covers the essential loads that are required to support the restoration effort and so allow **rapid recovery** of the system from a disruptive event. Rapid recovery must be underpinned by efficient and effective response planning to allow for a co-ordinated recovery to normal or near normal operation. This may include deployment of additional resources (e.g., mobile generators), defence systems (e.g., uninterruptible power supplies) or use of previously underutilised resources in restoration planning (e.g., distributed energy resources).

Finally, after disruptive events occur a key part of resilience is the ability to understand what lessons can be drawn and what adaptations can be made to improve resilience in future. Thus, a process of **adaptation** must be undertaken to update power system management, defence and operational regimes in light of lessons learnt. This may include upgrades of preventive measures, operational methods, and maintenance procedures.

2.3 Project aims in relation to R&R

The HVDC-WISE project seeks to provide new evidence to update thinking on power system reliability and resilience, reflecting the changing nature of the power system – especially the large-scale integration of HVDC systems – and new and emerging threats to system integrity.

The provision of reliable and resilient access to electricity by energy users is a fundamental objective of a power system and all the various actors involved in generation, transmission, distribution and balancing services. It is affected by many aspects of what these actors do and is a very large subject, covering logistics, asset management, workforce planning, and stakeholder communication and interaction in addition to the definition and implementation of technical standards and codes, design decisions and procurement and commissioning actions.

HVDC-WISE will concentrate on technical aspects of R&R in future hybrid AC/DC systems, and on how HVDC architectures and technologies can enhance it and reduce the likelihood of interruptions to supply, or make it easier for the impact of events and disturbances to be contained and any interrupted supply to be restored. 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 appropriate design of architectures, controls, and protection to ensure that the integration of HVDC does not introduce any new risks.

The introduction of HVDC plant into a power system adds new components and types of component and possible outage events that may require security standards to be revised to include additional contingencies and avoided consequences in order that R&R is not degraded. Similarly, grid codes may need to be revised. This will be addressed as part of the HVDC-WISE work.

In general, HVDC plant and systems can enhance R&R relative to today's power systems in the following ways:

1. By reducing the likelihood of an outage
2. By minimising the impact of outages through R&R centred design principles and control methods
3. Through enhanced response to an event or disturbance.
4. Through control of system conditions during a restoration process.

The first of the above might most notably be achieved through use of underground or subsea cables that are, in general, less vulnerable to weather-related outages than overhead lines although repair times may be significantly longer. In many use cases, the desire or need, because of circumstances or public or policy preference, to use cables makes use of HVDC a necessity, e.g. to avoid issues with electrical performance of AC cables or to minimise losses.

In relation to the second point, the effectiveness of HVDC in enhancing R&R depends on how HVDC elements of a combined, hybrid AC/DC system are designed, configured and protected. Topological and technology design choices will influence the extent to which adequacy can be improved through the sharing of disparate resources while the chosen protection philosophy will influence the extent to which individual faults on the system propagate. For example, without DC breakers, a fault anywhere on a multi-terminal HVDC system would lead to a rapid fall in voltage across the entirety of that system and a need for all of it to be isolated by the action of protection on the AC side of each converter station. Thus, while the probability of a fault within a system using underground cables might be lower than if overhead lines had been used for similar distances, the impact of a fault might be greater.

A further way in which, in principle, the probability of an outage can be reduced is by better control of power flows and loading across multiple circuits, and better control of voltage. These can both be achieved in a pre-disturbance manner via the controllability of HVDC.

The third and fourth of the above means of enhancement – through post-disturbance responses – relate to the ability of HVDC systems to contribute via, for example, the control of voltages and power flows, the damping of oscillations or aiding energisation. These features in turn depend on how converter controls are designed and operated and on the current rating of converters.

The HVDC-WISE project will address the use of HVDC architectures and technologies to enhance R&R in future hybrid AC/DC systems. Advanced tools will be used to demonstrate and assess the power system performance benefits offered by different options and guide the high-level specification of HVDC-based solutions. It will also make recommendations on how technical codes, standards, and industry tools and practices could be updated to support the adoption of new solutions and improvement of R&R.

2.4 Relevant Past Research

There have been several research projects in recent years relevant to HVDC-WISE and the development of R&R thinking in future AC/DC grids.

The **Generally Accepted Reliability Principle with Uncertainty modelling and through probabilistic Risk assessment (GARPUR)** project funded by the European Commission started in September 2013 and lasted until September 2017. The project designed, developed, and assessed new probabilistic reliability criteria to be progressively implemented over the next decades in the pan-European power system.

https://www.sintef.no/projectweb/garpur/

The EU-funded project **Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks (TWENTIES**) aimed to advance the development and deployment of new technologies to support widespread integration of onshore and offshore wind power into the European power system.

http://www.ewea.org/fileadmin/files/library/publications/reports/Twenties_report_short.pdf

To overcome the challenges of renewable power integration in the power system, the **BEST PATHS** project developed novel network technologies that enables high-capacity transmission networks for the European power system.

http://www.bestpaths-project.eu/

The **Progress on Meshed HVDC Offshore Transmission Networks (PROMOTioN)** project addressed the technical, legal, regulatory, economic, and financing challenges in the development of a meshed offshore HVDC transmission network in the North Sea.

https://www.promotion-offshore.net/

Another EU-funded project, **Massive Integration of Power Electronic Devices (MIGRATE)** aimed to provide solutions for the technological challenges that the transmission grid is currently facing and expected to face in future.

https://www.h2020-migrate.eu/index.html

3 TSO Perspectives

This section presents issues of concern and highlights events and disturbances of relevance to reliability and resilience (R&R) in future widespread AC/DC systems, based mainly on the current views of the Transmission System Operators (TSOs) involved in HVDC-WISE, supplemented by contributions from all project partners.

Transmission network planning and operation, including R&R requirements, is driven by the relevant codes, standards, policies and processes that apply in each area. These are discussed in section 7.

3.1 Project TSOs

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

3.1.1 Continental Europe

Amprion GmbH, TenneT TSO GmbH and Energinet are TSOs of the synchronous grid of continental Europe. This is one of the largest synchronous electricity networks in the world with a geographic expansion from Denmark to Italy and Turkey to Spain (Morocco, Algeria and Tunisia are loosely synchronized via AC-connection). The latest grid expansion was the emergency synchronisation of Ukraine and Moldova in 2022. A synchronisation of the Baltic states is planned for 2025. The AC voltage levels are mainly 380 kV and 220 kV although there is a trend towards replacing the 220 kV infrastructure by 380 kV. With the extension projects of Ukraine/Moldova and the Baltic states 750 kV and 330 kV infrastructure is being integrated into the system. Beside the AC infrastructure, there are several HVDC point-to-point links within the system and to neighbouring synchronous areas, with a mixture of LCC and VSC technologies.

The power system operated by Energinet in Denmark has two separate areas. The DK1 area, which covers Jutland, is part of the continental Europe grid. The DK2 area, which covers Copenhagen and the islands in the east of Denmark, is part of the Nordic synchronous grid.

In July 2021, the European Commission launched the Fit-For-55 programme, setting out different legislative proposals to reduce the European Union’s (EU) net greenhouse gas emissions by at least 55% by 2030. To meet this goal, the national governments in Europe have elaborated ambitious targets for the extension of Renewable Energy Sources (RES). For example, the installed capacity in the German NEP2023 scenarios is assumed to be 400-445 GW for PV, 160-180 GW for onshore wind, and 70 GW for offshore wind in 2045. The main future challenge is to ensure a cost-efficient integration of this huge amount of RES in the system while ensuring a high level of resilience and reliability. This includes (non-exhaustive list):

- Ensure system stability in situations with little synchronous generation (some areas without synchronous generation at all)
- Ensure adequacy (transmission and generation)
- Handling of highly volatile infeed of RES and the resulting power flows (static and dynamic compensation of reactive power)

3.1.2 Nordic Area

Statnett is the TSO in the Norwegian electric power transmission system. Statnett is a state enterprise owned by the Norwegian state through the Ministry of Petroleum and Energy. Statnett's mission is securing power supply through operations, monitoring and preparedness, facilitating the realisation of Norway's climate objectives, and facilitating creation of value for our customers and society in general. Statnett is responsible for maintaining and investing in the high voltage 300 kV and 420 kV electricity transmission network in Norway. Statnett operates around 11,000 km of high-voltage power lines and 3,000 km of subsea cables, and more than 170 substations. In addition, Statnett is responsible for HVDC subsea interconnectors to Denmark since 1976 (Skagerrak 1-4), the Netherlands since 2007 (NorNed), Germany since 2020 (Nordlink), and the United Kingdom since 2021 (North Sea Link (NSL)). These include both LCC (Skagerrak 1-3 and Nordned) and VSC (Skagerrak 4, Nordlink, and NSL) technologies.

Norway is part of the Nordic synchronous area including Sweden, Finland, and parts of Denmark. The Norwegian government has signalled that Statnett would be given a formalised role as the system operator for offshore wind power to efficiently safeguard operational reliability in the entire power system. Based on this mandate, Statnett will contribute to the development of rational grid solutions for connecting offshore wind power in close collaboration with other parties.

3.1.3 Great Britain

SSEN Transmission (the trading name for Scottish Hydro Electric Transmission) is part of the SSE plc Group. SSEN-T is responsible for maintaining and investing in the high voltage 132 kV, 220 kV, 275 kV and 400 kV electricity transmission network in the north of Scotland, which extends over a quarter of the UK's land mass, crossing some of its most challenging terrain. The area is home to vast renewable energy resources including wind, hydro and marine sources. SSEN-T works closely with the GB Electricity System Operator to enable new connections to the transmission system and allow electricity generated by them to be transported to areas of demand across the country.

Scotland's transmission network has a strategic role to play in supporting delivery of the UK and Scotland's net zero targets. It is already a mass exporter of renewable energy, with around two thirds of power generated in the SSEN-T network area exported to demand centres further south. There is currently around 7 GW of renewable generation connected in the north of Scotland. By 2050, the area is expected to need 40 GW of low carbon energy capacity to support net zero delivery.

The GB transmission network already has multiple HVDC interconnectors to the Irish, Nordic and continental European systems, being a mixture of older LCC and newer VSC technology. There are also HVDC links between points within the GB synchronous area; an LCC link on the west coast boosts the power transfer capacity between Scotland and England while the SSEN-T area hosts the first multi-terminal VSC scheme outside of China.

3.2 Common Issues of Concern

The following sections discuss a range of issues of concern shared by the project TSOs regarding the reliability and resilience of future hybrid AC/DC transmission systems. These topics provide a high-level guide to what the TSOs need addressed and where improvements are required in HVDC grid architectures, technologies, and associated functionality. As the project proceeds with developing and demonstrating new solutions, there can be consideration of the impacts on these issues of concern. These high-level requirements are reflected in the work reported in Deliverables 2.2 and 3.1 on Key

Performance Indicators (KPIs) with much greater detail on how to evaluate specific reliability and resilience metrics [1] [2].

3.2.1 Dominance of Power Electronics

Integration of an increasing amount of RES will mean more generation connected at distribution level as well as many large new generation connections to European transmission networks. Most of these, from small-scale PV to the largest wind farms, will use power electronics in their connection to the network. Combined with the growing use of HVDC and other equipment like STATCOMs, power system behaviour will be increasingly dominated by power electronics.

European power systems are going to see a significant increase in offshore wind capacity between now and 2050. As the capacity and distance from shore increases, a greater proportion of these connections will be HVDC. For example, the GB system expects to add between 80 and 140 GW of offshore wind capacity. This will result in an overall HVDC converter capacity connected to the GB onshore system greater than system peak demand.

This is occurring at the same time as conventional fossil-fuelled resources with synchronous generators that provide valuable network stability contributions are being retired. At present these are being incrementally offset by a series of initiatives and bespoke services addressing inertia, short circuit strength, voltage angle stability, voltage regulation capability, and dynamic voltage regulation capability. It is recognised that enduring solutions, including the delivery of new markets for new services, will be required.

In a future net zero power system, HVDC converters will represent the single largest power electronic device connected and the most prevalent form of power electronic device in aggregate. Their control, dynamics, behaviours, and vulnerabilities are likely to dominate system behaviour, in the same way as synchronous generators do now. HVDC converters offer the potential to act as the foundation of stability in the future AC/DC system with a scale and effect that more dispersed and smaller power electronics are unlikely to compare with. Thus, a positive contribution to reliability and resilience needs to be ensured.

HVDC is not new, with numerous existing HVDC converters interfacing with the AC system across interconnectors and transmission reinforcements. In addition to considering the opportunities from future specification, it is necessary to consider and adapt to the existing HVDC links, which are a mix of LCC and VSC type converters designed according to the codes, policies and standards that applied when they were commissioned. The majority of existing systems are designed to operate in AC systems dominated by synchronous generators with a focus on transmission of power at low losses and low cost, they were not designed to dominate system behaviour as future HVDC is expected to do. This requirement to stabilise and maintain operation of the older converters within their designed capability represents an additional requirement for future HVDC systems.

To become the new basis of stability, it may be appropriate to specify HVDC converters to maintain performance above and beyond normal operating limits to the extremes of frequency and voltage disturbance so they can support emergency actions and restoration if needed. Capabilities such as inertial grid forming and the potential to provide collective actions coordinated via wide area control are also key considerations (the impact of control functions is reviewed in section 0). Further emphasis will be required on monitoring and flexibility of tuning these critical HVDC components along with effective modelling and testing.

As they grow in influence on the system, HVDC behaviour will also become more important in network codes and standards, just as synchronous generator behaviour has influenced current standards based on decades of experience. However, time is limited to build experience with HVDC and translate that into updated codes and standards. Pilot projects and early developments must be fully exploited in terms of learning opportunities. This can inform the development of planning methods to better manage system operation with widespread RES and HVDC.

3.2.2 Technology Limitations

Unlike the synchronous generators that were the previous foundation of system capability, HVDC converters do not inherently provide beneficial behaviours to an AC system, nor do they naturally respond to conditions on the DC system. Performance depends on programmable control software and related transitions in priority and sequencing of action within the range of protective limits applied to the technology. Unlike synchronous generation, HVDC converters do not have an inherent overload capability that avoids protection actions or the risk of control transitions across steady state and transient operation. For HVDC devices, there is minimal capability beyond device steady state operation and this, combined with the frequencies against which valve firing is controlled, result in fast control and protection behaviours measured in tens of microseconds. There is a risk of very fast changes in condition from acceptable operation to failure, sometimes described as “cliff-edge” behaviour, where it would be preferred if there could be a more “graceful failure” process.

HVDC technology needs to respect both AC and DC network priorities of control simultaneously. The DC system has no other reference to control behaviour than its voltage, there being no equivalent to AC frequency tying the behaviour of the network together. At least one controller within a given DC system is needed to define the network voltage, and dependent on the topology, extent of DC network and multi-terminal control strategy adopted, this can have the potential to limit the number of terminals possible. For example, in offshore connections to a HVDC system it is normally the offshore HVDC converter that defines the offshore AC frequency and voltage, which means it is in effect a fixed power input to the DC system and accordingly may not contribute to DC voltage control. WP3 and WP4 of HVDC-WISE are considering alternative architectures and technologies that may offer new approaches.

While DC circuit breakers (DCCBs) at the voltage levels required for high power transmission have been implemented in China, they are not yet a viable and readily available option in Europe. This limits the HVDC architectures that are currently possible and the scope of DC networks. DCCBs and other fault separation devices (FSDs) that offer a means of selectively isolating parts of a DC network will have a potentially significant impact on R&R in future hybrid AC/DC systems.

3.2.3 Protection and Control

The behaviour of HVDC systems is dependent on the programmed control and protection, and that control can act very quickly. The nature of HVDC control is very different to the control systems on synchronous generators where the automatic voltage regulator (AVR), governor and power system stabiliser (PSS) typically operates much more slowly. In a way, HVDC control systems are more like existing AC network protection, which acts very quickly and results in very sudden and significant changes of state. This raises questions around how HVDC control should be tested and approved for use. Rather than apply testing and compliance approaches like existing AC generator control systems, to ensure adequate R&R on the overall system it may be more appropriate to apply approaches like those currently used with AC protection.

As multi-terminal HVDC becomes more common, there is greater HVDC interconnection between areas, and with the possibility of systems being expanded incrementally, it will no longer be the case of viewing each HVDC system as an individual project. Rather, it will be necessary to consider HVDC as a network of devices. This has numerous implications for control and protection.

One of the greatest concerns with current HVDC projects is the risk of control interaction with other converters that are electrically close on the AC side. This problem will get worse unless control and protection philosophies are devised that allow for harmonious operation in close vicinity to other converters, including accounting for the very wide range of conditions that may occur on the AC and DC networks.

AC network protection typically has main and backup functions provided by two different means, sometimes more, and often using devices from different manufacturers to ensure diversity and therefore dependability of behaviour. Current HVDC systems are typically supplied by a single vendor, who provides all control and protection. They are likely to include redundancy in their designs, possibly including different means of protecting against a given condition, but there is a question over whether this approach can provide the same dependability of the more diverse AC network protection. For fault detection on DC networks, there may not be multiple different ways of detecting faults fast enough.

AC transmission protection schemes have typically been designed with N-2 security, so even if there is failure of multiple protection systems the equipment and overall system stability is ensured. Future DC systems need to be designed with similar levels of redundancy and dependability. There must also be fall back cover for failure of any higher-level grid controller or communications. In multi-terminal HVDC schemes, which may involve terminals from different vendors, there must be suitable coordination and compatibility between the separate control systems. For example, DC voltage droop control may need to distribute power changes across multiple converter stations.

An HVDC system that utilises DCCBs (or other types of FSD) requires detailed consideration of the impact of device failure, especially when power flows on the system are high. This will have a significant impact on the grid layout and protection scheme design. Further work is required to inform decisions on whether to install multiple FSDs in series or if the redundancy inside the FSD is sufficient.

3.2.4 System Stability

Due to its electromagnetic characteristics, and the energy stored in the rotating masses, a synchronous generator inherently contributes to AC system stability. The characteristic of a converter is, in contrast, defined by its control system. Therefore, an adequate control behaviour must be implemented in HVDC control loops. However, the following limitations exist:

- For the provision of inertia, additional stored energy is required (e.g., in a supercapacitor).
- The semiconductors are not able to withstand high overloads so current limitation needs to be implemented, which leads to a limited capability (and non-linearity) in the response to disturbances, including the provision of short circuit current.
- Behaviour of a converter depends on control and automatic protection at different control levels that may interact.
- It is important to ensure that models used for simulation correspond to real device behaviour to ensure predictability.
- Since the control of converters encompasses all time domains it is important to understand and align the models to different stability phenomena.

- Typically, there is almost no reactance in an HVDC circuit or grid, so the propagation of a fault is much faster than in AC grids. This means that any DC fault will have an impact on all connected AC systems (with interaction via each converter). This new phenomenon of very widespread fault impact needs to be assessed and appropriate countermeasures developed.
- The risk of inter-area oscillations grows as more power flows from the peripheral areas of AC grids to the centre. This risk will grow as more offshore wind is integrated in the system and more HVDC interconnectors to other synchronous areas are constructed.
- Due to volatile RES infeed, new mode shapes of inter-area oscillations and dynamic changes of modes and damping in the AC system may occur, with an impact on HVDC system control.

The frequency containment reserve (FCR) in an AC system is usually designed for the biggest active power event that the system should be able to handle in normal operation. System planning and operation will need to consider what is the worst case of active power loss (or gain) for the AC grid due to failures on meshed HVDC structures. This will include consideration of temporary losses, with reliable performance required on the time taken to restore power, or partial power.

HVDC converters will also contribute to reactive power compensation. A possible loss of (multiple) converters at the same time as loss of power infeed (with consequential load flow changes in the AC grid) might have an impact on voltage stability. System planning and operation must consider how to ensure voltage stability on the AC and DC systems after a loss of (multiple) HVDC converters. One question will be how fast the converters can return in STATCOM operation and provide reactive power to the AC grid even if active power is lost.

As power systems transition from domination by synchronous generation to HVDC converters, there is growing interest in determining how much “grid forming” capability is required. While grid forming HVDC converters are already used for offshore wind, some island connections, or in black start mode, it is expected that this mode of control will need to be used more widely to ensure overall system stability. Achieving the desired R&R will require consideration of disturbances and operational conditions that affect the availability of grid forming sources.

All of these issues need to be addressed in the design of future widespread hybrid AC/DC systems. Deliverable 2.2 [1] goes into more detail on different stability phenomena and methods that can be used to assess the impact of HVDC on system performance.

3.2.5 Power Quality

Power quality is considered relevant to R&R in future hybrid AC/DC systems because if problems arise then it may affect the availability of equipment or its acceptable operating range, with an impact on overall system capability.

While modern VSC links do not need harmonic filters like those required on older LCC links, there is still a risk of new HVDC links causing power quality problems. Harmonic resonances may arise due to the interaction of different HVDC links, other power electronic equipment, and passive network components. Suitable models of HVDC converters, or other representations like frequency-dependent impedance characteristics, must be made available to allow full assessment of harmonic resonance or other power quality risks. The opportunities to improve power quality using HVDC should be fully explored.

3.2.6 Cyber Security

Within the energy system, there are traditional physical subsystems that are well understood and accounted for in R&R. System performance requirements in terms of frequency, voltage and power quality are clearly defined, although they may need reassessed for the hybrid AC/DC systems of the future. The physical characteristics of individual components are also clearly defined, based on decades of experience in construction and maintenance of AC system equipment. HVDC equipment presents some new challenges but TSOs are comfortable with the management of physical assets.

An increasingly important subsystem is concerned with the digital information (including systems and software) used to control and monitor the grid. This digital information is becoming increasingly important due to ongoing digitalisation. As a result, dependence on it for the functioning of the entire system is increasing. A basic requirement is that there should always be a fall-back to a local control mode where no further external signals are needed but the local measurements.

The dependency on software in HVDC control and protection raises concerns around cyber resiliency. This includes protecting against malicious cyber-attack, but it must also include the risks associated with routine upgrades. If vendors can upload and implement a software change independently without reference to the TSO or other authority, then there will be a greater risk of unwanted interaction or cascade impact. TSOs and regulators are still developing their policies on digital reliability and resilience.

3.2.7 Readiness of Tools and Methods

The transition towards future widespread hybrid AC/DC networks will require various new tools and methods to be developed and adopted by TSOs and other stakeholders. One of the primary goals of the HVDC-WISE project is to propose and demonstrate new toolkits to support assessment of reliability and resilience to inform system planning decisions. This is expected to include the development of new methods and models across a range of analysis tools, from optimsation based on steady state studies, through RMS, dynamic phasor and EMT dynamic simulation, to the use of real-time environments with vendor hardware or software in the loop.

With minimal scope for operator action during a fast-changing system event involving HVDC, there is a reliance upon modelling of both control and protection and the automatic actions taken. It is important to ensure that simulated behaviour corresponds to real device behaviour, and both anticipate that behaviour and specify the device such that its performance is sufficiently predictable and not de-stabilising for secured events. WP4 and WP5 will support the development of new models to represent new technologies and functionalities.

It is important that new tools developed in academia or elsewhere are made ready for proper use by TSOs. There is a long history of research projects producing prototype tools or complex methodologies that are not fully adopted by TSOs and others because they do not meet the requirements of commercial-grade software. Industrial use of new tools and methods requires software that is mature and can be deployed within corporate IT systems. Training and ongoing support will be required as tools and methods are trialled and applied to real-world circumstances. The transition of tools and methods from the research domain to real-world use should be considered fully.

3.2.8 Other Issues

There are various other issues that will affect R&R in future hybrid AC/DC systems but will not be focus areas for the solutions development, testing and demonstration activities later in the HVDC-WISE project. Some of these are discussed briefly here.

3.2.8.1 Inter-operability

HVDC projects are now being proposed that will require, or at least enable, multi-terminal HVDC operation with converter stations from different vendors. Achieving successful multi-vendor multi-terminal (MVMT) interoperability will require new approaches to multi-terminal and other supervisory control, specification of interfaces and performance requirements, modelling, analysis, and testing. This need for innovation and new solutions implies some additional risk so there is a need for thorough testing and proving of inter-operability.

In HVDC-WISE it is assumed that the challenges of inter-operability will be addressed in other projects, such as the European InterOPERA project and Aquila in GB [32] [33].

3.2.8.2 Shared Responsibility

In existing systems, most aspects of reliability and resilience are defined on a regional basis or within the boundaries of each TSO's area of control. Obviously, there are inter-area power transfers and significant work has been done on security and stability across large synchronous systems covering multiple TSO areas, for example through ENTSO-E. Further expansion of HVDC interconnection and growing levels of power transfer across large areas will mean a greater degree of shared responsibility for R&R. This will require even more coordination and closer working between TSOs to ensure disturbances in one area receive the support needed from other areas without having a significant negative impact on those areas.

3.2.8.3 Deliverability and Maintainability

The desired level of reliability and resilience of the AC/DC system will only be achieved if HVDC projects are delivered successfully, on time and with the required quality. This requires sufficient capability and robustness in the whole supply chain, from the manufacture of individual components through installation and commissioning. The HVDC industry is undergoing a period of massive growth and is exposed to significant pressures. The ability of the industry to deliver all the proposed projects is a common issue of concern.

Furthermore, once an HVDC scheme is in operation it must undergo regular maintenance and any problems must be rectified quickly if the desired level of R&R is to be achieved. This requires designs that allow for convenient and cost-effective maintainability, and the HVDC supply chain must include the required capacity to support all the installed systems. As HVDC becomes more widespread there may be a shift towards TSOs taking on more of the maintenance responsibilities themselves, similar to what is currently done for the AC system.

3.3 Events and Disturbances

In this section we outline events and disturbances that are of interest with relation to hybrid AC/DC system design. The purpose is to identify the conditions or contingencies that are of interest to TSOs, as these help to define the R&R needs and objectives. These events and disturbances can inform the various studies that will be performed later in the project to evaluate the capabilities of the proposed grid architectures and R&R tools. As experience and understanding of hybrid AC/DC systems grows, we may identify other events and disturbances important to R&R that are not currently being considered.

As described in chapter 2, power systems must deal with relatively low-level events and disturbances all the time. These are dealt with through normal design and operation with the system expected to remain within its normal operating limits. The responses to these **high probability, low impact** events determine system **reliability**.

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

The sections below briefly discuss some of the root causes, responses, and system consequences that are considered of greatest relevance and importance to future hybrid AC/DC systems. Factors that should be considered when assessing risks include:

- The amount of notice and visibility that a system operator has, which will determine their ability to plan for and handle a disturbance. For example, it may be possible to operate the system defensively given advance weather warnings.
- The speed at which an event or disturbance propagates. Some events happen slowly, allowing a managed response. Other events could be very fast with a higher risk of widespread impact.
- The vulnerability of different assets to different events. For example, the distribution system may be more vulnerable to bad weather than transmission. HVDC cables (underground or subsea) are protected from extreme weather but may be vulnerable to other things.

3.3.1 Root Causes

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

3.3.1.1 Routine Faults and Operational Events

Future networks will continue to see regular faults on circuits and in substations for a wide range of reasons. Planning tools are required that support analysis of issues such as:

- Fault propagation in DC grids, which can be very fast and widespread, and the interaction with AC grids, which depends very much on the behaviour of the converter stations
- Loss of power infeed (or power export) from HVDC systems, which may affect multiple connection points in the same AC grid, or several different AC grids
- The relatively high fault rate for HVDC converter stations (at typically 3 occurrences per year this is much higher than other components of the power system)
- The potentially very long repair time for subsea HVDC cables, which are much more difficult to access than overhead lines or onshore cables
- Failures on new types of components like DC circuit breakers

The long-standing approach to N-1 or N-D (double circuit) contingency analysis may need to be revised. This will depend on the physical structure of new HVDC infrastructure, with discussions already considering issues like the distance between the positive and negative pole cables of bipole links.

It is important that the industry collects and shares data on the fault rate and performance of components that will be used more widely in future, such as that presented in Figure 3 from the North Sea Wind Power Hub project.

Type of fault	Failure rate*
Line fault	**3.5** f/100y/100km
Active fault on a DC breaker	**1.5** f/100y
Busbar fault	**0.74** f/100y/bay
Line fault + DC breaker failure	**$2*10^{-4}$** occ/100y/100km
Spurious Trip	**1.4** occ/100y
Sympathetic Trip	**$1*10^{-4}$** occ/100y/100km
Busbar fault + DC breaker failure	**$1*10^{-4}$** occ/100y
Converter failure	**3** occ/1y

(*) y=year; f=failure; occ=occurrence

FIGURE 3: FAILURE RATE INFORMATION FOR A VARIETY OF HVDC COMPONENTS[2]

The complexity of HVDC control and protection, with associated interaction and inter-operability risks, means that problems may arise due to "normal" operational conditions or events, without there having to be any specific fault or a clear triggering action. Such conditions may arise due to routine operational events like maintenance or changes to the AC or DC system configuration. Maintaining R&R requires understanding how apparently benign conditions and events may be the root case for undesired behaviour.

3.3.1.2 Extreme Natural Events

Power systems must be designed to operate in the natural environment, which poses a range of threats.

3.3.1.2.1 Extreme weather

Extreme weather events that cause damage to the network infrastructure, whether AC or DC, will have an increasing impact on the planning and operation of electrical power systems. Climate change is expected to result in more extreme environmental conditions with greater risk of flood, strong winds or extreme temperatures.

The design and operation of a hybrid AC/DC system must take account of the risks posed by extreme weather events. This is noted in power systems planning in the USA, for example [34], where it has been proposed that American TSOs will need to examine extreme heat and cold weather events as part of their system reliability assessments. Some studies have been conducted in the USA as to the potential impacts of extreme heat events [35]. Table 3 summarises extreme weather events and their possible system impact. Appendix 2 presents some real-life examples of weather events resulting in severe impacts.

[2] https://northseawindpowerhub.eu/knowledge/nswph-validation-technical-requirements

TABLE 3: SUMMARY OF EXTREME WEATHER EVENTS

Types of Event		System Impacts	Examples
Extreme cold	Snow / ice	Risk of co-incident line trips, Damage to towers /poles, Icing on lines reducing isolation gap High system loads	Northern Ireland- March 30/31 2010 Cortina d'Ampezzo, Italy, Dec 24-26, 2013 Emilia Romagna & Lombardy, Italy, 6 Feb 2015
	Deep Freeze	Risk of co-incident asset unavailability (generators, fuel supplies etc). High system loads	Texas January 2021
Extreme heat	Heatwave	Risk of co-incident line trips (sag), Risk to cooling supplies (e.g. nuclear), High system loads	USA/Canada 2003 France 2022 (Nuclear) Iberian peninsula System split 2021
	Wildfire	Risk of co-incident line trips, Risk of damage to substations, High system loads	Australia 2009
Extreme water	Drought	Risk to availability of generation assets, particularly hydro power and nuclear	France 2003, 2022
	Flooding	Risk of damage to multiple assets / lines	Australia (Queensland), 2011 South Africa, 2019 Romania, 2005
	Tsunami	Risk of damage to multiple assets / lines	Japan 2011
	Heavy Rain	Risk to asset performance	Brazil/Paraguay - 2009 (*heavy rainfall may have degraded insulation flashover protection performance)
	Pollutant deposit	Risk of co-incident line trips	Sardinia, 2001 (saline conditions + humidity causes tripping)
Extreme winds	Hurricanes, tornadoes, cyclones, storms	Risk of co-incident line trips, damage to towers / poles	Spain/France 2009 15 major events listed in Cigre TB 833 alone Algarve, North Lisbon, Portugal, 2009
	Sand / dust storms	Risk of damaged or buried assets	NW China 1993
Lightning		Risk of line trips leading to cascade	GB 2019 Australia 2016

3.3.1.2.2 Dunkelflaute

In a renewables-dominated system, there is increasing concern over how to maintain security of supply in times of low renewables production. The so-called "Dunkelflaute" refers to prolonged conditions of calm winds and overcast conditions, with the knock-on effect of resultant low wind and solar output in grids. Although a type of extreme weather condition, this will not damage the infrastructure, but it will put stresses on the system in terms of how energy needs to be moved around.

This has had considerable attention in recent years in places like the UK and Germany that have high penetrations of wind and solar [36] [37]. However, Dunkelflaute is not yet a concern everywhere. The Nordic grid, for example, has a lower share of wind and solar and higher share of hydro and thermal sources.

As noted in [38] however, Dunkelflaute conditions in Northern Europe do not tend to be correlated. There is obvious relevance for large, interconnected hybrid AC/DC grids, where renewables-based electrical power could potentially be transported from geographically distant grids during times of localised low wind and solar production (as well as potentially connecting geographically dispersed large scale storage). It reinforces the value of having Multi-Purpose Interconnectors (MPIs) where the same infrastructure can be used to collect power from offshore wind (when it is available) and move power between markets.

Much of the focus of Dunkelflaute has been capacity based [39] with less focus on grid impacts when transmitting large volumes of power. Such a study could potentially be very revealing regarding the performance of different DC grid architectures. Several scenarios with different weather conditions should be considered in the grid planning process to ensure robust results.

3.3.1.2.3 Other events

There are various other specific events that need special measures but will not be a focus area for the HVDC-WISE project, like:

- Solar eclipses, with their potential impacts on PV generation and demand across a very large area.
- Geomagnetic storms, which affects assets in different ways depending on their orientation.
- Earthquakes, with their associated risk of damage to multiple assets across a power system (as experienced in Japan in 2007, 2011 and 2018).

3.3.1.3 Physical and Cyber Attacks

All electricity infrastructure is at risk of malicious attack, whether that is through physical attacks or through attacks on the communications and control systems. The geopolitical situation will have an impact, as it always has, but risks may also arise due to domestic unrest or community objections. HVDC installations offshore, including subsea cables, may be at greater risk of attack, including sabotage performed in secret without clear attribution.

The HVDC-WISE project will not focus on specific physical threats but will explore more fully the risks associated with cyber attacks [40] [41] [42].

There are typically two-way communication channels between HVDC stations, control centres, and other control facilities. As an example, HVDC power outputs are typically controlled remotely by control centres. The configuration of HVDC substations, including HVDC controller parameters, is also transmitted to a control centre for grid stability analysis. Therefore, HVDC station configurations are becoming more accessible to a broader range of entities as more HVDC-based applications for improving the entire grid operation are proposed, developed, and deployed. Similarly, the HVDC controller can potentially be accessed by multiple application entities linked to the HVDC substations through communication links. The increasing number of remote and local access points to HVDC stations will significantly increase the attack surface that malicious inside and outside attackers can potentially exploit. Two examples of the HVDC systems cyber threats are given below.

3.3.1.3.1 Cyber Threats for HVDC Controllers

Any measurement, parameter, or control command can be tampered with by a cyber attacker from any accessible point on the paths between the sensors and actuators to the HVDC controllers. Tampered measurements and parameters may result in HVDC control instability and potentially costly equipment damage. For example, consider the following cyber-attacks on HVDC controllers:

- Incorrect measurements to HVDC controller
- Incorrect voltage, current or power set point commands from the HVDC controller
- Incorrect control action on circuit breakers at AC terminals
- Incorrect switching of capacitor banks, harmonic filters, or reactive compensation (LCC)

The dependency on software in HVDC control and protection raises concerns around cyber resiliency. This includes protecting against malicious cyber-attack, but it must also include the risks associated with routine upgrades. Given the risk of simple human error, if vendors can upload and implement a software change independently without reference to the TSO or other authority, then there will be a greater risk of unwanted interaction or cascade impact.

3.3.1.3.2 Cyber Threat for Inter HVDC Stations Communication

HVDC systems carry large amounts of power over long distances and the converter stations are located very far apart. These stations must communicate with one another to operate reliably and economically, which necessitates the exchange of information between stations over a long distance.

One instance of information exchange occurs during a permanent fault on the inverter's AC side (remote station). For DC faults, the converter station must perform a shutdown to de-energise the HVDC link, which includes blocking the thyristor/IGBT valves, followed by opening the respective AC circuit breaker, among other things. This is not necessary for AC faults because the fault is isolated on the AC side of the link. If a fault is detected on the AC side of the remote station, a command to prevent the DC line protection from initiating a shutdown sequence is normally received. An attacker can tamper with this block command (e.g., by conducting a Denial of Service (DoS) attack) and endanger the operation of the HVDC lines. Therefore, there should always be a fall-back level to a local control mode where no further external signals are needed but the local measurements.

3.3.2 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 the HVDC schemes, particularly the converters at the interface between the AC and DC networks. The expansion of HVDC and its growing influence on the power system means the risks associated with unforeseen or adverse behaviour is a significant threat. Even relatively minor, routine faults or changes of system state may trigger responses that could lead to the following:

- **Underdamped oscillations**. Oscillatory behaviour may occur in a local area or at a large scale across a wide area. There have been several examples in recent years involving HVDC connections, particularly in conditions when the AC system at the point of connection is "weak" with low short circuit level. There are multiple possible causes, including errors in the design, configuration and tuning of the control systems.

- **Sub-synchronous torsional interaction (SSTI)**. This is a specific case of oscillatory behaviour where the control actions of an HVDC converter, or other power electronics-based system, excite the torsional modes of the turbine-generator shaft of a synchronous machine. This can damage the machine over time or, in the worst cases, lead to catastrophic failure. The risk can be mitigated through more advanced analysis to inform control system tuning and real-time monitoring.

- **Control interactions**. The risk of interaction between HVDC converters, or between HVDC and other equipment on the power system, is well known and there have been several instances of problems arising. The significant complexity of HVDC control and protection, especially when considering two or more systems that may interact, makes it extremely challenging to test and fully explore all possible circumstances. The future hybrid AC/DC system may see new phenomena between AC and DC grids.

  For example, if inertia in an AC grid is being provided by a grid forming HVDC converter that is part of a widespread DC grid, then without energy storage in the DC grid, any injection of power to provide an inertial response in one location will have a direct impact on the power flow at the other HVDC converters, which may then interact with controllers in other AC grids. The propagation of inertial response across the AC/DC system will be very different from what is currently seen in the mainly AC grid.

- **Converter blocking**. If exposed to conditions that exceed its operating limits, an HVDC converter will block, causing a sudden and potentially very large change in power flows and voltages on the AC and DC grids. This may be caused by faults on the AC or DC equipment, or by some other phenomena that the HVDC control and protection systems interpret as being a risk to the plant. This can have a significant effect on other nearby plant. For example, an offshore wind farm that suddenly has no exit route, or a limitation, for its energy must act to prevent damage. The downward ramp rate of the wind turbines may be relatively slow (typically between 0.1 and 0.25 pu/s) so it may be necessary for the wind farm to be disconnected, which will impact on the equipment and the time taken for it to return to service.

- **Common mode protection or control behaviour**. Multiple HVDC schemes that are exposed to the same disturbance may all respond in a similar way, possibly blocking or disconnecting altogether. The sudden "digital" change of state that occurs with power electronic, software-controlled equipment is different to the "analogue" response of conventional synchronous generation. Such common mode behaviour has been observed across multiple wind farms exposed to an AC network fault.

- **Triggering of system automatic controls**. Power systems are configured with an array of automatic control and protection schemes to aid the response to large and fast-acting disturbances. For example, under-frequency load shedding may be triggered automatically if frequency drops below specified thresholds. Generators connecting to constrained parts of the network may be subject to automatic curtailment of their output. These systems are intended to improve overall R&R but growing complexity introduces risks of them being triggered in error or at times when they may make problems worse rather than better.

- **Non-compliant behaviour**. Many TSOs have reported problems with new equipment failing to perform as expected, as specified in grid codes or connection agreements. This is sometimes due to limitations in technology or misunderstandings of what is required. On the assets with greatest potential impact, like large HVDC schemes, it is especially important that they perform as expected.

Given the above risks, understanding the physical risks to HVDC assets may be simpler than understanding risks like control system interaction and cascade operation of protection across multiple HVDC schemes. Simulation and modelling tools will be required that support analysis of these different types of responses to events and disturbances.

3.3.3 System Consequences

Depending on the root cause event or disturbance, and the responses of connected equipment, there could be a range of system consequences. This section highlights some of greatest interest that could inform the scope of studies performed later in WP6 and WP7.

3.3.3.1 Impact on transmission system performance

All TSOs need to report on transmission system performance, which accounts for routine faults as well as rarer events and disturbances. The measures used vary according to regulatory requirements, but a typical set might include:

Availability

% Annual / Monthly System Availability

% System Availability at time of Peak Demand

Planned and Unplanned System Unavailability

Security

Reportable System Events (as defined by the relevant code/standard)

Number of Loss of Supply Incidents (plus a brief description of those incidents)

Total Estimated Unsupplied Energy

Quality of Service

Voltage excursions outside normal limits

Frequency excursions outside normal limits

Network Constraints

Measures of how network capacity limitations restricted generator dispatch or required changes in the market position

For European TSOs, information on transmission system performance is published on the ENTSO-E Transparency Platform. These existing system performance metrics can help inform the specification of KPIs to be used in the project, as described in deliverables 2.2 and 3.1 [1] [2].

3.3.3.2 Over voltages in offshore energy hubs

Given the expected development of offshore wind and HVDC interconnection in Northern Europe, one specific system consequence of concern is the risk of over voltages on offshore energy hubs. These may host many GW of generation but will rely on HVDC connections to evacuate that power.

During a large disturbance caused by either an onshore or offshore converter fault, which is one of the most frequent type of faults with up to three occurrences per year, offshore wind turbines are requested to reduce their power output as fast as possible. With typical down regulation speeds of only 0.1 to 0.25 pu/s, it could result in excess power being fed into the system with limited evacuation capacity, leading to over voltages on the offshore DC and/or offshore AC networks.

The type of network topology that could face this problem is further examined in section 4.1.3. Chapter 5 summarises technologies being examined in WP4, which include energy dissipation systems that will help address this problem.

3.3.3.3 System splits (AC or DC)

Past events, like the system split in November 2006 [43] and the separation of Italy in September 2003 [44] as well as more recent events, like the East-West separation in January 2021 [45] and the Iberian separation in July 2021 [46] demonstrate that system splits events, even though they are very rare, cannot be prevented in all situations. Therefore, it is important that these events do not result in an extended blackout and the effects on the total system can be mitigated.

To allow the emergency control schemes, designed for keeping frequency stability in out-of-range events, to react, it is essential to limit the Rate of Change of Frequency (RoCoF) resulting from the system split. This is challenging with increasing power flows (possible power imbalances) and a decreasing level of inertia in the grid. Furthermore, the risk of (non-compliant) disconnections of generation units due to over or under voltages after the split should be minimised because they can potentially deteriorate the situation.

In the study in [47] global severe splits were identified in which a RoCoF higher than 1 Hz/s is reached in each region after the system split. The limit of 1 Hz/s is considered as the operation limit under which frequency stability can be ensured with the existing emergency control schemes (LFSM-O/ LFSM-U, load shedding). This must be distinguished from the RoCoF withstand capability of generation units (2-2.5 Hz/s) which is specified in the connection network codes.

Since DC Lines are controllable and not affected by the voltage-angle difference in the AC grid (which is the driver for cascading events) they have a potential to allow high power flows without increasing the risk of blackouts due to a system split. However, it should be noted in all the above the focus is on the capacity of the DC grid to aid in maintaining AC grid stability after system splits. With increasing DC interconnection between grids, DC side fault propagation may also result in DC side splits, and in future studies the impact of both DC and AC side splits may need to be studied.

3.3.3.4 Total or partial shutdown

The most severe system consequence is a partial or total shutdown of the transmission network, requiring the instigation of a system restoration process, often referred to as a “black start”. This is considered highly unlikely in Europe. In GB, for example, there has not been a complete shutdown since the very beginnings of the electricity industry. However, every few years there is a significant shutdown event somewhere in the world, caused by a variety of reasons. All TSOs must have robust plans for system restoration to ensure the impact of any widespread shutdown is minimised.

Modern HVDC technologies, and the resources they are being used to connect, like offshore wind, offer new opportunities for providing system restoration services. It is important to understand and demonstrate the role that HVDC schemes can play in system restoration in future hybrid AC/DC systems.

4 HVDC Architectures

In HVDC-WISE, when discussing future hybrid AC/DC systems we are mainly concerned with the electricity transmission networks in Continental Europe, Scandinavia, and Great Britain. In this context, we consider 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) to 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 (e.g., 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. Section 4.1 outlines the topology framework used in this project which considers point-to-point, radial, linear, and meshed network topologies.
    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
6. The **deployment plan**, specifying how to build such a grid in a stepwise manner.

In this chapter, various aspects of HVDC architectures are examined, highlighting a range of issues related to the design of large-scale hybrid AC/DC systems. These issues will be explored further through the course of the HVDC-WISE project, with a range of novel grid architectures developed in WP3 then tested to an advanced level in use cases in WPs 6 and 7.

An HVDC topology framework developed in WP3 is presented in section 4.1 and then used as the basis for review and comment in the remainder of the chapter. In Section 4.2, a survey of existing and planned DC links is presented (more detail from the survey is available in Appendix 3, an accompanying spreadsheet file [48], with analysis of the trends evident in the data. In Section 4.3 the topology framework is used as the basis for analysis in terms of R&R. Section 4.4 goes into more detail on control functions and section 4.5 reviews protection functions for hybrid AC/DC grids. Finally, in Section 4.7 research objectives for WP3 are outlined.

4.1 Topology analysis framework

This section outlines a topology analysis framework developed in WP3 to categorise AC/DC topologies (this was developed for Deliverable 3.1 [2] which will not be released publicly). The framework considers aspects 2 and 3a of the architecture definition above, i.e., topology and embedment level.

The framework aids in developing combinations of 2, 3a, and 4 to achieve 1, the purpose of the grid, and furthermore aids in predicting the control and protection system analysis needs for 5. The use of this framework for the development of control and protection is investigated in greater depth in WP3.

Finally, the framework can be useful in considering the deployment plan for a HVDC grid, aspect 6 of the architecture definition above. As a grid moves between different classifications in the framework, aspects of the grid architecture, such as risks related to control and protection design, may need to be re-considered, e.g, when developing a grid from individual point-to-point links (AC1-DC1 in the framework) to a meshed DC grid that connects those individual point-to-point grids (AC1-DC3 in the framework). The point-to-point grids typically will need to consider only the loss of the individual DC grids from an operational and planning perspective. With the meshed DC grid, the loss of individual lines within that grid (N-1 on the DC grid) need to be considered.

4.1.1 Framework description

While not exhaustive, a 4x4 style matrix for DC and AC grids is felt to be a useful framework for analysing various topologies (in WP3 this is also used for the development of control and protection concepts, and generic assessments/comparisons of their R&R impacts). This is based on previous work in a number of past projects (PROMOTioN, BestPaths, MIGRATE, TWENTIES). It provides a means of grouping and examining a wide variety of grids based on their *pre-contingency connection topologies* (and not considering market frameworks, line lengths, protections systems, etc.). Some possible extensions to this framework are outlined in Section 4.1.2. For further illustration of how a particular grid (e.g. from the literature, CIGRE brochures, or previous projects) may be classified within this framework, a range of examples has been provided in Appendix 1.

In the framework DC system topologies are split into four categories:

- **DC1**: Point-to-point links (P2P)
- **DC2**: Radial links
- **DC3**: Linear links
- **DC4**: Meshed links

These four types are represented graphically in Figure 4. Note in this diagram and the following illustrative diagrams that the elements coloured black represent the DC grid components and the elements coloured green represent AC grids.

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 hybrids of those. Each line could be either implemented as an overhead line or cable, and could have any length. Further, it is not specified whether the entire DC network is operated on the same voltage level or whether there are any DC-DC converters or load flow controllers. Also, protection systems are not specified. It is noted here that WP3 may consider further topological classification DC5-DCx which can consider further DC side configurations involving DC-DC converters and DC side loads, which are present in CIGRE TB804 [49].

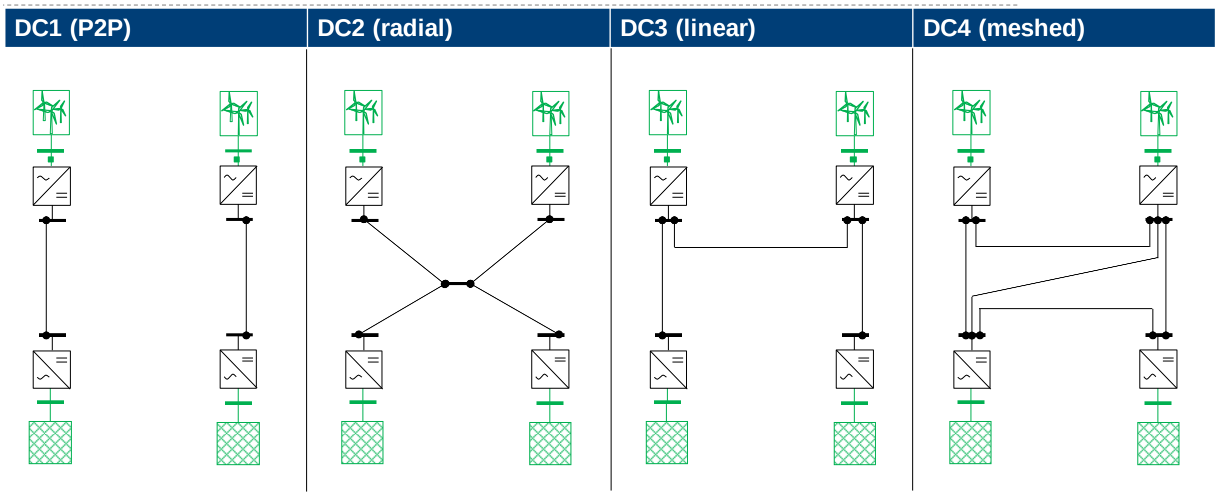


FIGURE 4: DC SYSTEM TOPOLOGIES (SINGLE POLE VIEW)

Radial and linear networks are multi-terminal networks that do not contain a mesh, which means there is only one path between any two terminals. In a meshed network, there may be more than one path between terminals, as illustrated in the DC4 diagram in Figure 4. Further, it can be said that:

- In radial networks, converters are only connected to a single line, and the DC node (or "star point") does not have any converters connected to it, it is a separate switching station.
- In linear networks, 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 the converter station.

It should be noted that there can be hybrids of linear and radial, e.g., as described in CIGRE TB804 [49] (see Appendix 1). The different configurations of linear or radial examples can result in the following characteristics, which are discussed in more detail in Section 4.3:

- The total line length for the same transmission "goal" is different.
- The number of required platforms (offshore) or properties (onshore) is different
- The load flow control potentially works differently.
- Redundancy in case of a DC fault is different (e.g., in terms of disconnecting wind power for a DC fault event).
- The DC fault behaviour is different, and/or the protection design may differ.

These topologies do not consider whether the DC links are of the LCC or VSC type. It is assumed that most future DC links in Europe, particularly those that are multi-terminal, will be VSC and the trend is towards the use of bipoles, either rigid or full; this is discussed more fully in section 4.2.

With regard to the AC side, offshore and onshore connections are limited to two connections for illustration purposes, but there could be any number of similar connections in a system (as illustrated in Appendix 1). 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 (e.g., in terms of different fault current level, inertia, share of RES, etc.). The AC systems to which the DC systems are connected are also split into four categories:

- **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. When the AC grid is composed of wind farms only (or is similarly dominated by other inverter-based resources) this presents particular challenges in responding to interruptions on the DC side.
- **AC3**: Fully embedded – All converter stations of the DC system are connected to the same AC grid.

The different combinations of DC and AC systems are illustrated below:

- Figure 5 shows DC1 P2P links with different AC systems
- Figure 6 shows DC2 radial 3-terminal links with different AC systems (AC2a and AC2b combined)
- Figure 7 shows DC3 linear 3-terminal links with different AC systems (AC2a and AC2b combined)
- Figure 8 shows DC3 linear 4-terminal links with different AC systems
- Figure 9 shows DC4 meshed links with different AC systems

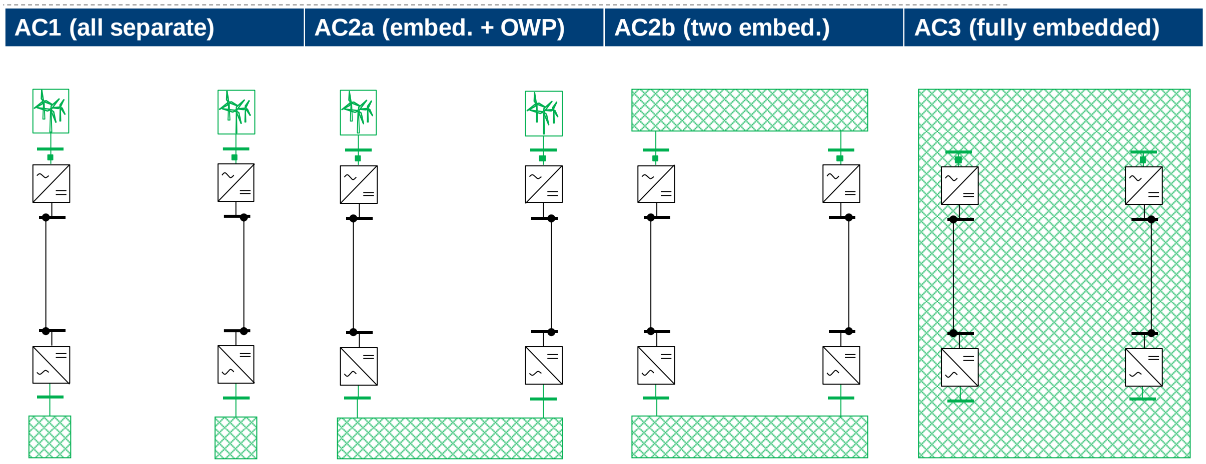


FIGURE 5: AC CONNECTIONS FOR DC1 POINT-TO-POINT LINKS (SINGLE POLE VIEW)

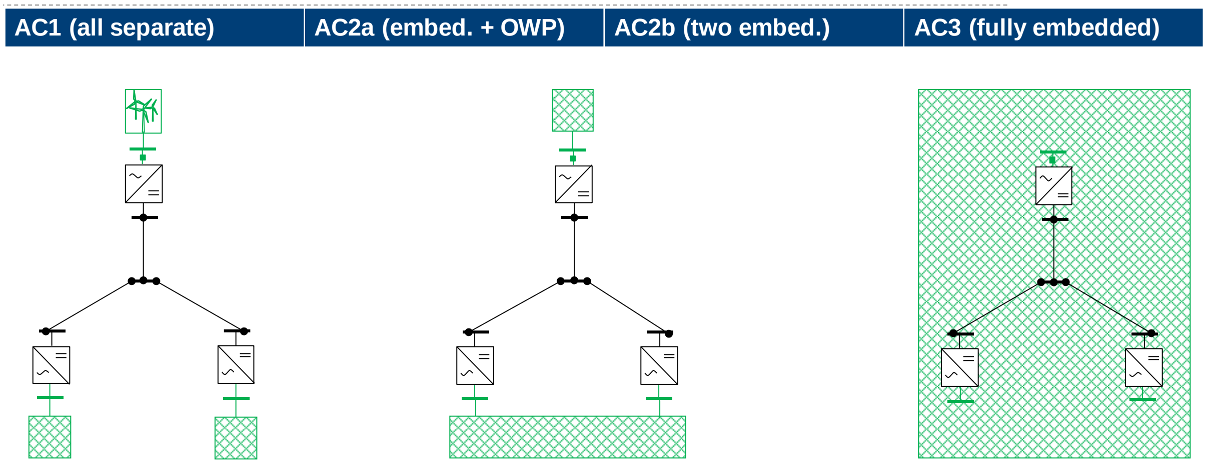


FIGURE 6: AC CONNECTIONS FOR DC2 RADIAL LINKS (SINGLE POLE VIEW)

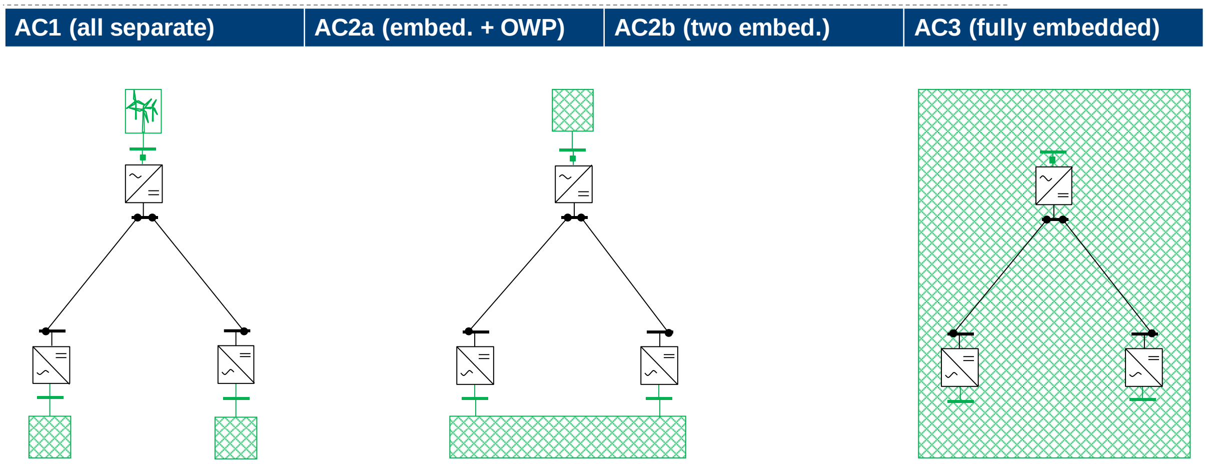


FIGURE 7: AC CONNECTIONS FOR DC3 LINEAR LINKS WITH 3 TERMINALS (SINGLE POLE VIEW)

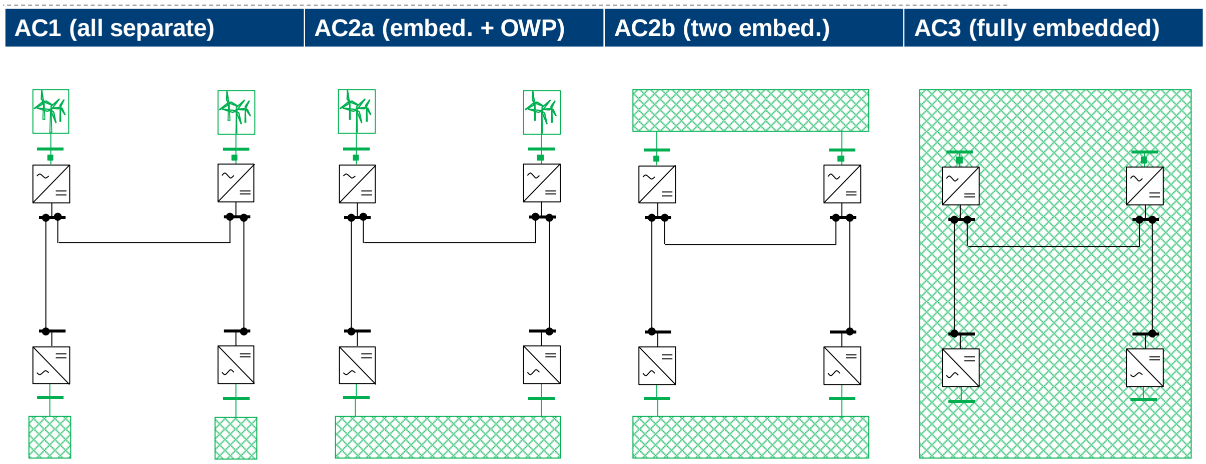


FIGURE 8: AC CONNECTIONS FOR DC3 LINEAR LINKS WITH 4 TERMINALS (SINGLE POLE VIEW)

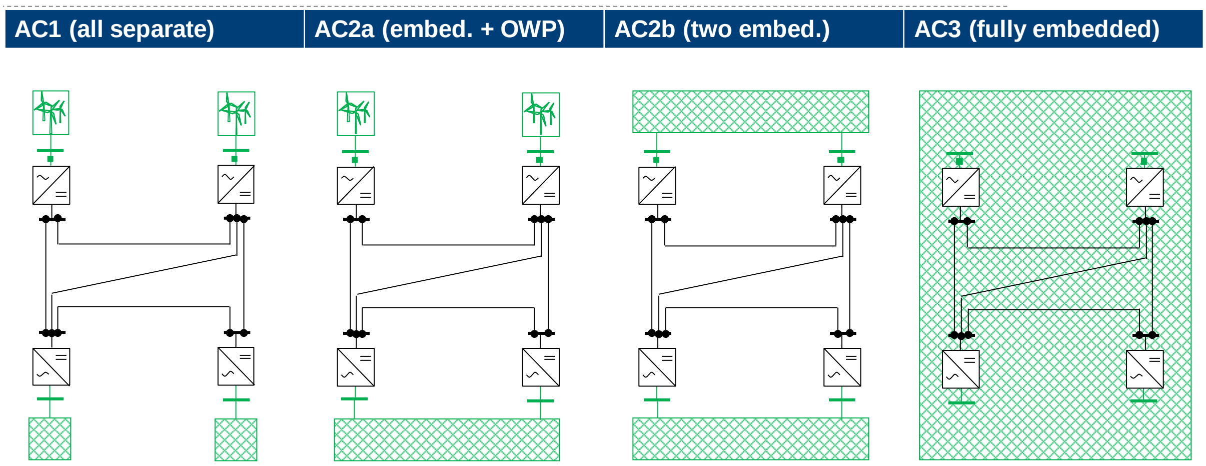


FIGURE 9: AC CONNECTIONS FOR DC4 MESHED LINKS (SINGLE POLE VIEW)

4.1.2 Extending the topology framework

The 4x4 topology analysis framework defined in WP3 (see D3.1 [2]) and outlined above is a useful basis for classification of different AC/DC systems, but does not capture all features and differences in HVDC architectures. As already noted, the simplified topology descriptions do not specify whether the HVDC links are monopoles, bipoles (with or without dedicated metallic return), or some combination. Other issues that could be considered as extensions of the framework include:

- **The purpose of the HVDC systems, its power rating and distances covered**
  - These are clearly very important aspects of HVDC system design and must be provided as supplementary information to the topology.
- **The nature of coupling on the AC side**
  - Topologies AC2a, AC2b and AC3 do not differentiate between different characteristics of the AC grid (e.g., inertia, fault current level, other inverter-based devices in close proximity).
    - Certain phenomena are caused more by the AC network characteristics than by the HVDC architecture.
  - There is higher risk of interactions between converters that are electrically closer to each other but converters connecting at two extreme parts of the mainland European system, for example, are unlikely to interact.
- **The nature of the converter stations**
  - These could be onshore or offshore, with consequential impacts on various aspects of design and expandability.
  - There is growing interest in multi-vendor systems where different converter stations, or other system components, from different vendors must operate together.
- **The use of DC switching devices**
  - The use of a Fault Separation Device (FSD), such as a Direct Current Circuit Breaker (DCCB), imposes various additional requirements such as fault location detection, fault clearing time, coordination between devices, series resonance and control system implications, etc.
  - The use of high speed switches on the neutral conductors or to allow reconfiguration during converter blocking.
- **The configuration of DC switching stations**
  - Different designs of DC switching station (DCSS) will allow for different configuration and interfacing options between DC links.
- **The use of DC/DC converters to link DC networks**
  - DC/DC converters could have a transformative effect on the topological and operational capabilities of HVDC grids. The use of these devices allows for the creation of interconnecting DC systems with different voltage ratings and potentially different line configurations (a bipole and monopole interconnection is illustrated in Figure 10). One can also consider interconnecting VSC and LCC links (although most planned HVDC links in Europe today are VSC based). In the example in Figure 10, interconnected DC systems are point-to-point, but multi-terminal (radial, linear and meshed) interconnections can also be considered. Interconnection of DC systems with different protection and control strategies is also possible [50]. This approach allows additional degrees of freedom when expanding the DC system with regard to voltage ratings, line topologies and possibly protection and control strategies. The protection

related R&R impacts of DC/DC converters are discussed later in Section 4.5.4, and Deliverables 3.1 and 4.1 discuss various aspects of DC/DC converters in greater detail.

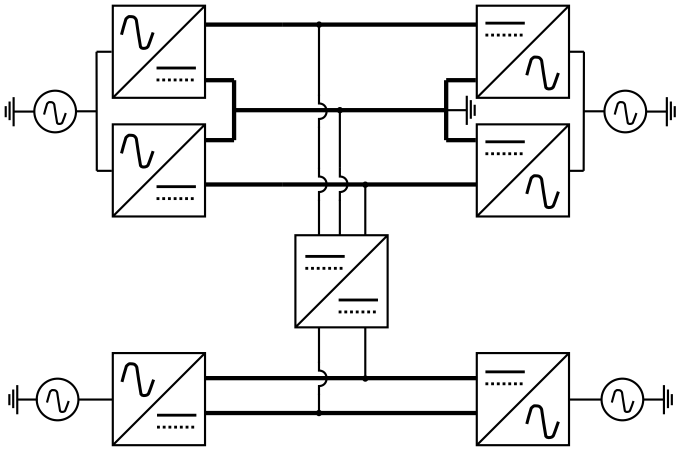


FIGURE 10: MONOPOLE AND BIPOLE CONFIGURATIONS INTERCONNECTED THROUGH A DC/DC CONVERTER

4.1.3 Topology influence on performance and resilience

The following example of a multi-purpose HVDC system connecting offshore wind farms to different countries helps to illustrate how differences in topology can have significant impacts on system performance and resilience. This example is based on work done at Energinet to consider the impact of large disturbances and energy dissipation strategies. It assumes full bipoles but with differences in the interconnection of the offshore AC and DC networks. For the sake of simplicity, this example does not explore all technical issues and alternatives, such as the need for switches on the neutral conductors, the positioning and sizing of reactors, protection philosophy, control interaction, etc.

Figure 11 shows the example HVDC scheme with two offshore DC hubs, each hosting a bipole converter station and offshore wind farm (OWF) connections through 400 kV busbars. The red circles indicate that the switch is open, with different switch positions in the figures below producing configurations with different performance. Each diagram represents two examples:

i. The onshore connection points are in Denmark (DK1) and Belgium (BE), so are within the interconnected AC grid of mainland Europe, although the electrical distance between the onshore converter stations is significant and each onshore connection is subject to different TSO control. With interconnection between the hubs on the DC side, the topology is of type DC3/AC2a (with the AC poles coupled or decoupled).
ii. The onshore connection points are in Denmark (DK2) and Germany (DE), which means they are in different synchronous areas. With interconnection between the hubs on the DC side, the topology is of type DC3/AC1.

In Figure 11, at each hub there is no AC coupling between the two DC poles. In this case, if there were to be an offshore converter fault, the OWF connected to the faulty converter pole is automatically disconnected. This example has DCCBs on each offshore DC circuit, allowing a fully selective protection strategy, but other approaches could be applied.

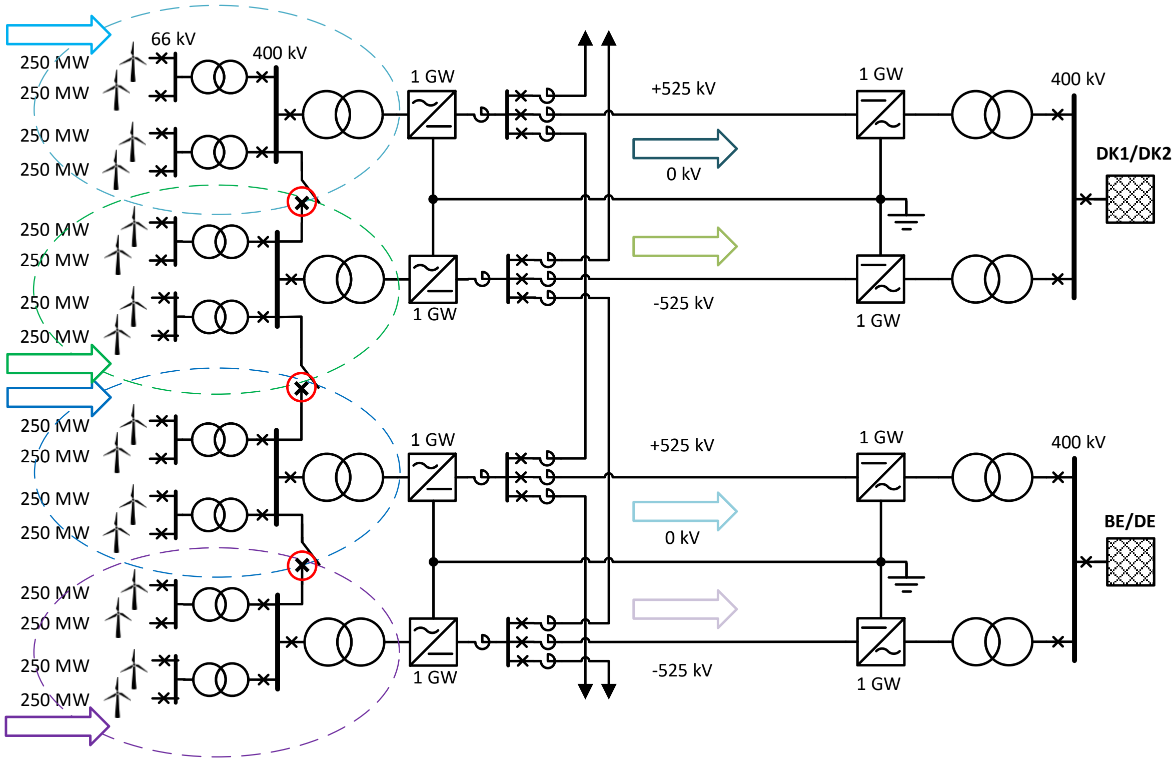


FIGURE 11: WITHOUT AC POLE COUPLING (DC3/AC2A FOR DK1/BE AND DC3/AC1 FOR DK2/DE)

Figure 12 shows the same example but with AC coupling between the DC poles on each hub. This configuration has a higher resilience to offshore converter faults but requires an energy dissipating strategy during high wind conditions as the OWFs cannot ramp down instantaneously. Alternatively, the OWFs must be tripped so that the healthy converters are not overloaded.

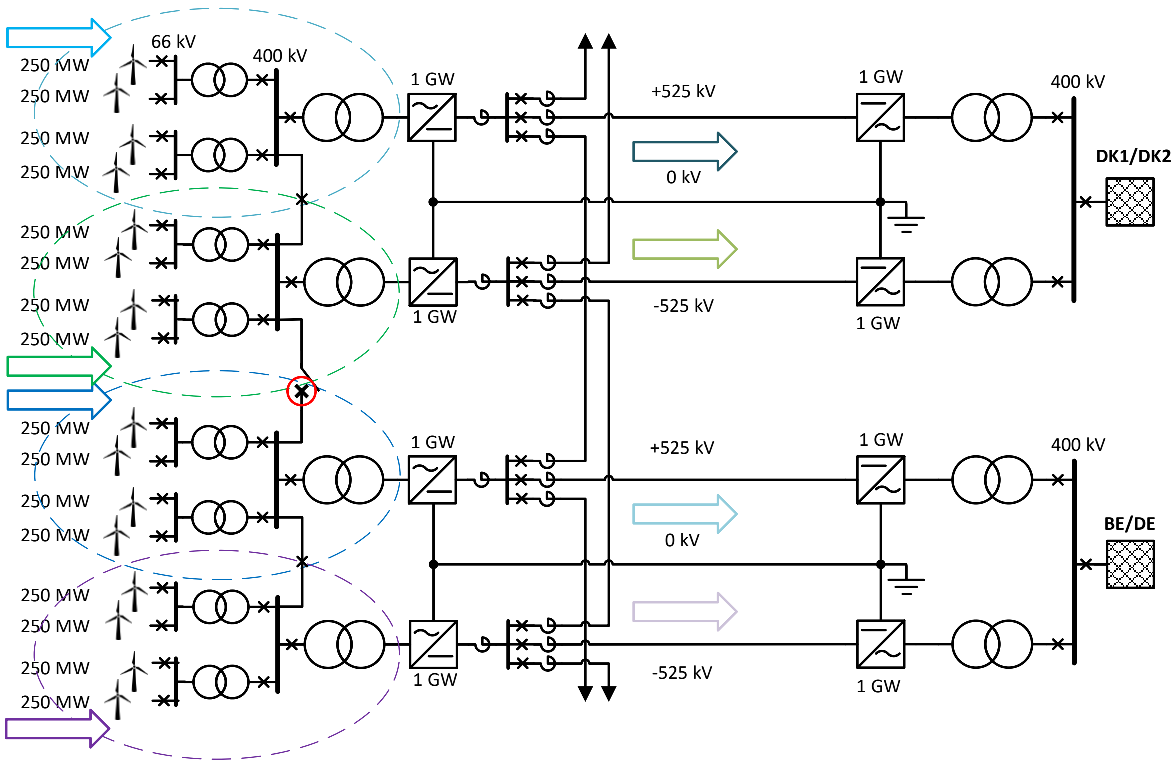


FIGURE 12: WITH AC POLE COUPLING (DC3/AC2A FOR DK1/BE AND DC3/AC1 FOR DK2/DE)

Figure 13 shows a different HVDC scheme for connecting the OWFs. There are two point-to-point DC links, one connecting to Denmark (DK1 or DK2) and the other to Belgium (BE) or Germany (DE). The two offshore hubs are interconnected on the AC side, allowing power flow between them, including in conditions of HVDC faults. This may present challenges in areas such as control interaction but these are not considered here.

Although the DK1 and BE grids are shown as separate in the diagram, these connection points are in the same large AC grid, so this is a specific version of topology type DC1/AC2b.

The DK2 and DE grids are in separate synchronous areas, but the offshore hubs are connected to the same AC system, so this is a specific version of topology DC1/AC2a.

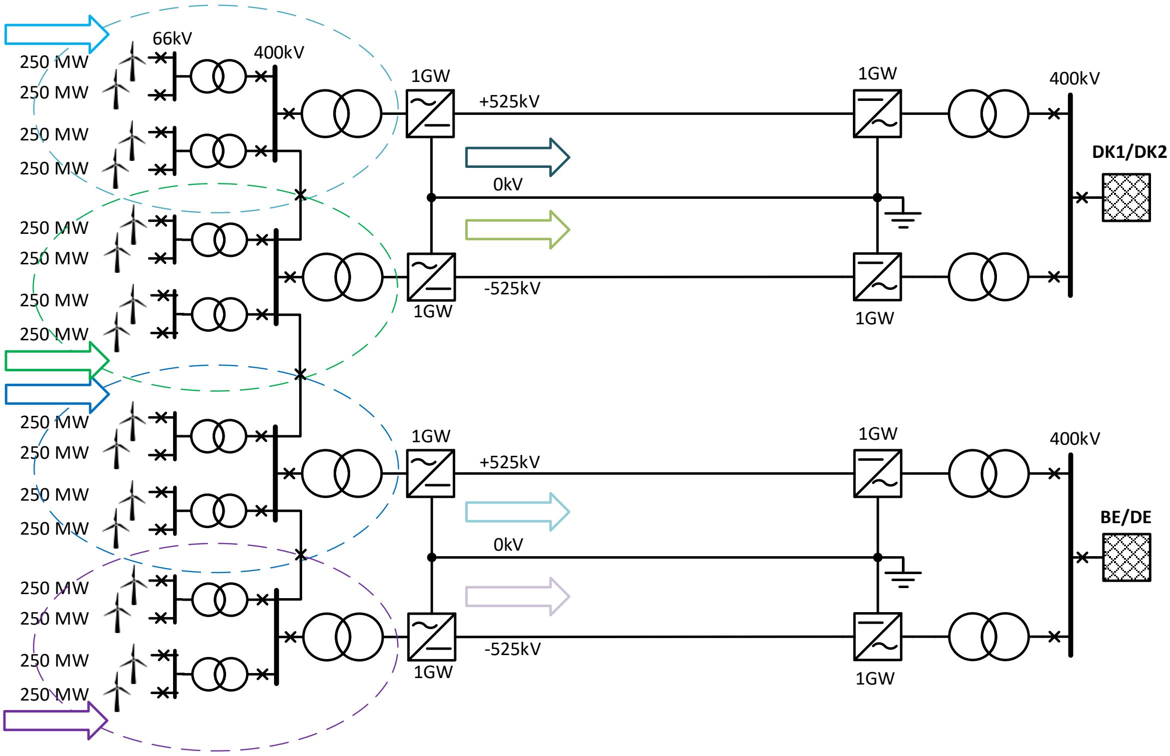


FIGURE 13: WITH OFFSHORE AC INTERCONNECTION (DC1/AC2B FOR DK1/BE AND DC1/AC2A FOR DK2/DE)

The three offshore hub structures have different capability (or resilience) to evacuate power from the OWFs during outage conditions. The charts below show the evacuated power against the wind power scenario (both shown in percent of maximum). In the charts:

- “DC only hub” is for a topology as shown in Figure 11, where there is no AC interconnection between any of the individual converter poles offshore
- “DC hub with AC coupling” is for a topology as shown in Figure 12, where there is AC interconnection between the poles of each bipole but the two bipoles are interconnected only on the DC side
- “AC hub” is for a topology as shown in Figure 13, where there is AC interconnection between all poles offshore and no interconnection on the DC side

Figure 14 shows the maximum power evacuation with the three hub structures during an onshore converter or converter transformer fault or a single pole DC line fault. This reduces the available DC lines from four to three, i.e. only 75% available. By exploiting the coupling on either the DC or AC side of the offshore hubs, it is possible to evacuate up to 75% of wind capacity with the three remaining DC lines loaded at 100%. See also [51].

Figure 15 shows the maximum power evacuation during an offshore converter or converter transformer fault. The DC only hub and DC hub with AC coupling (between the poles of each bipole only, not between bipoles), are a bit less resilient in comparison to the AC hub topology with full AC interconnection between hubs – assuming there is sufficient capacity and resilience in the AC interconnection offshore.

Thus, as can be seen, different topological designs can result in significant differences in system performance and resilience.

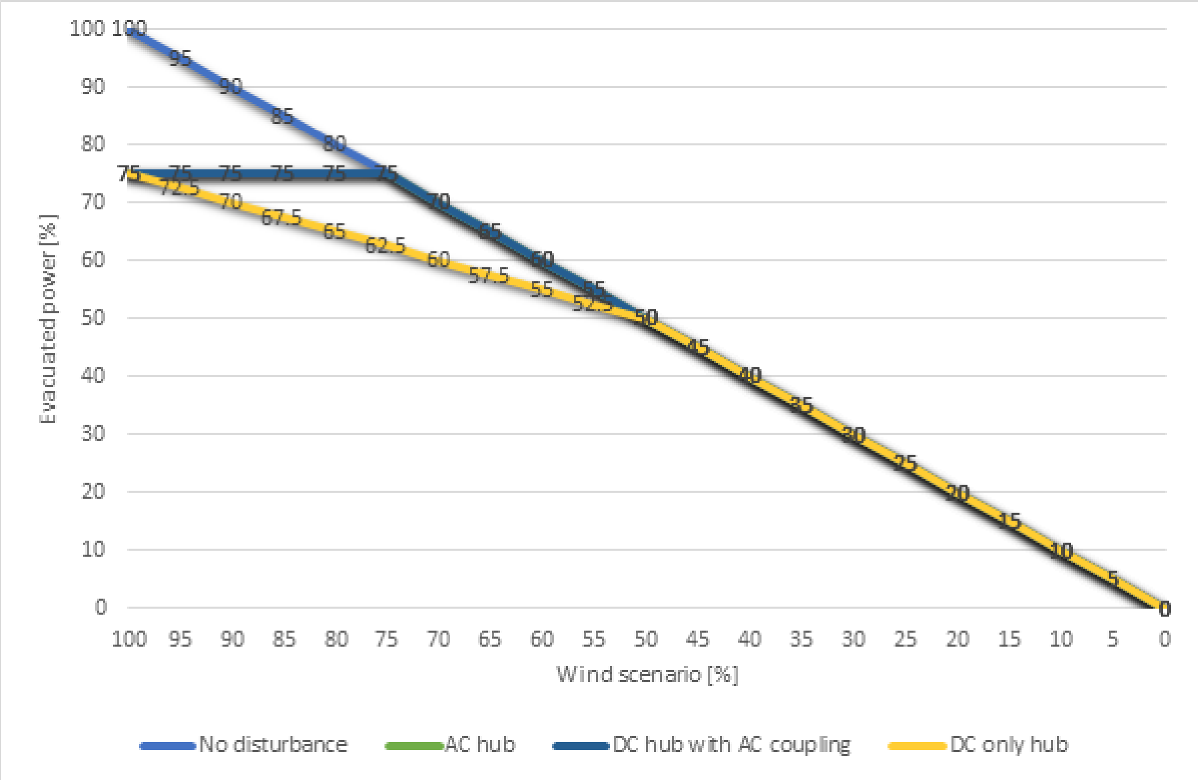


FIGURE 14: EVACUATION CAPACITY OF DIFFERENT HUB STRUCTURES FOR A DC LINE SINGLE-POLE OR ONSHORE CONVERTER FAULT

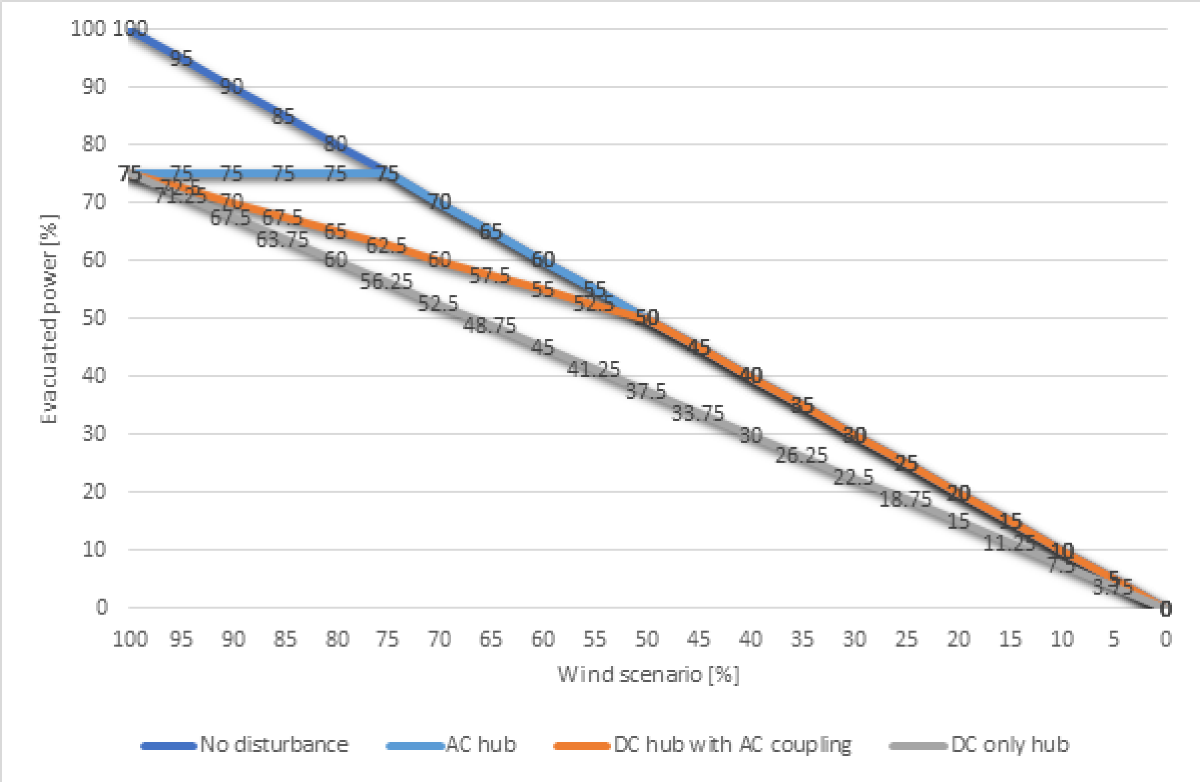


FIGURE 15: EVACUATION CAPACITY OF DIFFERENT HUB STRUCTURES FOR AN OFFSHORE CONVERTER FAULT

4.2 Survey of Existing and Planned DC Links

A survey was conducted of existing and planned DC links. A spreadsheet with details and references on all the projects can be found in Appendix 3 [48]. Each project has been assigned a category as per the topology analysis framework.

4.2.1 Trends in HVDC architectures

The trends for HVDC projects from the 1980s to the present day and future are, in general, towards higher MW capacity and higher voltages, as can be seen in Figure 16 and Figure 17. It can clearly be seen that most future planned HVDC links are VSC (blue) rather than LCC (red) in nature (further discussed in 4.2.3.4). There is also a trend towards more multi-terminal HVDC developments coming onstream, with the associated flexibility these grids give on both AC and DC sides.

It can be seen from Figure 16 that quite a number of projects are taking advantage of the potential for HVDC to transfer larger MW capacities, with capacities of HVDC installations continuing to increase, the highest existing project found to be 8 GW (Kunliulong China, 2020) for VSC and 10 GW (Changji-Guquan, 2018) for LCC. Most future planned HVDC grids are in the 1-2 GW range (further discussed in 4.2.3.4).

Some larger projects are highlighting the capability to transfer at very high voltages (up to 800 kV planned for VSC, and 1100 kV in existence for LCC in the Changji-Guquan project). However, there is a notable trend towards transmission voltages of 320 kV and 525 kV (further discussed in Section 4.2.3.3). The higher voltages used in present day projects allow for the transfer of large quantities of power within or between power systems in an efficient (low loss) manner, particularly over large distances, versus traditional AC transmission.

Finally, it is notable that a number of projects are taking advantage of the capacity of HVDC to transfer over very long distances, as can be seen in Figure 18 (with the AAPowerlink between Singapore and Australia the largest at 5000 km). However, the vast majority of these 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 commonly the single largest infeed/outfeed of the power system, meaning that the system operator must protect against increasingly large disturbances should the HVDC link be disconnected. There is also a trend towards an increasing number of terminals for planned HVDC projects versus the present day HVDC installations. Multi-terminal HVDC projects currently comprise 10% of the existing HVDC installations but comprise 13% of the planned HVDC projects.

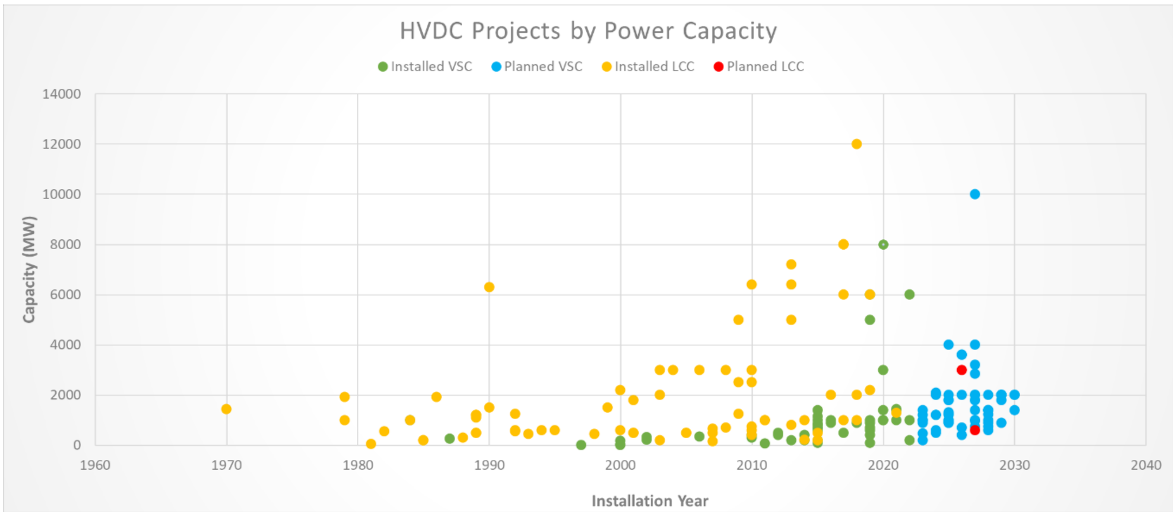


FIGURE 16: VSC-HVDC PROJECTS CAPACITY OVER TIME

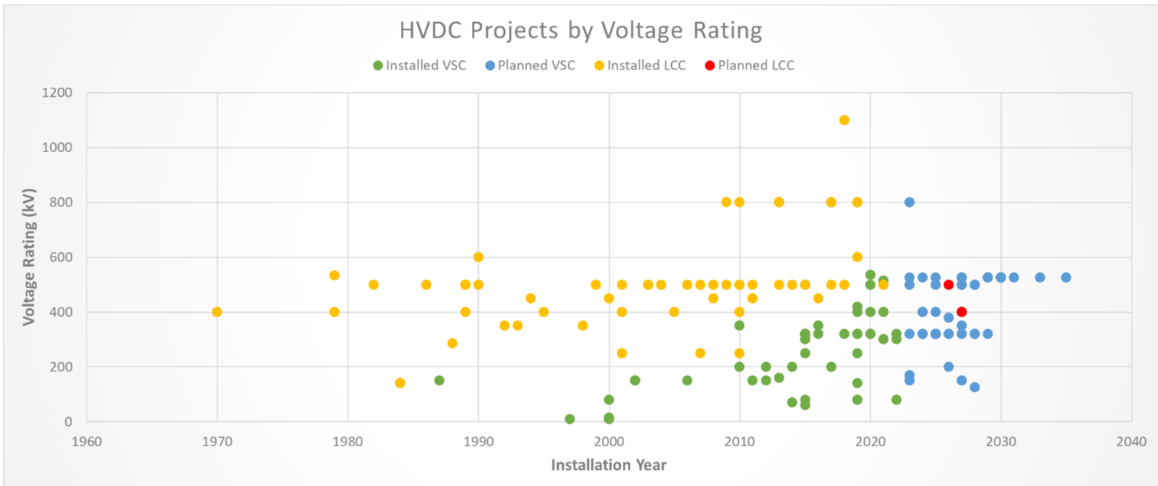


FIGURE 17: VSC-HVDC PROJECTS VOLTAGE RATING OVER TIME

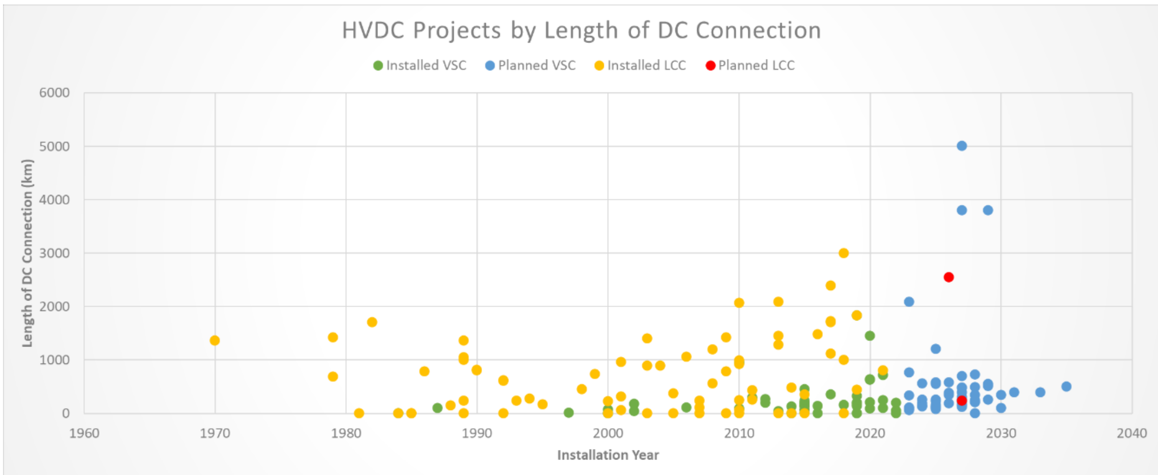


FIGURE 18: VSC-HVDC PROJECTS DC CONNECTION LENGTH OVER TIME

Table 4 presents summary information on the numbers of different types of topologies and the purposes served by the VSC HVDC projects identified in the survey. The purpose of most existing and planned HVDC links is energy trading or the connection of offshore renewables. Point-to-point/Back-to-back links dominate but meshed links are increasingly being developed. With the flexibility these grids provide it may give rise to a wider variety of associated purposes associated with HVDC development.

TABLE 4: PURPOSES ASSOCIATED WITH GRID TOPOLOGIES

		Energy trading	Connections to offshore renewables	Energy transmission power to load	Energy transmission renewables to load	Energy transmission within power system	Grid stability and control
DC1: P2P / B2B	AC1: All separate	31	7	6		10	4
	AC2: Two embedded	6	22				3
	AC3: Fully embedded						
DC2: Radial	AC1: All separate	2	2				
	AC2: Two embedded						
	AC3: Fully embedded				1		
DC3: Linear	AC1: All separate	4					
	AC2: Two embedded	1					
	AC3: Fully embedded			1	2		
DC4: Meshed	AC1: All separate						
	AC2: Two embedded						
	AC3: Fully embedded	1					
Totals		**45**	**31**	**7**	**3**	**10**	**7**

4.2.2 R&R implications of HVDC trends

Some broad trends have been noted from the survey and the R&R opportunities and vulnerabilities associated with these include:

Increasing trend to multi-terminal links

Grid design goal:

- Allows several points of connection improving DC grid N-1 reliability
- Eases power system congestion through offering parallel transmission paths

Opportunities:

- Higher power transfer efficiency
- Increased N-X and fault resilience regarding power transfers
- Enables many AC grids to be interconnected through DC
- Improving asset utilization factor
- Usage of flexibilities
- Increased system stability

Vulnerabilities:

- Increases vulnerability of contagion between multiple AC grids or connected devices where protection devices fail
- Necessitates more complex and not yet state-of-the-art DC-side protection, with the associated risk of failure/unforeseen behvaiours.
- Adverse multi-vendor interoperability issues (e.g. oscillations, trips, etc.)
- Increased number of replicas needed for planning.
- Need of knowledge staff.

R&R implications:

- Increase DC protection P-n style monitoring
- Need of agreed ranges (voltages, insulation,…), topology ((rigid) full bipole, (asymmetrical monopole,…)

Increasing active power transfer capacities of DC links

Grid design goal:

- Allows increased transfer of power from generation to load centres, including increasingly large offshore renewables installations
- Allows transfer of large amounts of power around the power system in response to faults/contingencies

Opportunities:

- Increased resilience to faults regarding power transfer
- Increased potential for power from remote renewables to be transferred to load centres in a low loss manner

Vulnerabilities:

- Large capacity HVDC are commonly the single largest infeed/outfeed in the network, meaning the system operator must provide for increasingly large N-1 contingencies
- Impact on AC grids increase

R&R implications:

- Potentially larger loss of infeed or reduction in network capacity
- Higher system impacts lead to the need of more enhanced functionalities

Increased voltage ranges

DC grid design goal:

- Higher transmission capacity
- Lower losses-particularly over long distance submarine routes

Opportunities:

- Capability to transfer larger powers over large distances, potentially connecting very distant areas

Vulnerabilities:

- Increased number of outages due to insulation breakdown
- Energy stored in cable systems increases ~U^2 which increases short circuit contribution

R&R implications:

- Similar to increased capacities above
- Increased number of outages could lead to system adequacy issues

4.2.3 Emerging Common Designs

The survey of existing and planned HVDC links shows there are commonalities in the design of planned HVDC projects. These commonalities are summarized in the following.

4.2.3.1 Converter and submodule technology

Different converter technologies like direct rectifiers, LCC or VSC and – in case of VSC based on modular multilevel converters – half bridge or full bridge submodules can be found in current HVDC installations in the world. Despite direct rectifiers and LCC applications being cheaper to build, they are unsuitable for the type of multi-terminal and flexible HVDC systems needed to connect offshore wind and support weaker AC systems. One reason is that half or full bridge VSCs enable fast reversal of power flow, in contrast to diode bridge or LCC applications. This enables the provision of more grid services between AC areas that may be located far away from each other. The VSC technology allows for reactive power control, grid forming and black start capability, which are not possible with the older technologies. Hence why the project will focus on modern VSC-based technologies, from which the half bridge VSC seems to emerge as the current state of the art and preferred technology, for cable connections at least. Deliverable 4.1 goes into more detail on the latest technologies.

Half bridge converters are more economical than full bridge due to the reduced number of semiconductor devices. Additionally it means lower losses. To address DC fault clearing strategies, the half bridge technology is dependent on DC circuit breakers (DCCBs) or other DC fault separation devices (DC-FSDs) which allow for DC fault current interruption. With DC-FSDs either partial or fully selective DC grids may be achieved, as explained in section 4.5 and more fully in D3.1 [2]. The full bridge technology is capable of reducing the DC fault current due to the provision of counter voltages [52] [53] [54]. This requires a DC-FSD with less fault current capability in comparison to a DC-FSD in combination with the half bridge technology. The drawback is the temporary shut down of the DC grid until the DC-FSD is able to clear the faulty zone.

4.2.3.2 Connection mode

Based on VSC technologies, the main connection modes that have evolved over time are:

- **Symmetrical monopole**
- **Rigid bipole**
- **Bipole with Dedicated Metallic Return (DMR)**

Considering the planned projects in the survey, future systems are mainly expected to be bipoles with DMR. The main advantage is the increased system availability as in case of a pole to earth fault on the DC side the system can be kept in operation as an **asymmetrical monopole**. Also, rigid bipole operation can be used during maintenance of the DMR.

Furthermore, for normal operating conditions in German offshore DC connections the use of a DMR is a mandatory requirement by the BSH[3] due to the interference of vagrant currents into fixed installations in the North Sea.

4.2.3.3 DC voltage

For current HVDC projects in Europe, three voltage levels are most common: ± 320 kV; ± 380 kV; and ± 525 kV. While ± 320 kV is used for symmetrical monopole operation, ± 380 kV appears for the special application of hybrid AC/DC towers to minimize couplings between the DC and AC voltages. Future DC projects are mainly planned with ± 525 kV, and this voltage is the current focus for development of cables. Methods used for control and protection (C&P) are similar at either 525 kV or 320 kV so there is no difference in the time required to implement or costs for C&P. Higher voltages provide increased transmission capacity, which is needed to evacuate the high amount of offshore wind power to onshore connection points, and is found to be more optimal in cost benefit assessment.

A challenge with ± 525 kV is the larger dimensions of equipment. Offshore platform topside sizes are limited, especially for deep water appplications. Here construction and refurbishment could be easier to carry out with ± 320 kV.

4.2.3.4 Active power per converter station

The survey shows that current developments for DC projects are tending towards an active power per converter station of up to 2 GW. The Technology Readiness Level (TRL) for 2 GW means that it is considered market ready. While vendors may offer to build converter statsions with higher active power rating, these are currently not often considered as the market-ready cables are based on a 2 kA rating and because the loss of active power for an HVDC failure needs to be kept within the infeed loss limits of the relevant grid codes.

[3] Bundesamt für Seeschifffahrt und Hydropgraphie

4.3 Review of topologies in terms of R&R

In this section, the different types of HVDC system as per the topology framework (see section 4.1) are reviewed in terms of goals, opportunities and vulnerabilities from a reliability and resilience (R&R) perspective. This highlights advantages of certain grid topologies, and some of the design considerations that may need to be considered as a result of identified vulnerabilities. The following three subsections tabulate the goals, opportunities, and vulnerabilities in Tables Table 5, Table 6, and Table 7, respectively.

4.3.1 Goals

TABLE 5: R&R GOALS FOR DIFFERENT TOPOLOGIES

DC Grid	DC1: Point-to-point				DC2: Radial				DC3: Linear				DC4: Meshed			
AC Grid	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3
Transfer Goals																
Interconnector between AC grids (main grid or large resource such as wind).	■	■	■		■	■	■		■	■	■		■	■	■	
Increase transfer capacity within an AC grid.				■		■	■	■		■	■	■		■	■	■
Scope for multi-purpose use.					■	■	■	■	■	■	■	■	■	■	■	■
Adequacy Goals																
Improve security with more than one connection between areas.			■			■	■			■	■		■	■	■	
Provide ancillary services to AC grid.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Relieve congestion on AC grid with DC power flow control.			■	■		■	■	■		■	■	■		■	■	■
Redundancy Goals																
Compared to DC1, fewer converter stations needed.					■	■	■	■	■	■	■	■				
Compared to DC1-2, increased redundancy in case of faults.									■	■	■	■	■	■	■	■
Compared to DC1-3, increased redundancy in case of faults.													■	■	■	■

4.3.2 Opportunities

TABLE 6: R&R OPPORTUNITIES FOR DIFFERENT TOPOLOGIES

DC Grid	DC1: Point-to-point				DC2: Radial				DC3: Linear				DC4: Meshed			
AC Grid	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3
System Adequacy opportunities																
HVDC control capabilities can improve AC stability.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Multiple AC embedded VSCs coordinate to enable grid services such as line emulation.		■	■	■		■	■	■		■	■	■		■	■	■
Improved interconnection utilisation* and loss of largest infeed security.		■	■	■		■	■	■		■	■	■		■	■	■
Improved DC N-1 security			■	■		■	■	■	■	■	■	■	■	■	■	■
Improved AC N-1 security			■	■		■	■	■		■	■	■		■	■	■
In case of system split straightforward control concept.		■	■	■												
Improved AC/DC grid power routing capabilities.		■	■	■		■	■	■		■	■	■	■	■	■	■
Operational opportunities for considering use of grid services over multiple asynchronous areas.			■			■	■			■	■				■	
Potentially increased supply from DC side as supplies multiple systems.					■				■				■			
VSCs at all connection nodes in DC grid improve controllability (versus radial).									■	■	■	■	■	■	■	■

*Loss of largest infeed constraints may constrain interconnector utilisation, so the presence of multiple links improves the capacities interconnectors can supply.

Protection opportunities

Straightforward protection design, as can trip full network for faults.	■	■	■	■												
Potential to prevent AC side faults affecting entire DC grid by switching out VSC connection.	■				■				■				■			

4.3.3 Vulnerabilities

TABLE 7: R&R VULNERABILITIES FOR DIFFERENT TOPOLOGIES

DC Grid	DC1: Point-to-point				DC2: Radial				DC3: Linear				DC4: Meshed			
AC Grid	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3	AC1	AC2a	AC2b	AC3
DC system fault risks loss of AC grid ancillary services.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Loss or malfunction of communications risks DC system maloperation.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Potential for maloperation due to software or firmware reconfigurations.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Risk of cyber-attacks on protection, control, communications, etc.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
DC circuit fault results in loss of all power transfer capability from one AC grid.	■	■			■	■	■		■							
AC or DC system fault or loss of infeed may impact multiple AC grids.		■	■		■	■	■		■	■	■		■	■	■	
Potential interaction between converters electrically close on AC side.		■	■	■		■	■	■		■	■	■		■	■	■
Potential for AC circuit overloading for loss of DC circuit.			■	■		■	■	■		■	■	■		■	■	■
Potential for DC circuit overloading for loss of DC circuit (may need energy dissipation strategy).									■	■	■		■	■	■	
Compared with DC1, greater DC system complexity introduces greater risk.					■	■	■	■	■	■	■	■	■	■	■	■
Compared with DC1-3, greater DC system complexity introduces greater risk.													■	■	■	■
Greater extent of DC cable capacitance increases potential DC short circuit current.					■	■	■	■	■	■	■	■	■	■	■	■

4.4 Control impacts on R&R

While the key role of HVDC is to provide the efficient transportation of large quantities of electrical power over large distances, there is a range of additional grid services that HVDC grids can provide to electrical grids, due to the high level of controllability offered by VSC interfaces [55]. In this section an overview is given of a variety of HVDC grid services and their associated control schemes:

- Frequency control
- AC voltage support (reactive power)
- AC line emulation
- Power oscillation damping
- Grid-forming capabilities
- Black start

The following subsections outline R&R related opportunities as well as the vulnerabilities / threats / risks for each of these control functions. Vulnerabilities / threats / risks and barriers common to all of the grid services are outlined in Table 8.

TABLE 8: COMMON R&R VULNERABILITIES/THREATS/RISKS AND BARRIERS FOR GRID SERVICES

R&R Vulnerabilities/ Threats/Risks	• Active or reactive power headroom of converter allocated for use of service. Potential impacts on system adequacy. • Loss of the service when HVDC links are lost. (e.g. in case of faults) • Potential issues due to cyber-physical security issues, e.g., cyber attacks or unintentional consequences of firmware updates (some application specific attacks are noted where relevant for an application). • Malfunction (e.g., sudden power changes) or loss of VSC controllers • Loss of communications to VSC controllers. • Unintended controller and harmonics interactions where VSC controllers are electrically close on grids.
Barriers	• Many of these AC grid services rely on active power management (e.g., frequency control, AC line emulation, etc.), while DC grid stability also depends on active power management. Proper coordination of active power resources is necessary to provide both AC grid services and maintain DC grid stability. • Models provided by vendors and open-source or standard library models may not be accurate enough or may not contain all the relevant functions to cover the real life behaviour of control functions. • Certain analyses for control design at a systemwide level may be limited by black box models. For example, state-space models may not be readily available for devices, due to vendor IP concerns (it should be noted that some black box models allow for the entering of setpoints and the return of the linearised (A,B,C,D) state-space matrices). In this case, if users wished to perform an eigenvalue analysis of the system, they could employ state-space system identification approaches of the unknown area to facilitate such an analysis (or alternative methods such as impedance-based methods [56] could be used for analysis).

4.4.1 Frequency control

By using a droop style control, it is possible to use HVDC to provide frequency regulation services to grids [57]. This cannot be provided by a fully embedded HVDC link, as there must be a connection to a source of energy outside the relevant AC grid, e.g., a storage source, primary reserves on another AC grid.

The provision of frequency control is available across a wide number of existing links. A good demonstration of the capability HVDC based frequency control to form part of a system's frequency regulation response came during the January 8th 2021 continental Europe synchronous area separation event [45] (it is referred to as Limited Frequency sensitivity mode (LFSM) in this reference). Here the Nemolink between the GB and Belgium automatically responded to supply 57 MW from the GB grid to help stabilise the EU grid after the separation incident.

Table 9 outlines the R&R opportunities and vulnerabilities with frequency control using HVDC.

TABLE 9: R&R OPPORTUNITIES & VULNERABILITIES WITH FREQUENCY CONTROL

R&R Opportunities	• Due to quick active power regulation capability of HVDC systems (up to 2000 MW/s), they can be utilized for grid frequency regulation. • As conventional units are displaced by HVDC links, this approach ensures sufficient frequency regulation reserves are maintained in systems.
R&R Vulnerabilities/ Threats/Risks	• As HVDC capacities increase, loss of HVDC links providing frequency control will have a knock on effect on reserves for FRR, FCR and N-G-1 system security. • As conventional units are displaced by VSC controllers, displacing inertia, VSCs will need to be designed and incorporated into grids to limit frequency nadirs after events. • Loss of PLL synchronism with the grid, following system faults, may risk power delivery instability, with potential consequences for frequency stability. • An attacker can launch a cyber attack to disturb the power grid frequency by tampering with the data sent by PMUs to HVDC controllers [58]. • Limited amount of guaranteed capacity due to inconsistent availability of energy provided by renewables may not allow fulfilment of services.

4.4.2 AC voltage support (reactive power)

The capability of HVDC VSC devices to provide AC voltage support is well established. At the point of grid connection, the VSC allows for the adjustment of the reactive power setpoint of the converter to respond to AC voltage disturbances. This functionality is especially important for weaker networks where AC voltage is susceptible to instability. This has been implemented in a range of projects including INELFE, Skaggerak 3-4, Krieger's Flak, the Cross-sound link, Caprivi DC and Estlink, to name a few [55] [59] [60] [61].

There are notable documented examples of this capability in the literature. In October 2003, after an AC fault in Connecticut, the Cross-sound HVDC link supported the AC voltage by providing reactive power while simultaneously regulating its active power output [59]. In [62], the difference between the voltage fluctuations in substations near the INELFE HVDC connection and those far away from it are reported.

Table 10 outlines the R&R opportunities and vulnerabilities with AC voltage support through HVDC links.

TABLE 10: R&R OPPORTUNITIES & VULNERABILITIES WITH AC VOLTAGE SUPPORT

R&R Opportunities	• Allows HVDC links to displace conventional units in providing reactive power support.
R&R Vulnerabilities/ Threats/Risks	• Potential for instability in areas with low system strength. • Loss of PLL synchronism of grid following controller may risk voltage instability, and potentially frequency and power delivery stability as a result. • Poorly tuned controller gains may result in localized voltage instability. • The measured reactive values used by the HVDC control system can be maliciously changed by a cyber attacker and may result in voltage instability issues [63].

4.4.3 AC line emulation

HVDC lines can be designed to emulate the response of AC circuits or networks. This is achieved by automatically adjusting the power setpoint of the HVDC link to be proportional to the angle differences between the AC systems at each converter station. In comparison to the examples in Sections 4.4.1 and 4.4.2 which required only local communication, this requires communication between both VSCs involved in the process.. This is especially useful when a power disturbance occurs (e.g., load changes) as AC line emulation control provides real-time adaptation to power disturbances without manual intervention from system operators.

AC line emulation has been used in both the Mackinac [64] and INELFE [62] projects. It is documented [62] how, in April 2017, after losing a 1000 MW Spanish nuclear plant, the INELFE HVDC link increased its power setpoint, mitigating overloading on the AC lines.

Table 11 outlines the R&R opportunities and vulnerabilities with AC line emulation through HVDC links.

TABLE 11: R&R OPPORTUNITIES & VULNERABILITIES WITH AC LINE EMULATION

R&R Opportunities	• Allows HVDC links to respond naturally to changes in system conditions. This simpler real-time operation allows the HVDC to adapt its active power without requiring any manual action from operators. • Less need for coordination between control centres to manage HVDC flows. • Fast response to events in the network. AC emulation automatically reacts to changes in load/generation and grid topology, e.g., line trips. • Customizable tuning can enable the oscillatory response of the overall system to be tuned in a fashion not possible with AC circuits. • In case of a system split, HVDC can help the reconnection process by helping to resynchronize areas. • Ramping of the DC system is proportional to the AC line's ramping. This reduces additional stress to the grid that might be introduced by fast HVDC set point changes.
R&R Vulnerabilities/ Threats/Risks	• Loss of communications link between converters responsible for providing this service. • This approach can introduce active power oscillatory behaviour due to measurement delays of the angle difference. Therefore, proper choice of the controller time constant is key to avoiding inter-area oscillations [65]. • A fail-safe mode is needed in case of the failure of the AC line emulation, to send manual or optimised set points to fulfil security criteria in real-time operation.

4.4.4 Power oscillation damping

By analysing the system modes of oscillation of a system, it is possible to design HVDC links to damp undesirable modes of power oscillation. This can be achieved by the modulation of either active power signals (POD-P), reactive power signals (POD-Q), or a combination of both. This capability has been implemented in a number of projects including INELFE, the Pacific DC Intertie, the Fenno-Skan link, BritNed and the Western Alberta Transmission Line (WATL) [66] [67] [68]. In [69], the capability of the Fenno-Skan link to improve damping after disconnecting an AC line is highlighted (while there were extensive interconnection flows to Sweden).

Table 12 outlines the R&R opportunities and vulnerabilities with power oscillation damping through HVDC links.

TABLE 12: R&R OPPORTUNITIES & VULNERABILITIES WITH POWER OSCILLATIONS DAMPING

R&R Opportunities	• HVDC links can aid in improving damping of dynamic response (real and reactive power). • Reduced risk of nearby protections being triggered as a result of oscillations.
R&R Vulnerabilities/ Threats/Risks	• Damping of power oscillations may trigger protections. • Damping in one area via POD-P may propagate oscillatory modes in other areas • Potential issues if more than one VSC link in a system is used to do this, due to communications errors, vendor misalignment, etc. • HVDC systems that provide oscillation damping functions are susceptible to cyber attacks such as timing attacks (e.g., DoS attacks), replay attacks, and FDI attacks [70].

4.4.5 Grid-forming capabilities

A grid-forming converter is a converter that has been designed to act as an independent voltage source, in a similar fashion to a synchronous machine. As such, where grid-following controllers measure the system frequency and attempt to inject power at that frequency, grid-forming controllers can set the frequency of their power injections, with the key challenge being to synchronise with the remaining generation sources in the grid. They are capable of providing both an inertial and primary response, although these responses need to be driven by an energy resource, such as a battery or the reserves of another DC connected AC grid. A range of other capabilities for grid-forming converters have been identified including contributing to fault levels, acting as a sink to counter harmonics, inter-harmonics, and imbalances in system voltage, and aiding in preventing adverse control interactions [71].

A range of different approaches to grid forming control for grid synchronisation have been proposed including droop control, power synchronisation control, the virtual synchronous machine, virtual oscillator control, and matching control [72] [73]. Grid-forming VSC controllers can also be used to black start systems [74] and to improve system strength in weak AC networks [75].

Currently, a range of grid-forming inverter application pilots and test projects are being implemented around the world [76]. Noteable projects include Dersalloch, Scotland, where a 6 week test between May and June 2019 operated 23 direct drive full converter wind turbines, totalling 69 MW, in Grid-Forming Mode (GFM). It was found that the turbines responded autonomously and immediately to a range of contingencies [77]. Similarly, the capability to use wind turbines to black start the same system was demonstrated in [78]. Several demonstration projects using battery storage in grids have been conducted in the USA and Australia [76].

Table 13 outlines the R&R opportunities and vulnerabilities with grid forming control using HVDC.

TABLE 13: R&R OPPORTUNITIES & VULNERABILITIES WITH GRID FORMING CONTROL

R&R Opportunities	• Ensures that, in systems where conventional generation is replaced with IBRs (particularly with large scale HVDC connections), the system frequency and voltage stability is maintained. Similarly ensures that HVDC can connect and operate reliably in weak system conditions. • Improves system strength • Ensures that 100% converter systems can be black started. • Capability to provide inherent inertia • Counteract system voltage imbalances. • Can aid in preventing adverse control system interactions.
R&R Vulnerabilities/ Threats/Risks	• System synchronisation issues (may depend on approach used) • Loss of wide range of grid supports provided by GFM with loss or malfunction of control. • Grid-forming VSC controllers are susceptible to Denial of Service (DoS), Man in the Middle (MITM), and False Data Injection (FDI) attacks as mentioned in some references [63]. • Grid-forming tends to more closely couple DC voltage with AC system dynamics. This may impact on HVDC controls where multiple grid-forming VSCs couple to the same DC grid.

4.4.6 Black start

HVDC links can help re-energize AC networks after a partial or system-wide blackout. This capability has been implemented in a range of projects including Estlink, the Cross-Sound cable, the Caprivi DC link, INELFE, Mackinac, Kriger's Flak Combined Grid Solutions, Skagerrak and EWIC. Documented examples of black start operation are the use of the Cross-Sound cable, August 14, 2003 after the northwest blackout in the USA [79], the black start of the wind farm at Tjaereborg in Denmark [80], an operational test of the ALEGrO link between Germany and Belgium to verify the re-energization capability of the link after a partial black out [81], and an operational test of the Skagerrak 4 link between Norway and Denmark [82].

Table 14 outlines the R&R opportunities and vulnerabilities with black start using HVDC links.

TABLE 14: R&R OPPORTUNITIES & VULNERABILITIES WITH BLACK START

R&R Opportunities	• Capability to black start grid using HVDC connections for re-energisation.
R&R Vulnerabilities/ Threats/Risks	• Black start capability is dependent on sufficient energy sources being available at the other end of the HVDC link. • Black start capabilities driven by renewables require grid-forming behaviour of e.g. offshore wind parks.

4.5 Protection related R&R impacts

Protection devices and strategies are key to ensuring the secure operation of future HVDC systems. The ability to contain faults and cascading events, such as voltage collapse, will be necessary in such grids to ensure the protection of AC and DC side grid assets, and to ensure that future large-scale hybrid AC/DC systems can be operated in a reliable and resilient fashion, as was discussed previously in Section 3.2.3. Ongoing developments in both protection devices and the protection approaches that are used in the design of hybrid AC/DC systems are of interest in this regard.

A (non-exhaustive) range of protection functions have been identified as relevant to the project goals and are reviewed here in terms of opportunities, vulnerabilities/threats/risks, and barriers:

- AC Circuit Breakers for DC grid protection
- DC Circuit Breakers for DC grid protection
- Fault-blocking converters for DC grid protection
- Energy dissipation / dynamic breaking systems
- DC/DC converters for DC grid protection
- VSC HVDC grids for “firewall” protection

With relation to the above, Deliverable 4.1 provides significantly more technical detail on the technologies used to deliver these protection functions, Deliverable 3.1 [2] a more in depth analysis of HVDC protection concepts and classifications, and Deliverables 3.1 and 2.2 [1] go into more depth on the KPIs that will be used to assess protection system performance.

In reviewing protection philosophies, it is important to note the concepts of selectivity for DC grid protection as outlined in the Cigre TB739 document produced by the Joint Working Group B4/B5.59 [83]:

- Non-Selective (NS): This philosophy considers the complete HVDC grid as one protection zone for fault clearance. In case of a DC side fault, the whole HVDC grid is de-energized.
- Partially-Selective (PS): For this philosophy, the DC grid is divided into several protection zones or sub-grids. The loss of the whole HVDC grid can be avoided by quickly isolating the healthy zones from the faulted zone.
- Fully-Selective (FS): In a fully selective philosophy, protection zones are defined to individually protect each DC branch and node. Fully selective fault clearing is likely to require the use of DC circuit breakers or other Fault Separation Devices (FSDs).

The authors note the recently published CENELEC [84] standard in relation to classification of protection system impact on the AC grid. Deliverable 3.1 considers this in greater depth.

4.5.1 AC Circuit Breakers for DC grid protection (NS)

The most widely applied approach currently is to protect DC grids using standard AC circuit breakers. This disconnects the entire DC grid although the maximum power loss at each AC point of connection is limited to the converter rating. Using this approach to secure continuous operation of the AC grid in terms of frequency and voltage stability remains practical only for small multi-terminal DC networks (i.e., with a total power rating connected to the same AC network of less than the respective grid codes limits, for continental Europe currently 3 GW) [51] [83]. An example is illustrated in Figure 19.

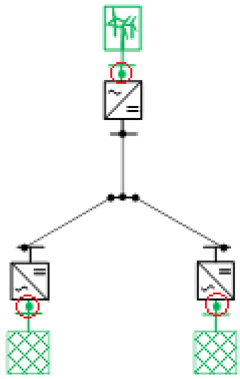


FIGURE 19: SMALL NETWORK USING NON-SELECTIVE AC CIRCUIT BREAKER APPROACH

Consider a pole-to-pole or converter-internal fault in the above system. Each of the two AC grids will lose power infeed from the offshore wind farm. However, this would happen anyway with a point-to-point system, and each AC grid must be tolerant to the loss of infeed from a single point-to-point link. The NS approach using AC breakers is probably sufficient, with both AC grids secure to the worst-case loss (of a P2P link), and there is no urgent need for a different approach. A PS or FS approach might ensure continuation of power supply to one of the AC grids and would therefore improve the overall reliability of the system, but this improvement may not be necessary, from a security perspective, or cost effective. Introducing DCCBs/FSDs may be more expensive than the financial risk associated with losing the infeed. However, as networks get larger and more complex, an NS approach with ACCBs does not adequately scale.

Table 15 outlines opportunities, vulnerabilities and potential barriers with the use of AC circuit breakers for NS protection in DC grids.

TABLE 15: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH AC BREAKERS FOR NS PROTECTION

R&R Opportunities	• High reliability of protection, as all technologies are mature and known.
R&R Vulnerabilities/ Threats/Risks	• In case of pole to pole DC faults, the entire DC network is temporarily lost. This would also imply the loss of associated grid services such as grid-forming control. • The free wheeling diodes and thyristors of the converters are being exposed to higher fault currents than with DCCBs or DC-FSDs isolating the fault. • The trip signals sent to the circuit breakers might be maliciously altered by a cyber attacker.
Barriers	• Limited scalability for larger DC grids.

4.5.2 DC Circuit Breakers for DC grid protection (PS/FS)

DC Circuit Breakers (DCCBs), which are the most commonly discussed type of DC Fault Separation Device (FSD), are an enabling technology for the creation of large scale meshed HVDC grids, due to their ability to isolate DC faults, thus preventing further contagion of the fault in the remaining connected DC and AC networks [51] [83]. FS, PS, and NS strategies can all be implemented with DCCBs.

In the FS case, each DC line/cable can be isolated individually to ensure continued supply of power on unfaulted DC circuits and to the AC side. This allows for more secure and continuous operation of the AC grid with minimal disturbances in case of a fault on a single DC line. However, this comes at certain financial cost, as each DC line or cable needs its own DCCBs, although the cost of DCCBs is expected to be less than the cost of full-bridge converters.

For the PS case, there is a trade-off between the performance of the protection system and the cost of the DCCBs that are installed. Sections of the DC grid are grouped and breakers installed accordingly, such that if there is a fault in one of these sections the DCCBs will isolate the affected section. The goal is still that both frequency and voltage stability will be maintained within the connected AC grids, and that any DC side disturbance will be minimized outside of the affected zone, but naturally some performance degradation in comparison to an FS scheme is to be expected.

Table 16 outlines opportunities, vulnerabilities and potential barriers with the use of DCCBs for PS/FS protection in DC grids.

TABLE 16: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH DCCBS FOR PS/FS PROTECTION

<table>
<tr><td>R&R Opportunities</td><td>PS/FS DCCB protection allows for fast isolation of the DC fault minimising the impact on the AC network and the remaining DC system.
Enables development of more complex meshed grids that can be used to enhance system R&R.</td></tr>
<tr><td>R&R Vulnerabilities/ Threats/Risks</td><td>Need for complex protection algorithm to rapidly detect and locate the faults.
In contrast to FS, PS additionally requires
Extended reach
Communication between line IEDs
Series inductors are needed for each DCCB to limit fault current.
Inductors interfere with control dynamics and DC-side control stability
Compared to FS, with PS less inductors are needed
Possible alternative is superconducting fault current limiters (FCL) instead of inductors
Future DCCB technologies may not require series inductors
DC circuit breaker failure (requires backup protection)
Converters block although DC circuit breaker has cleared the fault
The trip signals sent to the circuit breakers might be attacked by a cyber attacker.</td></tr>
</table>

4.5.3 Fault-blocking converters for DC grid protection (NS/PS)

The majority of existing MMC-HVDC systems are based on half-bridge submodules (HB-SMs). In the event of a low-resistance DC fault, the HB-SMs are usually blocked as soon as the fault is detected to prevent uncontrolled discharge of the capacitors and protect them from overcurrent [85]. When blocked, their anti-parallel diodes conduct due to the DC undervoltage and the converter behaves like an uncontrolled diode rectifier [54], and the AC network feeds the DC fault. AC or DC circuit breakers are needed to protect the system's components and extinguish the fault current [83]. As a consequence of converter blocking there is also the loss of its controllability and therefore its reactive power support to the AC grid [86].

As an alternative, for example, a full-bridge (FB) based fault blocking converter (FBC) can be used [53], [52]. Since FB submodules have additional IGBTs, they can insert their capacitors both with positive and negative polarity and are therefore able to block fault currents [54]. Another advantage of most FBCs is that they are able to control DC current even during fault situations. Thus, these converters can control their fault current contribution to values very close to zero [54], [86]. This allows fast-acting switches to be opened on the DC grid to isolate the fault. Another advantage of controlling DC fault currents instead of blocking all power electronic devices is the uninterrupted reactive power controllability of the converter in STATCOM mode [86].

FBCs in combination with DC-side isolation switches can help limit DC side fault contagion to AC grids by acting within a few hundred milliseconds [87] [88]. FBCs can be considered in an NS or PS configuration. In an NS configuration, FBCs would be used at all converter stations connected to the same MTDC network. An alternative would be to consider a defined zone within a MTDC network that would allow the deployment of a PS strategy.

Table 17 outlines opportunities, vulnerabilities and potential barriers with the use of FBCs for NS/PS protection in DC grids.

TABLE 17: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH FBCS FOR NS/PS PROTECTION

R&R Opportunities	• FBCs may improve fault impacts on AC side stability due to possible limitation of DC fault time. • The converter can continue in STATCOM mode on the AC side during the DC fault clearance.
R&R Vulnerabilities/ Threats/Risks	• Failure of a FBC could have widespread impact on the DC and AC grids. • As for NS with Half Bridge MMCs, the entire DC power flow is reduced to zero upon DC faults, but the recovery is significantly faster. • Requires FBC at all stations. Potential multi-vendor issues. • Power loss can get very large (e.g. >> 3 GW, but only for ~200 ms)

4.5.4 DC/DC converters for DC grid protection

DC/DC converters (discussed briefly in Section 4.1.2) can act as a protection buffer between DC systems (enabling the containment of disturbances from healthy zones after a fault) and can provide fault blocking capability (the devices make fault currents through the converter go to zero). It can also help black start AC systems, if the other DC system is live. Finally, on the DC side these can form a core element with regard to the use of VSC HVDC grids as protection "firewalls" (see next section).

Table 18 outlines opportunities, vulnerabilities and potential barriers with the use of DC/DC converters in DC grids.

TABLE 18: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH DC/DC CONVERTERS

R&R Opportunities	• During fault provides a firewall between DC systems (avoids disturbance in healthy zones after a fault) and can provide fault blocking capability (makes fault current through the converter going to zero), much the same as DC CBs. • Allows power flows between systems with different characteristics. • An appropriate converter design allows to operate the monopole when a pole of the bipole is faulty. • Can support system restoration.
R&R Vulnerabilities/ Threats/Risks	• Failure in the DC/DC converter can affect both DC systems.
Barriers	• Interoperability/converter interactions to be managed.

4.5.5 Energy dissipation systems

In the case of a fault to an AC network in which an onshore converter station is connected, the resultant undervoltage in the system will limit the power transmission capabilities of the converter. This will lead to an energy build up in the MTDC grid, which in turn leads to a voltage rise in the DC system. This voltage rise needs to be promptly dissipated, as otherwise it may lead to further disconnections on the DC grid, as connected devices' protection mechanisms are prompted into action to disconnect the DC grid connected equipment. It is important that DC connected offshore power sources are not disconnected, since loss of these facilities may in turn affect system adequacy in connected AC systems. Over and above this, is it also a requirement by European Commission regulation 2016/1447 that HVDC connection must be able to provide Fault Ride Through (FRT) for AC onshore faults [89]. The VDE-AR-N 4131:2019-03 requirement [90] also stipulates that the HVDC system must be able to absorb its nominal rated power for at least 2 s.

Energy Dissipation Systems (EDSs) [91] [92] [93] [94] allow DC voltages to be kept under a certain threshold after such an AC side fault, or can help to manage AC voltages in an offshore grid after faults on the DC side. The main goals of these protection systems are to absorb excess energy and enable fault ride through; they can also be used for pole rebalancing after pole-to-ground-faults in symmetric monopole systems [95]. Chopper controlled resistors have been used as braking resistors to dissipate the braking energy in variable frequency drives [96]. Such controlled resistances are called dynamic braking resistances or more commonly DC choppers and have been used in point-to-point HVDC connections [97].

The installation of EDSs will be key in future MTDC grids and offshore AC grids to ensure a secure supply of power from large-scale hybrid AC/DC grids. While EDSs can be installed either onshore or offshore on AC or DC grids, to date, installation on the onshore DC side has been chosen due to:

- Space and weight being at a premium in offshore platforms
- For an onshore AC installation it would pose significant difficulties in isolating between the onshore AC fault and the AC side of the converter station

AC choppers installed to dissipate energy from offshore wind farms after faults on HVDC connections will need to be located offshore.

Table 19 outlines opportunities, vulnerabilities and potential barriers with the use of Energy Dissipation / Dynamic Braking Systems in DC grids.

TABLE 19: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH ENERGY DISSIPATION SYSTEMS

R&R Opportunities	• Ensures excess energy is dissipated and voltages in AC/DC system are maintained within safe limits to achieve the required fault ride through performance.
R&R Vulnerabilities/ Threats/Risks	• Failure of the energy dissipation protection could result in disconnection of devices, and in turn this could impact on grid adequacy and stability. o Additional risks to grid services if other VSCs connected on the DC side are affected o Potential for associated contagion of grid supply issues to other AC grids connected to the affected DC grid. • The rating of these devices may need to be rated to one or multiple events. For bigger DC networks there's an increased risk that the network may see more fault-ride-through events, increasing the complexity and uncertainty in relation to determine the rating of the device. • For larger DC systems, and various topologies, the question of where to locate these devices becomes increasingly problematic. One must consider trade offs between addressing fault-ride-through capability, and the need to avoid undue instability within the DC networks. The question of what level of redundancy is pertinent in this regard (N-1, N-2, etc) further complicates this issue.

4.6VSC HVDC grids as "firewall" protection

VSC HVDC grids have often been cited as potential "firewalls" for protecting electrical grids; as such they are considered to provide a promising means of containing and mitigating against the worst consequences of power systems contingencies, through the combined application of their control and protection capabilities. In the previous section, it was illustrated how various protection devices offer the potential to act as a "firewall" on the DC side of the grid, preventing the contagion of contingencies on the DC side of the network. In this section we outline the possibilities offered by VSC HVDC grids in providing this "firewall" protection for the AC side of the grid.

VSC HVDC based grids can provide a range of protection capabilities to AC grids, as noted by ENTSO-E [55]. One of the key capabilities of VSC HVDC grids is their capability to link asynchronous AC grids. This normally ensures that frequency disturbances experienced in one AC area do not spread to others. However, where HVDC controllers are tuned to respond to frequency events, there is the possibility for such disturbances to spread between areas connected by the HVDC links.

In the case of embedded HVDC, i.e., links whose AC terminals are in the same AC synchronous area, frequency decoupling does not apply. However, the controllability performances of the HVDC, especially the rapidity of active power variation, open new opportunities for firewall actions to prevent disturbance propagation. Control capabilities, such as those outlined in Section 0, have the potential to modulate the active and reactive powers in the system to alleviate system stresses.

In general, for both asynchronous and embedded HVDC, several functions can be designed for normal or emergency control, in either case aimed at stabilising the AC system(s). The HVDC controls designed to operate in case of emergency can be regarded as System Protection Schemes (SPSs), part of the defence plans of the power system [98] [99] [100] [101]. ("A System Defence Plan is a set of automatic or manual and fast acting schemes, which are designed to maintain system stability in case of severe contingencies that may trigger a cascading event that would bring the power system towards blackout state" [98]). Where multi-terminal HVDC grids are concerned, the opportunities and challenges increase further.

The EU network code on HVDC [89] outlines the following priority and ranking of protection and control functionality that should be supplied by HVDC devices (Article 35(2)):

a) network and HVDC system protection
b) active power control for emergency assistance
c) synthetic inertia, if applicable
d) automatic remedial actions as specified in Article 13(3)
e) LFSM (Limited Frequency Sensitive Mode)[4]
f) FSM (Frequency Sensitive Mode)[5] and frequency control
g) power gradient constraint

and Article 13(3) states:

> […] the control functions of an HVDC system shall be capable of taking automatic remedial actions including, but not limited to, stopping the ramping and blocking FSM, LFSM-O, LFSM-U and frequency control. […]

As discussed in [55] (and in Section 4), HVDC systems can provide curative measures to have local (voltages, currents) or global (frequency) remedial effects on the system. Possible disturbances encompass AC or DC line tripping and active power imbalances. The objectives of an SPS can be:

- Preventing thermal overloading of assets in the vicinity of the HVDC link (local) following line trips occurring in a stressed pre-contingency situation
- Preventing a voltage collapse next to the converter (local)
- Containing a frequency deviation (global)

[4] " 'limited frequency sensitive mode — overfrequency' or 'LFSM-O' means a power-generating module or HVDC system operating mode which will result in active power output reduction in response to a change in system frequency above a certain value; 'limited frequency sensitive mode — underfrequency' or 'LFSM-U' means a power-generating module or HVDC system operating mode which will result in active power output increase in response to a change in system frequency below a certain value" [120].

[5] "The operating mode of a power-generating module or HVDC system in which the active power output changes in response to a change in system frequency, in such a way that it assists with the recovery to target frequency" [120].

Typical actions carried out by the converters are:

- full run-back of active power
- full run-up of active power
- inductive/capacitive reactive power boost
- run to a specific active and/or reactive power operating point
- parameter modification of power control (e.g., AC line emulation)

SPS rules can be predefined in terms of contingency events, thresholds, and action, or they can be computed online, thus being adaptive with the operating condition.

To counteract overcurrents, full reduction/increase of active power to zero or to a specific limit can be implemented by the converter. To counteract voltage violations, active/reactive power boosts can be activated. As far as frequency is concerned (in HVDC links connecting asynchronous AC grids), active power injection variations are carried out.

The robust design of SPSs is a major challenge, especially with regard to coordination amongst multiple HVDC systems. All relevant disturbance scenarios must be considered, including further events (possibly triggered by other SPSs) that might occur as the disturbance unfolds.

In [102] an emergency control strategy for embedded VSC-HVDC links is proposed, aiming to minimize the impact of disturbances on the AC network with benefit for long-term voltage stability. The strategy relies on different PQ control logics of the converter for normal and low voltage operation.

Reference [103] proposes a dynamic closed-loop corrective control (DCC) to alleviate congestions in hybrid AC/DC power systems. HVDC can also be applied to automatically support the AC system during unintended significant power flow changes by applying an additional offset to the normal set point of the converters.

Another example of HVDC links suitably controlled to relieve congestions in an AC grid are the “DC loop flows” described by ENTSO-E in [55] and illustrated here in Figure 20. The minimum requirements for this kind of action are two asynchronous AC grids linked by two HVDC links. AC grid congestion is relieved by shifting part of the power flowing in the congested AC grid to the non-congested AC grid via the HVDC links. This is presented as a preventive solution to address congestion, typically initiated after market closure. Indeed, the loop flow is viable only if the new schedule is compatible with security constraints. Suitable planning studies would be necessary to identify this compatibility.

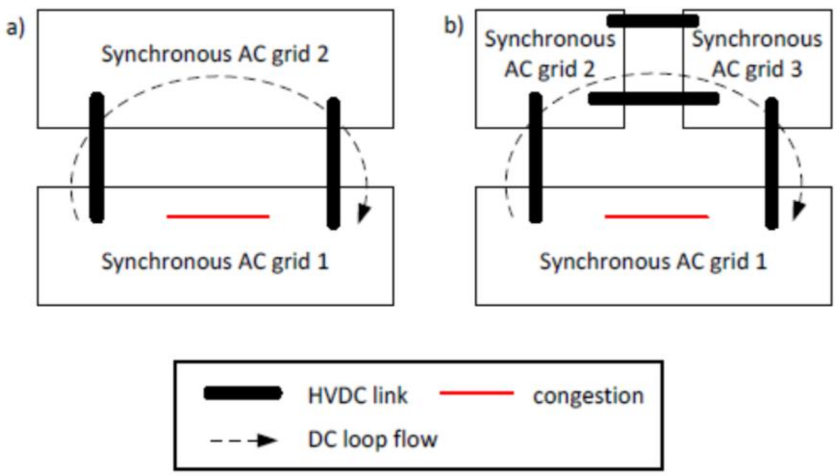


FIGURE 20: DC LOOP FLOWS TO ALLEVIATE AC GRID CONGESTION [55]

Worldwide, examples of HVDC involved in SPS include the Murraylink (embedded VSC-HVDC link in Australia with two run-back schemes to prevent current or voltage issues), Basslink (monopolar HVDC link in Tasmania/Australia with online computation of the corrective actions following contingencies, aimed to correct overloading), INELFE (embedded HVDC between France and Spain: in addition to AC line emulation, automatic reactive power support is provided, also in dynamics), Great Belt (HVDC in Denmark, implementing a fast runback function to face overloads and a stop ramping function in case of frequency issues).

Table 20 outlines opportunities, vulnerabilities and potential barriers with the exploitation of HVDC firewall capability for AC grid protection.

TABLE 20: R&R OPPORTUNITIES, VULNERABILITIES & BARRIERS WITH HVDC FIREWALL CAPABILITY

R&R Opportunities	• The range of capabilities offered by DC system protection components and the control capabilities of VSC HVDC links offer significant flexibility in both mitigating and containing large scale system faults. • VSC HVDC grids can ensure frequency disturbances are contained between asynchronous AC grids. • The wide range of active and reactive power controllability can be utilised to limit AC grid violations after contingencies across multiple grids. • Custom system protection schemes can be designed to combine a range of VSC HVDC grid capabilities to protect systems after contingencies that have been identified as problematic.
R&R Vulnerabilities/ Threats/Risks	• Where protection may rely on the interaction of a number of DC devices and controllers, the potential for unpredictable responses due to these interactions is increased. • Control or protection actions used to limit system violations in one AC system may result in violations occurring in other asynchronous AC systems connected by HVDC. • The assumption by one TSO may be that other connected TSOs can provide a particular service when necessary. However, it may be the case in times of constrained power production across wide areas, e.g., periods of low wind and solar, that this is not possible. • The necessity for complex actions, such as DC loop flows, to act in a rapid fashion, may have unintended consequences when system conditions deviate significantly. • The firewall protection schemes mentioned in this section need some measurements from the AC/DC system and send back some control commands (e.g., relay tripping, change in fire angles, etc.). These measurements and control commands might be attacked by a cyber attacker and disrupt the system operation.
Barriers	• Legislative arrangements and coordinated planning between interconnected TSOs need to be in place to ensure that protection or control actions can be enacted to protect asynchronous AC grids connected by DC grids.

4.7 Research objectives for WP3

The research objectives that WP3 of the HVDC-WISE project will undertake to enhance the reliability and resilience of future hybrid AC/DC grids are outlined in the following:

- A range of novel HVDC architectures will be proposed. These architectures will consider the technologies identified in WP4 for further development, and form the basis of the use cases to be considered in WP6.
- The architectures will be classified and analysed based on topology and the nature of connections to AC systems. A KPI matrix will be used to perform a high-level qualitative analysis of the identified AC/DC architectures
- Control and protection approaches will be developed for the novel HVDC architectures.
- Cyber attack risks will be assessed and tested on the control and protection approaches and strategies to mitigate the effects of these attacks will be proposed.

This research will be documented in greater detail over the course of the project through the WP3 deliverables.

5 HVDC Technologies

Work Package 4 (WP4) of the HVDC-WISE project is concerned with the enabling technologies for future AC/DC hybrid systems. This chapter outlines the HVDC technologies that are of interest within the project, model standardisation efforts that will be conducted, and finally the research objectives that WP4 will seek to address over the course of the project. The goals are to improve the TRL of a selected range of technologies and develop model standardisation and a structured database related to HVDC systems modelling.

While WP3 is concerned with higher level system architectures, i.e., the system topology, control, and protection design, WP4 considers the building blocks of hybrid AC/DC grids, i.e., the component parts of the system. WP4 will consider internal converter controls (e.g., energy control in MMC), whereas WP3 will work on system level control (i.e., involving several converters). Regarding protection, WP4 will focus on hardware developments (e.g., available technologies for DC circuit breakers and related performances), and WP3 will focus on protection strategies and algorithms (i.e., selective vs non-selective protection approaches, fault localization, etc).

WP4 will focus on the individual physical devices in the system such as DC circuit breakers, DC current limiting devices, AC/DC converters and their internal controls, and how these devices are modelled. A range of promising devices has been identified in Deliverable 4.1, and over the course of the project actions will be taken to improve existing modelling and simulation techniques for some of these. WP3 will develop architectures that use combinations of these system devices to achieve system-wide goals with consideration of the R&R of the whole system.

5.1 Technologies of interest

Various building blocks of interest for the development of hybrid AC/DC grids have been identified:

- Building blocks enabling DC architectures
- New building blocks for AC systems
- Well-established solutions for AC systems
- Elements related to costs for planning processes.

An overview of these technologies and their further development over the course of the project will be documented in the WP4 deliverables. Deliverable 4.1 provides significant detail on the technologies outlined below.

5.1.1 Building blocks enabling DC architectures

The following is a list of building blocks that have been identified as being highly relevant to build the DC part of future AC/DC grids:

1. VSC AC/DC converters
    a. MMC
    b. Grid following control of VSCs
    c. Grid forming control of VSCs
2. DC circuit breakers
3. DC fault current limiting devices
    a. Superconducting fault current limiters
    b. DC inductors
4. Energy dissipation systems

   a. DC side converters
   b. AC side converters
5. Energy storage
   a. Energy storage in AC/DC converters
   b. Energy storage connected to HVDC links
6. DC/DC converters
   a. DC/DC converters HVDC/HVDC
   b. DC/DC converters HVDC/MVDC
7. Power flow controllers (meshed HVDC grid current flow controllers)
8. Cables and overhead lines
   a. DC cables
   b. DC superconducting cables
   c. DC overhead lines

5.1.2 New building blocks for AC systems

The following new building blocks for AC systems have been highlighted for the impact they may have on the use cases that will be developed in the course of the project:

1. AC current limiting devices (superconductors)
2. Systems in grid forming mode
   a. Wind farms
   b. STATCOMs
3. Energy storage
4. AC cables and overhead lines: AC superconducting cables

5.1.3 Well established power systems solutions

The following are well established AC system building blocks that will have a large impact on the development of hybrid AC/DC systems:

1. LCC based AC/DC converters
2. AC Protection
3. Flexible AC transmission systems (FACTS)
4. AC cables
5. AC overhead lines

As these building blocks are well known, they will receive less attention in the project as relevant models are already available.

5.1.4 Elements related to costs for planning processes

The further development of cost models for the following will be relevant from an economic analysis point of view:

1. Substations
2. Equipment
3. Conversion of existing AC lines to DC

5.2 Model standardisation

To be able to conduct adequate modelling for R&R analyses, it is necessary that sufficient modelling of equipment is standardised in a format that is agreeable across the industry. The IEC CIM/CGMES standards have been converged upon in both industry and academia as a standard means for defining power systems models.

WP4 will use the IEC CIM/CGMES as much as possible for quasi steady state and RMS models considering the different models and libraries already in existence and the future needs of the project. At the same time, WP4 will explore the potential extension of the IEC CIM/CGMES standards to include dynamic phasor models or EMT models (offline and real-time). If the developed models cannot be contained within the IEC CIM/CGMES standard, an agreed structure among all the partners will be used.

5.3 Research objectives for WP4

The research objectives that WP4 of the HVDC-WISE project will undertake to enhance the reliability and resilience of future hybrid AC/DC grids is outlined in the following:

- Enabling solutions will be identified as relevant to the architectures proposed in WP3. Solutions currently at low TRLs will be developed (e.g., modelling, control, sizing procedure) in line with the needs identified for system architectures.
- A modelling framework will be developed, incorporating existing and new models, to consider different KPIs including model accuracy, speed and complexity. The framework will be used to assess and recommend models depending on the simulation needs.
- Realistic parameterisation of models will be undertaken for key parameters to enable the selection of grid configurations in the planning processes developed.
- Model standardisation and development of a structured database through extensions to the IEC CIM/CGMES standards, with a view to creating a public library of models.

This research will be documented in greater detail over the course of the project through the WP4 deliverables.

6 Methods and Tools

Work Package 5 (WP5) will develop methodologies to conduct R&R analyses and the tools capable of implementing these methodologies, based on the needs identified for R&R assessments of hybrid AC/DC grids in the project. This section outlines the drivers, methodologies, tools and objectives for R&R analysis that will be considered as part of this work package.

The HVDC architectures, control, and protection functions developed in WP3 and WP4 will be modelled and simulated within the platforms developed in WP5. Techno-economic analyses will use static forms of the provided models to determine the architectures and technologies that provide best trade offs between cost and technical performance. Security and resilience analysis will be undertaken considering cascading contingencies and dynamic performance, using the cascading event and dynamic analysis tools developed in WP5.

The analyses conducted in WP5 to analyse and rank candidate architectures will feed into the three use case studies in WP6, where the impacts of various HVDC architectures will be evaluated in detailed grid simulations. Situations from WP6 that are deemed to require further investigation will be identified for use in WP7, where detailed offline EMT screening simulations will be conducted first. The most relevant of these cases will be fed into real-time Hardware in the Loop studies, with a view to testing control and protection concepts that have been developed as part of the project.

6.1 Conceptual architecture

Deliverable 5.1 proposes a conceptual architecture for a framework that will integrate different tools and methods used for planning hybrid AC/DC power systems, as shown in Figure 21. A “Master platform” coordinates the overall process management. It implements the analysis workflow by managing the different analysis modules, suitably preparing their inputs and processing their outputs. The input consists of detailed models and data of the power system, R&R related information, and the predefined HVDC architectures to be analysed. Each architecture is individually assessed, assuming it is connected to the base power system model through the nodes specified by the architecture itself. The output of the platform consists of the list of detailed indicators computed for each analysed architecture. Indicators (KPIs) have been defined in WP2/WP3 [2]. In particular, ranked lists can be obtained by sorting the indicators.

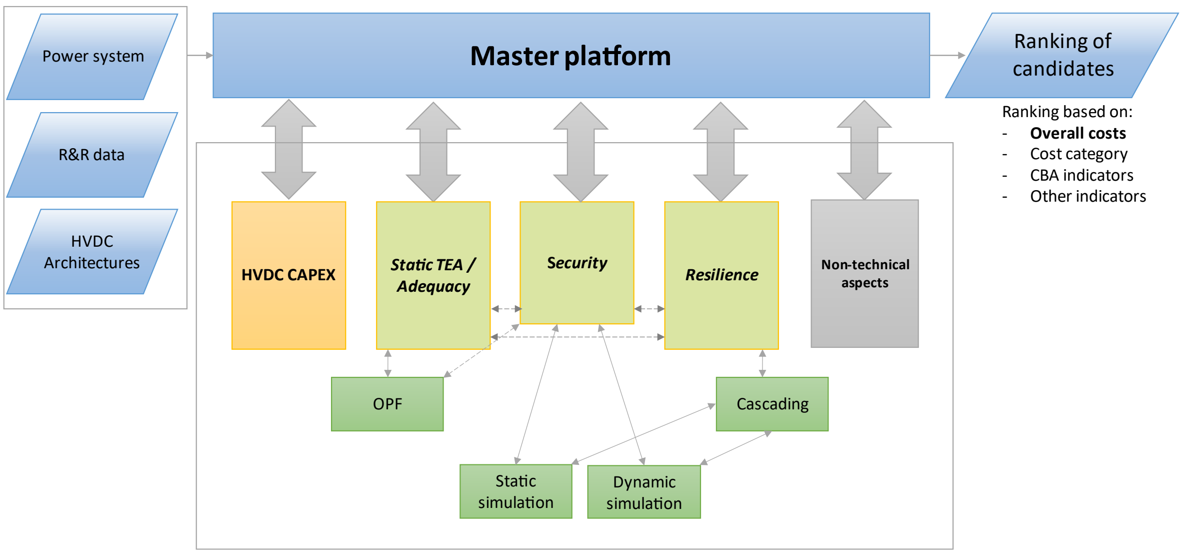


FIGURE 21: HIGH-LEVEL CONCEPTUAL ARCHITECTURE

The project aims to provide two major upgrades to conventional approaches and tools:

- the integrated view of different aspects of R&R
- the specific contribution of HVDC grids considered in each of the R&R aspects

Investment costs are a major component in CBA. The module “HVDC CAPEX” in Figure 21 is devoted to estimating the investment costs of the HVDC architecture, starting from the expected costs of individual equipment or systems, combined with the amount or extent of such equipment as required by the specific architecture under analysis.

Operating costs and other KPIs related to power system operation are assessed by three modules related to static techno-economic analysis (TEA) and adequacy, security, and resilience. A top-down approach has been proposed, where TEA/adequacy-oriented analyses are performed first, followed by security and resilience analyses for a subset of operating states.

The evaluation of adequacy and other techno-economic indices relies on static analyses performed by an Optimal Power Flow (OPF) routine. Security analyses are aimed at checking potential stability issues related to DC or AC faults, typically N-1. The resilience module provides for the evaluation of power system performance indices accounting for system degradation and service recovery in the case of extreme contingencies (N-k). Damage to the infrastructure and consequent loss of power supply to the users is considered, possibly resulting from common mode multiple contingencies followed by cascade tripping. A static security analysis can be performed prior to the dynamic security and resilience analyses, considering the expected steady state of control, protection, and defence systems following N-1 contingencies to make sure that the considered subset of operating states are N-1 secure from a static analysis viewpoint.

6.2 Tools overview

Although the methodologies developed by HVDC-WISE aim to be tool-independent, dedicated tools for the quantification of R&R indicators will be upgraded during the project to demonstrate the application of these methodologies. Most of these tools have been used by project partners in past projects; however, they must be upgraded to include the proposed HVDC-based grid architecture concepts and to be compatible with the standardized library of HVDC models.

Table 21 gives an overview of the simulation capabilities of the existing tools developed by project partners. In this table, with regard to economic analyses, “CAPEX” and “OPEX” stand for CAPital and OPerational EXpenditure, respectively. TEP stands for Transmission Expansion Planning. For environmental analysis “CO2” is related to carbon dioxide emissions, and “RES” stands for Renewable Energy Sources integration. Reliability aspects are handled by adequacy (“Adeq”) and security analysis (“Sec”). Finally, the resiliency aspects deal with static simulations (“Static”), dynamic simulations (“Dyn”) and so-called High Impact Low Probability (HILP) events.

The next sections give brief introductions to the existing tools. The interested reader is directed to Deliverable 5.1 of the HVDC-WISE project, which documents these tools in greater detail.

TABLE 21: CAPABILITIES BETWEEN CONSORTIUM TOOLS AND CBA

Tool (partner)	Optimisation (O)	Economic		Environmental		Reliability		Resilience		
	Simulation (S)	CAP	OPEX	CO2	RES	Adeq	Sec	Static	Dyn	HILP
OpTEA soft (SGI)	O (TEP of the DC grid)	✓	✓	(✓)*	✓	✓	✓			
FlexPlan (RSE)	O (TEP of AC grid + HVDC links)	✓	✓	✓	✓	✓				
AC-CFM (UCY)	S				✓		✓	✓		
D-CFM (UCY)	S				✓		✓		✓	
HY_ACDC_SIM2 (COMU)	S						✓		✓	
DPsim Tool (RWTH)	S						✓		✓	
Market-Grid Toolchain (RWTH)	O (OPF for congestion management)/S	✓	✓	✓	✓		✓	✓	✓	
RESILIENT (UCY)	O (OPF)/S		✓					✓		✓
RELIEF (RSE)	O/S				✓		✓	✓		✓
Eurostag/Smart flow (ENGIE)	S						✓	✓	✓	✓

*CO2 : This indicator needs CO2 emissions for each generator (or zone) and more development within the HVDC-WISE project. See Deliverable 5.1 for further details.

6.2.1 OpTEA soft Grid (SGI)

SHORT DESCRIPTION:

Unlike planning tools that seek to define a set of grid reinforcements from a generation/demand adequacy and integration of RES perspective, and unlike project assessment tools with the objective of ranking a set of reinforcement projects, the primary focus of OpTEA soft Grid is on providing a ranking of technological solutions. The tool tries to answer the following questions:

- How should a given project be built?
- What are the best architectures, topologies, technologies, components to build this project?

From a general point of view, the user could use OpTEA soft Grid for the following types of analyses:

- Comparison of the architectural principles of electrical networks with regard to techno-economic criteria or performance indicators
- Optimization of architectures with regard to techno-economic criteria or performance indicators
- Techno-economic and performance assessment of a DC network design

FUNCTIONALITIES:

The tool is developed in Python (an open-source language) and includes the following functionalities:

- Optimal Power Flow: considers line constraints (maximum/minimum current, maximum/minimum power, etc.), node constraints (maximum/minimum voltage, etc.), and a set of objective functions (maximum power flow, cost generation, etc.).
- TEA assessment: including CAPEX (for converters, cables, platforms, transformers, DCCBs etc.), losses (for cables, converters and transformers) and energy curtailment (Expected Energy Not Transmitted, EENT). This also considers the protection system assessment.
- Busbar topologies/design: performs a busbar topology design (single busbar, double busbar, one and half, etc.)

6.2.2 FlexPlan Tool (RSE)

SHORT DESCRIPTION:

The network expansion planning tool proposed as a starting point for modification and integration within HVDC-WISE is the tool developed within the FlexPlan European project [104]. The tool builds on open-source packages written in the Julia language, namely *PowerModels* [105] for static analysis of AC power grids and its expansion *PowerModelsACDC* [106] dealing with embedment of DC into AC grids. These two packages are called by the *FlexPlan package* [107], also written in Julia, in order to perform sequential and Monte Carlo simulation.

The tool selects the optimal grid expansion plan out of a set of candidates (“automatic” expansion planning) consisting of:

- AC lines (overhead/cable)
- DC lines (overhead/cable)
- Storage units
- Demand response resources

FUNCTIONALITIES:

The open-source tool aims to perform "automatic" expansion planning of large power systems as specified above. Moreover, it can accomplish Technical-Economic Analysis (TEA) of a given expansion configuration. This is the function that will be exploited in HVDC-WISE. FlexPlan already manages DC grids.

6.2.3 AC-CFM (UCY)

SHORT DESCRIPTION:

The AC Cascading Failure Model (AC-CFM) [108] is specifically designed for resilience analysis by integrating seamlessly into established resilience metric frameworks. It is stable for very large contingencies or extreme conditions by efficiently addressing convergence issues (e.g., power flow convergence which is dealt with in the tool using specifically designed techniques). The tool follows the approaches developed by the IEEE PES working group on cascading failures [109] and it is compared and cross-tested with other AC-based models, explicitly incorporating dynamic phenomena such as voltage and frequency protection mechanisms in a static representation (depending on values provided by the user, or alternatively automatically estimated by the tool). The tool is computationally faster than dynamic cascading models based on comparisons performed with reported tools in the literature.

FUNCTIONALITIES:

- Full AC cascading with protection mechanisms in a static way.
- Simulation and impact assessment of random events (e.g. windstorms).
- N-k security analysis, where k can be in the order of tens or hundreds of assets, still obtaining a feasible power flow solution.

6.2.4 D-CFM (UCY)

SHORT DESCRIPTION:

A dynamic cascading failure model (D-CFM) has been implemented in DIgSILENT PowerFactory via the Python API. It automatically develops cascading mechanisms, simulates sets of failure scenarios and processes results, and has good scalability, such that it can be easily applied to any power system model.

FUNCTIONALITIES:

- Implements automation mechanisms for cascading failure analysis, including model development of power system components, assembly of controllers and protection devices, creation and simulation of various network disturbances, and data visualization of obtained simulation results.
- It supplements the existing cascading failure models by providing the flexibility to rapidly develop power system models, batch modify system topology and component functions, and examine advanced remedial control measures in different networks.

6.2.5 HY_ACDC_SIM2 (COMU)

SHORT DESCRIPTION:

PSS/E is a widely used commercial simulation tool for the simulation and analysis of large power systems. In its current version, no model for multi-terminal VSC-HVDC systems (MTDC) is available in PSS/E and only a VSC-HVDC point-to-point model is offered. HY_ACDC_SIM2 is a PSS/E-oriented tool that models MTDC for power flow and dynamic simulations. The tool proposed has been validated against a detailed electromagnetic model in Matlab + Simulink + *SimPowerSystems*, which includes the switching of 3-level power converters, and compared to an existing model in *PowerFactory*.

With respect to modelling for power-flow analysis, each converter is connected to the AC grid and to the DC grid. The AC side is modelled by a voltage source coupled to the AC bus through a phase reactor, a capacitor and a transformer. The DC side of the converter is modelled by a current injection into the DC grid.

FUNCTIONALITIES:

- A PSS/E based dynamic model for MTDC systems, intended for electromechanical dynamic simulation, which covers time constants from 0.01 s to 10 s.
- Electromechanical models of a power system, which take into account the slow dynamics of synchronous machines, their controllers and other devices, where AC branches are assumed to be quasi-static.
- Models are split into converter models and the DC-grid models.

6.2.6 DPsim Tool (RWTH)

SHORT DESCRIPTION:

Most system-level (non-commercial) dynamic simulation tools do not consider electromagnetic dynamics when the primary goal is to increase the simulation speed and efficiently simulate power systems. Dynamic phasors (DP) enable the simulation of large-scale system dynamics in an efficient manner by reducing the high sampling rates of electromagnetic transient (EMT) simulations and using the frequency shift introduced by the DP approach to simulate the envelope of the signal instead of the instantaneous quantities. It can be seen as Intermediate between detailed time-domain EMT circuit representation and the quasi-static sinusoidal steady-state approximation [110]. This can have several advantages for co-simulation applications and large-scale scenarios [111], as well as power electronics simulation [112].

The tool [113] is capable of running detailed dynamic simulations on commercial off-the-shelf hardware without neglecting electromagnetic dynamics. It also enables larger simulation steps compared to EMT simulations by using dynamic phasors according to shifted frequency analysis.

FUNCTIONALITIES:

- Dynamic phasor, EMT, RMS, and powerflow solver library.
- C++ for high-performance simulation.
- Parallelization methods, e.g., for the computation of higher order harmonics to accurately represent switching power electronics.
- Python interface for simulation management and analysis.
- Distributed simulation via integration with VILLASframework.

- Fully open-source code.

6.2.7 Market-Grid Toolchain (RWTH)

SHORT DESCRIPTION:

This is a scenario generation and market simulation toolchain that can derive power plant dispatches, by considering exchange capacities, load and RES feed-in time series. Hybrid AC/DC power flow calculations and congestion management can be employed to avoid or remedy grid congestions. Afterwards, system stability analysis can be conducted using RMS time domain simulation for different event cases.

FUNCTIONALITIES:

- Based on future scenarios (load and RES feed-in time series), simulations of power plant dispatches in Europe considering increasing penetrations of renewable energies, exchange capacities, and different market coupling approaches (Flow-Based Market Coupling, NTC) can be conducted.
- Hybrid AC/DC power flow for each hour (DC point to point connection).
- Congestion management optimization to determine the redispatch and RES feed-in management to guarantee (N-1) secure grid operation.
- Plausibility checks regarding system stability, post redispatch, for different event cases (short circuit, generator outage, system split), with respect to grid-forming control of power electronic interfaced devices.

6.2.8 RESILIENT (UCY)

SHORT DESCRIPTION:

RESILIENT stands for Realistic Event Simulator for International Location-Independent Energy Network Testing. RESILIENT is being developed in the H2020 EUniversal project [114] and it is a fully flexible and modular simulation tool capable of spatio-temporal modelling of extreme weather across transmission and distribution networks. This is coupled with fragility-based models and multi-temporal/multi-spatial OPF models for capturing and quantifying the impact of the event on the network using different risk and resilience metrics.

6.2.9 Functionalities

- Automatic geographical projection of any power system to real coordinates.
- Spatial and temporal modelling of extreme weather, with existing focus in the tool on windstorms but it can be expanded to other events.
- Fragility-driven assessment of the event impact on power system assets (e.g., lines, towers/poles).
- Coupled with AC-OPF models for quantifying the spatial and temporal load shedding.

6.2.10 RELIEF (RSE)

SHORT DESCRIPTION:

RELIEF is a tool for resilience assessment and enhancement, which supports both **long-term planning** and **operational planning** analyses. It allows for probabilistic modelling of different types of threats, vulnerability of grid components to the same threats, as well as various countermeasures used for mitigation purposes.

Combining threat and vulnerability models allows for the identification of the components with the highest failure probabilities, as well as the multiple, dependent, contingencies affecting these components. The tool calculates risk and resilience indicators and provides useful information, such as indications of the grid portions where interventions are needed in long-term planning contexts, or anticipation of critical situations in operational planning contexts.

FUNCTIONALITIES:

- **Long-term:** Efficient **selection** of the set of the most representative multiple, dependent **contingencies**, accounting for the extension of past weather events; evaluation of contingency probability (applicable to planned lines as well); evaluation of **long-term resilience indicators**
- **Operational planning:** Anticipation of critical grid situations, by identification of both the components with the highest failure probabilities ("critical" components) and the riskiest **contingencies** based on weather forecasts; evaluation of **risk/resilience indicators**
- **Long term / Operational planning:** Quantification of the **benefits** brought to resilience metrics by **countermeasures** that mitigate the effects of different threats (e.g. anti-torsional devices and superhydrophobic coatings against wet snow, tower support hardening against wind and/or snow)
- Probabilistic modelling for a wide range of threats (wet snow, strong wind, floods, debris-flows, etc.)
- Probabilistic modelling of component vulnerability to threats
- Probabilistic modelling of the processes for the recovery of grid infrastructure and electric service considering weather forecasts and organizational uncertainties (in particular, for operational planning application)

6.2.11Eurostag/SmartFlow (ENGIE)

SHORT DESCRIPTION:

Eurostag is a dynamic power system simulator (RMS/phasor) developed by Tractebel Engineering capable of considering multi-terminal and meshed HVDC systems. It is coupled with the SmartFlow toolbox, comprising AC/DC power flow and Security Constrained OPF modules. Eurostag is already used for probabilistic security and resilience assessment, with the consideration of dynamic cascading outage phenomena (including the action of protection systems).

FUNCTIONALITIES:

- Power flow for hybrid AC/DC systems (PLAIRE module)
- Security Constrained Optimal power flow (OPF) for hybrid AC/DC systems (IPSO module)
- Dynamic simulations of hybrid AC/DC systems (Eurostag)
- Can run on high-performance computers for probabilistic risk assessments (e.g., using Monte Carlo simulation).

6.3 Opportunities for tool integration

Outlined in Table 22 are the technical analysis capabilities of the tools introduced in the previous section with respect to economic analysis, linear load flow, non-linear load flow, dynamic RMS analysis, EMT simulations, N-1 and N-k contingencies. It also shows to what extent each tool can handle AC or DC systems. The boxes in green highlight where opportunities have been identified within the HVDC-WISE project to integrate existing analysis capabilities between tools (e.g. in the top left entry, under OpTEA soft, the potential to combine OpTEA soft and Flexplan to allow integrated economic and AC analysis is highlighted).

WP5 will further investigate how the individual tools can be integrated to enable the implementation of the R&R methodologies that will be developed over the course of the project. Further details on the potential integration of the tools is outlined in Deliverable 5.1.

6.4 Research objectives for WP5

The research objectives that WP5 of the HVDC-WISE project will undertake to enhance the reliability and resilience of future hybrid AC/DC grids is outlined in the following:

- A methodology for the R&R-oriented planning of hybrid AC/DC power systems will be developed with a conceptual architecture of the tools involved in planning and operation of hybrid AC/DC power systems.
- The tools of the partners will be further developed and appropriately interfaced or integrated according to the conceptual architecture to implement the methodology.
- The analysis tools for the project will be upgraded with the latest VSC and HVDC models where relevant. The models considered will be in line with the technologies developed in WP4 and DC architectures developed in WP3. The underlying tools for security and resilience analysis need to combine and coordinate different solvers for the dynamic simulations given the arising fast dynamics in DC systems, which can be achieved by either simplifying detailed EMT models for large-scale phasor domain simulations or setting up a co-simulation environment.
- A range of simple test systems will be developed for testing R&R planning and operation tools, control and protections approaches, etc., across the project.

This research will be documented in greater detail over the course of the project through the WP5 deliverables.

TABLE 22: CAPABILITIES OF TOOLS AND OPPORTUNITIES FOR CROSS-TOOL INTEGRATION

		OpTEA soft	**FlexPlan**	**AC-CFM**	**D-CFM**	**HY_ACDC_SIM2**	**DPsim**	**Market-Grid Toolchain**	**RESILIENT**	**RELIEF**	**Eurostag/ Smartflow**
Economic analysis	**AC**	FlexPlan	✓	FlexPlan	FlexPlan	FlexPlan		✓	FlexPlan	FlexPlan	FlexPlan
	DC	✓	✓	FlexPlan	FlexPlan	FlexPlan, OpTEA soft		✓	FlexPlan, OpTEA soft	FlexPlan, OpTEA soft	FlexPlan
Linear load flow	**AC**	FlexPlan	✓				FlexPlan, Market-Grid toolchain	✓	✓		✓
	DC	✓	✓				FlexPlan, Market-Grid toolchain	✓	(✓)		✓
Non-linear load flow	**AC**	FlexPlan	✓	✓	✓	✓	✓	✓	✓	✓	✓
	DC	✓	✓	(✓)	(✓)	✓	FlexPlan, Market-Grid toolchain	✓	✓		✓
RMS-type dynamic analysis	**AC**		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain		✓	✓	✓	✓		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain	✓
	DC		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain		(✓)	(✓)	(✓)	(✓)		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain	✓
Dynamic phasor	**AC**		DPSim	DPSim	DPSim		✓				DPSim
	DC		DPSim	DPSim	DPSim		(✓)				DPSim
N-1		✓	(✓)	✓	✓	✓	D-CFM	✓	AC-CFM, D-CFM	✓	✓
N-k		✓	RELIEF, RESILIENT	✓ RELIEF, RESILIENT	✓ RELIEF, RESILIENT	D-CFM	D-CFM	D-CFM	AC-CFM, D-CFM	✓	✓

✓	CURRENT TOOL CAPABILITIES
(✓)	POTENTIAL TOOL CAPABILITY (FOR DEVELOPMENT IN PROJECT)
	TOOL INTEGRATION OPPORTUNITY

7 Codes and Standards

This section presents a preliminary review of current codes and standards relevant to the HVDC-WISE project. These will be considered more fully in a later project deliverable.

The European Network Codes are relevant technical rules for the harmonisation, integration and efficiency of the European electricity marked drafted by ENTSO-E and ACER. The most relevant are listed in Table 23.

TABLE 23: EUROPEAN NETWORK CODES

Connection	Demand Connection Code sets requirements for connecting large renewable energy production plants as well as demand response facilities
	HVDC-Connections sets requirements for long distance direct current (DC) connections
	Requirements for Generators is harmonising standards that generators must respect to connect to the grid
Operations	Emergency and Restoration fixes the processes that the transmission system operators must follow when they face a severe incident on their grid
	System Operations specifies what transmission system operators should do in managing their grid
Marked	Capacity Allocation & Congestion Management sets out the methods for calculating how much space market participants can use on cross border lines without endangering system security.
	Electricity Balancing is about creating a market where countries can share resources used by transmission system operators to ensure generation always equals demand.
	Forward Capacity Allocation deals with rules for long term markets
Cyber security	Network Code on Cybersecurity aims to set a European standard for the cyber security of cross-border electricity flows

7.1 Norway (Statnett)

Statnett SF is owned by the Norwegian State through the Ministry of Petroleum and Energy (MPE). The supervisory authority is the Norwegian Water Resources and Energy Directorate (NVE). Statnett owns all grid facilities and manages capacity in the transmission grid. In addition, Statnett owns some facilities outside the transmission grid. Statnett is also the transmission system operator (TSO) for the entire power system, which means Statnett is responsible for monitoring all interfaces with both the transmission grid and the regional grid. The TSO is also responsible for other aspects of the grid, such as frequency management, voltage regulation, protection and relay plans, functional requirements for systems and facilities, data collection, etc.

7.1.1 NVF and European network codes

The Norwegian grid codes are implemented in the Norwegian Law. For utility owners wishing to connect to the Norwegian power grid, the technical requirements are currently described in the supplementary document **Nasjonal veileder for funksjonskrav i kraftsystemet** (NVF), which is a guideline for all owners and developers who plan to:

a) install new electrical installations
b) perform changes to existing electrical installations

As per 2022, the European network codes are not implemented into Norwegian law. In the future, it may be relevant to make adjustments in the NVF related to European connection regulations, Requirements for Generators (NV-RfG), Demand Connection Code (NC-DCC) and High Voltage Direct Current Connections (NC-HVDC), when these are to be implemented in Norway.

The NVF describes the technical requirements for, but not limited to:

- Voltage and frequency tolerance
- Frequency dependent active power regulation
- Reactive power regulation
- Reactive power capability
- Fault ride through capability
- Fast fault current injection
- Design of flexibility/redundancy in substations

7.2 Denmark (Energinet)

In Denmark, the connection of HVDC facilities is subject to 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. This includes annexes on voltage quality, reactive power control and simulation models. There are no specific codes and standards addressing R&R.

https://en.energinet.dk/electricity/rules-and-regulations/regulations-for-new-facilities/

7.3 Germany (Amprion and TenneT)

The German transmission grid is divided in four parts, owned and operated by: Amprion, 50Hertz, Transnet BW and TenneT. The setting of national rules for technical grid aspects and grid operation is done by the technical regulator for power grids in Germany (VDE FNN). The drafted rules and applications are a formalisation of, or intended to complement, the European Network Codes. The Connection Conditions for Generation, Demand, Storage and Mixed Units are included in the TAR (technical connection rules). There are different rules for extra-high voltage (TAR HöS, VDE-AR-N 4130), high voltage (TAR HS, VDE-AR-N 4120), medium voltage (TAR MS, VDE-AR-N 4110), low voltage (TAR NS, VDE-AR-N 4100) and rules dedicated for HVDC-Systems (TAR HVDC, VDE-AR-N 4131).

7.3.1 Systematic expansion of the German transmission grid

Based on the planning principles for the expansion of the German transmission grid the four German TSOs take the European legislation into account and formulate a framework for changes to the power system. This includes a legal obligation to draft and publish a joint grid development plan (NEP) for long-term grid planning every two years. The approval of projects in the NEP is done by the Regulator (BNetzA). The inclusion of projects in a legal act (Bundesbedarfsplan) is done by the Federal Ministry for Economic Affairs and Climate Action in close cooperation with the BNetzA, which thereby obliges the TSOs to take actions for realizing the projects.

The prioritisation, coordination, and monitoring of the project realisation as well as adequacy analysis is done in a year-ahead planning process.

7.3.2 Integration of single plants into the grid

The VDE FNN is a committee within the central standardisation and norming organization VDE which provides the following for all topics related to energy infrastructure:

- VDE application rules
- Notes papers
    - The FNN Note offers manufacturers, operators, and planners in particular the opportunity to implement the expected amended requirements in the TARs in good time and to plan for these in connection with the certification of the installations.
- studies
- position papers

In the following the different steps to integrate Point to Point HVDC systems into the TenneT grid area is described:

VDE 4131

The VDE 4131 “Technical requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (TCR HVDC)” is the formalisation of the European network codes (e.g. NC HVDC) for Germany.

FNN Hinweis "Spannungseinprägendes Verhalten von HGÜ-Systemen und nichtsynchronen Erzeugungsanlagen mit Gleichstromanbindung"

In addition to the VDE 4131 this FNN note paper defines the voltage imprinting behaviour of HVDC systems and non-synchronous generation plants with DC connection.

Network Connection rules TenneT

To further clarify and confirm the process for connection requests the Network Connection rules TenneT takes the VDE application rules and FNN note papers into account.

Appendices to Network Connection rules TenneT

The appendices to the Network Connection rules TenneT describe in detail the procedure of studies to be conducted like Annex B.415 “Interaction study with nearby converters”.

7.4Great Britain (SSEN-T)

In the GB transmission system, the onshore network and embedded HVDC links are owned by several Transmission Owners (TOs) while connections to offshore wind farms are owned by Offshore Transmission Owners (OFTOs). The whole system is operated by a single Electricity System Operator (ESO), who also has responsibility for co-ordinated strategic planning.

Two documents, the Security & Quality of Supply Standard (SQSS) and Grid Code, form the basis of network design, planning and operation. The rules and standards in these two documents provide the basis for reliability and resilience (R&R) within the GB system, including HVDC. They are not explicitly probabilistic in nature but include deterministic rules and performance requirements that are founded on probabilistic analysis as well as impact analysis and cost benefit assessment.

The **Security & Quality of Supply Standard (SQSS)** is the main standard for design and operation of the National Electricity Transmission System (NETS).

https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standards

The SQSS sets the principles by which the reliability of the transmission system in response to secured event conditions is ensured. Secured events represent a range of deterministic conditions: N-1, N-D (double circuit), N’-1 (depleted condition), and N’-D. The SQSS also refers to less deterministic assumptions such as “conditions that might reasonably be foreseen” across a given period of operation, and “prevailing network” conditions of operation, which require additional cost-benefit assessment and risk assessed consideration in implementation. The SQSS covers the onshore and offshore transmission systems, requirements for new connections of generation and demand, transmission boundary capacity, and voltage and stability across the system. The SQSS is concerned mainly with reliability and does not explicitly define resilience requirements.

An area requiring further work is how to consider more co-ordinated offshore networks that combine offshore generation or demand connection with offshore transmission boundary capacity, arrangements which HVDC networks can clearly enable. Another area of limited requirement relates to the use of automatic systems in the operation and planning of such systems. Whilst automatic systems providing inter-tripping and other functions are not uncommon in the onshore system, including measures required to support stability, these are considered operational enhancements rather than measures that provide underlying transmission capacity. Within HVDC networks, automatic systems and their resilience are fundamental to the capacity and so require guidance in their reliability also.

There are always various modification proposals being discussed with current topics including offshore DC connections and a review of the criteria for frequency control that determine the reserve, response, and inertia services to be maintained on the GB system. A more comprehensive review of the SQSS will be undertaken over the next few years in the context of the industry shift towards net-zero carbon operation.

A recent supplement to the SQSS is the **Frequency Risk and Control Report (FRCR)**. This assesses the magnitude, duration and likelihood of transient frequency deviations given changing operating configurations and patterns on the network, including the growing influence of HVDC and how to treat multiple losses across the period of a frequency event.

https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standards/frequency-risk-control-report

The **Grid Code** details the technical requirements for connecting to and using the NETS. These define aspects of reliability required of users and what the TOs and ESO must present to those connecting to the system to achieve a reliable overall system.

https://www.nationalgrideso.com/industry-information/codes/grid-code

The Grid Code defines common technical performance obligations, including requirements like Fault Ride Through (FRT) and others very important to R&R. Resilience to multiple such events is an implicit rather than explicitly defined expectation covered within the broader obligations of the Code.

The frequency range defined in Grid Code is one example of where there is a requirement to withstand a short-term deviation to quite extreme values that overlaps with emergency action (in this case low frequency demand disconnection. Users are required to be able to operate in a range up to 52 Hz and down to 47.5 Hz while the normal operating range is expected to be within 0.2 Hz either side of 50 Hz. The overlapping of the required operating range with emergency measures helps to avoid "cliff-edges" in performance where support from a given device might be lost at the same time the ESO requires time to respond with emergency measures. These resilience aspects are very relevant to the future power system where the timeframes could be shorter and the losses of capability from sources of support more sudden.

The Grid Code refers to various other standards documents that apply to users, with some differences across GB depending on the TO in each area.

https://www.nationalgrideso.com/industry-information/codes/grid-code/electrical-standards-documents

The Grid Code undergoes constant change through the modifications process. A notable recent example is GC0141, which revises the compliance processes and modelling requirements in response to the significant disturbance events that occurred on 9th August 2019. This includes measures very relevant to R&R in future AC/DC systems including requirements for more EMT simulation and improved compliance processes, in-service monitoring, and verification. This was developed following various reviews of the events, including a report from the government's Energy Emergencies Executive Committee (E3C).

https://www.nationalgrideso.com/electricity-transmission/industry-information/codes/grid-code-old/modifications/gc0141-compliance-processes-and-modelling

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/855767/e3c-gb-power-disruption-9-august-2019-final-report.pdf

The E3C is a partnership between government, the regulator and industry that co-ordinates resilience planning across the energy industry. It ensures a joined-up approach to emergency response and recovery, identifying risks and processes to manage the impact of emergencies affecting the supply of gas or electricity. There are several key stakeholders in the energy sector that collaborate through the E3C forum and discuss the strategic drivers of future resilience, including:

- The UK Government (through the relevant departments responsible for energy)
- The industry regulator, the Office of Gas and Electricity Markets (Ofgem)
- The Electricity System Operator (ESO)
- Transmission Owners (TOs and OFTOs)
- Distribution Network Operators (DNOs)
- Generators and Suppliers
- Gas Distribution Networks Operators (GDNs)

Each stakeholder plays a key role in ensuring the security of the network and its resilience to ever evolving risk profiles. This is essential, given the interdependency between services and the reliance that other critical industries have on electricity supply.

Another recent Grid Code modification important to the development of R&R with HVDC is the specification of GB Grid Forming (GBGF) capability in GC0137. This has now been adopted and implemented in the Grid Code.

https://www.nationalgrideso.com/electricity-transmission/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required

It is notable that this modification tries to specify requirements based on grid forming devices remaining connected throughout a disturbance, including an extreme frequency event. It is intended that grid forming generators, or HVDC links, can continue to provide some frequency support after a given duration of responding to a rate of change of frequency (RoCoF) or low frequency event. This may necessitate slightly bigger converters and stored energy. It is an example of a resilience decision that can be made in a code.

GB remains subject to the Third Energy Package of European legislation that created a need for European Network Codes (ENC). Implementation activities in GB are ongoing but there has been harmonisation of the technical requirements in Grid Code and work on market mechanisms continues.

A wide range of policies and procedures across different parties will affect the overall R&R of the transmission system. The ESO uses various techniques and services to maintain security and quality of supply, which are constantly evolving and adapting to the challenges faced.

For example, within the Grid Code, Operating Code No. 6 (OC6) specifies the requirements for demand control. This places obligations on the DNOs to provide for reduction in demand in conditions of stress on the system. This includes automatic low frequency demand disconnection, which will be implemented through each of the DNOs having appropriate policies and procedures, and the necessary monitoring and automation in place on their networks.

The ultimate mitigation for a failure in R&R is to be able to restore the electricity system after a total or partial shutdown. The Grid Code imposes various obligations on users but ultimately it is the ESO's responsibility to ensure there are sufficient restoration services (formerly known as black start) available, which they procure through a rolling process of regional tenders according to a published strategy and procurement methodology.

https://www.nationalgrideso.com/industry-information/balancing-services/system-security-services/restoration-services

In 2021 the UK Government set out the need to strengthen the current regulatory framework by introducing a legally binding target for the restoration of electricity supplies in the event of a nationwide or partial power outage on the national electricity system. This is known as the Electricity System Restoration Standard (ESRS). This new ESRS requires the ESO to have sufficient capability and arrangements in place to restore 100% of GB's electricity demand within five days, with an interim target of 60% of regional demand to be restored within 24 hours. The ESO must ensure that everything is in place to comply with this standard by no later than 31st December 2026. To implement the new standard and meet the agreed deadline, the ESO is reviewing its restoration plans and expects to procure additional restoration services from traditional and non-traditional sources, likely to include HVDC interconnectors.

As part of the industry-wide effort to develop the transmission network, including making fullest use of new HVDC links, the ESO is leading an initiative called "Pathway to 2030 Holistic Network Design (HND)". It sets out a single, integrated design that supports the large-scale delivery of electricity generated from offshore wind, taking power to where it is needed across GB. The HND facilitates the connection of 23 GW wind, helping to deliver the Government's ambition for 50 GW connected offshore wind by 2030. This is a first step towards more centralised, strategic network planning that is seen as critical for delivering affordable, clean, and secure power.

https://www.nationalgrideso.com/electricity-transmission/future-energy/the-pathway-2030-holistic-network-design

The TOs and ESO in GB operate under the terms of a licence granted to them by the government through the industry regulator, Ofgem. The licence imposes conditions on the companies covering a wide range of issues. There is a standard set of conditions then each company may have special conditions applied for specific reasons. Standard condition C17 is concerned with transmission system security and quality of service. This includes a requirement to produce a report each year providing details of system availability, security, and service quality of the NETS. System performance reports are collated and published by the ESO. This includes information on the performance of HVDC interconnectors and offshore systems.

https://www.nationalgrideso.com/industry-information/industry-data-and-reports/system-performance-reports

The regulatory framework in GB requires each of the TSOs to produce a business plan for the next upcoming price control period. The most recent set of plans were produced for the so-called "RIIO-T2" period running from April 2021 to March 2026. These plans set out each company's goals for the regulatory period, including what plans they have regarding reliability and resilience. For example, Scottish Hydro Electric Transmission (SHET) has "Aim for 100% transmission network reliability for homes and businesses" as one of its five primary goals for 2021-26.

https://www.ssen-transmission.co.uk/information-centre/riio-t2-plan-and-uncertainty-mechanisms/

The SHET plan refers to the UK Cabinet Office definition of Resilience:

"Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event."

It then describes how building resilience reduces vulnerability to natural and man-made threats, and sets out actions in four areas (quoted directly from the SHET plan):

1. ***Reliability**: the design and operation of the network. To enable our transition to risk-based operations, we will establish new network control facilities, including the capability to collect and analyse real time information from remote monitoring equipment on critical assets.*
2. ***Redundancy**: the availability of back-ups or spare capacity. We intend to establish two specialist warehouse facilities to securely and safely store spares for critical assets.*
3. ***Resistance**: pre-emptive protection from hazards. A range of measures are required to improve physical security at substations and of overhead lines, to upgrade protection and control and communications systems, and protect against natural and environmental events such as flooding and landslides.*
4. ***Response and Recovery**: able to respond effectively to disruptive events. Our business continuity planning, coordinated with Government and national services, requires us to extend the duration for which our substations can operate without mains electricity.*

The other GB TSOs have similar plans, with reference to UK government guidance and noting the threats and opportunities due to issues like climate change and digitalisation.

8 Conclusions and Next Steps

Work Package 2 of the project is concerned with identifying requirements, opportunities, and demonstration needs for R&R in future AC/DC systems. This report presents the outcomes of our work in the first six months on:

- TSO expectations for R&R with the deployment of HVDC solutions within their networks
- Identifying opportunities, risks and barriers for HVDC in delivering R&R benefits
- Initial views on codes, standards and regulatory framework issues

Following a review of power system reliability and resilience definitions, we conclude that the project shall build on the outcomes of CIGRE Working Group C4.47, which defines power system resilience as the "ability to limit the extent, severity, and duration of system degradation following an extreme event". The definition is in terms of system outcomes rather than in relation to the nature of the initiating disturbance, so any event that has an adverse impact, beyond specified performance targets, on system performance, component integrity, operational capabilities and unsupplied customers is defined as an "extreme event".

Based on the perspectives of the five TSOs in the project consortium, supplemented by input from all project partners, this report provides a high-level guide to what the TSOs need addressed and where improvements are required in HVDC grid architectures, technologies, and associated functionality. Key issues identified 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.
- 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.
- Multiple issues relating to system stability and power quality in hybrid AC/DC systems must be addressed.
- 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.
- Dependence on digital information for the functioning of the entire system is increasing, which raises concerns around cyber resiliency.
- It is important that new tools are made ready for proper use by TSOs, with appropriate training and ongoing support.

Events and disturbances of interest in hybrid AC/DC system design are discussed. Root causes include routine faults and operational conditions, natural events like extreme weather, and physical or cyber attacks. It is noted that very complex combined AC and DC systems may react inappropriately to even minor disturbances and the growing influence of HVDC means the risks associated with unforeseen or adverse behaviour is a significant threat. TSOs highlight energy dissipation in offshore hubs and wide-area system splits as being of interest, noting also the importance of understanding the role that HVDC schemes can play in system restoration in future hybrid AC/DC systems.

We present a topology analysis framework developed in WP3 and use it as part of a survey of existing and planned HVDC projects. A review of trends shows the increase in voltages and power rating and the emergence of common designs, with 525 kV VSC bipoles being the technology likely to be deployed most widely in Europe the next 5-10 years. The topology analysis framework is used to conduct an initial review of R&R-related opportunities, risks and barriers for different HVDC topologies and the control and protection functions of greatest interest.

We list the HVDC technologies subject to preliminary investigation in WP4 and summarise the work done in WP5 on reviewing existing methods and tools. This report presents an initial review of codes and standards across the TSOs involved in this project.

The next phase of work for WP2 will see further collaboration with the other work packages to translate the high-level requirements presented in this report into more specific success criteria and characteristics of the three use cases to be studied later in the project. This will be reported in an updated version of Deliverable 2.2 due in September 2023. The review of codes and standards will be progressed and recommendations reported in Deliverable 2.3, also in September 2023.

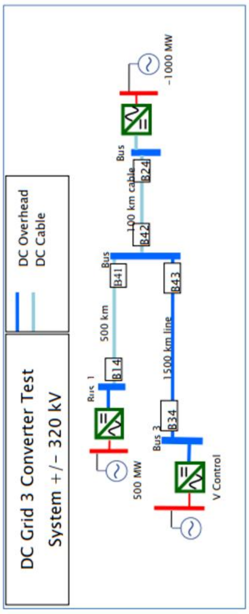
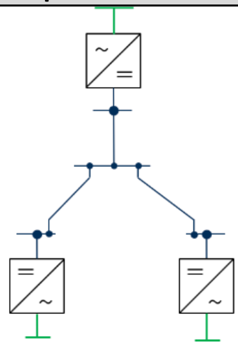
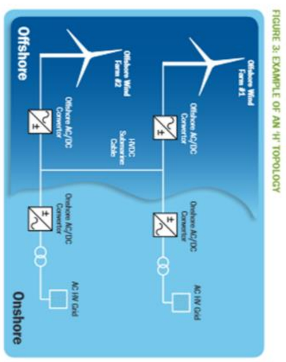
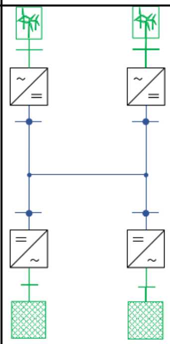
This report and the ongoing work in WP2 will support the research underway across the project. The research objectives for WP3, WP4 and WP5 are summarised in chapters 4, 5 and 6 respectively. Together, these will provide the basis for for WP6 and WP7 to assess the performance of different HVDC architectures and technologies in the three project use cases.

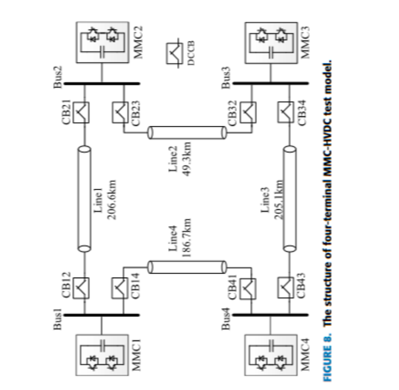
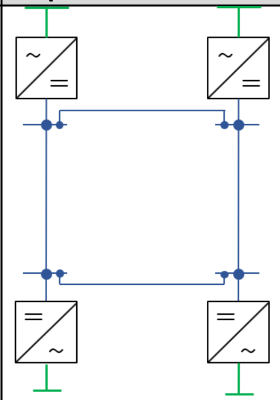
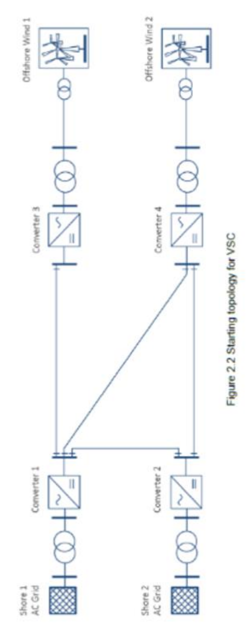
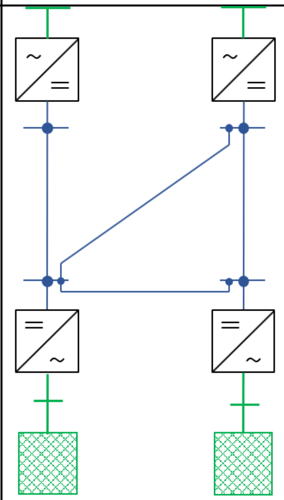
Appendices

1. Topology analysis framework examples

A range of examples are presented to illustrate how various grid topologies, from the literature and from existing or planned grids, fit within the topology analysis framework that has been developed in WP3 and is described in section 4.1 of this report.

1.1 DC architectures within AC1 framework

Source	Original	Simplified	DC 1-4
Cigre 739			DC2
TWENTIES "H" Grid			DC3

Source	Original	Simplified	DC 1-4
S. Teng, Z. Zhang and L. Xiao, "Research on a Novel DC Circuit Breaker Based on Artificial Current Zero-Crossing," in *IEEE Access*, vol. 8, pp. 36070-36079, 2020			DC3 Ring
PROMOTION "minimal Mesh"			DC4

1.2 DC architectures within AC2 framework

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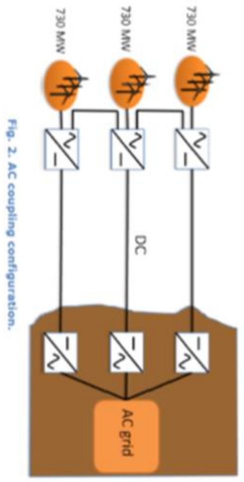
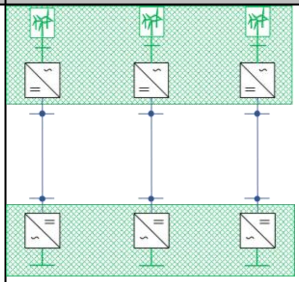
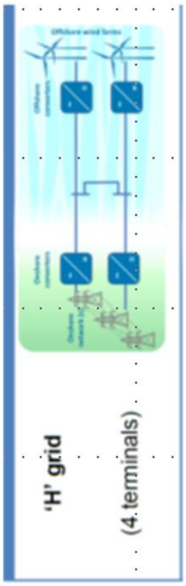
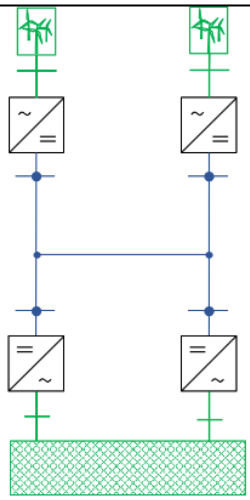
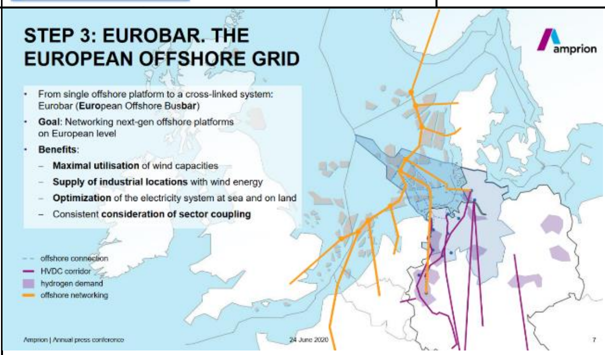
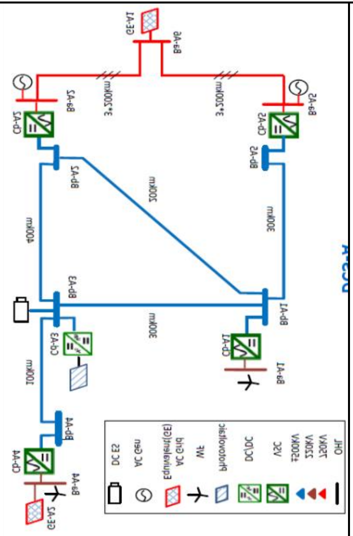
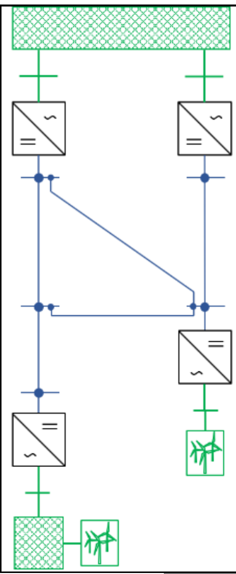
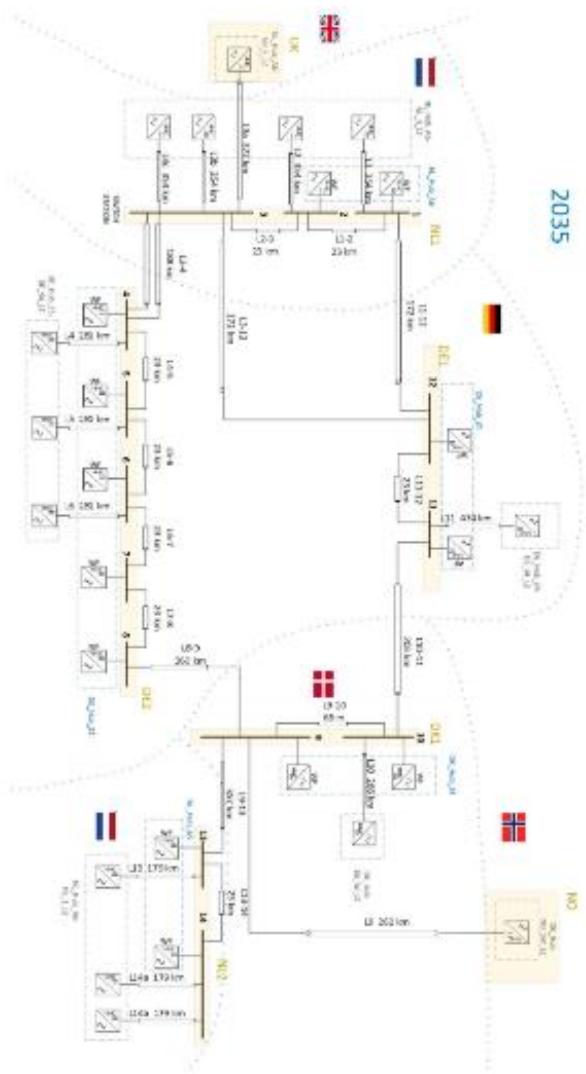
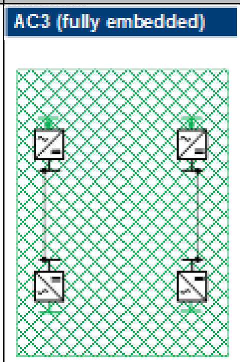
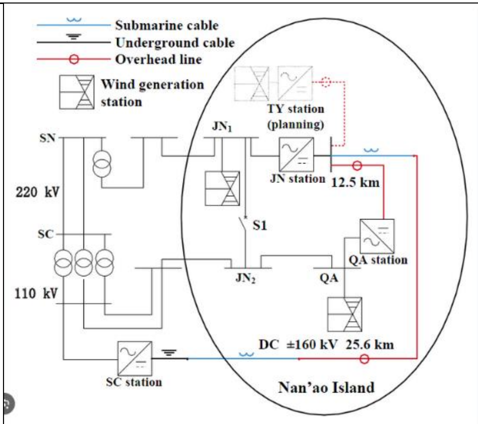
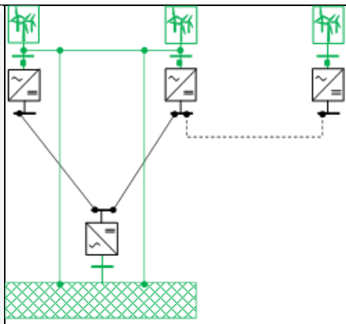
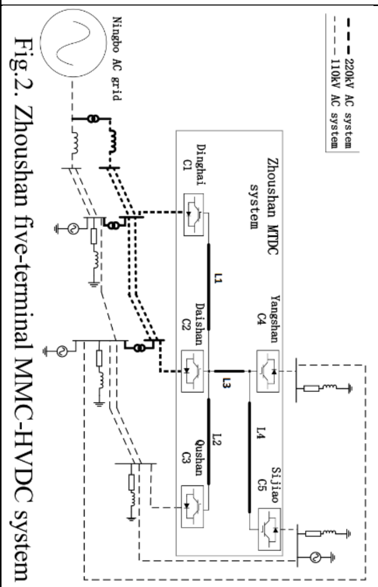
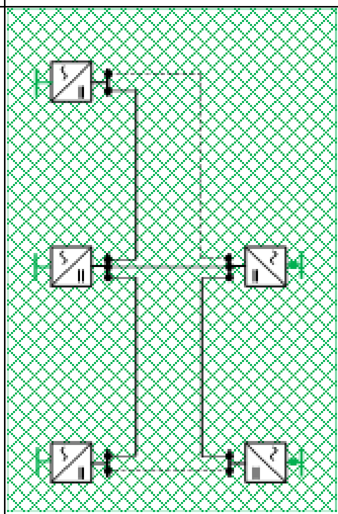
Best Paths project			DC1
TWENTIES EU project "H" Grid			DC3
Eurobar *"We aim to design a collective, modular and flexible approach to evolve projects based on current regulation, like point-to-point connections interlinked in an European offshore grid – a "busbar-like system"*." From https://eurobar.org https://www.amprion.net/Bilder/Netzjournal/2020/Eurobar/Eurobar_Handout_final_EN.pdf			DC3

Cigre 804 BM1	 	DC4
NSWPH See for instance https://northseawindpowerhub.eu/sites/northseawindpowerhub.eu/files/media/document/NSWPH-VTR_3636_SoW%20A%20Final%20Feasibility%20Report-Rev05.pdf		DC4

1.3 DC architectures within AC3 framework

Source	**Original**	**Simplified**	**DC 1-4**
German Network Development plan, etc., e.g. • SuedLink • SuedOstLink • Ultranet	Several included in Appendix 3 list of existing and planned HVDC systems	 	DC1
No architectures found in AC3-DC2 form			DC2
Nan'Ao [Link1]() [Link2]()	 		DC3
Zhousan 5 terminal embedded MTDC network, China, https://orca.cardiff.ac.uk/id/eprint/91726/1/07339929.pdf (note DC3 now, future DC4)	 Fig.2. Zhoushan five-terminal MMC-HVDC system		DC4

2. Weather events that impact power grid operation

The following provides descriptions of some examples of severe weather and other environmental events affecting power system infrastructure that led to power outages. These cases are relevant to highligh how weather events impact power system resilience.

2.1 Snow, ice

Cortina d'Ampezzo (Italy), 2013

About 60,000 users lost power supply in the Cortina d'Ampezzo (Italy) area between the 24th and 26th of December 2013. The event was caused by the combination of wet and heavy snow, which caused the formation of sleeves on the line conductors and the fall of numerous trees on the high and medium voltage lines. The trees fell from the weight of the snow and from the fact that the ground was not yet fully frozen (on the contrary, frozen ground would have held the roots more firmly).

FIGURE 22: CORTINA EVENT WITH ICE SLEEVES ON THE CONDUCTORS

Emilia Romagna and Lombardy (Italy), 2015

On the 6th February 2015, intense and widespread snowfall caused significant electricity outages across the Emilia Romagna and Lombardy regions in Italy. Numerous power lines experienced the formation of snow sleeves resulting in broken conductors and structural damage to the supports.

Due to these outages, the energy not supplied to users was estimated at almost 990 MWh. This single event was responsible for 20% of the energy not served in 2015. The refunds paid, as a result of a discontinuation of service for more than 8 hours, involved approximately 100,000 users in Lombardy and 250,000 in Emilia Romagna and have been quantified in the order of 33 million euros, excluding structural damage to the network and restoration costs.

Northern Ireland, 2010

The Northern Ireland system was severely affected by heavy ice storms in the period March 29th to March 31st, 2010 [115]. This resulted in faults in both the transmission and distribution systems. Weather conditions significantly damaged 125 km of overhead lines, with around 138,000 customers experiencing a loss of power supply.

From approximately 19:00 on the 30th of March until 12:00 on the 31st of March, the system experienced over 100 voltage dips due to faults. Voltage dips prevented the return to service of generators and caused the unavailability of open cycle gas turbines.

85% of all pole damage was associated with conductor damage. This was primarily due to conductors experiencing stressed loading beyond the design limits, resulting from effects of the storm winds and wet snow accretion, causing the pole support and conductor to break.

The transmission network experienced an unprecedented number of faults, with 139 circuit trips in 15 hours, with 400 circuit breaker trip operations. The accumulation of wet snow was worst on conductors running east-west, which were perpendicular to the prevailing wind.

2.2 Pollution

Sardinia, 2001

On the 21st and 22nd of September 2001, a blackout occurred in the southern part of Sardinia, caused by saline pollution on the insulators, which resulted in many transmission lines going out of service.

The original causes of the out of service condition are to be attributed to exceptional negative atmospheric events, both due to the vastness of the area concerned and to the concurrence of a series of particularly acute adverse factors, despite these conditions being typical on the island, i.e. salt pollution, the humidity and strong winds. For several days, after about two weeks of mistral wind, during the night, and with an absence of wind, there was a high level of humidity which caused frequent trips to the high voltage lines due to surface charges on the insulators.

The extent of the blackout was due to a negative sequence of events that affected regional transmission and distribution lines, the HVDC SACOI (Sardinia–Corsica–Italy) connection used for power importation, and some production plants located in the north and south of the island.

Power supply was restored to most users within 8 hours, and to all users within 9 hours from the commencement of the blackout.

2.3 Wind storms

France and Spain, 2009

With wind speeds of up to 183 km/h, storm Klaus hit a large area on the border between France and Spain on 24 January 2009 [116] [117]. The consequences on the transmission network were enormous: 69 lines affected, with 35 supports knocked down (20 concrete poles and 15 pylons, of which 30 collapsed due to falling trees) and 141 supports compromised (119 concrete poles, 22 lattice towers; 134 were damaged by falling trees). 99% of the damage involved the high voltage grid. 88% of the damage was to lines on concrete piles over tree-covered areas with wind speeds exceeding 140 km/h. The impact on the French transmission system consisted of:

- a weakening of the south-west area. In particular, in the Toulouse area, several 400 kV lines were tripped and the transmission network operator limited the power of the Golfech nuclear power plant to avoid stability problems. Approximately 300 MW of load was disconnected in the Perpignan area for 7 hours and the load was restored using the interconnection with Spain through the Baixas-Figueres line.
- the shutdown of 115 substations (including one at 400 kV and two at 225 kV) and 116 overhead lines (of which 6 at 400 kV and 10 at 225 kV). The outages caused a total load loss of 800 MW, the loss of 100 MW of generation in distribution networks, and a total unsupplied energy of 10.1 GWh.

On the Spanish transmission system, the storm caused the collapse of 25 pylons, of which 17 belonged to the 400 kV grid and 8 to the 220 kV grid.

The restoration process, divided into three phases (re-energization and recovery of the connection of all substations, restoration of the safety of the overhead lines, final repairs) lasted about three months.

Portugal, 2009

Two storms struck Portugal [118] between 2 and 4 am on 23rd December 2009. The first storm affected Algarve area at 2:38 am and the secondaffected the area North of Lisbon at 4:34 am and 4:48 am. The storm in the Algarve area caused damage to 5 pylons of one 150 kV double circuit line, and to 9 pylons of one 400 kV double circuit line under construction. The second storm in the area of North of Lisbon caused damage to 2 pylons of one 220 kV single line, 6 pylons of one 220 kV double circuit line, and of 6 pylons of one single 400 kV line.

REN pylons are designed to withstand 150 km/h winds, but during the storm wind gusts of 190 km/h were measured. In 60 years this was the first time that pylons failed due to wind (except one mini-tornado affecting two pylons only). Some older pylons failed at the foundations.

The main consequences on power system secure operation are:

- The double axis running from North to South was affected, creating generation profile distortions
- The 7-line corridor north of Lisbon was reduced to 3 lines
- In Algarve, at peak time, sometimes local gas turbines were needed to ensure N-1 security
- To ensure grid security in Lisbon and in eastern Algarve it was necessary to re-dispatch, by replacing cheap hydro in the north with expensive thermal in the south:
    - 2.9 M€ in 2009
    - 9.5 M€ in 2010

Also, the distribution network at 60 kV lost some pylons: around 350,000 customers mainly located in Center West region were affected. The service restoration period lasted 132 hours.

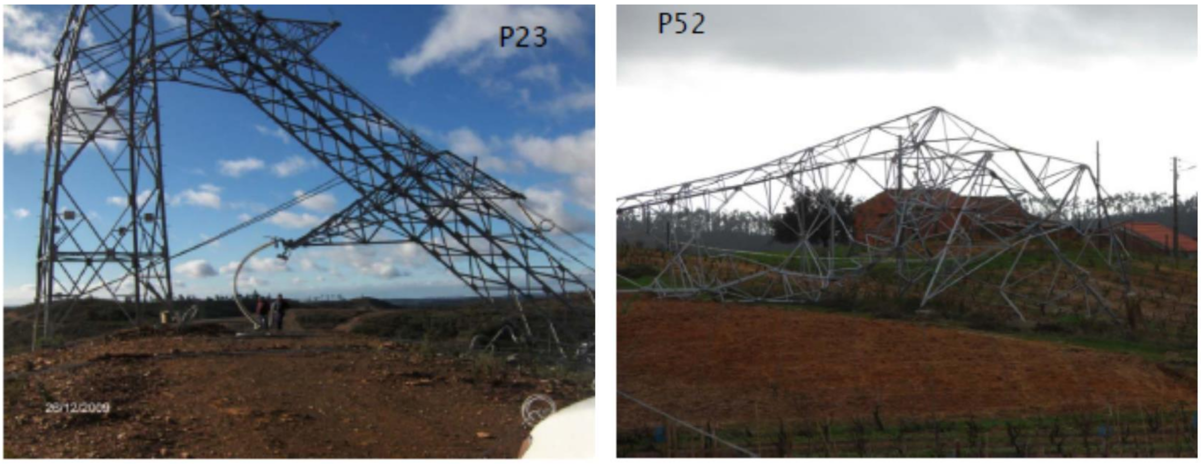


FIGURE 23: COLLAPSED TOWERS IN DECEMBER 2009 STORM IN PORTUGAL [118]

2.4 Heat waves

Australia, 2009

From 27th January to 8th February 2009, South Eastern Australia experienced an unprecedented heat wave [119]:

- For the first time in recorded history Melbourne experienced 3 consecutive days with maximum temperatures in excess of 43 °C – representing a 1 in 100 year condition.
- Adelaide equalled its 1908 record with 6 consecutive days with maximum temperature in excess of 40 °C – representing a 1 in 50 year condition.
- Northern Tasmania recorded its highest ever maximum temperature of 40.4 °C breaking the previous record by 3.1 °C – representing a 1 in 100 year condition.

These most extreme temperatures occurred on 29th and 30th January 2009 and had a number of impacts on the electricity supply demand balance:

- Unprecedented temperatures in Tasmania reduced the capacity of the Basslink DC cable between Tasmania and Victoria from 600 MW to zero.
- Total potential demand in Victoria and South Australia was above the expected 1 in 10 year peak demand used for reliability planning (14.0 GW vs 13.9 GW).
- The available capacity of generating plant was considerably less than the value assumed for reliability planning (12.7 GW vs 13.5 GW).
- This meant that instead of reserve for Victoria and South Australia of about 500 MW as expected under the reserve planning process (1 in 10 year peak conditions) there was a shortfall in supply of about 400 MW on these days.
- Load shedding was thus required across Victoria and South Australia for about 5 hours over the afternoon load peak on both 29 and 30 January 2009.

The transmission system experienced several physical failures and service outages:

- On 30 January whilst load shedding was taking place there was an explosive failure of a 500 kV line capacitor voltage transformer (CVT) in western Victoria.
- The loss of the line did not cause a problem at that stage and the power flows were rearranged to ensure that the system was secure for the loss of the next line.
- However, unknown to the operators, the explosive failure had damaged the CVT in the adjacent bay causing the failure of a second 500 kV line about 4 hours later. To then secure the system against the loss of a further line it was necessary to shed about 1,000 MW of load for about 6 hours.

Extreme weather conditions continued for the following week but these were not as severe as on the 29th and 30th of January. On 7th February the temperatures rose again in Victoria and South Australia accompanied by very low humidity with maximum temperatures exceeding 48 °C in some areas. In one case the maximum temperature was the highest ever recorded in such southern latitudes. Areas of Victoria were very dry, with Melbourne experiencing its second longest recorded period without rain (35 days), resulting in the driest ever beginning to a year on record. These presented ideal bush fire conditions.

On Saturday 7th February there were severe bushfires throughout Victoria leading to widespread loss of life and property. In the case of the transmission network, it experienced the loss of three 220 kV lines, two 330 kV lines, and one 500 kV line.

The loss of these circuits resulted in the separation of the network into two electrical islands for about 1 hour. As the events occurred over a weekend there was no significant loss of load. However, if the events had occurred on a weekday the impact could have been very severe (over 1500 MW of load shedding).

Under extreme high temperature conditions, reductions in supply capacity can be a bigger issue than increased demand.

- Reserve planning based upon 1 in 10 year conditions cannot guarantee reliable operation in very extreme conditions –1 in 20 year conditions are now also being considered.
- There is the possible risk that extreme ambient temperatures may lead to simultaneous transmission plant failures – though subsequent review and specific type tests did not identify this as an issue in this case.

2.5 Floods

Romania, 2005

During 2005 exceptional weather conditions occurred and affected the centre and east of Romania and a great part of the power distribution network, from April to September in successive waves.

The massive quantities of rain with storms and high intensity lightning were followed by floods, and a 20-30 times increase in the average water flow on rivers. These climatic challenges significantly affected the power network's normal operation. Some of the 110 kV overhead line pylons fell into the riverbed and a great number of power substations (also at medium and low voltage levels) were damaged. In the abovementioned period, two 110/20 kV substations and 750 MV/LV power substations and about 72,000 MV and LV line pylons were damaged.

FIGURE 24: 110 KV PYLON COLLAPSE DUE TO RIVERBANK EROSION IN 2005 ROMANIAN FLOOD

3. Survey of Existing and Planned DC Grids

Please see the accompanying spreadsheet file for full details of the survey, available [48].

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