READY4DC

# Deliverable D3.2: Multi-vendor Interoperability Process and Demonstration Definition

## ABOUT READY4DC

The future electricity network envisioned by READY4DC will be characterized by a growing role of multi-terminal multi-vendor (MTMV) HVDC solutions within the current AC transmission networks both onshore and offshore. READY4DC is contributing to this synergistic process by enabling commonly agreed definitions of interoperable modelling tools, model sharing platforms, clear processes for ensuring interoperability, and an appropriate legal and political framework.

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The views and opinions expressed in this article are those of the authors and the WG3 members, and do not necessarily reflect the official policy or position of specific project partners, nor that of the European Union.

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# Deliverable D3.2: WP3 – Multi-vendor Interoperability Process and Demonstration Definition

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**AUTHORS:**

Nico Klötzl, Engineer, TenneT TSO GmbH
Johannes Welsch, Engineer, TenneT TSO GmbH
Daniel Stenzel, Engineer, TenneT TSO GmbH
Michael Baranski, Engineer, Amprion GmbH
Benjamin Marshall, Technology Manager, National HVDC Center, SSEN-Transmission

**REVIEWERS:**

Andrea  Urbanelli, Head of Central South Planning Area, Terna
Christian Wikström, R&D Project Manager, Hitachi Energy
Dimitar Kolichev, Adviser, T&D Europe
Denise Giubilato, Engineer, Terna
Eoin Hodge, Supernode Energy
Ervin Spahic, Grid Planning Manager, WindGrid, Elia Group
Holger Schuldt, Technical project manager R&D, Siemens Energy Global GmbH & Co. KG
Idun Deildokk Vetvik, Project Engineer, Statnett
Ivan Soløst, Project Engineer HVDC&FACTS, Statnett
John Moore, Project Manager, SuperGrid Institute
John Ging, Head of Interconnection, EirGrid
Knut Styve Hornnes, Section manager, Statnett SF
Laurids Dall, Senior Engineer, Energinet
Li Zou, GE Renewable Energy
Maria Kotofolou, Manager - Offshore System Integration, WindEurope
Paulius Butkus, Grupės plėtros ir inovacijų vadovas, EPSOG
Philipp Ruffing, Amprion GmbH
Piotr Rzepka, PSE
Sebastian Bille Sørensen, Senior Engineer, Energinet
Sebastien Silvant, Project Coordinator, SuperGrid Institute
Simon Wenig, Managing Director and Senior Consultant, Mosaic Grid Solutions GmbH
Tankut Yalcinöz, TenneT TSO GmbH
Temistocle Baffa Scirocco, Head of Power System Development, Terna
Wilhelm Winter, Lead Electrical System Design, TenneT TSO GmbH
Yin Sun, Sr. Electrical Engineer, Shell Global Solution International B.V.

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# EXECUTIVE SUMMARY

This paper outlines the joint perspectives of stakeholders across industry, research and academia. It first addresses the selection criteria and the demonstration proposal of the first multi-terminal, multi-vendor (MTMV) demonstrator. Also, a generalized approach to achieve functional specifications beyond the first demonstrator is proposed. Moreover, this paper suggests the steps required for the implementation of the first MTMV demonstrator. This includes the sharing of roles and responsibilities. Finally, a roadmap towards largescale MTMV HVDC networks is presented by different options which could be followed after.

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***MTMV HVDC is considered as an opportunity of introducing extended functionalities - compared to current P2P systems - which further enables large scale wind integration from offshore and the interconnection between/within synchronous areas.***

***First:*** ***To achieve MTMV it requires a common technically realizable vision across all relevant stakeholders. This vision requests a shared objective by TSOs and the support of HVDC vendors, consultants and third parties to review the objectives. Overall effort for strong collaboration across stakeholders to overcome the technical hurdles is needed.***

***Next:*** ***The core requirement to achieve MTMV is to demonstrate it. Several options exist for that. It is seen as necessary to take a step by step approach by 1.) Setting up MT systems 2.) Gain experience by operation 3.) Introducing MV***

***Finally:*** ***MTMV is established by clear technical requirements, agreed planning standards and responsibilities across stakeholders.***

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Within the **definition of selection criteria for the first MTMV demonstrator section 4.2** considers two concepts available within the framework of this project. For both concepts the planned MT projects are collected.

The first concept uses basic criteria for a preselection of the planned MT projects. Resulting options are to be converted to type of projects. In a next step more detailed needs will reduce them to a set of most probable type of projects. This approach is straightforward but could in the preselection phase already disregard the needs of stakeholders and exclude promising projects from the beginning.

The second approach defines the selection criteria in a functional way from high level to detailed with a.) Soft criteria and b.) Functional requirements. So, the needs of all stakeholders can be considered. Additionally, the design impact of the solutions to each functional requirement ensures a thoughtful procedure. Table 0-1 shows exemplarily for two functional requirements the recommendations regarding the design impacts.

**Table 0-1**

Selection criteria for the first MTMV demonstrator

| Functional requirement | Design impact | Recommendations |
|---|---|---|
| Compliance to system operations guideline | DC fault protection | > Introduction of DC-FSD<br>> Enable connection of new terminals |
| | DC control | > minimising dependencies on communication<br>> behaviour is predictable |
| Fulfilment of transmission request | DC voltage options | > 320kV or 525kV<br>> DC control easier with one voltage level |
| | Selection of active power per converter station | > TRL level for 2GW considered market ready<br>> No specific power rating recommended<br>> For verification purposes minimum active power rating of some hundreds MW |
| ... Further requirements ... | … | … |

After having defined the selection criteria the aim is to indicate a **demonstration proposal in section 0**. Though this can be straightforward, the lack of TSOs providing possible MTMV projects leads to the issue of having only three proposed projects, namely: Bornholm Energy Island, North Sea Energy Island and Project Aquilla. Also, a generic MTMV system was proposed. So, a selection of projects is not needed as the goal is to recommend a list of up to three potential candidate projects.

Further this document provides a generalized **procedure for selecting functional specifications for MTMV in section 0**. The initial approach to obtain functional specification for MTMV is based on generic use cases a.) multi-infeed HVDC system with single AC grid b.) Multi-infeed HVDC system with multiple AC grids. The aim is to derive the functional needs of these basic use cases. Despite reducing the complexity by this approach, prioritizing certain criteria can't be conducted objectively. It rather follows the prioritized needs of each stakeholder.

Therefore, a second approach is to apply adjustments to the basic generic use cases with the information out of TSOs planned real-life projects. This results in most probable types of MTMV demonstration projects. Their functional needs are then translated into mandatory & non-mandatory specifications for MTMV. If these specifications are not part of available standards, they need to be tested (offline or real time) to show practicability. This approach is strongly dependent on detailed information from the TSOs which may not be available in early planning stages of a project.

The focus of **chapter 5** is to provide **key milestones** which are needed **for the implementation of the first MTMV demonstrator**. The first steps comprise 1.) the clarification of key roles 2.) the setup of a legal and regulatory framework which includes the alignment of different system operation guidelines and the proposal of a MTMV demonstrator project as project of common interest (PCI) in the TYNDP/grid development plans 3.) a standard language for MTMV projects: Herein interface definitions are proposed with regard to model sharing and grid/station level control 4.) the need for system adequacy studies to ensure optimal placement of the demonstrator.

The following steps are focused on the planning & development of a MTMV system. At first, basic MT functional requirements are to be collected and converted into a basic MT specification. Herein, recommendations from chapter 4 may be used. In the following, a conceptual MTMV system design will be provided by the TSOs as a first draft. Vendors are supposed to review the proposal and - by iterative refinement - a coordinated result is being achieved. This results in basic MTMV functional requirements and specifications. After that, a prequalification of vendors can be conducted. This includes the task if vendors can fulfil MTMV interoperability based on the defined functional specifications. It might also lead to iterative adjustments of the specifications so that in the end detailed MTMV functional specifications are obtained. The detailed specifications might include aspects like energization/shut down, protection concepts, coordinated control, operating requirements, etc. The following tendering procedure will reveal if offers are available to enable MTMV interoperability. If not, modifications within the previous steps are needed otherwise a procurement procedure can be initiated.

The next development steps suggest how to come from a conceptual to a project specific MTMV system design. Herein, the C&P development is of special interest which will be verified by integration tests. The functional and dynamic performance will be demonstrated by offline, SIL and HIL system testing.

The final steps towards a MTMV demonstrator contain aspects from the construction till the end of lifecycle. Especially during commissioning sufficient training for operators is needed to get familiar with the amount of complexity within MT systems. A possible further point of consideration are expansions of the existing system with regards to a.) possible new functions and software upgrades b.) novel technologies such as fault separation devices and DC-DC converters c.) the addition of further cubicles.

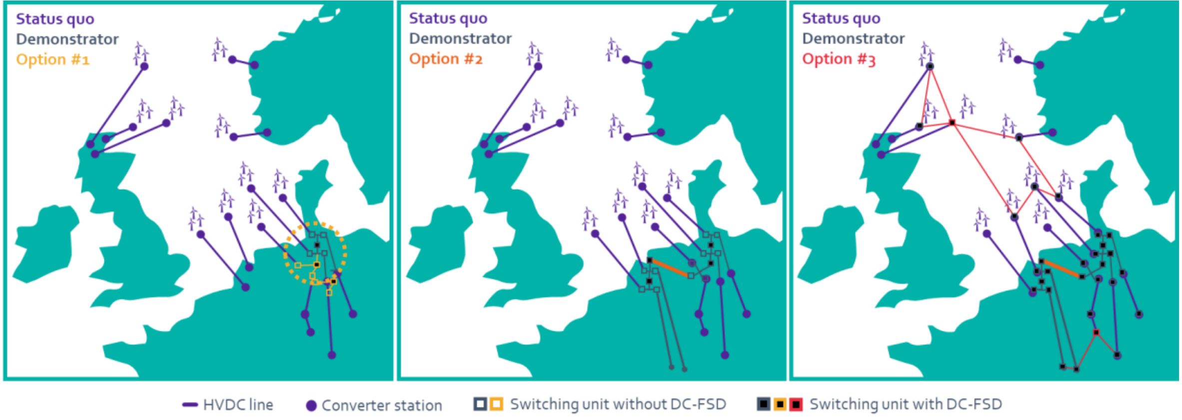
Expandability needs to be considered already in the planning phase of the first MTMV demonstrator. Otherwise commercially optimised solutions and further restrictions might result in locked-in solutions.

Finally, a timeline of key milestones is presented which depicts the duration of each formerly mentioned step as seen by the stakeholders.

Finally, **chapter 6 provides a roadmap towards rolling out future expandability**. The stakeholders consider three phases as relevant. Phase 1 is about gaining experience from the first MTMV HVDC demonstrator. This means that interoperability is proven. Also, necessary adjustments can be made to the existing requirements so future linking of hub projects is enabled.  Phase 2 is encompassing the development of an overall system design. Here Figure 0-1 suggests three options bases around various priorities.

**Figure 0-1:**

Options for the development of an overall system design



Phase 3 finally leads to standardization of modular sub-systems. Standardized technical and regulatory requirements are needed to ensure modular expandability of the system. Moreover, the compatibility of converter stations and separate DC switchgear is of special relevance. The protection design is supposed to be modular to not be restricted within certain system topologies. And finally, the overall goal is to achieve modular HVDC building blocks with compatible I/O interfaces which include interoperability by design.

To achieve these development phases essential requirements are mentioned which can be divided according to Figure 0-2 in technical requirements, planning standards, roles of key actors and further requirements. Examples are provided from currently planned projects like Aquilla in UK and Heide in Germany on how to achieve compliance to system operations guidelines with regard to further expansions of these systems by interconnection/selectivity concepts.

**Figure 0-2:**

Essential requirements to be considered for rolling out future expandability

Technical requirements:
- System rating
- Power flow control
- Dynamic stability
- Protections and Equipment
- Operational philosophy

Roles of key actors:
- Policy makers
- Energy regulators
- Standardization bodies
- Academy and research centres
- TSOs
- Vendors
- Consultants

Planning standards:
- Definition of technical terms and descriptions
- Strategy of potential interfaces for the exchange of signals and data
- Standardization of integration studies for future projects
- Standardized regulations for network connection
- …

Further requirements:
- External threats
- Cyber security
- Cost/business case

Finally, also recommendations to regulatory bodies are provided with regards to 1.) Connection 2.) Operations 3.) Market and 4.) Cybersecurity aspects which may be needed amendment to cope with future MTMV system needs.

It is intended that this white paper - by covering these topics - helps create and build a common understanding across all stakeholders that can then be applied to the next stage of the demonstration project. Concrete, READY4DC WG3 white paper is supposed to support the InterOPERA project which has started in January 2023 within the following topics:

- ✓ MTMV functional specifications
- ✓ Standardized HVDC and PPM models
- ✓ Physical MTMV demonstration (Interoperability proved)
- ✓ Grid forming control features
- ✓ Recommendations to grid codes & technical standards

In summary **chapter 7 Lessons learned** addresses two points which need further attention in InterOPERA and further research projects: 1.) Technical hurdles have been addressed but how they can be met on contractual/legal side is still pending. 2.) Project timeline has been too short to get into depth.

# 1. INTRODUCTION AND STRUCTURE OF THE DELIVERABLE

The climate neutrality is a crucial task, so many countries are trying to achieve these goals by using electricity from renewable energy sources and, naturally, the offshore renewable energy strategy in Europe. In this respect, the distribution of offshore wind is beneficial by interoperable HVDC systems. For the future power system, the integration of multi-terminal multi-vendor (MTMV) HVDC systems will require cooperation between stakeholders to find appropriate solutions for planning, commissioning and operation, which will be a major challenge. For this reason, the READY4DC project plays an important role in defining applicable MTMV-HVDC system definitions, so that the project creates a platform where all stakeholders can reach consensus on common definitions of functional specifications and interoperable models.

> The main objective of this whitepaper is to consolidate the stakeholders' agreements on the Multi-vendor Interoperability Process and Demonstration Definition as an outcome of the READY4DC project work package 3. This whitepaper considers the current state of technology and research.

First of all, this white paper highlights background information and previous activities in the MTMV HVDC system, which play an important role in the discussion with stakeholders. As such, challenges on realising the first of its kind full scale multi-vendor HVDC demonstration project are discussed. The lessons learned up to date from on-going R&D projects are collected and assessed. In this point there are links to the joint ENTSO-E, T&D Europe and WindEurope report on "The development of multi-vendor HVDC systems and other power electronics interfaced devices" as well as to existing regulations and requirements, which set the scene for further discussion in the following issues [1].

Secondly, this report presents guidelines for the integration of the multi-vendor HVDC demonstration project into the European transmission grid. The selection criteria for a new demonstration project agreed among the participating stakeholders in the READY4DC project are proposed together with a short list of possible candidate projects. Furthermore, the whitepaper collects experiences to date from existing interoperability technical standards, functional requirements (e.g., CENELEC/TS 50654 [2]) and defines a procedure for selecting functional specifications. The section tries to achieve contribution to existing standards and regulation.

Thirdly, the key milestones in implementing a real life MTMV demonstrator provide a step by step approach coming from preconditions over planning & development to project specific needs as well as the final steps till the end of lifecycle. The roles of different stakeholders are defined and a common pathway agreed.

Fourthly, to achieve future expandability of MTMV projects beyond the demonstration project different phases of experience are being requested. The requirements to achieve these phases are also discussed in detail. An additional outlook is given how to expand MV to the medium voltage level.

Finally, the lessons learned from the stakeholder management review are presented.

This report underlines the results of the started dialog with potential project owners to ensure commitment on projects realisation. As an outcome of this work, the white paper represents the agreement among all key stakeholders (TSO community, Technology manufacturers, Offshore generation developers, Standardization bodies, Academy and research centres, Software developers, Energy regulators, Policy makers etc.) on the planning and interoperability development process of the first real-life full-scale installations and the deployment of the Multi-Terminal Multi-Vendor HVDC systems with Grid Forming Capability in the European transmission grid.

# 2. CONTEXT AND OBJECTIVES OF THE WHITEPAPER

## 2.1. Policy context and goals

At a meeting in December 2019, EU leaders agreed to achieve climate neutrality by 2050 and asked the European Commission to put forward legislative proposals for a European Green Deal, which continues to be the driver of Europe's climate and energy policies. In June 2021, the European Climate law came into force, establishing a legal commitment to achieve climate neutrality before 2050 and setting a binding target of reducing EU's domestic GHG emissions by at least 55% before 2030 compared to 1990 and to set a 2040 target. A month after, in July 2021, the European Commission tabled its more than 3,000 pages long Fit for 55 packages of legislative proposals aimed at meeting the Climate Law targets.

These proposals were still running through the legislative processes of the European Parliament and Council, when Russia invaded Ukraine which, in March 2022, made EU leaders in the European Council agree on ending Europe's dependency on Russian fossil fuels in the form of coal, oil and gas, as soon as possible. Subsequently, the European Commission published a set of additional measure known as REPowerEU [3], with the overall intentions becoming independent by:

- Saving energy
- Accelerating the deployment of renewables
- Diversifying EU's energy supply

All pathways to meet Europe's agreed 2050 decarbonisation target, would imply a 2040 energy system largely dependent on a fully decarbonized electricity supply, predominantly based on variable wind power and intermittent solar power.

With REPowerEU's measures to accelerate renewables and diversify energy supplies, it continues to be a driving force for European Energy Infrastructure change. The recent adoption of the Renewable Energy Directive alone, means that Europe must increase its share of renewable energy to minimum 42.5 by 2030, up from 22% in 2022. This has substantial impact on EU grid infrastructure in terms of [4]:

- Improving gas & electricity interconnections – completion of critical links, full synchronization of power grids etc.
- Faster rollout of solar, wind & heat pumps & decarbonising industry (through electrification, renewable H2 etc.): faster wind energy deployment, supply chains to be strengthened and accelerate permitting
- A Hydrogen Accelerator for infrastructure, storage facilities & ports

The expected RES capacity will grow from current 511 GW to 1236 GW by 2030 [3]. This includes not only development of wind energy, but also extensive increase of solar capacity to 600 GW by 2030. Beyond 2030, a continuation of the growth in renewable energy is expected. In its draft TYNDP scenarios for 2024, ENTSO-E and ENTSO-G published 'high', 'low' and 'best estimates for renewables, including solar and wind. The following table shows the ENTSO's 'best estimate' out to 2050 [5]:

**Table 2-1 :**

TYNDP "best estimate" scenario for different years up to 2050

| MW | 2030 | 2040 | 2050 |
|---|---|---|---|
| Solar | 671,585 | 1,091,031 | 1,398,656 |
| Onshore Wind | 391,462 | 552,512 | 618,841 |
| Offshore Wind | 155,620 | 370,084 | 480,358 |
| Total | 1,219 GW | 2,014 GW | 2,498 GW |

In January 2023, EU Member states announced indicative 2030, 2040 and 2050 targets for offshore renewable energy deployment in European Sea Basins and the ENTSO's have been tasked with coming up with a strategic grid plan by 24 January 2024, to accommodate this capacity and ensure its integration with the onshore grid. In addition, the REPowerEU calls for 130 TWh of H2 production, which might lead to 65 GW of electrolysis running 3100 hours compared to the 40 GW of the EU Hydrogen strategy. Producing 330 TWh would therefore require at least 150 GW of electrolysis by 2030 if EU aims for green hydrogen only.

Under such boundary conditions, the REPowerEU will strongly increase not only wind, solar and electrolyser capacity, but also overall electricity consumption and participation in energy system management due to underlying higher electrification of other sectors. As result, the REPowerEU by default is accelerating the deployment of AC/DC power converters in generation and on the demand side. It calls for massive deployment of such Power Electronic Interfaced Devices (PEIDs), bringing the need to overcome existing hurdles due to vendor-specific technical design and operation concepts, as well as architecture-related interfaces for control and protection of major power equipment between vendors. Common to the policy requirements of growing offshore wind capacity and the use of onshore and offshore hydrogen electrolyser capacity is the use of High Voltage Direct Current (HVDC) systems. These systems enable bulk power transmission across long distances for which AC cabled transmission solutions would not be applicable.

HVDC technology is not new and has been available to transmission systems for around 60 years. It has historically been used to connect two asynchronous areas of network operating at a different frequency/ basis of frequency regulation, overcoming stability considerations related to alternative long AC routes between net generation and net demand areas of networks, and providing interconnection between TSO areas.

In the last decade, application of HVDC has grown further connecting high capacity offshore wind to the onshore systems. Growth in such a use is inevitably connected to growth in offshore wind and hydrogen electrolyser activity as larger capacities of these resources are harnessed. At larger distances from the onshore system a growing volume of HVDC cables may be anticipated. Much like the onshore AC network, there is an efficiency gain in integrating these cables together into DC "networks" where multi-terminal connections may be brought together within the DC system. Such networks however are unlikely to be built by one party alone, at one point in time. Rather, the DC networks will need to be constructed in stages with the flexibility that each stage is delivered by a separate project. Also, it is required to deliver each stage with separate vendor solutions, or evolutions to the design of the original vendor project in each next new stage as versions of technology update. To achieve this objective, multi-vendor, multi-terminal HVDC interoperability between vendors is needed.

Unlike the existing AC systems for which each of the components of the AC network has clear functional specification across TSO areas, HVDC projects have tended to be bespoke in specification from project to project. Only now, as the scale and pace of HVDC project delivery is increasing, are standard solutions being developed. In China, a series of multi-terminal DC networks have been developed across indigenous vendors[1], demonstrating that interoperability may be achieved in principle. In practice however, this approach requires each vendor to have access to the other vendors' (basic) control and protection design and associated intellectual property. Allocating overall design responsibility to the last vendor and last stage of the networks' development is not an approach that is easily translate-able nor sustainable within our highly integrated and diverse European networks and associated energy markets. Accordingly, the energy transition policy in turn drives a need to technically address how HVDC interoperability needs to be achieved in Europe.

Today, most HVDC systems are designed by European HVDC suppliers as point-to-point transmission systems and are provided by a single vendor. As result, READY4DC stresses the need for European multi-terminal HVDC systems to be future-proof and extendable to multiple vendors.

## 2.2. The objectives of this whitepaper

There are currently several plans and concepts for future development of large HVDC grids in Europe. Only throughout the implementation of these projects the full set of requirements and the corresponding challenges will be revealed. It is necessary to start the assessment already now, to give an initial basis for these projects to start. This whitepaper targets the following challenges of such projects:

- **Challenge 1.** The concept of interoperability is not new to transmission networks however it is more vaguely defined for HVDC and its interactions with other power electronic devices. Interoperability was achieved based on experience, requirements and standards surrounding the classical stability of conventional synchronous generation before the network was set on a trajectory to integrate large amounts of PE connected generation. The performance and characteristics of power electronic devices, particularly modern HVDC converters, is very different from synchronous generators. TSO past experience of planning and designing of AC systems and the principles of DC network operation are different and can be dependent on the AC system requirement also. Large, interconnected areas will potentially involve different TSO areas and offshore areas with wind generation, hydrogen electrolyser and offshore grids. Thus, roles and responsibilities in MTDC networks need to be clearly defined and the concept of interoperability has to encompass the modern definition of grid stability which is relevant to power electronic converter interactions. The response from HVDC converters may also be dependent of the operational state of the AC system.
- **Challenge 2.** It is critical to define meaningful and realistic scenarios of testing of Multivendor HVDC systems at industrial scale to unlock the next step in the maturity of DC technology. Thus,

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[1] definition of vendors in the Chinese context seems to be different to the European context

criteria to define meaningful industrial scale multi-vendor HVDC testing are needed to be clarified, so that a clear plan of development can start.

As mentioned above, the intention of this whitepaper is to pave the way for the development of a high-voltage industrial multi-vendor HVDC demonstrator project. With the support of a large and diverse community of stakeholders from different sectors, the white paper corresponds to the challenges mentioned above by aiming on delivery of the following objectives of READY4DC project [6]:

- **Definition of roles, responsibilities and methods needed within the interoperability process (Objective 3 in** [6]**)**
  The paper provides the potential interoperability issue list that might emerge during interoperability process. The paper also presents consensus on proposed solutions considering different stakeholders' roles, schema of responsibility and methods needed to be applied within the interoperability process for overcoming these issues.
- **Enable from a technical and commercial perspective the first multi-terminal multi-vendor multi-purpose HVDC system with Grid Forming Capability (Objective 4 in** [6]**)**
  The paper provides a suggested process to enable the first multi-terminal multi-vendor multi-purpose HVDC solution(s). The identified scenarios "test" and "verify interoperability issues" are discussed for the complete multi-vendor HVDC interoperability process definition, including the provision of grid stability aspects.

The results are also used for the contribution to the Definition of required activities to develop a vision for the future of the European Energy system [7] to create the conditions for a wider penetration of renewables.

# 3. LESSONS LEARNED FROM FORMER R&D AND HVDC RELATED PROJECTS

The number of R&D projects and applications for HVDC grids is continuously rising all over the world. The planned DC projects in Europe are listed in Appendix 8.1. As the number of HVDC grids increase, their role in the grid also is changing, while HVDC offers many additional benefits. There are several plans and ideas for future development of large HVDC grids in Europe. The execution of these plans will result in an integration of high number of converters delivered by various manufacturers.

The current HVDC systems are procured as single vendor turnkey solutions for point-to-point connection. The single vendor ensures optimised system settings, provides control and protection systems developed in-house with specific settings, limits, communication latency and based on individual technology choice. This results in both hardware and software being available as black-box solutions protected by Intellectual property rights (IPRs) and bound by individual contractual responsibilities on performance.

At the same time, the current experiences from R&D projects[2], operating P2P HVDC projects[3], the MV HVDC project Johan Sverdrup[4] (Norway) [8], and Caithness-Moray-Shetland[5] [9] show that the interoperability issues need to be considered and highlighted. Without addressing interoperability effectively, this creates risk to the entire system performance due mainly to limited field experience, namely:

- In provision of interoperability of converters provided by different vendors under varying grid operational modes.
- In detection and mitigation methods to protect from undamped adverse control interactions between AC/DC converter connected equipment and other converters through the AC system (resonances, harmonic interactions, etc.).
- In harmonised and standardised way for multi-terminal, multi-vendor and multi-purpose HVDC projects.
- In system stability management under high penetration of PEIDs.

Above mentioned HVDC projects demonstrate, that the interoperability issues are solvable, but require a project specific approach by a.) detailed real-time testing and b.) exhaustive and iterative offline simulations to identify and solve issues. Such an approach requires significant simulation capability, system specific replica(s) and thus results in a complex, time consuming testing and adaptation process. As a tailored solution, it is also not scalable for multiple installations. Therefore, current approach is only possible as long as complex HVDC installations are relatively rare and unique projects.

To ensure cost-effective deployment of EU policy goals (REPowerEU, Green Deal, Fit-for-55), there is a need to seek for a generic solution where TSOs and system developers could rely on single component (to be specified) testing. As such, future HVDC systems may need minimum standardised functional requirements for further individual components such as DC-FSDs in addition to, HVDC converters and switching stations of multiple vendors. Also, adequate interfaces with the onshore electrical grid are

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[2] e.g., Best Paths [10] and PROMOTION [20]

[3] like INELFE (Spain-France) [102], different BorWin projects [78] [82] [87] (Germany)

[4] only AC connected

[5] Europe's first multi-terminal VSC-HVDC project, designed to enable further future HVDC vendors within a potentially multi-vendor arrangement

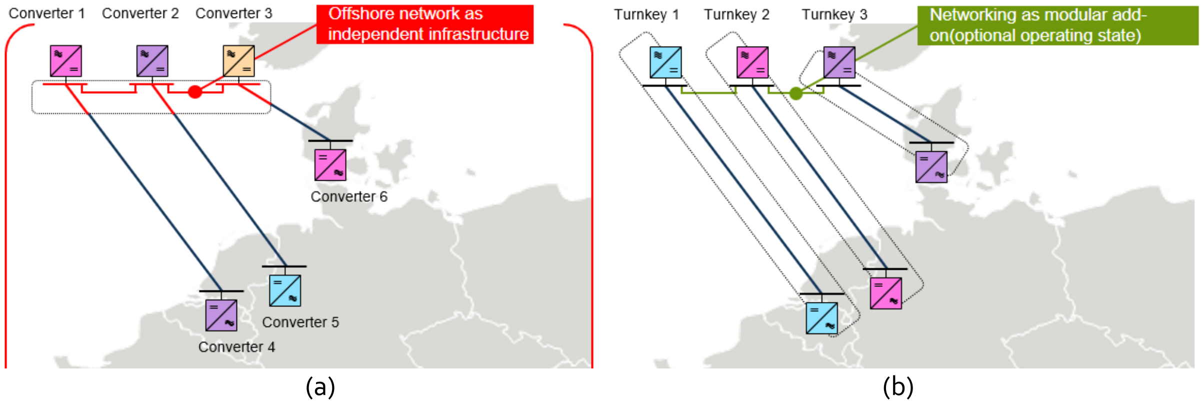
required to ensure interoperability and stability. The specific range of requirements will depend on the project itself and whether it includes all of these components.

In 2018, the Best Paths R&D project [10] delivered several aspects regarding the interoperability of converters for multi-vendor DC systems, which supports some aspects of a real industrial project. In 2021, ENTSO-E, T&D Europe and WindEurope have jointly proposed a "Workstream for the development of interoperable multi-vendor HVDC systems and other power electronics interfaced devices", to ensure a reliable research focus to enable the delivery of future meshed HVDC grids [1].

There are different ways to test and explore multi-vendor interoperability (see Figure 3-1). As a starting point, an independent infrastructure or modular network can be deployed resulting in different levels of risk because of the possibility of having a fall-back scenario or not.

**Figure 3-1**

An example of Multi-vendor HVDC systems interoperability risks and fallback possibilities under different set-up arrangements (source: Amprion GmbH, P. Ruffing), (a) Independent infrastructure with fallback and (b) Modular network without fallback



# 4. GUIDELINES FOR PLACING THE DEMONSTRATION PROJECT IN THE EUROPEAN TRANSMISSION GRID

For decades, numerous HVDC projects have been built in e.g. Europe, China, USA, India and Brazil. Nowadays, several multi-terminal HVDC systems have also been implemented or projected (see Appendix 8.1). For the implementation of widespread multi-terminal, multi-vendor (MTMV) HVDC systems within Europe, a demonstration project sets the basis. To engage stakeholders to be the first movers, section 4.1 outlines the benefits of a demonstration project and tackles the risk compensation. The subsequent section 4.2 describes possible criteria needed for the selection of the first full-scale demonstrator project. These selection criteria are described on a functional level to answer the grid needs when introducing a first MTMV demonstrator. This is tailed by the presentation of potential MTMV candidate projects in section 0. Such projects may be placed in the European transmission grid in upcoming years. Future MTMV grids may require functional specifications which are going beyond the ones listed in section 4.2 for the first demonstrator. Therefore, a procedure for selecting an all-encompassing set of functional specifications is proposed in section 0.

## 4.1. Benefits and risk compensation of a demonstrator project

Laying down the basis for the deployment of a meshed HVDC grid across Europe, a MTMV demonstration project can offer a broad range of advantages. On top of that risk compensation methods will further encourage the different parties to be the first to take the risks.

### 4.1.1. Advantages of a first MTMV demonstrator

The first and most important benefit gained through the implementation of an MTMV demonstration project is the innovation support in the field of HVDC through valuable lessons learned to establish the necessary operational, technical, regulatory, functional and regulatory frameworks. In the future, many HVDC projects and MT projects are planned to be developed. Therefore, the demonstration project develops and implements these innovations to achieve a widespread MTMV DC grid across Europe.

There are also several advantages of a MTMV HVDC system that may boost the reliability, efficiency and stability of the grid, in comparison to a collection of single vendor point-to-point HVDC arrangements. Further, the implementation of a MT HVDC system will significantly improve the flexibility of the offshore grid in terms of power allocation. A multi-terminal HVDC system can also provide higher utilisation of HVDC lines.

The implementation and development of the demonstration project will contribute to the development of HVDC grid codes (in addition to the CENELEC 50654-1 [2]) and HVDC grid planning standards for MTMV HVDC systems. The HVDC grid code and standards would allow TSOs to gain more flexibility in planning, e.g., the possibility to expand a system with another vendor and reduce the overall costs.

### 4.1.2. Risk compensation methods for the first MTMV demonstrator

One initiative could be to introduce a common funding scheme supported by the EU, the TSOs or other stakeholders. The financing created in this way will therefore support high investment costs. Also, the costs of the standardisation and harmonisation activities for the MTMV projects can be covered by joint funding from the EU, the respective countries, TSOs or other stakeholders. On top of that it leads to a joint interest in completion of this demonstration project.

Several EU regulations and the national implementations of the regulations specify regulatory boundaries for HVDC grid connections across Europe. However, it is expected that these regulations may be more flexible for a demonstration project, as more flexibility for subsequent qualification of the technology (converter stations, DC switchgear, etc.) and there could be fewer penalties for delays.

Some form of compensation for choosing over scaled or over specified and hence non-optimal and potentially more expensive solutions could be considered to ensure the MTMV HVDC project. Although a single-vendor project may be better for EU grid customers in the short term, the legal and competition implications can be improved to achieve better prices and procurement implications for multi-vendor projects in the long run.

To reduce risks within the procurement process it may be beneficial to disaggregate a project into smaller (component or subassembly) lots. This encourages different manufacturers to ensure delivery of each component in the supply chain, such as converter stations, transformers, cables, protection devices, DC switchgear, DC filters, etc.

TSO staff may have limited experience and expertise in HVDC systems and components at this level; therefore, it may be required to train them before commissioning the first MTMV demonstrator to achieve experience and/or deep knowledge of HVDC systems or offshore HVDCs. TSO staff may also need education in how a power electronics dominated power system behaves and possible system impacts from converters. This also represents a shift in responsibility from the traditional turnkey vendors to the asset owner, and thus a consequent builds up / shift in resources.

In a MV environment, it is expected that a common consensus will be reached by discussing topics such as who is responsible for developing specifications, implementation of the different components, testing, etc.

Finally, the knowledge gained from the first demonstrator allows the parties to de-risk their future projects.

The points addressed in this section may also be included in deliverables D2.2 and D4.1 of READY4DC. As the risk compensation is such an important topic for the first MTMV demonstrator it is meant to be complementary to the outcomes of the other deliverables.

## 4.2. Definition of selection criteria for the first MTMV demonstrator

In the process of defining selection criteria for a potential full scale demonstration project it has been agreed on to use two different sets of criteria. The first set, soft criteria, defines the general needs of a MTMV demonstration project which will be used as a basis for a widespread DC grid within Europe. The second set of criteria is high level functional requirements, which the demonstration projects should strive to fulfil as much as possible, to be suitable for further standardization towards realizing much larger MT and MV DC grids.

### 4.2.1. Soft criteria

The developed soft criteria set the basis for agreement between the different stakeholders. They define on a high level what is understood by the stakeholders when discussing the first MTMV demonstration project. The outcome is to differentiate between *Must-have* and *Optional* soft criteria. In the following, the "*Must- have Soft Criteria*" are highlighted first:

#### MULTI TERMINAL

A multi-terminal system is understood in a first stage to consist of three or more terminals [1]. It may be expanded in future stages. Uncertainties with regards to realising widespread DC grids are highly related to the concept of having multiple HVDC terminals. Therefore, the demonstrator project, should be multi-terminal to help close some of the many gaps.

#### MULTIPLE VENDORS

Along with multi-terminal, the realization of multi-vendor interoperability is essential for realising widespread DC grids. Therefore, the demonstrator project should be multi-vendor, meaning that at least two vendors (see definition of the first stage) will be in position to provide converters and the associated control & protection [1]. For expansions of the first MTMV demonstrator it may be beneficial to also include further vendors.

It should be mentioned that when an HVDC system is built with multiple vendors, competition has the potential to lead to new solutions, improvements and optimisations.

It is also worth noting the various challenges that arise when an HVDC system is set up with multiple vendors. For example, which vendor is responsible in the event of a failure. Project implementation could be accelerated by working with a single vendor; it is likely that the number of repetitions will increase and the operating staff would certainly need more knowledge in managing a multi-vendor solution. The responsibility for the DC system is also easier to be handled in the case of only one vendor. In a multi-vendor project, there needs to be clear division between the responsibilities of each vendors convertor control within an overall DC system control philosophy and operation. It also includes a greater role from the TSO and/ or others acting on their behalf in defining the functional requirements and operational needs of the DC system supported by the assets delivered by the various vendors

But with respect to future meshed DC system design, where a system operator will be responsible for the operation of a wide meshed DC grid, there has to be a transition phase from single vendor P2P systems or limited MT system of one vendor toward interconnected DC grids. Within these interconnected DC grids vendors and the system operator will have to share the responsibility among each other via subcontracting or other special modes of operation.

### EXPANDABILITY

In the future, it is expected that an HVDC system would be built by multiple vendors, in stages and in this situation, the expandability of HVDC systems would be one of the crucial issues [1]. There are multiple wind farms and multiple onshore connections in terms of expandability for HVDC systems. Here, the possibility of a new configuration for the MTMV HVDC system may be explored. Moreover, it should be determined which functions of the MTMV HVDC system are important and which may be of limited usage. For example, focus can be placed on the protection and control of the HVDC system. During the lifetime of the HVDC components it is vital to consider how any required refurbishments will be carried out and which part(s) of the HVDC system will be refurbished by which vendor. In the case of the expandability of HVDC systems, it is required to avoid vendor locking, on the other hand, the project may be delayed when working with multiple vendors.

### RECONFIGURABILITY OF PARAMETERS

Installations in the electricity transmission grids are built for a lifespan of decades. Due to this fact and the agreed expandability towards a meshed DC grid across Europe it is considered necessary by some stakeholders to design a first demonstrator being adjustable with regards to new arrangements.

The benefits are enhanced system and asset performance. Additionally, it is expected to achieve a longer service life of the equipment installed. Finally, and most important compatibility with future extensions/connections will be achieved by that.

This will most likely include adjustments of parameters in the control and protection system of the first demonstrator. Online and offline changes of the parameters can be foreseen and tested in the demonstrator.

A) Online reconfigurations: Based on the actual grid situation (e.g., high/low load, high/low inertia, SCR level of the grid, high/low wind...) different control and protection parameters could be arranged. This may include ramping rates, gain factors, K-gradients, protection schemes, et al.
B) Offline reconfigurations: During maintenance cycles/repair the demonstrator may be updated to cope with developments and future installations of DC components.

For reconfigurability, there are increased risks which have to be considered:

- Unpredictability of behaviour
- Manmade failure / forgetting to change back
- Complexity of the control and protection increases as well as entire system planning
- Time frame of system plays a role
- For the first demonstrator: It might be very complex to address different online characteristics that could be adjustable for all MTMV converters.
- Incorporation of new technologies

In addition to the "Must Soft Criteria" listed above, some "Optional Soft Criteria" have also been detected. This means that the first demonstrator would beneficially enable the following setups.

### OPTIONAL: MULTI-PURPOSE

When planning future HVDC systems, the project may be designed for multiple purposes, e.g. power exchange, transmission of power from offshore wind farms to land, P2X plants and other services. When planning future HVDC projects serving multiple purposes, there are some opportunities, such as higher efficiency, socio-economic benefits and the possibility of power exchange from one side to the other.

Also, multi-purpose HVDC projects bring some challenges, such as prioritising national interests in case of energy shortages and generation oversupply. Moreover, there is a major challenge in handling real-time operation and coordination, protection, monitoring and control of a multi-purpose HVDC project. It is worth mentioning that additional market-based options may generate significant opportunities beyond the scope of this paper. These are of course accompanied by many challenges.

### OPTIONAL: MULTI TSO CROSS-BORDER/INTER-AREA PROJECTS

The first MTMV HVDC demonstration project may be located in the EU offshore wind farm region. Therefore, it becomes very difficult to establish a single HVDC system operator when more than one country or transmission grid is involved. Multi-TSO cross-border or inter-area projects offer some opportunities, e.g., a possibility for provision of frequency reserves between asynchronous AC grids and harmonisation of international regulations and procurement approaches. Furthermore, the project will contribute to improving the procedures for the development of HVDC projects in the future. The resultant new HVDC network structure would create a certain complexity for the TSOs, and their grids could be affected by the influences of the neighbouring grids.

## 4.2.2. Functional specifications and DC grid needs

Formerly selected soft criteria are needed to ensure that the demonstrator project can help to solve the most relevant challenges with regards to realising a widespread European DC grid. The subsequent defined functional specifications are crucial for a compliant integration of the MTMV demonstrator project into the European transmission grid. Further they should help ensure the demonstrator is a proper representative of the expected future DC grids and their functionality. In the following subsections first, the functional requirements are described before indicating design impacts i.e., functional specifications.

As of today, the recommended reference for designing the HVDC grid needs are the CENELEC (CLC/TS 50654-1, -2) standard [2] [11] and the IEC 63291-1, -2 [12], [13] where the latter is the latest updated document within this topic. This standard is still very much open and needs to be detailed and matured further in the coming years. However, it is recommended that upcoming demonstrator projects base its functional specification on this reference and focuses on applying solutions within the CENELEC framework.

### Legal and regulatory compliance

The first demonstrator project must comply with current regulations or a new legislative framework needs to be created. The coordination and governance aspects regarding MTMV are covered in READY4DC WG2 [14]. Therefore, within this working group the discussions have been concentrated on the technical aspects.

### Technical functional specifications – Electrical

The below listed and in this section in detail explained electrical functional specifications provide a summary of the most important topics to be considered for deploying the first MTMV demonstrator. Although named *functional requirements* the following can be considered as a description of the system needs and required functionalities from a high-level power system perspective. They contain for every functional requirement a non-exhaustive set of design impacts:

- **Functional requirement: Compliance to system operations guideline (SOGL)**
    - *Design impact: DC fault protection*
    - *Design impact: DC control*
- **Functional requirement: Fulfilment of transmission request**
    - *Design impact: DC voltage options*
    - *Design impact: Selection of active power per converter station*
- **Functional requirement: Provision of grid services**
    - *Design impact: Submodule technology selection*
    - *Design impact: Trade-offs in converter station function selections across DC network*

**Control concepts as functional requirements**

- **Functional requirement: Grid Forming Capability**
    - *Design impact: Topology selection*

**Further electrical functional requirements**

- **Functional requirement: Improvement of ancillary services**
    - *Design impact: Overplanting of windfarms and deloading below MPP*
- **Functional requirement: Redundant coupling**
    - *Design impact: Offshore AC connection*
- **Functional requirement: Functions requiring use of technology components currently of low technology readiness level**
    - *Design impact: Include technologies not being operated in the European transmission grid up to now*
- **Functional requirement: Reduction of technical complexity/risk**
    - *Design impact: Demonstrator project for first MTMV project doesn't aim to solve all issues from the beginning*

## FUNCTIONAL REQUIREMENT: COMPLIANCE TO SYSTEM OPERATIONS GUIDELINE (SOGL)

The starting point for all discussions as to why and how to introduce a first MTMV demonstrator in the existing AC grid(s) are the system needs. This includes among other needs how much generation capacity is allowed to be lost and for how long, also often referred to as maximum loss of infeed limits. Table 4-1 and Table 4-2 present a non-exhaustive set of relevant grid code compliance criteria based on the grid codes used in different countries and the ENTSO-E system operations guideline. The specification of planned MTMV projects may be squared against these values to quickly identify compliance to existing grid codes.

**Table 4-1**

Comparison of grid codes used in different countries

| | Allowed loss of permanent transmitted power | Allowed loss of temporary transmitted power | Allowed loss of permanent generation capacity | Allowed loss of temporary generation capacity | Allowed loss of permanent demand |
|---|---|---|---|---|---|
| Denmark | 700/600 MW | 700/600 MW | 700/600 MW | 700/600 MW | 700/600 MW |
| Germany[6] | ≤2000MW [15, p. 38]; [16]; [17] | NA | ≤2000MW [15, p. 38] | NA | ≤2000MW [15, p. 38] |
| Netherlands[7] | 1500MW, max. 6h, busbar trip | 1500MW, max. 6h, busbar trip | 1500MW, max. 6h, busbar trip | 1500MW, max. 6h, busbar trip | 1000MW <2h;<br>500MW 2h;<br>100MW 6h |
| Norway | 1400MW | 1400MW | 1400MW | 1400MW | 1400MW |
| Poland | 1100MW [18] | 1100MW [18] | 1100MW [18] | 1100MW [18] | NA |
| UK[8] | 1800MW | NA | 1800MW | NA | 1400MW |
| Ireland | 500MW | 500MW | 500MW | 500MW | NA |

Table 4-2 shows a comparison of allowed maximum power transfer capacity, voltage tolerance and frequency tolerance with regard to the national implementations of the EU system operations guideline.

**Table 4-2**

Comparison of grid codes used in different countries

| | Allowed maximum power transfer capacity | Allowed AC Voltage tolerance | Allowed Frequency tolerance |
|---|---|---|---|
| Denmark | 600/700 MW (per transmission system, e.g. line/cable) | CE:<br>1.05 – 1.0875 p.u.: 60 min<br>N:<br>1.05 – 1.1 p.u.: 60 min | CE/N:<br>47.0 – 47.5 Hz: ≥60 sec<br>47.5 – 48.5 Hz: ≥90 min<br>48.5 – 49.0 Hz: ≥90 min<br>51.0 – 51.5 Hz: ≥90 min<br>51.5 – 52.0 Hz: ≥60 min |
| Germany | 2000 MW [16] | 390 kV – 420 kV (n-0)<br>380 kV – 420 kV (n-1) | NA |

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[6] Includes MT-systems

[7] See explanation in section 0

[8] for GB- max loss of generation classed as "infrequent infeed loss" is 1800MW; frequent infeed loss 1320MW; there is also a normal loss of 1320MW generation accepted - which currently is the maximum loss as a result of an offshore system fault. under SQSS change GSR030 (currently in workgroup review) a full Bipole, suitably specified is to be classed as a 2 circuit loss risk- with the loss of the whole Bipole not being considered as a credible event. as a result a single symmetrical monopole HVDC arrangement could be rated up to 1800MW compatible with the proposed standard, and a Bipole up to 3.6GW (not that ratings of these scales are yet proposed to be designed)

| | | | |
|---|---|---|---|
| | 4000 MW per route (cable trench) [16] | > 370 kV (exceptional contingency or bus bar fault) [16] | |
| Norway | 1400MW | 0.93-1.0 p.u. cont. / 0.9 p.u. for 4 hours / 1.05 p.u. for 60 min | 49.0-51.0 Hz cont. / 47.5-51.5 Hz for 90 min / 47.0-47.5 Hz for 60 sec / 51.5-52.0 Hz for 15 min |
| Poland | NA | For HVDC connected to 400 kV grid:<br>0,85 pu – 1,05 pu - no limited<br>1,05 pu – 1,10 pu – 60 min<br>For HVDC connected to 400 kV grid:<br>0,85 pu – 1,118 pu – no limited<br>1,118 pu – 1,15 pu – 60 min | For HVDC:<br>47,0 Hz – 47,5 Hz: 60 s<br>47,5 Hz – 52 Hz: no limited |
| UK[9] | 2000MW, up to 2030 | > 300kV 0.9pu – 1.05pu unlimited<br>> 300kV 1.05pu – 1.10pu 15min | 47.0Hz – 47.5Hz 60 sec<br>47.7Hz – 49.0Hz 90min & 30sec<br>49.0Hz – 51.0Hz unlimited<br>51.0Hz – 51.5Hz 90min & 30sec<br>51.5Hz – 52.0Hz 20min |
| Ireland[10] | 500MW | 400 kV system:<br>0.85 p.u. – 0.9 p.u. (60 minutes)<br>0.9 p.u. – 1.05 p.u. (unlimited)<br>1.05 p.u. - 1.15 p.u. (not allowed)<br><br>220kV system:<br>0.85 p.u. – 0.9 p.u. (60 minutes)<br>0.9 p.u. – 1.12 p.u. (unlimited)<br>1.12 p.u. - 1.15 p.u. (not allowed) | 47.0 – 47.5 Hz: ≥60 sec<br>47.5 – 48.5 Hz: ≥90 min<br>48.5 – 49.0 Hz: ≥90 min<br>51.0 – 51.5 Hz: ≥90 min<br>51.5 – 52.0 Hz: ≥60 min |

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[9] A Holistic Network Design for Offshore Wind | ESO (nationalgrideso.com); issue 6 revision 16 https://www.nationalgrideso.com/document/162271/download

[10] Per Grid Code version 12

### DESIGN IMPACT: DC FAULT PROTECTION

If the power ratings of the planned MTMV system exceeds the ratings defined in Table 4-1 and Table 4-2 as well as further requirements in the country specific grid codes a DC fault protection is obligatory for MTDC grids to limit the loss of generation infeed and comply with system security constraints.

Therefore, the following options to achieve these functionalities are proposed. So, the demonstrator project may have either a partial or fully selective fault detection and separation strategy based on the system needs and local system security constraints. Also, different converter technologies are available to achieve the required separation strategies. Different HVDC station topologies may provide continuation of operation even in the case of faults.

Moreover, one of the key challenges in implementing MTMV and meshed HVDC networks is the requirement for the system to react to DC-side faults in ways that preserve as much of the original functionality of the network as possible. The responses and capabilities of the converter station impact several network performance criteria, including the reactive power support that the converter station is capable of providing to the AC system during a DC-side fault (reactive power can be supplied continuously to surrounding AC systems in STATCOM operation mode). This capability may have advantages in terms of increased AC system voltage stability and control during the fault ride-through process, as well as allowing the converter stations to provide other ancillary services while there is a fault on the HVDC network.

### SEPARATION STRATEGY OPTIONS

MTMV HVDC systems staying within the power limits defined in the national grid codes may clear DC faults with their respective AC fault clearing device. For HVDC systems exceeding the limits of power ratings in the national grid codes a selectivity concept on the DC side needs to be applied. In general, there are three selectivity concepts available:

- No selectivity
- Partial selectivity
- Full selectivity

The choice of selectivity is to be based on a system security risk assessment on a project and national level, where the security of supply gained with higher selectivity is to be compared to the higher cost of equipment. Thus, it will be the functional requirements to system security level in the project specific setting that will dictate the final selectivity.

It is acknowledged by all parties that DC-FSDs will introduce more complexity to the system design and architecture. Furthermore, the requirements for the vendors of HVDC systems as well as vendors for DC-FSDs are currently not clear. This includes information like the location of the DC-FSD, required fault clearing time, required fault location detection, coordination between the converter station and the DC-FSDs, coordination between different DC-FSDs to be non-exhaustive. Thus, introduction of the DC-FSD can only take place after the functional requirements based on the corresponding operation philosophy are defined and within close cooperation between TSOs, HVDC manufacturers and DC-FSD manufacturers.

Despite the increased complexity it is recommended that the first demonstrator project involves the installation of a DC-FSD for the purpose of testing and verifying the applicability of this technology as a sub-system in the multi-terminal HVDC grid to solve the functional requirements for protection and selectivity while securing future expandability.

### CONVERTER TECHNOLOGY OPTIONS

Different converter technologies like, LCC (Line Commutated Converters) or VSC can be found in operational HVDC installations in the world [2] [19]. The reason for the current use of VSC in planned DC projects is given in the *Design impact: Submodule technology selection* paragraph.

In the case of VSC technology based on modular multilevel converters two main categories exist, namely half-bridge or full-bridge submodule-based VSC. To make a decision which type of VSC technology to choose, crucial aspects to be reflected are expandability, fault separation and fault ride through behaviour, maximum interruption time and maximum loss of in-feed, DC voltage operating range, system losses and total costs of ownership.

Further, it needs to be considered how hybrid cable/overhead lines will additionally impact this decision and influence the system behaviour. This point has been addressed in the Promotion project [20] and requires additional attention.

### HVDC STATION TOPOLOGIES

The available HVDC station topologies have evolved over time. Currently there are four available:

- Asymmetrical Monopole
- Symmetrical Monopole
- Rigid Bipole
- Bipole with DMR

Considering the planned DC projects in Appendix 8.1 the future systems are mainly planned with Bipole including DMR. The main advantage of the Bipole with DMR is the overall increased system availability as in case of a Pole to Earth fault on the DC side. In this case the system can be kept in asymmetrical Monopole operation. Furthermore, in case of maintenance of the DMR the system could be operated as a rigid Bipole.

Furthermore, for normal operating conditions in German offshore DC connections the use of a DMR is a mandatory requirement by the BSH (Bundesamt für Seeschifffahrt und Hydropgraphie) due to the interference of vagrant currents into fixed installations in the North Sea.

Challenges with the use of Bipole HVDC converter topologies lies in the risk of losing a full converter station as in both poles of the Bipole. This has a greater impact than with symmetrical Monopole topologies due to the increased power capacity of currently up to 2 GW may impose challenges for compliance to current grid codes, in situations where the full bi-pole converter station is tripped. The HVDC-Wise project tackles this issue and will deliver information how to deal with this challenge. Also, the GB SQSS [21] provides statements on this. On a European level it must be discussed if the loss of a full bi-pole is defined as a normal contingency (N-1) or an exceptional contingency (N-2), similar to AC overhead lines with double systems on the same tower. In either case the system operator must be able to handle the contingency, but the requirements are different under the system operation guideline (SOGL) whether it is defined as normal or exceptional contingency. The system operator has the freedom to handle the contingency by different means, such as activation of frequency reserves, disconnection of load or bi-lateral agreement for cross-border reserve sharing.

### EXPANDABILITY OF DC FAULT PROTECTION

The DC fault protection shall be expandable in the sense that it shall be possible to connect new DC terminals and reconfigure the existing protection schemes.

## DESIGN IMPACT:  DC CONTROL

Unlike an AC network where all synchronous elements of the power system are bound together by a common system frequency (for example 50Hz in Europe) DC system has no common basis of reference. This means that in practice a voltage and or power flow related basis for coherence across the DC system needs to be derived to maintain coherency across the convertors contributing and influencing the DC system behaviour. Such systems are referred to as Multi-terminal Controls, and by their nature rely on communication between control systems and points of measurement and control within the DC system. Further communication may be required should selective protection approaches and fault clearing devices such as DCCBs be integrated into the DC system.

Control philosophies relying on communication can be summarised as one of two kinds: active or supervisory control.

- For an active control approach, the control is constantly measuring the DC system and in response to transient events, voltage steps and other disturbances, taking decisions at each convertor based on an overall control philosophy. This control strategy needs to be constantly available, with either back-up controls not relying on the same communication infrastructure or additional fall-back controls being in place to ensure it meets the overall resilience needs of the TSOs operating that network. For an active control, overall control failure results in DC network instability. This is similar to the experience of TSOs designing stability intertripping within their current AC networks where their failure would similarly result in instability and as a result their use and specification is carefully controlled in standards and specification.
- For a supervisory control, a differing approach is used where the control system measures and periodically updates the overall DC system such that in any secured event it will respond stably regardless of further information being communicated or initiated by the control. In such control strategies the DC system is less reliant upon the availability of communication. If communication is loss the network can be "frozen" its present operating state and operate safely. Such supervisory control may be duplicated as "advice tools" to control rooms to provide advice on other operating states such that in the event of the control being lost, manual intervention is also an option.

Regardless of the approach the resilience of the function of these controls is a key consideration to specification and design of the Multi-vendor Multi Terminal DC networks as it supports in real time operation clearly communication and coordinating across the convertor behaviour. Allocating responsibility to specify and deliver the objectives of this control are key aspects in the delivery of the multi-terminal control. The more complex this control becomes, the harder it becomes to test the overall behaviour of the control and the HVDC convertors, both together and separately. It also increases complexity of the design of both.

A physical control scheme will need to sample measurement over windows of time, refresh that measurement at a given rate, take account of communication latency, time synchronisation of measurement, measurement data loss and measurement inaccuracy. A physical measurement device will include filtering adding delay. The communications may include further delays if there are differences in communication protocols between vendors involved in that system. In practice the multi-terminal control also requires separate testing for robustness which includes testing these practical scenarios of delay, data loss and loss of data coherence, for operating conditions that the multi-terminal control would need to operate over, such that its behaviour is known, can be modelled and can be understood from post event data should a post event investigation of performance become necessary.

We would recommend minimising the dependencies on communication; less communication leads to a more robust system. Also, it is preferable to ensure that the multi-terminal control is not overly complex and its behaviour is predictable and easily understood across the operator of the DC system and the vendors connecting technologies into that DC system.

In practice, one approach for achieving this (the approach as taken by Project Aquila in GB) is to ensure that the system is designed with stability. This means stable behaviour across a range of conceivable and secured operating circumstances, such as voltage profile drift that might arise under normal operational variation of output of wind resource. Such a situation could result in a distributed droop response to support the network. Other benefits are securing the system against a single terminal loss, AC fault ride through, or frequency/ voltage step impacting the DC system. Stability which includes thermal exploitation and focussed multi-terminal system ensures operational reliability and resilience in function. It also means that should communications be impacted, the operating state of the network may be "frozen" and remains stable to credible scenarios. This approach allows the multi-terminal system to slowly "course-correct" an inherently stable starting point, and to provide a "forward guidance" in a sequence of operating states, e.g. for supporting a fast ramping action in response to an AC system fault/ scenario. This approach also lends itself to a "digital twin" of the control within a TSO control room which identifies the intended actions of that control to such events such that the control engineer can anticipate how a DC network will respond to changes of dispatch of the AC or DC systems.

This is not the only approach that can be selected to response. Other options such as a highly reliable rapidly acting interventionalist (i.e. based on measurement it directly intervenes to override the response of the convertor to the event). This form of centralised control could be contemplated, but such a control would both need to avoid communication loss risks and delays in synthesising multiple similar communications needed for reliability. Also, the measurement itself needs to be functioning with a speed similar to that involved in selective DC protection concepts. Such centralised schemes would have significant risks in overriding necessary individual converter terminal functions. So, they could not be straightforwardly implemented without strong understanding of both inner and outer control functions of all vendor convertors involved. These centralised systems would not be easy to understand or anticipate by a control engineer.

Another option would be to implement a control concept in a non-centralised manner known as a distributed control. Hereby each terminal has its own version of the multi terminal control which acts in the same way but independently. This in concept is a more robust solution to avoid a single control loss. However, if part of the control concept is not able to ensure inherently stable operation in that scenario, a distributed control is unable to provide any additional value.

## FUNCTIONAL REQUIREMENT: FULFILMENT OF TRANSMISSION REQUEST

### DESIGN IMPACT: DC VOLTAGE OPTIONS

With MMC technology the DC voltage range can be selected arbitrarily. Cigré TB684 [22] gives a comprehensive recommendation for HVDC grid voltages but was published in 2017 and does not account for HVDC converters commissioned after 2021 (planned at the point of publication). For existing HVDC converters and current HVDC projects in Europe, five voltage levels in the 320-525 kV range are identified as follows:

- ± 320kV
- ± 380kV
- ± 400kV
- ± 500kV
- ± 525kV

While ± 320kV is currently used for symmetrical Monopole operation, ± 380kV appears for special application [23]. The Nemo Link between Belgium and the UK is the only European HVDC connection at ± 400 kV. Future DC projects, according to Appendix 8.1, are mainly planned with ± 525kV, and this voltage is the current focus for development of overhead lines / cables. 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 applications. Here construction and refurbishment could be easier to carry out with ± 320 kV.

However, the functional requirements shall be independent from the voltage level selected. Thus, for the demonstrator it is recommended that the DC voltage range lies within the transmission level range of 320 kV to 525 kV.

Recommendations:

- The widest range of vendor experience in delivery of HVDC to similar specification relates to 320kV and 525kV specifications. For the demonstrator alignment on voltage level is preferred to achieve interoperability faster and easier given aligning at 320kV or 525kV allows more vendors to start from current products and not have to reverse engineer their product to new voltages which today have little standardisation across the vendors.
- DC control easier with only **one** voltage level.

### DESIGN IMPACT: SELECTION OF ACTIVE POWER PER CONVERTER STATION

Current developments for DC projects according to Appendix 8.1 tend to an active power per converter station of up to 2 GW. This has to do with the fact that the TRL level for 2GW converter is considered market ready [24] [25] [26]. Higher active power rating is currently not considered as the cable ratings are based on a 2 kA limit. Larger power capacities may be available in the future through new technologies like higher voltage cables or higher current cable technology, such as superconductor-based transmission and their respective power conversion systems. A specific power rating is not recommended for the first multi-terminal multi-vendor project. However, for verification purposes it is recommended that the power rating matches transmission level projects with a minimum active power rating of some hundreds MW.

### DESIGN IMPACT: TRADE OFFS IN CONVERTER STATION FUNCTION SELECTIONS ACROSS DC NETWORK

At all times of operation, the DC system needs to respect the hard limitations of device rating and the physical capability of the technologies connected. For example, somewhere within the system a convertor or a collection of convertors there must be control of the DC voltage profile- and those same convertors (assuming half-bridge design) may not also be providing an AC system grid forming control. This means that it needs to be clear at a given operating point of a DC network what the AC system support/ control priorities are and how they relate to the DC network requirements at that time. There will need to be compromises between what is ideal for the AC system and what is optimal for the DC system. For TSOs/ developers this will require their functional needs for the AC system to be clear at each HVDC convertor terminal for a given condition of operation for the DC system, and their expectations of the functional resilience of the DC system to events at that time. For the vendors it will be important to communicate the range of trade-offs that need to be made between these two objectives.

The recommendation would be to ensure from this a clear order of prioritised functions is created for each HVDC terminal within the DC network such that it is clear for given situations of operation what functions it is fulfilling. These functions can then be both separately and collectively tested within the DC system to ensure the overall response is co-ordinated and interoperable.

## FUNCTIONAL REQUIREMENT: PROVISION OF GRID SERVICES

The provision of grid services sets the compliance to existing HVDC grid codes as a basis and touches upon the following non-exhaustive list: reactive power support, FCR, FRR. It is pointed out that further development needs to be achieved to have extra high voltage PEI devices having the same or more beneficial provision of grid services than conventional synchronous machines.

### DESIGN IMPACT: SUBMODULE TECHNOLOGY SELECTION

VSC is the current state of the art technology which is shown in the table of the planned DC projects between the years 2019-2039 in Appendix 8.1. One reason might be 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. Other benefits of the VSC technology in general are easier and quicker power flow reversal, reactive power control, grid forming and black start capability. Additionally, the LCC technology requires minimum system strength to operate (especially in case of fault ride through) which contradicts modern system needs where PEI devices should contribute to grid forming behaviour. Thus, for the demonstrator it is recommended that only VSC converter technology is considered, and not LCC or direct rectifier.

### CONTROL CONCEPTS AS FUNCTIONAL REQUIREMENTS

As the behaviour of power electronics can be mainly influenced by their control system, future reliable and resilience-oriented DC grids require a beyond the state-of-the-art control concept. This could mean to include capabilities like grid forming and black-start in the first demonstrator. This would not only lead to an increased power system stability, but also a reduced number of other assets (e.g. STATCOM with storage, synchronous condensers) to be implemented in the grid. Former projects like VerbundNetzstabil and the ENTSO-E proposal on grid-forming have tackled some aspects of the behaviour of power electronic interfaced power sources and control concepts [27] [28].

## FUNCTIONAL REQUIREMENT: GRID FORMING CAPABILITY

To cope with the rising share of PEI interfaced devices in the European transmission grid the need of grid-forming control methods has been identified as a necessary stabilizing measure [1] [29]. In the context of the first demonstration project, grid-forming control mode is seen as a potential add-on demonstration to the multi-vendor capability. Regardless of the topology of the demonstrator it will be beneficial for supporting measures of the AC grid(s).

However, a commonly agreed definition for grid-forming control is currently missing. For onshore and synchronous systems a definition is proposed by CIGRE [30]. Additionally for normal operation a constant frequency support is mentioned in the CENELEC 50654 [2], however it is questionable whether this can be defined as grid-forming. Development of grid-forming functional requirements for multi-terminal HVDC grids is part of the interoperability workstream, where functional requirements for both HVDC converters and DC connected power park modules will be developed. Finally, recommendations for grid-forming functional requirements in upcoming amendments to the HVDC grid-code will be proposed.

### DESIGN IMPACT: TOPOLOGY SELECTION

With the respect to the demonstrator, it is beneficial if the topology either allows for

1) Contribution of grid-forming in the form of stabilizing and synchronizing power (e.g. synthetic inertia) cascaded from one synchronous area to another via the multi-terminal HVDC grid, or
2) Contribution of grid-forming in the form of stabilizing and synchronizing power cascaded from offshore power park modules to the onshore system via the multi-terminal HVDC grid

Demonstration of grid-forming capability of multi-terminal HVDC grids is not a strict requirement for the very first multi-terminal multi-vendor HVDC grid but should be considered as a non-mandatory option.

## FUNCTIONAL REQUIREMENT: IMPROVEMENT OF ANCILLARY SERVICES

### DESIGN IMPACT: OVERPLANTING OF WINDFARMS & DELOADING BELOW MPP

To overcome the drawbacks of current P2P HVDC installations with low full load hours, it could be beneficial to overplant windfarms. This may lead to an improved socioeconomic welfare for the project and improved business case for the power plant owner, while reducing the cost for the transmission systems and the environmental footprint. Especially in the context of hybrid interconnectors this could be a preferable option. Whether this is a desired solution or not depends on the project specific setting and details which influences the overall business case of the project. Furthermore, there is a higher availability of active power to support the AC grid according to instantaneous power demands in case of fault or an exceptional contingency, when the wind turbine generators are running in supressed mode and could increase the injected power immediately.

## FUNCTIONAL REQUIREMENT: REDUNDANT COUPLING

### DESIGN IMPACT: OFFSHORE AC CONNECTION

An alternative, or supplement, to DC connected converters could be an AC offshore connection. Based on offshore DC topology and its design (e.g. distance between offshore converters/platforms, protection concept, power exchange between converters, etc.) a selection between DC or/and AC offshore connections will be made. An AC connection may lead to interaction of nearby converters which could require an adjusted grid forming control mode. Despite the increased risk of control-interactions, the opportunity to be able to interconnect multiple wind-farms on the remote-end of the multi-terminal

HVDC system can provide some operational flexibility during contingencies or planned maintenance. Thus, for the purpose of MTMV demonstration, the ability to couple potential remote-end HVDC converters on the AC-side shall be allowed.

## FUNCTIONAL REQUIREMENT: FUNCTIONS REQUIRING USE OF TECHNOLOGY COMPONENTS CURRENTLY OF LOW TECHNOLOGY READINESS LEVEL

### DESIGN IMPACT: INCLUDE TECHNOLOGIES NOT BEING OPERATED IN THE EUROPEAN TRANSMISSION GRID UP TO NOW

Introducing new technologies into the electrical transmission grid is a time-consuming process. The technologies undergo various stages of so-called technology readiness levels. At the same time the speed for connecting offshore wind energy needs to be tremendously increased to cope with the goals of climate neutrality in Europe 2045. This results in the need of installing products, e.g. DC fault separation devices, which have only been tested in laboratories at lower rating, or outside Europe. Another example are High Temperature Superconductor (HTS) DC power cables which are at TRL5 to 6 according to ENTSO-E's Technopedia [31]. As the goal is to *demonstrate* a MTMV HVDC project it is accepted by the community of stakeholders that also technologies will be included which may not be at the final stage of the development process.

## FUNCTIONAL REQUIREMENT: REDUCTION OF TECHNICAL COMPLEXITY/RISK

### DESIGN IMPACT: DEMONSTRATOR PROJECT FOR FIRST MTMV PROJECT DOESN'T AIM TO SOLVE ALL ISSUES FROM THE BEGINNING

The implementation of several technologies that have not been used before or not been used together may lead to an overall enhanced complexity. This could simultaneously lead to also a higher risk for failure which needs to be taken into account. It is the aim to reduce the overall risk to the possible minimum while achieving advancements on the agreed criteria. Thus, the demonstrator project for the first multi-terminal multi-vendor project should not aim at solving all issues from the beginning.

Subject areas in this context could be:

- Primary equipment

Hereunder the use of novel types of primary equipment like DC-FSDs can be mentioned. As previously mentioned unclarity in the context of the requirements to the DC-FSDs increase the risk of implementation. On top of that the technological readiness level needs to be further enhanced to implement such products in full scale applications.

- Control & Protection

As PEI devices depend mainly on their control implementation a high share of potential complexity falls under this topic.

To be mentioned here are the wide area- and grid forming controls.

Also, electrical proximity of converters may lead to interactions. This would require (superordinated) coordination.

Additional topics to be mentioned under a MTMV arrangement are energization of the DC grid, protection philosophy, communication interface, shut down, Master/Grid-controller design.

- MPI

The simultaneous requirements of asynchronous AC grids together with the integration of wind capacity may lead to increased optimisation tasks to be solved.

- Multiple TSOs

Introducing MTMV HVDC projects with multiple TSOs in the implementation plans will lead to an increased complexity on regulation.

- Number of vendors

Further, the more parties involved the higher communication and reconciliation effort.

Despite all the downsides which may result out of increased complexities and risks it is proposed by the community to also acknowledge the knowledge which can be gained, especially within the boundaries of a demonstration project.

### Technical criteria - Mechanical

In addition to the electrical criteria which define the functionality of the system the actual realisation in terms of construction needs also to be taken into account. Electrical functional requirements elaborated in previous sections will have direct impact on the mechanical design and construction of the HVDC systems. This topic is primarily important to the installation of newly added primary equipment. For example, definition of the protection concept will lead to different size of platforms and footprints (additional equipment needed). Furthermore, installation of DC cables can be directly impacted by the definition of transmission solution, redundancy and protection concept. Depending on that the DC cables can be buried as a bundle or separate having direct impact on the installation costs, permitting etc.
The corresponding space requirements are considered by the responsible bodies within their planning processes.

### Economic criteria

The market-based procurement process of HVDC projects includes in a relevant share economic aspect. For a MTMV demonstration project the following subjects may be of importance:

- Cost-Benefit analysis (CBA)
- Cross-Border cost allocation (CBCA)
- Procurement strategy of converters, cables, circuit breakers as wells as contractual set-up
- Optimal placement in the European grid (supporting the integration of wind power)
- recommendations for business case of grid forming needs to be given

As these aspects are part of the READY4DC WG4, the results of this work are referred to [7].

### Environmental and circularity criteria

Following the adoption of the recast Energy Efficiency Directive in 2023, EU Member States must ensure that the Energy Efficiency First Principle (EEFP) is assessed in planning, policy and major investment decisions of energy systems with a value of more than €100,000,000 (Article 3). The EEFP is defined by the EU Governance Regulation[1]

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[1] Article 2 (18) of Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action: "'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives

Member States are required to report to the Commission, as part of their integrated national energy and climate progress reports, on how the energy efficiency first principle has been into account in planning, policy and major investment decisions related to the national and regional energy systems. Moreover, they must encourage TSOs and DSOs to develop innovative solutions to improve the energy efficiency of existing and future systems through incentive-based regulations in accordance with the tariff principles established.

The Energy Efficiency Directive's Article 27 on Energy transformation, Transmission and Distribution also establishes that TSOs and DSO are required to:

- apply the energy efficiency first principle, in their network planning, network development and investment decisions;
- implement the energy efficiency first principle when approving, verifying or monitoring their projects and network development plans with regards to the Ten-Year Network Development Plan (TYNDP);
- assess alternatives in the cost-benefit analysis and take into account the wider benefits of energy efficiency solutions, demand-side flexibility and investment into assets that contribute to climate change mitigation;
- monitor, quantify and report the overall volume of network losses and, if technically and financially feasible, optimise networks and improve network efficiency;

### Location of the demonstrator project

According to the Interoperability workstream [1] the first MTMV demonstrator may represent an on- or offshore case. The characteristics of the AC network(s) to which the DC grid is connected may influence the ability to demonstrate various functionalities. In principle MTMV grids can either be:

1) Embedded within one synchronous area, where there are direct impedance paths around the interfaces of the DC grid.
2) Act as (hybrid) interconnector between different synchronous areas or electricity market price zones, which may be coupled or decoupled from a synchronous point of view.
3) Act as transmission connection for integration of large-scale renewable energy, where the HVDC converters interfacing towards power park modules are defined as remote-end HVDC converters. These are typically installed in an offshore environment where space is limited.

The functional specifications should to a large extend be universal, such that they are applicable to several variations of multi-terminal HVDC grids. However, it is likely that some project- and application specific designs are needed, depending on the overall use case of the multi-terminal HVDC project.

Similarly, it may influence if the DC switching station is located in an onshore or an offshore environment. On the onshore location the CAPEX and OPEX of equipment is lower, which leads to lower financial risks for the first project when deploying new technology such as DC fault separation devices.

On the other hand, onshore DC switching station are subject to higher acceptance problems than offshore installations due to the space requirements, visibility as well as the impact of the electromagnetic fields on health issues.

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and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions”

## 4.3. Selection of potential candidate projects

Based upon the selection criteria defined in chapter 4.2, it is now possible to propose a set of MTMV demonstration projects to be placed in the European transmission grid. Therefore, it is first necessary to collect all upcoming DC projects within Europe. These projects are listed in Appendix 8.1 after screening of the TYNDP, network plans at national and EU level, the German Network Development Plan (NEP), the HVDC Newsletter (SGI), TSO documents and receiving input of stakeholders. Out of these DC projects, possible MT projects are derived in Appendix 8.2. To further filter out the most likely projects for MTMV the purpose(s) of each needs to be clearly stated. Therefore, the following information to be outlined in a network diagram is minimally required to include a project in the selection process [1]:

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

Hereupon, the network diagrams can be compared to the selection criteria. The projects which can fulfil all necessary criteria defined previously will be further investigated.

Despite this approach being straightforward, the lack of TSOs providing possible MTMV projects has led to the fact of having only four proposed projects, namely:

- Bornholm Energy Island [32]
- North Sea Energy Island [33]
- Project Aquila
- Generic MTMV system hub

So, a selection of projects is not needed as the goal is to recommend a list of up to three potential candidate projects [1] including their locations and their suitability. These three possible MTMV projects are presented below.

### Bornholm Energy Island

Denmark and Germany's transmission grids may become connected via the Bornholm Energy Island, which has HVDC links to offshore wind farms in the Danish Baltic Sea. For the Bornholm Energy Island [32] a topological drawing was provided and can be found in Appendix 8.3. The Bornholm Energy Island consists of wind farms with a capacity of 3 GW, two converters connected in parallel per station and bipolar HVDC transmission systems with metallic return (2x600 MW (Denmark) and 2x1000 MW (Germany)). It will be expanded in a later phase. The nominal voltage of the AC grid is 400 kV, and the nominal voltage of the DC grid is ±525 kV.

### North Sea Energy Island

The North Sea Energy Island will operate as a hub in a network of 10 surrounding offshore wind farms in the North Sea, with connections to Denmark and Belgium with possible expansion to the UK, the Netherlands and Germany [33]. A topological drawing of North Sea Energy Island can be found in Appendix 8.3. In the phase1, the North Sea Energy Island consists of wind farms with a capacity of 4 GW, two converters connected in parallel per station and bipolar HVDC transmission systems with metallic return (2x1000 MW). It will be expanded in a later phase. The nominal voltage of the AC grid is 400 kV, and the nominal voltage of the DC grid is ±525 kV.

### Project Aquila

Project Aquila is a combination of two TSO HVDC Bipole +/-525kV projects - one between Peterhead, Scotland in the North East of UK, and the midlands of UK in South Humberside and another from the far north of UK at Spittal in Scotland connecting also to Peterhead. At the Peterhead location a "DC hub" will be established in 2030 consisting of running these two discrete projects through a discrete DC busbar within the Peterhead DC switching station to a vendor developed point to point control. Thereafter a multi-terminal multi-vendor control will be introduced to enable a 4-terminal multi-terminal, multi-vendor operation. The MTMV control approach has been developed in RTDS by the National HVDC centre GB, consulted upon and reviewed within the GB interoperability expert working group and tested against HVDC component, control and protection models of sufficient detail that modelled vendor code/ interfacing hardware replicas may substitute or be substituted with those models. This modelling approach is founded on the learning generated under the Best Paths and Promotion analysis and the de-risking and implementation of the Caithness-Moray-Shetland Project, and the development of new approaches to small signal modelling and device characterisation in the frequency domain undertaken by the Centre. Project Aquilla is further over this year (2023/24) testing the MTMV approach using vendor replicas- initially in a "virtual replica" format. A virtual replica represents an approach where real vendor code is integrated into a real-time wrapper via a modelled interface to the network simulation in real time and can in principle be provided in the same points that offline EMT models would be, requiring less adaptation/ flattening of the vendor code being introduced. Early work has supported an MTMV specification for the projects which will be further refined across subsequent project stages. The MTMV control approach under demonstration is a distributed and supervisory approach to control which looks to capture and characterise an individual converter response within the DC network and define conditions of efficient and stable operation across that network both to intact and post disturbance (N-1) operation. The Centre has patented the underpinning approach and control in order to protect the space for vendor solutions to be implemented across multiple vendors using these same techniques. The demonstration is "Safe to fail" given that operational switching can quickly re-establish single vendor point-point operation. The DCSS at Peterhead under Project Aquila has been built with flexibility for extension; these extensions being to accommodate further offshore wind generation convertor terminals within that network, with the possibility at a given point of generation connection scale to also extend to include DC Circuit Breakers within that same arrangement. This latter area of specification is being taken forward within a UK innovation project Network DC with outputs and testing against the intended specification

### Generic MTMV system (4 Terminal hub)

A more common approach to define a system can be done by describing a generic system, similar to the most probable system designs mentioned above.

At least two offshore wind parks, OWP1 and OWP2 should be connected, where OWP means the combination of WTGs, transformer and converter incl. converter platform. The OWPs WTGs are injecting MV/HV AC voltage (e.g. 66 kV to 132 kV) and are each connected via one or more transformers to an offshore converter station, which rectifies the extra high AC voltage to extra high DC voltage of the range from +/-320 kV to +/-525 kV or more. The WTGs of OWP1 and OWP2 could operate at separate AC voltage levels, the converter transformers will ensure the right voltage level at the AC side of the converter to be converted to DC, so that the DC voltages of the different converters could be connected together via an DC substation. The substation connects the same poles of the different systems, like plus pole to plus pole, minus pole to minus pole etc. each converter (Bipole or Monopole) has a connection to the DC substation, where both OWPs could be connected to two different AC grids via an HVDC cable or overhead line. In case of an offshore DC substation, a cable system is required. The converter stations need to have a compatible grounding connection to ensure proper operation. The transmitted active power of the DC cable or overhead line system (plus and minus pole) is limited to 2 GW for each one (e.g. 2 x 1GW for each pole). The two different AC network connections may not origin out of the same synchronous area. AC1 and AC2 could be different synchronous AC grids. The DC substation allows multiple configurations to run the DC grid. OWP1 could transmit its complete power to AC1, while OWP2 is only supplying AC2. In connected mode, the power transmission could be distributed between these four nodes. Even an AC1 to AC2 or vice vera power transmission is possible, if the OWPs are only running in standby mode during slackness of wind power. The requirements for a fault separation device (e.g. a DC-CB) should be derived from the minimum of the maximum allowed power outage of the two AC grids.

From the practical point of view, a MT system from one vendor would be the best solution to get a reliable DC system. But, with respect to future development processes, avoiding overwhelming hurdles will not lead to improvement and optimized systems. In this context, the first demonstrator project should find a compromise between ensuring reliable systems and including new interoperable methods to enable MV systems for the future.

To satisfy the requirements of a MTMV system, the converters of OWP1 and AC1 should be delivered by vendor V1, the converter of OWP2 should be delivered by vendor V2 and the converter at the AC2 point of connection should be delivered by a third vendor V3.

All of the above-mentioned projects have the task to transmit energy and power from the offshore to onshore and inject the power into existing AC systems. The impact to the AC system is the most important aspect for deriving the requirements to connect and run the DC grid. Since the most DC systems are point to point systems with only one two terminal stations, mainly two nodes of connection, one sending node and one receiving node, the effort of controlling a DC system with 3 or more nodes will increase the effort to drive the whole system in a secure mode will increase enormously.

## 4.4. Procedure for selecting functional specifications beyond the first demonstrator

To achieve aligned rules for the deployment of multi-terminal multi-vendor (MTMV) HVDC grids, namely a future DC network code, the starting point is to outline a procedure on how to select functional requirements. Within that procedure, which is described in this section, emphasis is put on including the position of all possible stakeholders.

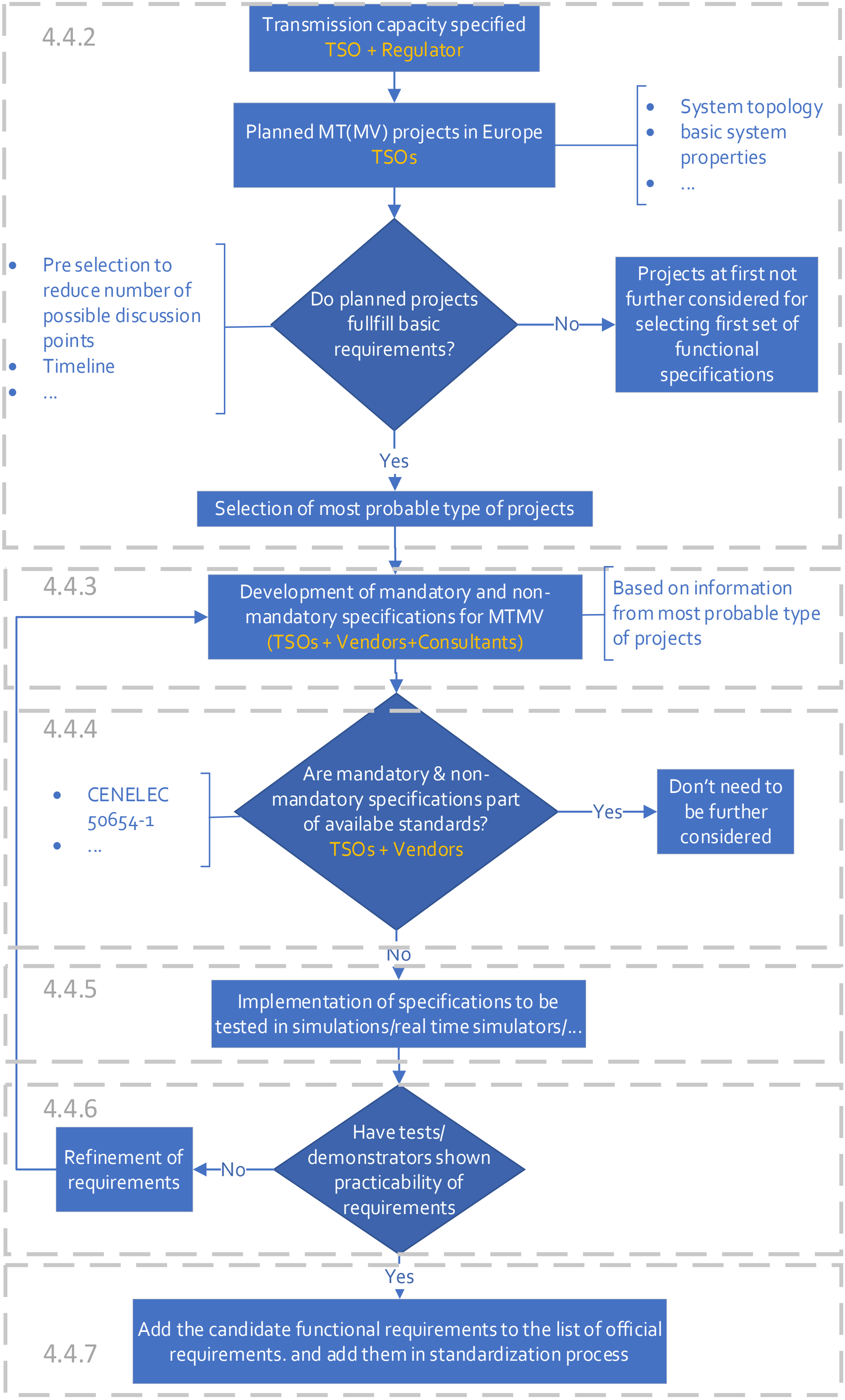
Subsequently, the process structure concludes out of the discussions in this working group. The approach is to first select the most probable MTMV types of projects currently planned in the European transmission grid and derive upon their detailed functional requirements necessary & beneficial (must-have and nice-to-have) specifications for MTMV. These necessary & beneficial specifications will be in a next step compared against available standards. The intention with this concept is that the gap analysis doesn't need to be conducted based on generic use cases with a wide range of variations. It rather takes the specifications of planned real-life project types provided by the TSOs; followed up by the other stakeholders providing support in identifying gaps to what is needed for MTMV grids.

The subsequent steps describe the process of using the identified gaps in (real-time) simulation and real-life projects to show their practicability. In the end, an outlook is given on how to handle the identified gaps by a.) Refining the requirements: This process is to assure that selected functional requirements are achievable with technical solutions having a sufficient level of maturity. This shall include individual components and sub-systems as well as their overall HVDC system integration. b.) If practicability/maturity is proven to integrate them in the standardization process.

The procedure shown in Figure 4-1 summarizes the identification of the functional requirements for MTMV grids.

**Figure 4-1**

Procedure for selecting functional specifications



### 4.4.1. Pick up Existing Standards

The development of guidelines and standards for HVDC grids has been performed worldwide for a long time. One of the first HVDC standards is the IEEE 1378-1997, which focuses on HVDC systems with 6-pulse or 12-pulse thyristor valve converters operating as a bipolar HVDC system [34]. In recent years, numerous other standards on HVDC systems have been developed in the USA, Europe and China. IEEE Standard 1378-2022, a new version of the IEEE 1378-1997 Standard [34], describes guidelines for the commissioning of high voltage direct current (HVDC) converter stations and associated transmission systems [35]. For many years, China has been established many HVDC projects and has mainly defined the HVDC design standard, HVDC electricity industry standard, HVDC equipment standard, HVDC construction standard and HVDC testing standard [36]. Recently, the China GB/T 40865-2021 standard has specified the terminology for HVDC transmission based on voltage source converters (VSC-HVDC) [37]. In parallel IEC has published in 2014 the standard 62747 on Terminology for Voltage Sourced Converters (VSC) for High Voltage Direct Current (HVDC) Systems.

In Europe, numerous publications on HVDC grid systems were presented, including CENELEC standards, CIGRE publications [38], [39], [40], European project reports and ENTSO-E publications. Especially, CENELEC technical specification CLC/TS 50654-1 [2] guideline for functional specifications and CLC/TS 50654-2 [11] parameter lists are technical reports providing guidelines and parameter lists for functional specifications of HVDC grid systems. CENELEC documents provide the basis for the development of HVDC standards by the International Electrotechnical Commission (IEC). The technical committee IEC TC 115, which has the task of preparing standardisation in the field of HVDC transmission technology above 100 kV, has been working on functional specifications for HVDC grid systems and connected converter stations [12] [13]. The publication of IEC TS 63291-1 ED1 and IEC TS 63291-1 ED2 on functional specifications for HVDC grid systems and connected converter stations are scheduled for publication in November 2023 [12] [13]. The documents of IEC TS 63291-1, which are based on the CENELEC documents of CLC/TS 50654, deal with the planning, specification and implementation of HVDC grids including multi-vendor HVDC grid systems. Currently the IEC TS 63291-1 (or CENELEC CLC/TS 50654) standard includes the technical aspects of the following points:

- Coordination of HVDC grid systems and AC systems
- HVDC grid system characteristics
- HVDC grid system control
- HVDC grid system protection
- AC/DC converter stations
- HVDC grid system installations
- Models and validation
- HVDC grid system integration tests

Using the IEC TS 63291-1 standard as a basis, the functional requirements for all components and subsystems will be specified for multi-terminal, multi-vendor HVDC structures. First of all, it is necessary to define what kind of specific issues are not covered by the CENELEC standard for MTMV HVDC projects. The READY4DC working group conceives that grid forming functionality is crucial for future power systems with more VSCs. However, the grid forming feature is not specifically addressed in the IEC TS 63291-1 standard or in the CENELEC CLC/TS 50654 guidelines. It may be expected that when IEC TS 63291-1 standard will be published in November 2023, the revised final document would include grid forming in the standard for HVDC grids.

In addition, the earthing concept of point to point and connected MT MV HVDC grids is a basic issue to be well defined with respect to insulation coordination during system faults, short circuit currents and interaction between the different poles in case of pole to ground faults.

### 4.4.2. Selection of most probable type of projects for MTMV

After having collected available standards, the next step is to derive possible *types* of MTMV projects whose functionalities can be compared against these standards. It is hereby important to mention that *types* of projects are being introduced as the future functional specifications need to be universally applicable and not based on project specific requirements.

For the selection of the most likely project types for MTMV three approaches are available:

1. Based on generic use cases
2. Based on planned real-life projects
3. A combination of the above

With regard to the first approach there is a lot of literature available which provide possible topological solutions for MTMV grids [41] [42]. To define a topology analysis framework and compare the solutions provided by their goals, opportunities and vulnerabilities was not considered useful in this project. The high number of variations to be discussed would have led to an inefficient and time-consuming process as prioritizing certain criteria can't be conducted objectively. It rather follows the prioritized needs of the single TSOs. On top of that, another parallel running EU funded project *HVDC Wise* [43] tackles this issue. The deliverables published by HVDC Wise will be incorporated as far as possible within the duration of READY4DC.

The second approach above may therefore be feasible for the selection of possible MTMV project types. As described in section 0 and according to the procedure of Figure 4-1, a selection of potential candidate projects can be conducted. Projects with similar specification will be in a next step converted to type of projects and sorted into classes. From this, the use-case that is most relevant for the given demonstrator project and the involved stakeholders can be chosen. There should be flexibility to make small adjustments to the chosen use-case to align it more with the interests of all stakeholders. Some example adjustments are mentioned further down in this section.

The third approach uses planned real-life projects as a basis for defining semi-generic use cases. This method can keep the initial variations of use-cases to a minimum by first choosing a real-life project, and then specific adjustments can be made to the chosen project to make the system for study more generic, providing more future-proof results. Alternatively, a generic use-case proposed in existing literature that is similar to the chosen real-life project can be used. This can also be done in reverse by first choosing a generic system and then applying adjustments to this based on one or more chosen real-life projects. However, this procedure can lead to the same issues with time-consumption as mentioned for approach 1.

#### CLUSTER TYPE OF PROJECTS WITH COMMON CRITERIA AND INTRODUCE CLASSES

Four generical MTMV layouts are introduced in Figure 4-2 – Figure 4-5. These project layouts show possible use cases for MTMV. Real HVDC systems are designed in a variety of ways based on project specific requirements (see the selected potential candidate projects in section 0). This leads to the fact that HVDC systems can have various DC and AC topologies, and HVDC system configurations differ based on the number and locations of the converters. Therefore, a harmonisation of the generic use cases together with the most probable type of projects, derived in a first step out of the projects in section 0, is applied in Figure 4-6 and Figure 4-7.

- **Multi-infeed HVDC system with single AC grid**: This HVDC system typology has multi-infeed and a single AC grid. This HVDC system typology can be used for large-scale offshore wind integration and transmission grid interconnection, such as Energy Island (see Figure 4-2(a) and Eurobar, an initiative of eight European TSOs [44], a meshed HVDC offshore grid project [20] (see Figure 4-2(b).

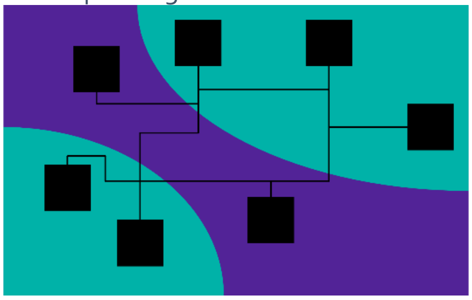
**Figure 4-2**

Multi-in-feed HVDC system with single AC grid, (a) energy island and (b) Euro Bar or Meshed

- **Multi-infeed HVDC system with multiple AC grids**: In this HVDC system typology as shown in Figure 4-3, the HVDC system consisting of multi-infeed and multiple AC grids is capable of interconnecting multiple asynchronous AC grids or multiple AC grids with different frequencies. This HVDC system typology can be used for large-scale offshore wind integration and transmission interconnection, such as the Ijmuiden Ver project, which may be used as a multipurpose interconnector [45].

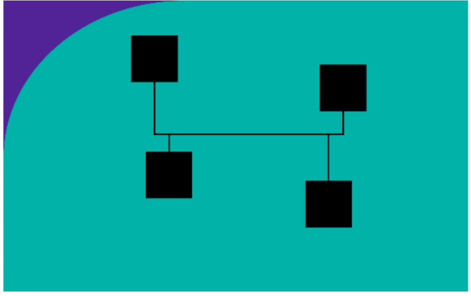
**Figure 4-3**

Multi-infeed HVDC system with multiple AC grids



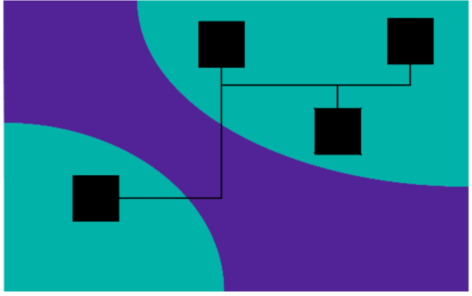
- **No-infeed HVDC system with single AC grid**: The other HVDC system typology, as shown in Figure 4-4, has no feeder and a single AC grid. This structure can be embedded in the same AC grid to improve the grid’s transmission capability.

**Figure 4-4**
No-infeed HVDC system with single AC grid



- **No-infeed HVDC system with multiple AC grids**: Finally, another HVDC system (see Figure 4-5) has no feeder and multiple AC grids and can be embedded in the different AC grids to enhance the transmission capability of the grid.

**Figure 4-5**
No-infeed HVDC system with multiple AC grids



Based on the planed MT projects in Appendix 8.2, the system layout of a first use-case should be based on a multi-infeed HVDC system, as shown in Figure 4-6. The converter stations should be provided by three or more vendors [1]. The proposed system consists of one synchronous onshore AC grid, but with potentially different market areas. A recommended adjustment to make this use-case more generic is to have two asynchronous AC grids onshore, as illustrated in Figure 4-7. This way, interconnection of the asynchronous European grids (GB, Nordic, continental Europe) will be considered. Another proposed adjustment is interconnection on the AC side of the PPMs, if this is in the interest of the stakeholders. A fallback option if the proposed use-case results in an unrealistic scope within the timeframe of the demonstrator project might be two separate P2P connections.

**Figure 4-6**

Multi-infeed HVDC system with one synchronous AC grid but with possible different market areas

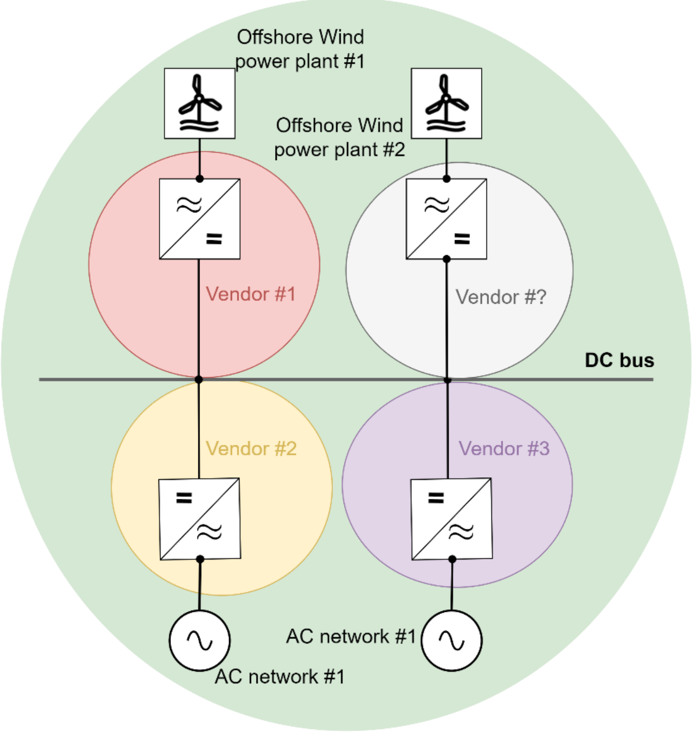
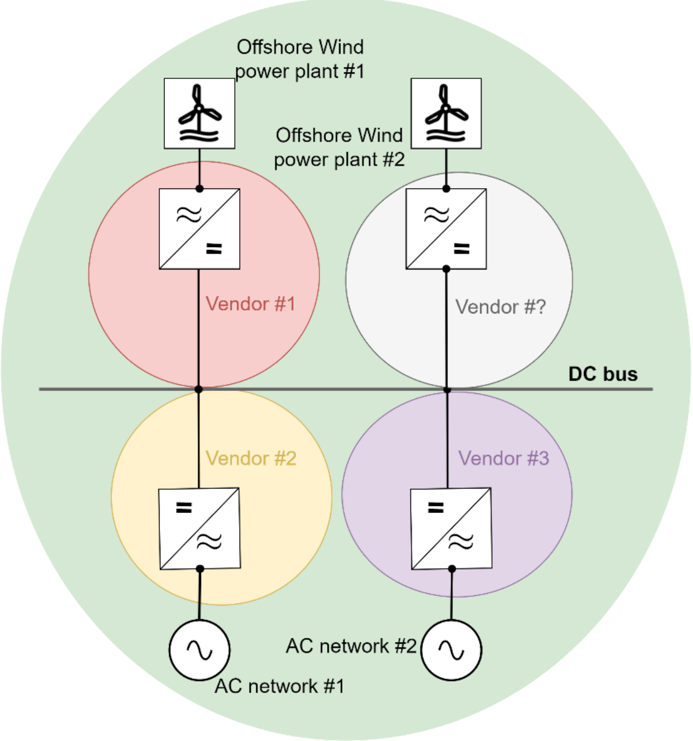


**Figure 4-7**

Multi-infeed HVDC system with two asynchronous AC grids



### 4.4.3. Development of mandatory & non-mandatory specifications

After having identified the most probable type of projects, like it has been exemplarily done in Figure 4-6 and Figure 4-7 , a set of mandatory and non-mandatory specifications for MTMV can be deduced.

In a first step it is agreed that the TSOs or project developers provide information on a range of minimum functional requirements based on the previously defined most likely type of projects. The information to be provided may be structured after Appendix 8.4. Together with the support of vendors and consultants the requirements will be divided in two groups of functional requirements a.) Mandatory and b.) Non-mandatory

In a second step the requirements will be translated into functional specifications. This will again be done by all relevant stakeholders.

This approach ensures that all relevant parties participate. To differentiate between non-mandatory specifications leads to enhanced speed of the process.

The above approach has been carried out in this project based on the type of projects in Figure 4-6 and Figure 4-7 to propose a first set of necessary functional requirements. The main difference between the two types of projects lays in the connected onshore AC networks. It is expected that the requirements will mostly diverge in the context of grid code compliance and dispatch coordination.

Table 4-3 shows a comparison of the requirements for the two different types of multi-infeed with a.) single AC grid and b.) multiple AC grids. The information on requirements collected in Table 4-3 may forthcoming be translated to functional specifications. Afterwards the developed functional specifications are to be compared to existence in available standards.

**Table 4-3**

Comparison of the functional specifications based on the defined requirements for the use cases a.) Multi Infeed with a single AC grid b.)Multi Infeed with multiple AC grids

| Requirements | Multi Infeed with a single AC grid | Multi Infeed with multiple AC grids |
|---|---|---|
| Power flow coordination | Coordination between converters needed | Top level DC grid controller to coordinate between the different AC grids and the converters |
| | In both cases top level scheduling control needed | |
| Grid forming control | Control system easier to operate as principle of grid forming the same for both onshore converter stations | Grid forming support more complicated as weakest network determines e.g. RoCoF; wide area control system needed |
| MPI | Hierarchy between different tasks (prioritization of transmission task/P2X needs/…) | |
| Energizing the DC Grid | Energization from several terminals (onshore/wind parks) requires coordination | Same requirements as Multi In Feed / Single AC but less impact on each single AC grid |
| DC protection / C&P | Different types of protection systems could disturb each other. | |

| | |
|---|---|
| | DC fault separation devices only needed for systems which can't fulfil grid code compliance.<br>DC fault ride-through capability to be coordinated between converter stations and possible DC fault separation devices |
| DC side interoperability | (Standard) Communication interface needed for coordinated behaviour of converter stations |
| HIL/SIL/offline | System behaviour to be initially verified by real-time simulations |
| Monitoring | Super visibility needed for operating staff to steer power flows |
| Fall back options | If interoperability is not achieved (e.g. DC-FSD cannot be included) fall back to P2P links is preferred |

### 4.4.4. Gap analysis to available standards

The existing CENELEC standard [2] [11] and IEC TS 63291 [12] [13] standard already contain a comprehensive overview of the requirements for HVDC networks, especially with regard to the overall structure of the document and its chapters. However, due to the immaturity of MTMV HVDC grid concepts, the standard remains vague in several aspects and descriptions beyond basic functionalities are not included.

During the work of this project the first attempt to point out gaps existing in available standards for the deployment of MTMV was to perform a general gap analysis to the CENELEC 50654-1 chapters [2], see results listed below. This approach provides the opportunity of stepping through each chapter/topic successively without forgetting issues. In addition, everyone can participate even without the knowledge of real projects. The challenge on the other hand is to neglect topics which are not already mentioned and are new to MTMV specific systems.

Consequently, another approach may be used, based on the necessary & beneficial specifications as well as use-case-specific gaps and their potential technical consequences. This provides the opportunity to more easily identify new and important topics which are not part of the available standards. The challenges could be for a limited number of suitable type of projects leading to difficulties of forming clusters of functional specifications. Furthermore, not all details may be allowed to be shared publicly.

Summarizing the basic needs of this approach, experts are required being familiar with the available standards. Additionally, a vision of what needs to be specified is needed to identify gaps. Therefore, as a first step, the information on already installed or currently constructed HVDC projects may be used for comparison, with Annex 8.2 listing the planned DC projects in Europe. Some of these projects are ALEGrO, Ultranet and A-Nord, BorWin4, Savoy Piedmont, IFA2, Sørlige Nordsjø II, Neu connect, Viking Link, Celtic Link, North Connect, Biscay Gulf, DolWin4, BalWin1, BalWin2, Suedlink DC3, Suedlink DC4, NOR 7-2 (BorWin6), Heide, etc.

#### PRELIMINARY RESULTS FOR GENERAL GAP ANALYSIS TO CHAPTERS OF CENELEC 50654-1

Upon a first screening of the chapters of the CENELEC 50654-1 document the following gaps could be identified which need to be considered in the future development of MTMV functional specifications. The resulting gaps are structure according to the chapters of the CENELEC 50654-1 [2].

# 4.0 Coordination of HVDC Grid System and AC Systems

## 4.3 AC/DC power flow optimisation

It is mentioned that less conservative attitude regarding available interconnection active power for hybrid MTMV HVDC systems may be entered.

TSOs may be able to reach agreements among themselves on the allocation of capacities and offshore grid codes (e.g. at which frequency the offshore wind farms are operated).

An important issue is who is responsible for topics such as DC power flow organized by voltage and droop characteristics. The control may by specified by a multi-master voltage controller which has to deal with certain voltage bands. In addition, it needs to be defined if one single master is responsible or multiple.

## 4.4.1 Basic operation functions – Converter normal operation state

Basic operating functions for the converter's normal operating state may be voltage control, power control including the inner control loops for the current, the voltage control of the converter arms, the energy control. Above listed points need further attraction in upcoming R&I projects to bring MTMV further.

## 4.4.2 Basic operation functions – Converter abnormal operation state

The basic operation functions for the converter abnormal operation state may take into account, for example, the grid forming functions, the grid forming detection method and the robustness of the grid forming. Currently the CENELEC 50654-1 mentions the gird forming methods but doesn't provide further details.

## 4.4.3 Ancillary services

There may be many opportunities for ancillary services in the environment of MTMV HVDC systems. It is worth mentioning that from a regulatory point of view, the coordination of services takes place across different synchronous areas, different market areas, inside or outside the EU.

Possibly an additional control and optimisation layer could be considered in order to exploit capabilities. Coordination between authorities could allow for better coordination to avoid discrepancies in terms of the power ramping rates.

For the MTMV HVDC system, it is crucial how the DC grid controller is connected to the wide-range measurements and what its priorities are.

The main constraint for the MTMV HVDC system is maintaining the balance of I/O active power in the DC grid, which has no large-scale storage on the DC side.

In case of a bipolar configuration having a fault on one pole, it shall be considered if it is possible to compensate with the healthy pole and combine with unloading of some AC connected areas.

## 4.4.3.2 Frequency control related services

The management of the voltage level according to the frequency support, the demand from the AC grid and the rate of change of the power need to be adapted to the capacity of the DC grid and the actual power of the connected DC feed-in points.

#### 4.4.3.4 Low frequency damping services

If several wind turbines are connected to the grid via a compensated line in series, the sub-synchronous torsional oscillations associated with the wind turbine generators shaft system should be taken into account.

It can be assumed that the setpoint of power transmission would not be located at the maximum and that a strategy would be followed to avoid oscillations generated by different DC feeding nodes (e.g. a random reaction time to start controlling the voltage drop).

## 5.0 HVDC grid system characteristics

As further gaps it has been identified that for HVDC grid scalability and for future interconnectability, there is a need to select and harmonize values for certain parameters, like DC voltage. Additionally, for scalability some safety margins may have to be integrated. As seen especially important are the cable specification as an important part to consider when selecting an "harmonized" DC grid voltage.

These topics are seen necessary to be solved for the pilot project, but not for all future HVDC systems. The gained experience could be used to address the scalability issues. Up to now only experience with small (maximum 3 terminals today) single vendor MT systems or single vendor P2P systems is available. Further experience will be especially useful to be able to specify consolidated safety margins.

### 5.4.3 Steady-state DC voltage

With regard to the steady-state DC voltage, the requirements must be aligned between, converters, DC stations and cables. These conditions include:

- voltage drop across cables (3-5 %)
- Max power to be transferred in all foreseeable power flows within DC grid
- Extension of DC grid
- Impact of harmonics
- Measuring errors
- Margin for flexibility in controls
- A possible prioritization of AC side voltage above DC side

### 5.4.4 Temporary DC voltage

For the temporary DC voltage, it would be noted that no specific curves are yet available to facilitate interoperability and expandability.

## 6.0 HVDC grid system control

### 6.1 Closed-loop control functions

In the context of possibilities for DC voltage droop the CENELEC 50654-1 [2] does not specify but only comments on droop based active power change. There are a variety of options available for dc voltage droop. Furthermore, a distinction between onshore and offshore requirements is not done in the CENELEC 50654-1 [2].

### 6.2 Controller hierarchy

A control hierarchy topic which has been classified of high importance is the TSO perspective on DC grid control requirements. It is questioned if it should include market optimization algorithms and what the relations are between this and other market platforms (PICASSO, NBM in Nordics etc).

### 7.0 HVDC grid system protection

Chapter 7 may miss in addition to the below mentioned gaps other topics which cannot be classified accordingly to the sections. One of these topics could be to include time periods in which a loss of active power infeed is allowed on the onshore AC grid side. This will then have a relevant impact on the whole system protection concept which needs to be addressed by e.g. the SOGL to address the impact on the HVDC system design.

#### 7.2DC Fault separation

It is observed that the CENELEC 50654-1 document [2] has no clear guideline on how to deal with DC faults and the corresponding separation of the system. It is mentioned that this depends on the dc protection strategy and dc topology if DC breakers are needed.

#### 7.4 HVDC grid system protection zones

For HVDC grid protection zones, correctly parametrised relays shall also be adjusted on the availability and the properties of the DC-FSD. Therefore, all specifications need to be adjusted according to the DC-FSD and vice versa.

#### 7.5 DC protection of the DC grid

In fact, it could be pointed out here that it is the impact of DC faults on AC networks that is not considered so critical for any AC connection.

### 8.0 AC/DC converter stations

#### 8.2 AC/DC Converter station types

The CENELEC 50654-1 document [2] does not state whether a bipolar or a monopolar with half bridge or full bridge technology is used for MTMV converters. Furthermore, the voltage level as well as power of the converter stations are not mentioned.

#### 8.5 Controls

A multi-master control of the voltage may be developed according to different grid control strategies in order to enable wide-area controls.

#### Use-case-specific shortcomings and development needs

In addition to the general gap analysis, it is seen as a complementary and beneficial approach to also address use-case specific gaps. The approach how to conduct is mentioned above. Within the time frame of this project results have not been obtained yet.

### 4.4.5. Indicate a way to move forward

Given the fact that identified MTMV projects are pushing technical boundaries beyond existing limits, recent standards do not yet cover all relevant details i) to avoid significant overregulation/-specification and still leave room for technical innovation, or ii) aspects are simply not fully captured as of today. Consequently, the development of a more profound understanding and a higher degree of experience must be aspired by pushing forward common specification activities or even real-life demonstrator projects.

In such projects, where uncertainties and technical hurdles can be experienced first-hand, the following tasks appear of upmost interest:

- Joint drafting of functional specification based on the procedure described in this chapter in a selected group consisting of highly relevant and HVDC-experienced stakeholders (e.g. HVDC vendors, TSOs, project developers/integrators, consultants, and research institutions)
- Performing of extensive testing prior to FST and commissioning utilizing the full spectrum of available tools
    - Initially, this includes in each case the set-up of a full-scale C&P replica involving multiple vendors for extensive testing and general validation purposes
    - Additionally, suitable offline-simulation frameworks shall be built, which are supposed to become more relevant to reduce hardware-related intensity and to be reliable in the long run. However, this is subject to achievable offline-simulation-model quality and accuracy needs.

In this context, the recently started project InterOPERA already fills a significant gap and is likely to contribute to a substantial experience growth in the right direction. Mainly, this is linked to the fact that:

- Several vendors are part of the InterOPERA consortium and work on functional specifications together with other relevant stakeholders
- Extensive replica- and offline-simulation-testing and -benchmarking is foreseen.
  Substantial experience is gained by gradually progressing along typical early project stages

### 4.4.6. Potential adjustments identified during the first demonstrator project

The common goal is to demonstrate correctness and adequacy of the initially compiled MTMV specifications during the first demonstrator project. This mainly includes C&P modelling aspects for replica- and offline-simulation platforms and requires that a MTMV C&P validation platform (initial MV test bench) is developed and clearly demonstrates compatibility with at least three vendors involved.

However, even though manufacturers are capable to provide appropriate C&P models for single-vendor applications as of today, several challenges or specification-related shortcomings might arise with respect to the substantially different setting and the overall complexity of the task.

Consequently, alongside the development and implementation phases of the first demonstrator, several options for action are to be kept open:

- MTMV specification updates: Based on the experience made or the challenges faced, critical parts shall be updated or at least further clarified
- Worst-case fall-back opportunities: To avoid stranded investments, several fall-back layers shall be incorporated, e.g. reduce MTMV complexity by splitting the DC-circuit into smaller subsystems like P2P schemes, reduce number of involved vendors, and reduce or refine advanced control as well as operational requirements
- Increased project-duration: To account for uncertainties, full-scale commissioning might be delayed. Nevertheless, parts of the system (e.g. subsystems like P2P) could be put into operation and expansions is made gradually.

It is important that for the first MTMV demonstrator that early demonstration making use of software in the loop real time simulations including virtual replicas, at the time of detailed design as updated through to commissioning with actual replica is taken. This is because it is possible to take an indicative collection of convertor designs and functions and as discussed within Project Aquila, use this to demonstrate a proof of concept of a practical basis for MTMV interoperability which can be further expanded upon across and following the detailed design phase therefore reducing the extent of iteration and re-work across vendors and providing further insight and demonstration across vendor and TSO of the given project approach. Finally, where such a demonstration is connecting to the onshore AC close to another HVDC project, this early demonstration will support early de-risking of interaction, informing other necessary control functions at an early stage in the project.

### 4.4.7. Beyond the first demonstrator

Depending on the outcome of the MTMV demonstrator project, different directions may have to be followed further.

At best, it is intended to obtain functional requirements that serve as a blueprint to enrich existing standards as they provide a meaningful and technically feasible common-sense agreed on between multiple highly relevant stakeholders. In that case, the publicly available demonstrator project deliverables and findings (e.g. specification documents, study results, development reports or logs) will present useful input to be reflected by the different standardisation committees. Furthermore, in case it has been identified that offline-simulations provide suitable results for a very wide range of required studies, replica-related activities can be narrowed down at least on a project-individual basis to avoid repetitive cost-intensive activities. However, an extended MV test bench (beyond the first test bench linked to the demonstrator project), which allows continuous inter-vendor compatibility tests and also allows additional vendors to test their MTMV interfaces, might be required [46]. Here, further aspects linked to hosting, supervising, operating and locating the mentioned extended MV test bench are to be discussed on a European level.

Assuming the most unfavorable case, the MTMV demonstrator project may not be able to fulfill the given functional requirements or might exceed the intended project duration or budget by an unacceptable margin. But even in this scenario, substantial experience and important findings may still be collected during project execution. Subsequently, a consolidation phase may be foreseen, and experience could be shared with other MTMV activities taking place around the globe. Based on a profound gap-analysis, feasible next steps might be taken to finally achieve the initially intended MTMV-readiness of the market.

Besides technical aspects, also administrative clarity is needed regarding the commitment, the role and responsibilities of different stakeholders. This aims to speed up planning and implementation phases including the exchange of relevant experience and shall foster meaningful collaboration among the different parties. Here, clear market rules including aspects like cooperation, aligned connection requirements, access for various parties to use and the possibility to share detailed simulation models for early stage or project-related activities, and commercially reliable market outlooks/ forecasts are needed. Otherwise, a risk remains that the required investments will not be unlocked.

# 5. KEY MILESTONES IN IMPLEMENTING A MTMV DEMONSTRATOR

This chapter focuses on the planning process for the first full-scale multi-vendor, multi-terminal HVDC system demonstrator. The process consists of multiple steps which need to be accomplished to achieve a successful operation of the first demonstrator project. Figure 5-1 depicts the steps required for the planning process in form of a flow chart. Each block of the chart is described in more detail in the subsequent sections. In addition, each step is assessed to address possible challenges and to mitigate risks to the first demonstrator project.

Section 5.1 covers preconditions and assumptions to be considered before starting the actual planning phase. This includes a clarification of key roles, a consideration of the legal and regulatory framework as well as the establishment of a standard language for the first demonstrator project.

Section 5.2 focusses on the planning and development of specifications for the first demonstrator. To this end, a conceptual MTMV system design is performed to define an adequate list of MTMV specifications. This list is iteratively refined and extended by gathering feedback from TSOs and vendors.

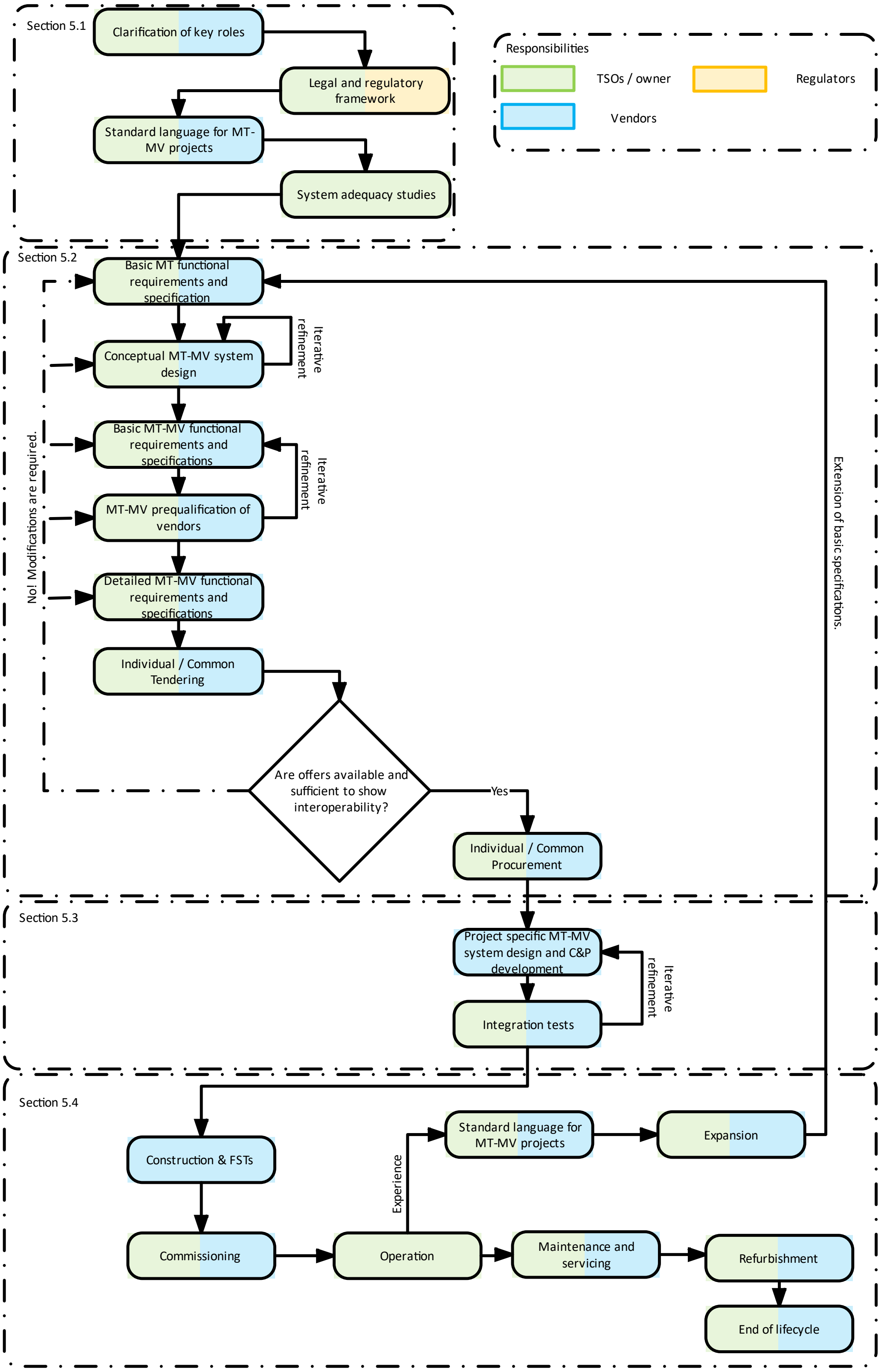
Section 5.3 addresses the project specific sub-system design for the demonstrator as well as the C&P development and necessary off-site integration tests. Especially for the first demonstrator this includes testing the C&P equipment from all vendors together in a hardware in the loop setup.

Section 5.4 contains the final steps of the planning process including the construction of the demonstrator, on-site tests and commissioning. In addition, possible expansion criteria for the demonstrator as well as maintenance, servicing and refurbishment topics are discussed.

Section 5.5 provides a timeline of key milestones for the planning process to indicate how much time should be scheduled for each step. Furthermore, potential overlaps of certain steps are described to identify which steps can be performed in parallel.

**Figure 5-1**

Flow chart of the steps required for the first MTMV HVDC system demonstrator. The roles and responsibilities of the stakeholders are marked in the corresponding color.



## 5.1. Preconditions and assumptions before planning phase

### CLARIFICATION OF KEY ROLES

At first, the key roles need to be specified. Also, the responsibilities and liabilities during all phases of the project must be clarified between the HVDC vendors, TSOs, project developers/integrators, consultants, certification authorities and others. A proposal for the responsibilities of the different stakeholders is given in Figure 5-1, with responsibilities marked in the respective colour.

### LEGAL AND REGULATORY FRAMEWORK

The development and operation of the MV-MT demonstrator involves various stakeholders and takes place in an environment with different national, legal and regulatory frameworks. The regulation can vary depending on the applicable national implementations which has a significant impact e.g. on the timeline for the demonstrator. Thus, it remains to be evaluated how the demonstrator is justified and executed within the various existing regulation regimes. A legal and administrative framework needs to be established to address the collaboration barriers such as implementation risks as well as time and cost impacts of the first project. Thus, it may be beneficial to include a MTMV demonstrator as a project of common interest (PCI) in the TYNDP on the European or on a national level within a grid development plan. This is part of WG2 of the READY4DC project and therefore not further discussed here. In addition to the regulatory framework, different system operation guidelines have to be aligned as well.

### STANDARD LANGUAGE FOR MTMV PROJECTS

Furthermore, a common agreement on a standard language for MTMV projects is necessary. CENELEC TS50654-1, -2, IEC TS 63291-1, -2 and grid codes could serve as a basis for the development of it.

On the one hand, a standard language includes a standard terminology for MTMV projects and assets. On the other hand, interoperability is dependent on establishing robust requirements and methodologies, as well as the development of appropriate control interfaces. Interoperability cannot be solved by such interfaces all alone, but they could build a framework to ensure a safe operation of the future European Energy system. In addition, the hereunder discussed interfaces may serve as beneficial keys to investigate potential interoperability problems. Two interfaces are discussed hereunder:

**i) Model sharing and workflow definition**

Generally model and workflow related aspects are important to investigate and resolve potential interoperability issues. Here, major associations like ENTSO-E and T&D Europe have published their different point of view within the last years.

**TSO perspective:**

From an TSOs perspective, it is recommended standardising a control interface via:

i. A strict separation between physical hardware from the control &protection

The inclusion of electrical power parts, e.g. valve representation, in DLLs could lead to numerical instabilities. Additionally, simplifications of modelling power parts should be traceable which is not possible inside a DLL.

ii. Divide the control layers in different blocks to separate the special functions

Having the control layers combined in one DLL could lead to simplifications and approximations. For TSOs performing the quality assurance and validation of the different subsystems it is therefore necessary to have the control blocks split up in multiple DLLs.

iii. Signal exchange via standardized interfaces

For TSOs handling their network models a standardized interface is required to achieve "Plug&Play" models of their assets, which has already been mentioned in the ENTSO-E position paper "ENTSO-E standardized control interface for HVDC SIL/HIL conformity tests" [47].

**T&D Europe perspective**

From a T&D Europe perspective, a documented interface for signals being identified as relevant is technically considered sufficient as described in the T&D Europe Whitepaper "Studies for Interaction of Power Electronics from Multiple Vendors in Power Systems" [48] as such - in case of need – can be adapted to project specific needs of today's highly customized and future interoperable systems while at the same time allow technical evolvements. Using different interfaces does not put any simulation goals at risk because state-of-the-art simulation tools are able to integrate several sub-models with different interfaces (e.g. coming from different vendors) into one large (simulation) model which can then be executed by a single instance of a simulation tool and creates the corresponding results. This functionality enables users to perform simulations not only from different vendors and / or system generations but also across domains (e.g. HV and MV systems). Nevertheless, on one hand, it needs to be further evaluated if an unique interface can be agreed and achieved (which could lead to an industry standard) while on the other hand, a workflow about how to handle models (e.g. defined time step across models) within the so far highly customized HVDC market needs to be defined and established. Also, it needs to be assured that the selected interface mechanisms (e.g. ENTSO-E interface or IEEE/Cigre/real code DLL Format + Wrapper) run stable irrespective of the tools, compiler (as far as possible), the version of the software environment, and the amount of electrical signals that are exchanged.

**ii) Interface between a grid level and station level control**

In terms of power flow optimization, it may be beneficial to also include an interface between a grid level control (e. g. a DC grid controller) and a station level control. For this purpose, different communication protocols could be utilized for such an interface. Potential protocols could be:

- IEC 61850 MMS or GOOSE
- IEC 60870-5-104
- OPC-UA
- Etc.

It is not in scope of this research project to properly evaluate the advantages and disadvantages of the mentioned protocols. Here, only a non-exhaustive list of potential protocols is given.

It might be beneficial, if these protocols could be used to control the converter station from outside the control system of the demonstrator and from outside the SCADA system of the network operator also, to limit control interactions over different synchronous areas. In order to operate the DC network, there needs to be a common dispatch setup and response to AC onshore wide area signals. Controlling the MTMV system from outside on a grid level is beneficial to assign dispatch power set points to the converter stations. Beyond that certain dynamic control of the grid might be necessary for which various strategies exists (e.g. Master-Slave control, droop control).

In that case adaptations of the TSOs cybersecurity requirements are necessary since those do up to now not allow a communication bus across the boundaries of the converter system. For more information, a reference to the ENTSO-E network code on cybersecurity [49] is given.

Additional clients should also be installed only to observe and record, without interaction, the traffic and information e.g. transmitted messages from all sending participants. These devices should be able to record defined timeslots to be able to analyse the exchange of relevant information between the controlling devices of the DC and AC network in case of a control problem or a fault situation.

Additionally, in case of a disturbance, all measured values could be recorded not only by the regular control and protection devices, but also by transient fault recorders, to collect data from independent sources and with higher resolution as at least required and to be able to analyse disturbances or contingencies in more detail. This helps to better understand and improve the functions of the devices for HVDC transmission, protection and control.

### SYSTEM ADEQUACY STUDIES

To assure optimal placement for the first MTMV demonstrator system adequacy studies need to be conducted. In Germany, this is partially covered by the regulatory processes which leads to the German grid development plan (Netzentwicklungsplan). These studies may include power flow, short circuit studies and also screening studies. By that, it is ensured that detrimental behavior of electrical installations is reduced to a minimum. At the same time, benefits like least economic cost and high utilization of the system are maximized.

## 5.2. Planning & Development of a MTMV HVDC system

To design an expandable MTMV HVDC system while limiting the scope of delivery of possible suppliers a proper definition of the converter and DC switching station behavior at the DC connection points is required to ensure that the overall system can perform in a sufficient manner. As no comprehensive knowledge (e.g. a DC grid code) exists yet, it is currently unclear what specifications are required at the DC connection point. This shortcoming will have to be overcome in the early planning phase of the first MTMV demonstrator. To this end, a first approach is presented in section 5.2, which covers the steps required for the planning & development of a MTMV HVDC system.

### BASIC MT FUNCTIONAL REQUIREMENTS AND SPECIFICATIONS

First, a basic set of high-level MT specifications is defined at a functional level based on available CENELEC or CIGRE documents. The aim of this step is to define appropriate specifications already at this stage that will be useful for the upcoming conceptual design of the MTMV system. The elaboration and assessment of the specifications will be predominantly performed by the TSOs using generic RMS, EMT or load flow models, with the vendors monitoring the feasibility to refine the proposed specifications.

Examples and recommendations for suitable functional specifications for the first demonstrator are stated in section 4.2.2. Those specifications are based on functional requirements listed in that same section. Functional specifications of the potential candidate projects for the first demonstrator (see section 0) may be used as well. If further mature specifications - which aren't listed in section 4.2.2 - are to be considered, a reference to section 0 is given. In this section, a generic approach for selecting functional requirements is described, which may be useful to define additional functional specifications.

## CONCEPTUAL MTMV SYSTEM DESIGN

Based on the defined basic MT specifications a conceptual MTMV HVDC grid system design is developed by the TSOs. It is suitable that the TSOs define the grid system design since only they are aware in detail about their system needs, which may result from operational philosophies or regulatory obligations, and since they will be responsible for the operation of the MTMV system. The first draft is then reviewed and commented by the vendors and iteratively refined with the TSOs. Additionally, to accelerate or cover a broader set of expertise, consultants experienced in design, testing and specifying operating requirements for HVDC systems can be involved. It is recommended starting with the development of a less complex system design to allow deliverable results and reduce the risk of failure. The level of detail can be increased step by step in future MTMV projects.

According to article 29 of the network code HVDC it must be guaranteed that no adverse interactions occur between multiple HVDC converter stations and other equipment located in close electrical vicinity. To achieve this, basic interaction studies should already be performed at this stage of the planning process. According to CIGRE B4.70, those studies could include control-loop interactions, non-linear interactions and harmonic interactions. These studies may be used for screening but do not cover all interaction studies required in achieving interoperability. In addition, references to CIGRE TB 909 (focus on small signal analysis like "Unit Interaction Factor", "Passive/Dynamic/Hybrid Frequency Scan" and "Radiality Factor" ) and IEEE 2800_2022 (focus on converter based resource connection) are given as these brochures provide valuable input for the interaction studies. The focus of those studies should at first lie on the AC-PoC to identify potential risks and issues when integrating a DC system into the AC network. The results are used to support the development of MTMV specifications at the AC-PoC.

Due to an unavailability of detailed models at that stage of the planning process, TSOs should perform the basic interaction studies using generic offline simulation models. Consultants can be involved if necessary. Detailed interaction studies analyzing more extensive phenomena of a MT HVDC system connected to an AC grid may be carried out at a later stage of the planning process, when vendors finished their detailed sub system design and detailed simulation models are available (see section 0).

## DEFINITION OF MTMV FUNCTIONAL REQURIEMENTS AND SPECIFICATIONS

Derived from the conceptual system design, a first set of MTMV specifications for the demonstrator is then defined by the TSOs. The basic MT specification serve as a basis for this. It has to be guaranteed that the developed MT specifications can also be fulfilled in an MV environment. For the first MTMV demonstrator the specifications are reviewed by the vendors. Consultants with adequate experience (see above) can be engaged by the TSOs if necessary.

## MTMV PREQUALIFICATION OF VENDORS

Following this step, a MTMV prequalification phase is initialized to examine if the vendors can fulfil MTMV interoperability with regard to the defined functional specifications. There may have been innovation projects performed beforehand using offline and hardware in the loop (HiL) simulations of the MT control using software in the loop (SiL) converter models to test interoperability. In addition, the prequalification phase may be used for the first demonstrator to tackle phenomena not being addressed previously.

Iterative adjustments of the specifications might be necessary depending on the feedback from the vendors. If required, an external test center or a consultant (profile as described above) can be engaged for the prequalification phase as well.

## DETAILED MTMV FUNCTIONAL REQUIREMENTS AND SPECIFICATIONS

After the prequalification phase, detailed MTMV specifications are to be developed. Detailed specification for the first MTMV demonstrator may include requirements dependent on operational conditions such as:

- Operating requirements for the individual HVDC stations (connection modes (Tables 44, 55, 59 from [11]), DC-Voltage vs. Power characteristics (Table 53 from [11])
- Energization and shut down requirements for individual parts of the system (Table 47, 50 from [11])
- Protection concept and protection zones (Tables 39, 40 from [11] )
- DC system restoration and reconfiguration requirements (Tables 37, 38, 45, 49, 50 from [11])
- Coordinated HVDC Grid System Control and Grid Controller functionality (Tables 30 – 36 from [11])
- System automatics, manual operation by operator
- Frequency related ancillary services – Emergency Power Control and POD (Tables 10, 14 from [11]) – coordination of DC power flows
- AC system restoration from blackout (Clause 4.4.3.5 from [11])

Several iterations with the suppliers must be guaranteed to assure the right requirements for the specifications are met.

## INDIVIDUAL / COMMON TENDERING AND PROCUREMENT

Next is the start of the tendering phase for the proposed demonstrator project. If no suitable offers can be provided by the vendors, changes at different stages of the specification process might be required since the specifications are too sophisticated. At the same time, it has to be assured that the functional requirements used for tendering are sufficient to achieve interoperability and thus enable a MV setup at all. Interoperability between vendors cannot be reached by design yet, thus additional time for development steps including according investigations which include all relevant stakeholders must be foreseen to find proper functional requirements. Only if different vendors can fulfill these requirements and their scope of responsibility is clear, Multi-Terminal Multi-Vendor HVDC systems can be realized. Otherwise changes of the MTMV specifications are necessary as well. Following a successful tendering the procurement phase is initialized. Both the tendering and procurement phase can be accomplished by the TSOs individually or commonly.

## 5.3. From a conceptual to a project specific MTMV system design

### PROJECT SPECIFIC, DETAILED MTMV SYSTEM DESIGN

The project specific work for the commercial MTMV demonstrator starts after the procurement process. Therefore, the vendor(s) carry out and provide a detailed sub system design (e.g. for the converter or DC switching station) based on the requirements and specifications they committed to in the tendering phase.

### C&P DEVELOPMENT

After the sub system design the vendors develop the control and protection software for converter and DC switching station. The functional performance will be demonstrated by software-in-the-loop and hardware-in-the-loop system testing. This will be done by the vendors individually. Software and hardware models may be exchanged based on the specifications agreed between the relevant stakeholders.

### INTEGRATION TESTS

Offline integration tests (e. g. load flow simulations, RMS, EMT), which will be extended in time for MTMV systems, are performed iteratively to refine and adapt the system design. Offline simulations of the detailed HVDC system are to be executed to assess possible performance issues and interactions. In addition, the correct functioning and performance of the C&P software for the complete MTMV demonstrator must be verified with offline studies. It is mentioned that more time needs to be scheduled for the C&P development and testing, especially in an MTMV environment.

If offline simulations are successful, integration tests on Real Time Simulations (RTS) may be carried out to examine and verify the converters and the MTMV systems performance and the compliance to AC grid codes in a hardware in the loop setup. Due to the complexity and the challenges inherent in a MV environment, it is recommended testing the C&P equipment from all vendors together as well as the MT control across the converters in a hardware in the loop setup (especially for the first demonstrator). Replicas of the real C&P cubicles from each vendor are used for this and installed together in one laboratory. They are connected to a real-time simulator and the functional and dynamic performance of the MTMV demonstrator as well as possible interactions are evaluated.

It is important to define test requirements for off-site and on-site tests. The requirements must reflect the specific system configuration, key design selections and intended operating modes (e.g. Bipole (with DMR), asymmetric Monopole etc.). For the different connection types, different off-site test scenarios could be considered, referring to [IEC TS 63291-1, Chapter 11.2.2.3]:

- Operating sequences as start, stop connecting and disconnecting HVDC stations and DC lines
- Power ramping
- Power and current step response
- HVDC grid controller functions
- AC fault performance
- DC line faults and recovery (if applicable)
- Small signal stability functions
- AC/DC and DC/DC intersystem faults

- Load rejections
- HVDC Grid protection performance and coordination

The following aspects may also be considered especially for the off-site testing:

- Test requirement for the communication system
- Test requirements for different load use cases
- Test requirements to verify fault clearing and fault protection behaviour
- Multi fault test cases and behaviour
- Special behaviour (e. g damping controls) of wind power parcs at different locations to be tested

In case of arising problems, detailed interaction studies need to be performed to analyze the interaction of the MTMV HVDC system. CIGRE B4.70, CIGRE TB 909 or IEE 2800_2022 could serve as a basis for potential study packages.

Practical real world and detailed insights into de-risking the testing procedure for UK's Project Aquila is given in the appendix 8.6.1.

## 5.4. Final steps from construction to the end of lifecycle

### CONSTRUCTION & FSTS & COMMISSIONING

Following the development of the MTMV system design the realization phase of the demonstrator begins. This includes the construction of offshore platforms, if any, as well as the required HVDC equipment. In parallel, the real C&P cubicles from different vendors are built and tested with factory system tests (FSTs). This means the vendors verify the implementation of the control and protection mechanism with a strong focus on the dynamic performance. An acceptance protocol is written after the FSTs. It is mentioned that for every sub system a FST is needed.

In addition, appropriate field tests verifying the compatibility of the systems on site need also to be considered. According to [2] on-site testing consists of three different phases. Pre-commissioning tests focus on electrical and mechanical tests as well as simple functional tests on all relevant items of an HVDC equipment. Subsystem tests are then performed to demonstrate a correct functioning of all individual items of an equipment within a subsystem. In the end, system tests are carried out including testing of the complete HVDC grid system. System tests focus on testing the initial energisation of the equipment as well as testing the total system in operation at different active and reactive power transfer according to the defined operating points of the MTMV system [2].

After the testing and commissioning phase of the individual systems and sub-systems the actual commissioning of the overall demonstrator can be performed. During this time the TSO staff and operators needs training from the vendors for first MTMV demonstrator. Before trial operation the operators need to gain sufficient experience and knowledge of HVDC systems.

### OPERATION & AND STANDARD LANGUAGE + EXPANSION

If the system testing is successful, the demonstrator can then be put into trial test operation for a defined time period and into regular operation afterwards. Based on the experience gained with the demonstrator in operation, adaptations of the standard language for MTMV projects and basic MT functional specification in terms of expandability can be performed. This includes possible new functions, software upgrades, cubicles and new technologies such as fault separation devices and DC-DC converters. Adjustments of the MT functional specifications during the lifetime of the demonstrator may also be required in case of major software updates. However, this is not discussed further in this document. If an expansion is foreseen the system shall be classified as expandable at the beginning of the planning phase to reduce refurbishment efforts later on. In this case it is beneficial to apply a modular approach for the MV-MT demonstrator, to ensure new modules work properly with the existing system.

### OPERATION & MAINTENANCE, SERVICING, REFURBISHMENT AND THE END OF LIFECYCLE

As the demonstrator continues to operate, aspects such as maintenance and servicing become a crucial part. Occurring faults, failures and incidents must be investigated in terms of servicing. Refurbishment as part of software updates, replacement of control and protection systems, primary equipment etc. must also be considered over time. Finally, the demonstrator reaches the end of its lifecycle and certain components or the demonstrator in its entirety need to be dismantled.

## 5.5. Timeline of Key Milestones

This section provides a timeline of key milestones for the first MTMV demonstrator to indicate how much time should be scheduled for each step of the planning process shown in Figure 5-1. In addition, potential overlaps of certain steps are highlighted to determine which steps can be performed in parallel. The interoperability workstream for MV-HVDC projects published by the ENTSO-E, T&D Europe and WindEurope (see [1]) is used as a first basis for the timeline. This first draft is then adjusted considering the feedback from all the consortium partners involved in this work package and the planning process described in section 5.1 to 5.4. The proposed timeline of key milestones is depicted in Figure 5-2. It is noted that the preconditions and assumptions covered in section 5.1 are assumed as fulfilled before starting the further steps of the planning process. Thus, the steps described in section 5.1 are excluded to figure 10.

The first three years of the timeline foresee a R&D phase including the conduction of the conceptual system design and the development of detailed MTMV specifications for the first MTMV demonstrator. It is recommended performing a first set of basic AC interaction studies in parallel to the R&D phase to further refine the conceptual system design. In addition, beginning in year 2, the MTMV prequalification phase will be executed. This parallel workflow gives the vendors the opportunity to provide feedback on their capability to fulfil the elaborated MTMV specifications at this stage of the project.

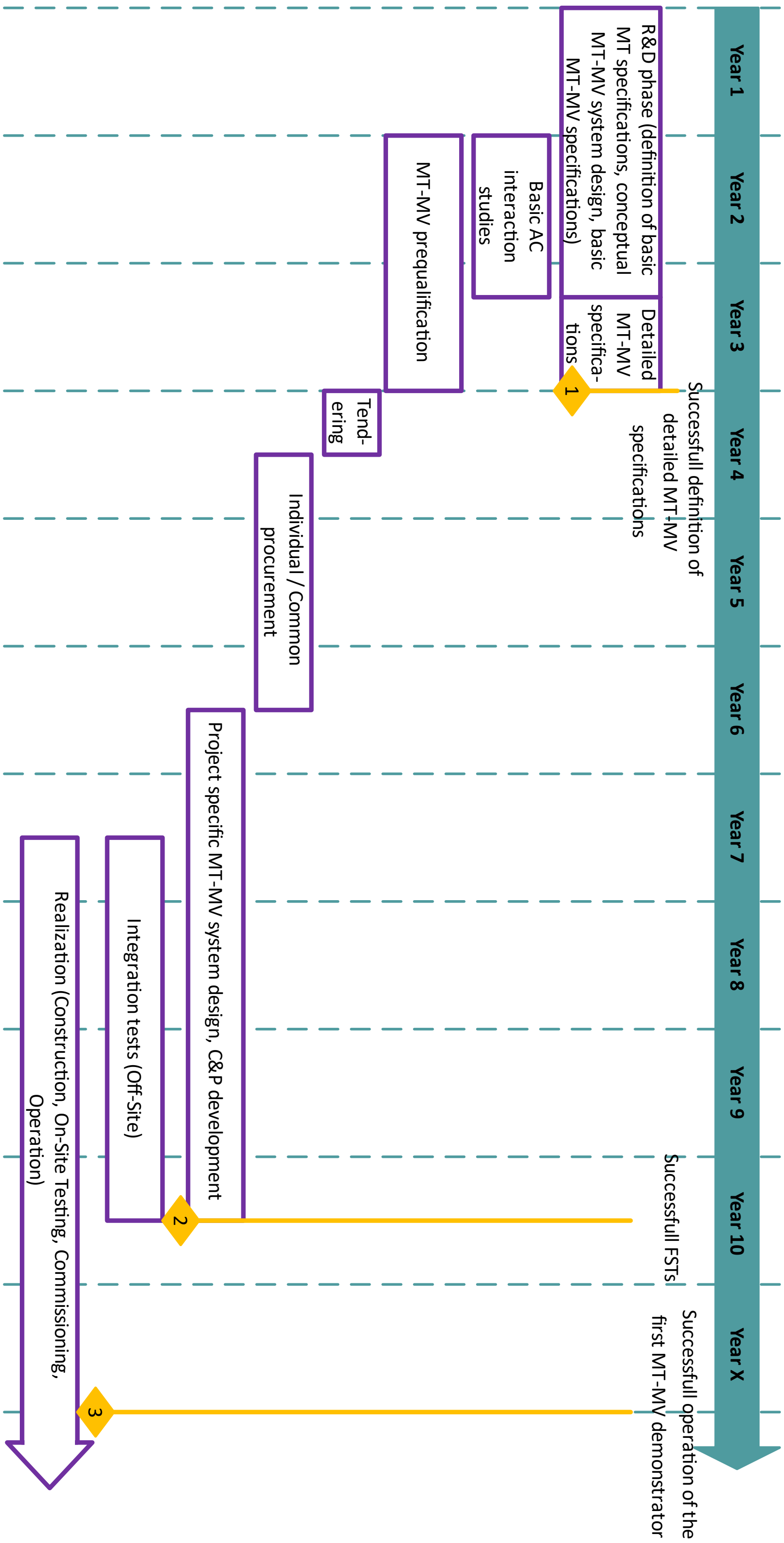
Starting in year 4, the tendering phase is carried out followed by the procurement phase. The project specific, detailed MTMV system design and the C&P development performed by the vendors start in year 6. Possible workstreams to be started in parallel at year 7 could be the integration tests as well as the realization phase. The latter one includes the construction of platforms and HVDC equipment, on-site tests and commissioning. Finally, the demonstrator can be put into operation.

It is noted that the proposed timeline is subject to uncertainties that cannot be avoided within this demonstrator project. These include:

- Timeline may be delayed due to different legal and regulatory frameworks in different countries
- More time needs to be scheduled if the demonstrator is to be placed offshore
- Timeline is heavily dependent on the actual topology of the demonstrator (number of converter stations, DC switching stations etc.)

**Figure 5-2**

Timeline of key milestones for a successful demonstration of the first MTMV HVDC project.



# 6. PROVIDING A ROADMAP TOWARDS ROLLING OUT FUTURE EXPANDABILITY OF MULTI-VENDOR HVDC PROJECTS BEYOND THE DEMONSTRATION PROJECT

The proactive planning and design of a first full-scale, multi-vendor, multi-terminal HVDC system demonstrator is an important milestone in the development of interoperable HVDC networks. The objective of this chapter is to identify the activities associated with such an undertaking and the necessary conditions. A potential roadmap is presented describing the issues that need to be addressed in order to move from a first demonstrator to a meshed European HVDC network. Based on this, key requirements such as the technical challenges, the necessary regulatory bodies and the roles of key actors are addressed. Recommendations are derived and a common vision of the stakeholders is developed to address relevant issues and initiate a basis for further discussion for upcoming projects. In addition, an overview of possible concepts for medium-voltage direct current applications is given in order to outline the current limitations that prevent the realisation of these applications.

## 6.1. Benefits of MTMV HVDC networks

The development of a European HVDC network is an essential component in achieving the long-term goal of full climate neutrality for Europe by 2050. This is the only way to transmit the large amounts of electricity generated by offshore wind farms through the interconnected European electricity system. Overall, a large-scale HVDC network offers the same benefits as an HVDC hub, as discussed in chapter 4.1. In addition, there is further potential associated with the increased interconnection of the European grid. These include the following aspects:

### FACILITATES RENEWABLE ENERGY INTEGRATION AND INTER-AREA TRADE

MTDC is one of the solutions that allows the massive integration of renewable energy sources in the European system, where large amounts of renewable energy are available on remote locations, often offshore or near the sea. These renewable energy sources mostly have a variable and, to a certain degree, unpredictable generation output.

Balancing is seen as one of the main issues in the integration of renewable energy sources. An MTDC system with VSC terminals makes the system more flexible, allowing quick and frequent changes in power flows and improving the stability and reliability of the power transmission system. This results in more efficient and flexible integration and use of renewable energy sources, such as offshore wind. For example, energy generated from the available wind resources of a low-pressure area extending across the North Sea region can be flexibly distributed and temporarily stored (e.g. energy storage in pumped storage plants or electrolysers). This will also allow better utilisation of existing point-to-point connections and has benefits for inter-area trading between different balancing zones. A large-scale HVDC network could compensate for demand shortfalls or store surplus energy. The use of European resources becomes more efficient and goes beyond national borders. On top of that the market coupling might reduce electricity prices, strengthen the collaboration between various European countries and thereby might increase the speed of the whole energy transition within Europe.

The second challenge is to transport the electricity generated offshore to the load centres. This increases the load on the AC grid, leading to higher grid losses and increased demand for reactive power. This is accompanied by additional costs for the necessary reactive power compensation. This problem can be partially addressed by conventional grid expansion of AC transmission lines to relieve particularly congested transmission corridors. However, this approach has an environmental impact and is increasingly unpopular with the public. A possible alternative is the construction of a superimposed HVDC network. In this context, MTDC systems become fundamental to transmit and integrate the generated energy from renewable sources in the power system, which reduces the costs associated with grid losses and reactive power compensation. Additionally, the environmental impact is expected to be lower over this long distances.

### INCREASE OF RELIABILITY AND RESILIENCE (R&R) IN THE EUROPEAN GRID

When a DC transmission is connected inside an AC-grid with AC lines parallel to the DC-link, the power in these lines can be monitored and the DC power can be automatically adapted to protect the AC lines from being overloaded [50]]. By adjusting the load flows in the HVDC system, the shift in power flows can be kept within tolerable limits for system stability, even in the event of a grid fault resulting in the loss of a heavily used transmission corridor in the AC grid. This can reduce the risk of cascading protection tripping, which has increasingly led to critical situations in the past [51]. It also reduces the occurrence of operating conditions in which the available reserves for static reactive power compensation are insufficient to maintain voltage and angle stability for grid faults. The new VSC technologies allow a dynamic reactive power compensation (such as STATCOM), thus providing localised voltage support around the interconnection points. An HVDC network meshed according to load centres could compensate for local power imbalances and frequency fluctuations in the short term in the event of a loss of power plant capacity

### TRIGGERS FURTHER DEVELOPMENT OF NETWORK CONNECTION CODES

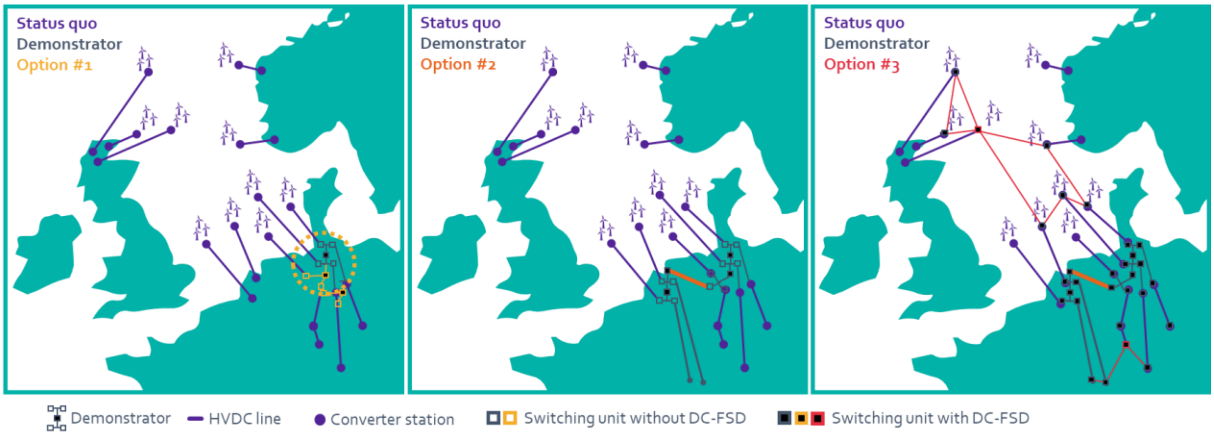
The development of a large-scale HVDC network requires some general rules to allow equal access for different market participants. The development of an HVDC grid would therefore trigger discussions on the harmonization of standards and rules for grid connection of equipment and modular grid extension. These rules are particularly relevant with an increasing share of converter-based elements in the transmission network. There are also new specifications for the necessary provision of grid-serving functions, which are not only applicable to HVDC converters. This is an important step towards meeting the challenges of reducing the number of synchronous machines in the networks.

## 6.2.Roadmap towards a large-scale MTMV HVDC network

The question arises as to what a possible roadmap to a large-scale HVDC grid might look like. Most importantly, it presents a European vision of what a transnational HVDC grid could look like. Finally, the relevant regulatory processes and requirements can be derived from this. This subchapter discusses different phases of the roadmap. According to the state of knowledge, relevant issues that have to be taken into account are addressed. The objective is to show possible levels of development and to create awareness of the issues involved. Figure 6-1 illustrates potential evolutionary milestones. In the following parts, the corresponding topics are indicated with bullet points in the colours as shown in the figure. There is a lot of work needed between the phases, which cannot be fully identified from now. It is not intended to prescribe a specific path, but rather to summarize the current status quo and establish a basis for further debate.

**Figure 6-1**

Illustration of different options to expand the demonstrator along a roadmap to a large-scale MTMV HVDC network.



We start from the status quo, in which **P2P HVDC connections** are used to transport power. This applies in particular to power generation by offshore wind farms. Connection points are located within a restricted area at the European borders of the transmission grid. During periods of high power generation by the offshore wind farms, there is consequently a high power transmission from the generating centre at the north sea coast to the load centres in the inland areas. That increases AC transmission line loading along with an increased reactive power demand, resulting in higher voltage and angle stability requirements. To mitigate this issue, onshore point-to-point HVDC links will be constructed that transport the generated power over long distances to the load centres.

## PHASE 1: GAINING EXPERIENCE FROM THE FIRST MTMV HVDC DEMONSTRATOR

The first phase will be driven by gaining experience with the first **MTMV HVDC demonstrator** from the first basic concept to the actual grid operation. The lessons learned will be used to create requirements and planning principles as well as knowledge that is needed to operate an MTMV HVDC system, as described in Chapter 5. The result is that interoperability is proven to enable the design and construction process for additional projects.

Before commissioning, system-critical issues must also be clarified, such as the design of protection concepts, interactions with power electronic devices and power plants, and the influence on oscillations in the transmission grid. Finally, practical grid operation of the demonstrator will allow the possible repercussions on the AC grid to be investigated. For this purpose, continuous measurement of the electrical quantities at the AC and DC-PoCs should be carried out and systematically evaluated during operation as well as for fault conditions. From this, necessary measures and regulations can be derived that are important for secure network operation. In addition, necessary adjustments can be made to the existing requirements. So that for example future linking of hub projects is enabled.

An expansion of the demonstrator project may require extensive refurbishment. For this reason, the development of a demonstrator must take account of possible expansion measures already within the initial demonstrator design. The design should be from the outset, catching up on relevant topics that are listed below:

- Extended voltage and power flow control concepts (e.g., combination of master-slave and droop control) need to be developed that can be used when connecting multiple subsystems.
- Oversizing of converters might be needed to consider the withstanding during contingencies or future extensions of the offshore or onshore connection points.
- Ensure an offshore platform design that has spare space for additional devices, such as DCCB or converters.
- DC FSDs should be designed to the expected maximum currents for the connection of multiple subsystems and to enable a full or partial selective fault clearing.
- Series reactors should be dimensioned and placed in a way that future expansions are possible.
- For the installation of measuring units reasonable locations should be considered. Otherwise, future expansion cannot be considered for a system state control.
- Assessment of the impact on the AC system, taking into account the current protection schemes based on AC circuit breakers. This approach does not work for MT HVDC systems.

## PHASE 2: DEVELOPMENT OF AN OVERALL SYSTEM DESIGN

The second phase involves consolidating the lessons learned from the operation of the demonstrator into an overall system design. Phases 1 and 2 run in parallel in some areas, as lessons learned from the field must be fed back into the requirements, which in turn influences lessons learned from network operations. At this point, the content is separated from the first MTMV HVDC demonstrator. In the following, the advantages and disadvantages of possible expansion options are discussed. A wide range of issues need to be clarified. There is no consensus so far about the potential options for further development. But it is possible to distinguish between three topics, based around various priorities.

One of the main questions that arise in the development of a future system design is which further steps and expansion options make sense and which represent unnecessary risks without significant added value for network development. Consideration must be given to whether potential challenges and risks should be addressed and resolved early, or whether less critical projects should be undertaken first. Since completely new issues arise from the measures described, there are a large number of unknown influencing factors that need to be identified and addressed. The problem is that a promising concept may prove impossible to implement in practice, or an initially unrealistic vision may turn out to be the right approach. Accordingly, different perspectives arise that can only be addressed in collaboration and direct exchange between transmission system operators and manufacturers. The following are some possible concepts for expansion of the first demonstrator hub. In addition, there are other issues that need to be addressed. These will arise over time as practical experience is gained.

### Option #1 Expansion of hubs by additional terminals

The successful implementation of the first MTMV demonstrator will lay the basis for all future proceedings regarding an interconnected MV DC network. Throughout an iterative process experience in every aspect of setting up such a demonstrator has been gained. The operation will additionally increase the knowledge of handling such a system. All that will serve as a basis to achieve expansions of that first demonstrator. The needs for expansions are stated in chapter 6.1. The evolvement of expandability however is not defined yet. One possibility could be by the installation of additional terminals to the existing demonstrator.

With that the benefits are:

- Stepwise expansion without increasing complexity too much
- Further introduction of new technologies, e.g., DC-FSDs and neutral bus equipment to achieve full selective systems
- Even higher utilization of assets
- Increasing AC network support
- Further integration of renewable energies

But also, further challenges arise such as:

- Compatibility with the existing HVDC system
- Adjustments to load flow control compared to existing P2P systems
- Some oversizing required to ensure future expandability
- Higher requirements for system protection in the event of faults

The expansion of the existing MT system with additional terminals will again provide further experience throughout an iterative process to achieve standardized sub-systems in the long term.

### Option #2 Hub to hub interconnection

As current planning of TSOs delivers several MT systems (see section 8.2) a next possible step towards meshed DC networks may be the interconnection of two hubs. Therefore, two possible demonstrator projects are required to be selected. The requirements to do this are dependent on

- Distance: Here physical and electrical distance need to be distinguished. Physical distance could be favourable in terms of shifted weather patterns. Electrical distance may be limited due to maximum voltage drop which is defined by the design of the converters.
- Compatibility: Basic technical requirements (e.g. voltage level) as well as the control & protection concepts are required to comply with each other. This will require extensive testing and verification throughout offline (and SIL/HIL) simulations.
- Expandability: Interconnection of two hubs and in the following further expansions require systems which have been planned on the premises of expansion. This means that beforehand possible constraints have been considered in the planning of these systems. The system design needs to consider this from scratch to reduce the need for refurbishment actions.
- Cost: A positive CBA is required in terms of energy trade, improved ancillary services, et al.
- Regulatory bodies: The political will to also achieve international connections will be required.
- Standardization: An increased standardization will lead to reduced timelines of project implementations.
- Experience: The experience of handling such systems will influence the possible choice of institutions.

The step of connecting two hubs will gain intensive experience in every aspect towards meshed DC networks. The beneficiaries will not only be on technical level for TSOs and vendors but also bring together policy makers, regulators, standardization bodies as well as academia and research.

### Option #3 Integration of other HVDC projects

The final step to an interconnected European HVDC network is the connection of further MTMV projects. Here the same requirements arise as for Topic #2 with the following additional needs:

- Possible integration of DC-DC converters to have a combined BP/SM-system
- Stepwise expansion based on the existing running system and useful extensions
- Replacement of old (sub-)systems
- Implementation of necessary measures for further networking
- Coupling between transmission voltages other than 525 kV to enable a holistic control across a broad network that may have been developed at lower voltages in segments

By the will and successful demonstration of the stepwise expansion of MTMV DC networks a path to achieve climate neutrality is given.

### PHASE 3: STANDARDISATION TO MODULAR SUB-SYSTEMS

Building on the experience of network operation and further discussion of extensibility options for the first demonstrator, the final step to achieve widespread HVDC networks is on standardization to modular sub-systems. While exceptions may be allowed in the first two phases in order to implement bilaterally agreed projects, the need for generally applicable regulations arises in the third phase. This should enable all potential participants to access the newly created market.

The aim should be to standardize technical and regulatory requirements. This will ensure the modular expandability of the system. The compatibility of converter stations and separate DC switchgear is important. The number of J-tubes and connection points must be designed according to the expected development. Due to the short time constants with which events propagate in the DC network, attention must also be paid to a modular protection design. Otherwise, in the event of a fault, the system voltage would collapse and a loss of power would become a danger to the AC system. This can be prevented by selective isolation of the affected stations. For this purpose, experience from the network operation is of great importance. In order to determine the state of the network, the relevant network variables must be monitored. Here the need for standardized measurement equipment which is not currently available in the market can be mentioned.

The overall goal is to achieve modular HVDC building blocks with standardized I/O interfaces which include interoperability by design. With that a widespread HVDC network in the simulation domain as well as in real life applications can be achieved.

## 6.3. Essential requirements

A number of basic requirements can be identified for the development of large-scale HVDC networks, which are essentially analogous to the first demonstrator discussed in the previous chapters. By basic requirements we intend to answer such questions as

- What are the minimum functions and capabilities of the HVDC network which a solution needs to satisfy?
- What are the concepts of coordination across HVDC controls that satisfy those functions and capabilities?
- What common interfaces and common control variables need to be visible and control-able to implement the approach?

In addition, there are issues specific to large scale HVDC which are discussed below.

### 6.3.1. Technical requirements

The technical requirements should be based on the current state of the art of technical possibilities and principles. This section discusses the technical aspects relevant to designing and operating a large-scale HVDC system, integrating it into existing AC grids and protecting against possible external influences.

- System rating: The first MTMV demonstrator will be based on a certain dimensioning of converters. The first thing that is important in the definition of the permissible voltage bands and the permissible current limits at the coupling points. The permissible voltage bands and current limits should be identified by consideration of the topology of the intended DC system, and its range of maximum and minimum power flows within it, such that the maximum voltage drop to satisfy a given transfer between terminals is included within the voltage band. Together with a voltage droop range that is capable of varying the power flow within the DC system subject to either a "master" voltage control at that node or a model of distributed droop control across the network. In doing this, suitable contingencies (e.g. N-1) should be included in the assessment. In addition, the possible range of voltage distortions needs to be understood that can occur away from 0Hz steady state DC operation, and ensure these behaviours are adequately damped across the DC system. For example, for Project Aquila has considered within its specification a DC voltage variation of approximately 5% taking into account 525kV DC cables within the remit of its control requirements of up to 350km in length. Current variations should similarly be dimensioned to account for the intended operation of the DC network and associated power flow variation. Future expansions of that demonstrator may lead to the need for DC-FSDs to achieve operability of a growth in the DC network connectivity and/or generation connected. In this case the effect of the "old" converters connected to that network in case of a fault will need to be taken into account, or else solutions to FSD and protection selected that are less sensitive to these considerations.
- Power Flow Control: The system state is defined by voltage amplitude. In P2P systems usually one terminal controls the DC link voltage, and the other terminal the power flow. However, in multi-terminal grids, a flexible PF control without a critical dependence on communication is needed. There are a range of approaches to address this consideration that. One is to deliver a centralised interventionist approach with a degree of communication duplication and /or partial operation in the event of a given failure. Another approach is to enact a distributed control where each terminal can act unilaterally to provide multi-terminal control. Both of these approaches requiring hierarchy management of signals and also sensitive to the type of signals being exchanged and any delays/ differences in information being distributed across the network. A further approach as adopted by Project Aquila is to have a centralised multi-terminal control providing a supervisory control. This control is not acting during any event but instead setting up the distributed terminal behaviours to respond to changes and contingencies within the DC network independently and stably. This supervisory approach includes the concept of a control room emulation of the control and its margins for stability, such that if local communication is lost, slower manual intervention to account for changes over time ahead of restoration of communication is possible. Irrespective of the option selected, a robust self-organising approach to power flow and voltage level control between MV terminal stations needs to be developed. Various control concepts can be used for this purpose (e.g., master-slave, droop control), the suitability of which needs to be investigated in more detail. Besides this, the development and application of Flexible DC Transmission Systems (FDCTS) could

provide advantages in more mature network structures. To ensure a stable power flow, a stable and controllable DC voltage is most relevant, because it determines the power flows.

- Dynamic Stability: The dynamic stability of a HVDC network is mainly determined by the dynamic performance of the converters. They have a much faster time response than synchronous machines in the AC system and tend to a discontinuous operation in the case of faults. Therefore, representative EMT models/ replicas are needed to describe the effect of individual converter controls/ protection, multi-terminal control and any further protections and controls related to FSD introduction where appropriate, in relevant offline and real-time simulation to evaluate the HVDC system stability. Relevant studies must define voltage stability criteria and then evaluate these criteria, as well as new stability problems, such as converter and resonance stability [52] . In power systems where AC/DC converters are installed increasingly densely, undamped adverse control interactions may occur.
- Protections and equipment: During a DC fault, a substantial reduction of DC voltages can be expected. Depending on the type of fault (e.g. pole-to-pole, or pole-to-ground or the operating mode of the inverter (e.g. monopolar, bipolar), there are different effects on the transmitted power. Also, a converter fault could trip a section of the HVDC grid. According to section 4.2.2 the maximum permissible loss of transmitted/generated power is limited according to the national "System operations guidelines". This requirement will need to be reflected in the design of the protections and equipment, Systematic studies may be performed to investigate selectivity in the tripping of DC lines and grid equipment, to determine the fault location precisely and to prevent DC fault propagation if such approaches are needed. Given for example the German MT projects the current planning comprises partial selective fault clearing strategies with half bridge converters delivered by one single vendor. To enable possible future MV expansions of these systems while staying within the limits of section 4.2.2 it is required to study a.) Coordination between DC-FSD and converters within one single vendor MT system and b.) the interaction with further MT systems. Conversely a further option is to limit the levels of complexity strictly necessary to protect the DC grid to a given standard. For an entirely cable based grid solution where single pole cable fault/ GRC loss are the credible scenarios it is possible to still have a resilient DC system without complex DC protections. This is achieved by using full Bipoles, limiting how much power is allocated to a pole, allowing for a pole fault the fault to be cleared on the AC side, and then via DCSS, isolating manually the identified faulted element after the event. Finally restoring as much as available can then be done via an asymmetric control strategy. That's the Project Aquilas initial approach to protection, compare section 8.6.2 which depicts Project Aquilla's protection approach. For future stages Project Aquila envisages a subsequent FSD arrangement implemented in a 4 switch ring on each pole. Such that each DCSS busbar may be connected via necessary series reactance and cabling to a "corner" in the 4x FSD mesh then present. The simplest of the protection strategies is to sectionalise the pole connections via a ring/mesh of FSDs. The DC fault is then separated by an immediate open action on the FSDs that sections the pole connections. Now there are still multiple ends but only one section of pole connections has a fault on it and has it further cleared on AC breakers. There is no need for new clever or fast protections to do that. On top of that it also can act fast on FSD without the need to wait for protection. It needs following attention at the remaining system isolated on AC breakers. Based on that reclose the ring of FSD except for the remaining system connecting to that faulted element. That is all happening in a few 100ms in total. The next steps are to identify the DC fault location, isolating on a DCSS and restore manually the faulted pole section. Beyond these simple

strategies it is possible to have partially selective (using series reactance to "shape fault infeed for a mesh-corner connected assembly of circuits to be isolated from the rest of the DC network) should sufficient time be available. Beyond these selective strategies with more FSD can be incorporated interfacing into the DCSS separately - in other words you can have as much complexity as your system requires. In this context, the dynamics of converters and the impact of DC reactors in combination with FSDs must be considered to determine how fast protection must be. In addition to the requirements for the protection devices, appropriate protection algorithms are required. These include appropriate fault detection procedures and selective tripping of the protective devices within a reasonable time. HVDC FSDs which can enable selectivity and therefore compliance to existing AC system operational guidelines are currently on a TRL 7/8 for voltages up to 350 kV, which was demonstrated in [53]. The technical scaling for voltages up to 525 kV is currently in development and tested in first pilot projects, such as the development of a prototype in the year 2018 in Zhanbei [54]. At this moment, a TRL 3 is assumed according to [55]. The German TSOs expect the first HVDC FSDs for a rated voltage of 525 kV with a high possibility from the year 2035 [56].

- System Integration: The expected development can be assumed like the development of AC networks. It starts from simple structures to a complex system. However, a much shorter time than in the case of AC networks can be expected. For this reason, it is necessary to clearly establish objectives, primary functions, and operational procedures. Moreover, interaction studies between the AC and DC networks must be performed. For example, AC fault propagation through the DC system and vice versa should be understood, and managed/ minimised within the design of the DC system. Also, slow and fast interactions between converters are a relevant topic. How can power system stability be ensured in grids with very high PEID penetration? Further points to consider are the vendor-specific architectures and control structures. To achieve AC integrated and interoperable MT systems the amount of information being shared/transmitted needs to be established. There is the need for signals with a common meaning across stakeholders.
- Reliability and resilience: A wide range of issues can affect the reliability and resilience of the electricity network. Some examples are equipment failure, climate & extreme weather impacts, technology changes, increased operational complexity, system user's actions, as well as actions of malicious actors. With these points a lot of questions arise, that need to be clarified.

### 6.3.2. Planning standards

There are no finalized planning principles for HVDC networks yet. Therefore, these must be coordinated between the European transmission system operators and described in a generally applicable manner. This should be based on the available planning principles (e.g., the current planning principles of the German TSO, CENELEC 50654-1/-2), which already contain partial aspects of the necessary requirements and regulations. Our aim is to increase the TRL level for meshed multi-terminal DC networks from the current 4 (Large-Scale DC Overlay Grid Concepts - ENTSO-E (entsoe.eu)) to a higher value.

The planning standards should include the following points:

- Definition of technical terms and descriptions
- Strategy of potential interfaces for the exchange of signals and data
- Standardization of integration studies for future projects
- Standardized regulations for network connection
- Open call for tenders to all vendors

- Transparent and freely accessible documentation
- Reserve space onshore and on the offshore platforms
- Standardization of requested designs and system functionalities for converter stations connected to HVDC grids to prevent highly optimized and customized systems.

**Policy requirements**

Any large scale HVDC network must have as its fundamental requirement the ability to support an energy supply and demand system that meets the politically agreed objectives of decarbonising Europe's economy before 2050 and achieve a 55% net reduction in greenhouse gas emissions by 2030. Within these overall objectives climate objectives, established by the 2021 European Climate Law[11],legislation has been passed that significantly impacts the scale and nature of Europe's deployment of grids, including high capacity HVDC and MVDC transmission technologies.

On 16 June 2023, the Council agreed on revising the Renewable Energy Directive, establishing by law an increased target of 42.5% renewable energy before 2030. The previous 2030 target was 32%. EU countries that choose to do so can complement this target with "an additional 2.5% indicative top-up that would allow reaching 45%. This would largely double the share of renewable energy from currently 21.8% renewables (2021).

On 19 January 2023, plans for the deployment of offshore renewables (mainly offshore wind) were submitted to the European Commission. The combined targets announced, excluding the UK and Norway are:

**Figure 6-2**

Offshore wind capacity targets (in GW)

| | 2030 | 2040 | 2050 |
|---|---|---|---|
| Northern Seas Offshore Grid | 60.3 | 134.9 – 158.3 | 171.6 - 218 |
| Atlantic Offshore Grids | 12.74 - 14.26 | 21.74 – 26.06 | 29.74 – 43.06 |
| Baltic energy Market Interconnection Plan | 22.4 | 34.6 | 46.8 |
| South and East Offshore Grids | 8.81 | 16.8 | 25.9 |
| South and West Offshore Grids | 5.15 – 6.15 | 6.7 – 12.6 | 6.7 – 20.1 |
| Total | 109.4 – 111.92 | 214.74 – 248.36 | 280.74 – 353.86 |

Adding UK (50 GW by 2030) and Norway (30 GW by 2040), Europe is approaching close to 500 GW offshore wind in Europe by 2050 (high case). Based on the Sea Basin plans, ENTSO-E is required by EU TEN-E Regulation (EU) 2022/869 to publish before 24 January 2024, 'high-level strategic integrated offshore network development plans' for each sea-basins. They shall provide a high-level outlook on offshore generation capacities potential and resulting offshore grid needs, including the potential needs for interconnectors, hybrid projects, radial connections, reinforcements, and hydrogen infrastructure.

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[11] Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality ('European Climate Law')

They must be assessed every two years and integrated into the Union-wide ten-year network development plans.

To add to the offshore wind energy ambition, a North Sea Summit of heads of governments was held in Ostend, Belgium on 24 April 2023, building on the Esbjerg Summit of 18 May 2022 (held between the Prime Ministers of Germany, Belgium, Netherlands and Denmark).,It expanded the "Esbjerg Group" to include France, Ireland, Norway and the UK. They agreed to increase offshore wind in the North Seas to 120 GW by 2030 and 300 GW by 2050.

The Declaration "welcome the initiative that the Transmission System Operators (TSO's) from Belgium, Denmark, Germany and the Netherlands have undertaken to develop a meshed offshore grid and to On identify the next steps for its realisation".

Finally, on 20 September 2023, the revised Energy Efficiency Directive[12] entered into force. Article 3 and article 27 will have significant impact on future grid investments in the EU.

Article 3 in EED establishes that Member States shall ensure that the Energy Efficiency First Principle is assessed in planning, policy and major investment decisions of energy systems with a value of more than €100,000,000. Article 27 in EED provides details on how Member States and National Regulatory Authorities apply the principle to gas and electricity infrastructure decisions.

The Energy Efficiency First Principle (EEFP) is defined in Regulation (EU) 2018/1999 on the Governance of the Energy Union, Article 2 (18)[13]. It requires Member States to ensure that energy efficiency solutions, including demand-side resources and system flexibilities, are assessed in planning, policy and major investment decisions relating to energy systems, thus contributing to a "modern, resource-efficient and competitive economy".

**Outlook**

Dividing the future development of requirements into two time horizons can be helpful. In each of these time horizons, projects should be handled in a different way in order to gain experience that can eventually be incorporated into the required framework:

- Short-term: During the first phase, HVDC projects could be undertaken according to the established planning principles. This involves the TSOs and vendors working together on planning network expansion projects based on joint agreements. In these projects, practical experience can be gained which is needed for regulatory bodies. Exceptions may exist during the first phase. It might be useful, as an example, to test lower TRL level technologies and to accept possible delays in projects. Oversizing of the infrastructure is also a way to ease future network expansion.

- Long-term: The second phase includes an existing HVDC network. Random customers could participate in the new market. This requires an appropriate regulatory environment to enable each participant access to the market while avoiding potential collisions of interests. Building on the experiences gained during the first phase, the required amendments are derived with a view towards future developments.

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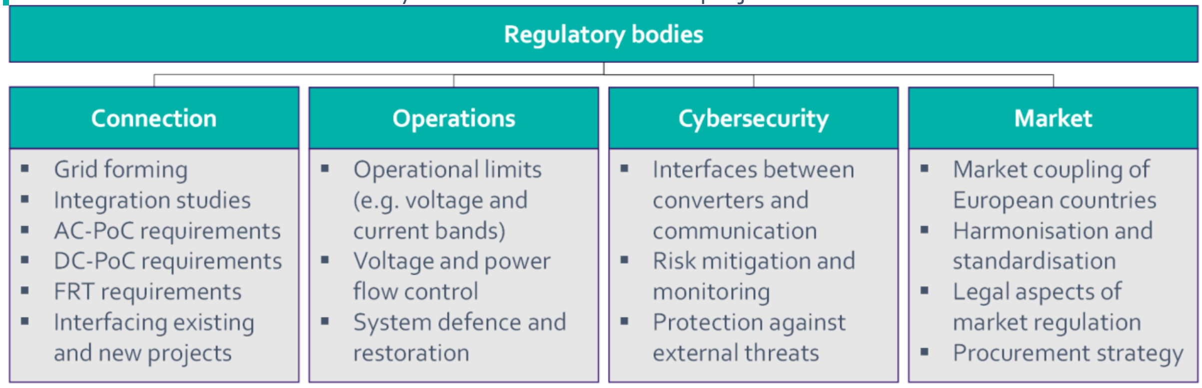
[12] Directive (EU) 2023/1791 on energy Efficiency

[13] Article 2 (18): 'energy efficiency first' means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions.

The development of large-scale HVDC networks will require the amendment of current regulatory guidelines and establish additional requirements. As a rule, the existing regulatory conditions should be incorporated, for example the VDE-AR-N 4131 [57], the HVDC network code [58],the system operations network codes [59] and the network code on cyber security [60]. Required amendments are especially related to interoperability aspects. To achieve this, a number of steps are needed to extend the current rules to allow for further technological development. To ensure a common understanding, we recommend to amend the following technical and legal requirements as shown in Figure 6-3.

**Figure 6-3**

Additional requirements that need to be amendment in the different groups of the regulatory bodies to enable MT HVDC networks beyond a first demonstrator project.



Regulatory bodies

| Connection | Operations | Cybersecurity | Market |
|---|---|---|---|
| ▪ Grid forming<br>▪ Integration studies<br>▪ AC-PoC requirements<br>▪ DC-PoC requirements<br>▪ FRT requirements<br>▪ Interfacing existing and new projects | ▪ Operational limits (e.g. voltage and current bands)<br>▪ Voltage and power flow control<br>▪ System defence and restoration | ▪ Interfaces between converters and communication<br>▪ Risk mitigation and monitoring<br>▪ Protection against external threats | ▪ Market coupling of European countries<br>▪ Harmonisation and standardisation<br>▪ Legal aspects of market regulation<br>▪ Procurement strategy |

### 6.3.3. Roles of key actors

As previously highlighted in Chapter 5 and visualized in Figure 5-1 – mainly to indicate a way forward towards the first MTMV demonstrator – , several stakeholders currently join forces in multiple research-oriented projects to develop first technically feasible MTMV specifications together and find common ground for future standards. However, in the long run a clearer separation of tasks and responsibilities is indispensable.

In the following, a brief description of main challenges to foster multibillion Euro investments in expandable MTMV networks and unlock single expansion projects linked to key actors are highlighted:

- Policy makers: Amendments to existing Network Codes are one elementary part to provide a proper frame for MTMV arrangements. This may involve both, supplements and novel aspects covering DC-side interface points. To enable a large-scale HVDC network, the preparation of connection agreements or grid codes is essential. These grid codes will may also require experience gained from real life projects and are not able to cover all aspects of future HVDC grids but will mention certain features to be taken into consideration which then need to be further detailed out on national level. General requirements and framework conditions for grid connection are also needed. Accordingly, the current grid connection rules need to be supplemented and revised. NC HVDC provides today the legal basis for the development of technical requirements for the connection of HVDC systems and DC connected PPMs for the European energy market. It is important to note that these technical requirements are currently defined only at the AC connection points. In the future additional technical requirements for DC side may be needed between relevant TSOs and the suppliers of a MTMV HVDC network.
- Energy regulators: As hybrid structures emerge covering both transmission tasks, AC grid integration of generation and maybe even enhanced ancillary services, existing regulatory

guidelines must anticipate and reflect these developments. There are multi-national differences in regulation. One major topic is the MTDC grid ownership and management. Multiple players exist, which makes it necessary to promote proper organizational mechanisms in an emergent market. The public and political support must be ensured, to establish a competition between those players, leading to enhance the technical and economic performance.

- Standardization bodies: In a continuous manner, standardization bodies must follow the existing best practice and enhance technical standards towards standardized solutions - as available today for AC technology - without narrowing down innovation potential.
- Academy and research centres: Due to the limited experience when building complex MTMV HVDC networks, the academic community shall accompany ongoing activities, critically assess, and propose potentially more beneficial solutions or methods like new tools, methods to analyse HVDC systems to tackle existing problems.
- TSOs: Due to the far-reaching impact of MV-MT HVDC projects, one key responsibility of involved TSOs is to define asset-specific and global operational requirements, having as starting point the NC HVDC. As an immediate consequence, this impacts the specification of individual asset (e.g. single HVDC converter or single HVDC circuit breaker) and overall system design and performance. For the latter, new responsibilities arise and must be carefully fulfilled by the TSO itself or delegated towards other supporting or novel entities (e.g. an HVDC grid operator for system performance or an HVDC integrator for the system design). The TSO community should prepare a modelled expectation of what the DC system is required to achieve. From that translate those results into clear functional expectations and specifications of each converter terminal. This is crucial to reduce engineering efforts on the vendor side and thus decrease project costs while increasing the execution and delivery speed.
- Vendors: With respect to the increasing market dynamics, vendors are urged to respond with easily adjustable and modular designs to build the core, participate in or expand existing complex MTMV HVDC projects. Therefore, it is crucial that the designs and functionalities (functional requirements) requested by the different TSOs within Europe and the rest of the world are harmonized between projects instead of tendering highly optimized and customized systems. This will then automatically lead to a significant reduction in project execution times. For key components (e.g. HVDC converters, HVDC circuit breakers) rapid customizability, short production time and continuous upgrade opportunities appear crucial.
- Consultants: The specification, design and implementation of MV-MT HVDC projects calls for a wide-range of competences and requires significant resources, which may not be feasible to achieve with internal resources in case of smaller entities. The consulting industry shall provide easily accessible experience for a wide range of customers to properly set-up and accompany projects.

### 6.3.4. Further requirements

- External threats: There is a real risk of environmental or external impacts on the infrastructure in addition to all these challenges. Particularly with the increase in installed capacity and interconnections, the risk of large power imbalances with disastrous effects on the European transmission grid in the event of converter failure increases. Some examples are equipment failure, climate & extreme weather impacts, technology changes, increased operational complexity, system user's actions, as well as actions of malicious actors. These issues must be carefully studied.

- Cyber security: The likelihood of cyber-attacks on critical infrastructure is increasing. The impact depends on the nature and scale of the systems affected. The problem is that a new system can only be considered secure at the time it is built. The methods and tools used by attackers are constantly evolving, which means that the security of systems against external attacks must also be constantly tested and improved. The Network Code on Cybersecurity (entsoe.eu) aims to set a European standard for the risk assessment, common minimum requirements, certification, monitoring, reporting and crisis management. It contains a definition of the roles and responsibilities of the different stakeholders. However, the network code should be revised with regard to additional requirements when operating MV MT HVDC grids.
- Cost: Building a European HVDC infrastructure is expensive and must be financed. The initial investment is much higher than in the case of AC grid solutions. Power conversion stations are currently still high-cost plant items., HVDC lines are normally less expensive, and in general a DC grid comes with lower grid losses, which allows a better thermal utilization of transmission lines. With an increasing development, those cost will reduce again. Several questions arise which are examined in detail in [7].

## 6.4.DC MV applications on medium voltage level

A DC network is generally understood to be an HVDC network. However, there are also possible applications in distribution networks and superconducting transmission networks. For example, concepts for medium voltage applications are discussed in the literature. For these networks, similar assumptions can be made about operation and system behavior as for HVDC networks. However, MV grids differ from HVDC grids in that they are much smaller in scale. However, compared to AC networks, they offer greater flexibility in load flow control, which leads to an increase in the efficiency of network operation. An MV DC grid can offer advantages for the connection of inverter-based generation plants and the connection of inverter-based loads (e.g. electrolyzes). Some advantages can be summarized as following [61]:

- Enabling more power transfer from the existing assets, to create access to networks for more distributed resources
- Enabling faster power charging for an electrified transport system (EVs and trains) through DC charging
- Providing a more controllable means to enable a more reliable supply
- Providing a more efficient and sustainable network by reducing overall system power losses
- Enabling more services that distribution system owners and the connected users can provide for the system operation, e.g. Distribution System Operation transition
- Coupling between low voltage (LV, e.g., 400 V) and transmission voltage (higher than 132 kV) to enable a holistic control
- Lower cost power conversion equipment and associated structural infrastructure, more compact landfalls for offshore connections, reduced size in transmission corridors and associated substations. [62]
- Enabling a broader supply chain across the suite of lower voltage electrical cable, power conversion and protection equipment

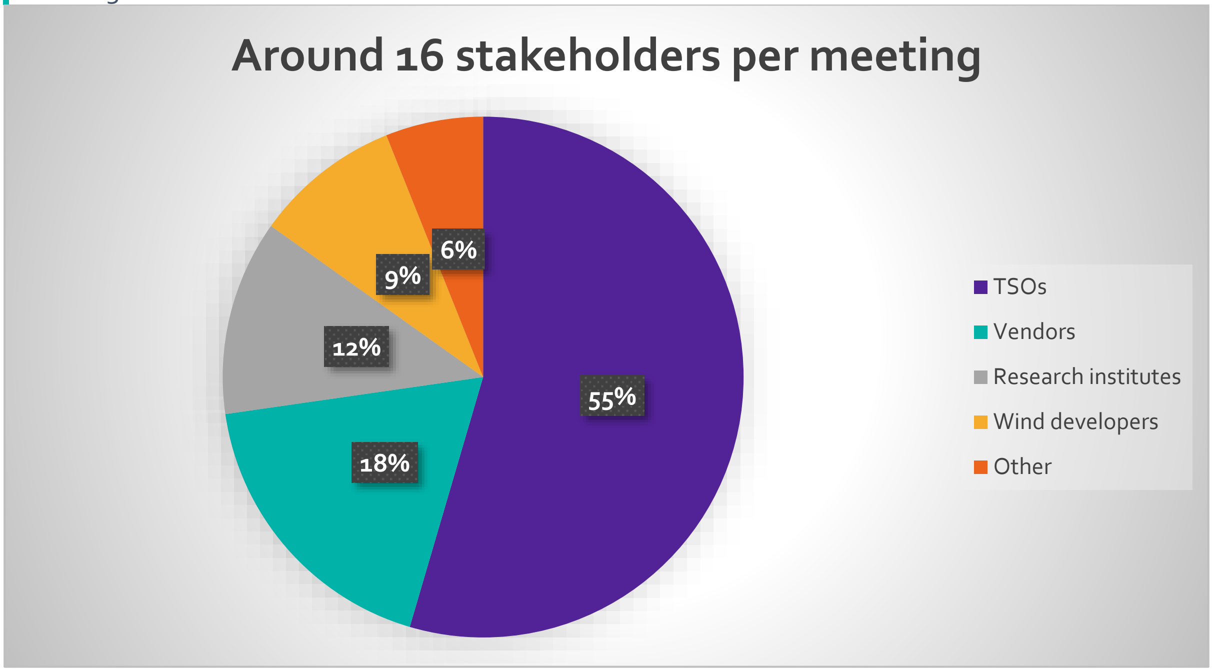
- Enabling a faster rollout of the network through release of supply chain constraints and through reduction in public objection delays that significantly impact timelines in delivering the more substantial infrastructure required for higher voltage transmission systems.

Followed by these advantages the market has already introduced solutions for MV DC applications [63]. Despite, according to the statements of vendors these solutions have not been requested up to now. Within this project concrete blocking points have not been identified as only TSOs which are responsible for HV applications were participating in the working group. The following points however could have hampered the practical implementation of these concepts. At first there is the lack of a regulatory framework. This includes the technical concepts for the structure and design of such systems, as well as the requirements for reliable and fast DC grid protection. There are also organisational issues, such as responsibility and liability for the interconnection of distribution networks of different distribution system operators. Also, it is necessary to reduce cost for equipment. In addition, it is not clear how the transmission grid will be affected and to what extent the concepts discussed will provide added value. This is essential if such concepts are to be implemented. A further development of HVDC applications will also provide benefits towards possible applications on medium voltage level.

# 7. LESSONS LEARNED - STAKEHOLDER MANAGEMENT

**Figure 7-1:**

Share of stakeholders in the WG3 meetings. On average there have been around 16 participants in the meetings.



The development of an MTMV HVDC system brings together a large number of stakeholders, such as TSOs, vendors, developers and research institutes. Therefore, READY4DC project is a crucial step to engage all stakeholders for the implementation of a successful first demonstration project.

A call was sent out to all stakeholders to encourage more interested parties to participate. Subsequently, weekly meetings were organised, meeting minutes, slides, documents and the white paper have been made available for all participants to express their views.

READY4DC provides a platform for dialogue between all participating stakeholders to discuss and review the most relevant topics for the initiation of MTMV projects. An important issue for all participating stakeholders is how to standardise the interface between the different components of HVDC grids (e.g. converter stations) for smooth system integration.

Overall, there have been great achievements obtained. These are:

- Collecting the planned projects and comparison of these lead to an aligned basic topology
- Complexity of DC MTMV systems has been showed up
- The views/opinions of different stakeholders were collected and inserted to the document.
- A variety of different options/opinions have been mentioned
- How to manage commenting

Nevertheless, also hurdles/barriers could be identified such as:

- Technical hurdles have been addressed but how they can be met on contractual/legal side is still pending.
- Too short to get into depth

# 8. APPENDIX

## 8.1. Planned DC projects in Europe

| DC Project Name | **Location** | **Year** [14] | **Nominal Voltage (kV)** | **Power (MW)** | **Converter Type** | Remarks |
|---|---|---|---|---|---|---|
| Caithness Moray HVDC Link [64] | Kergord, Spittal,Black hillock, Scotland | 2019 | ±320 | 800 / 1200 | VSC | Symmetrical Monopole |
| SavoiePiedmont, Italy-France [65] | Piossasco, Italy-f Grande Ile, France | 2021 | ±320 | 2x600 | VSC | |
| IFA2 [66] | Tourbe, France - Daedalus,England | 2021 | ±320 | 1000 | VSC | Symmetrical Monopole |
| North Sea Link (NSL) [67] | Blyth, Great Britain - Kvilldal, Norway | 2021 | ±525 | 1400 | VSC | Bipole without metallic return (can be run as a Monopole) |
| NordLink [68] | Ertsmyra, Norway and Wilster, Schleswig-Holstein, Germany. | 2021 | ±525 | 1400 | VSC | The system is designed to operate in the following modes:<br>o Bipolar mode<br>o Monopolar metallic return mode<br>o Reduced DC voltage operation<br>o STATCOM mode<br>o Black Start / Islanded mode |
| Neuconnect [69] | GB-DE Interconnector | 2022 | | | | HVDC Interconnector |
| NOR-3-3 (DolWin 6) [70] | North Sea-Emden/East, Germany | 2023 | ±320 | 900 | VSC | |

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[14] commissionned

| | | | | | | |
|---|---|---|---|---|---|---|
| Dogger Bank A [71] | North Sea - Teesside and Creyke Beck, UK | 2023 | ±320 | 1200 | VSC | Symmetrical Monopole |
| Viking Link [72] | DK to GB | 2023 | 525 | 1400 | VSC | TYNDP22 Reference Grid (RegIP-2022-NS.pdf page 14) |
| DKE, DE Westcoast [73] | TenneT-DE to Energienet DK | 2023 | | | | |
| NOR-1-1 (DolWin5) [74] | North Sea-Emden/East, Germany | 2024 | ±320 | 900 | VSC | |
| Shetland HVDC Connection [75] | Upper Kergord -UK – near Staxigoe, UK | 2024 | ±320 | 600 | VSC | Symmetrical Monopole (multi-terminal) |
| Greenlink [76] | Irish sea, Ireland to Wales | 2024 | 320 | 500 | VSC | Monopole |
| Sofia [77] | North Sea - Lazenby, England | 2025 | ±320 | 1400 | VSC | |
| NOR-7-1 (BorWin5) [78] | North Sea-Garrel/Ost, Germany | 2025 | ±320 | 900 | VSC | |
| Celtic Link [79] | Ireland - France | 2026 | ± 320 kV | 700 | VSC | |
| Dogger Bank B [71] | North Sea - Teesside and Creyke Beck, UK | 2025 | ±320 | 1200 | VSC | Symmetrical Monopole |
| North South Interconnector [80] | IE to Northern Ireland | 2025 | 400 | 900 | | AC or DC ? connects SONI and Eirgrid by overhead lines |
| Dogger Bank C [71] | North Sea - Teesside and Creyke Beck, UK | 2026 | ±320 | 1200 | VSC | Symmetrical Monopole |
| OST-1-4 [81] | Baltic Sea - Brünzow / | 2026 | | 300 | | AC Technology not an HVDC Project |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Kemnitz / Lubmin | | | | | |
| Ultranet [23] | Osterrath to Philippsburg | 2026 | 380 | 2000 | VSC | Full bridge Converters, Rigid Bipole |
| NOR-7-2 (BorWin6) [82] | North Sea-Büttel, Germany | 2027 | ±320 | 980 | VSC | |
| SuedLink DC3 [83] | Brunsbüttel - Großgartach, Germany | 2027 | ±525 | 2000 | VSC | |
| SuedLink DC4 [83] | Wilster - Bergrheinfeld, Germany | 2027 | ±525 | 2000 | VSC | |
| North connect [84] | Norway to Great Britain | 2027 | | 1400 | | |
| Biscay Gulf [85] | Atlantic Ocean - Cubnezais (France) and Gatika (Spain) | 2027 | 320-500kV | 2000 | VSC | Double symmetrical Monopole ? Not multi-terminal, 400km |
| IJmuiden Ver Beta [86] | North Sea-Amaliahaven (Maasvlakte), Netherlands | 2028 | ±525 | 2000 | VSC | |
| NOR-3-2 (DolWin4) [87] | North Sea-Hanekenfähr, Germany | 2028 | ±320 | 900 | VSC | Symmetrical Monopole |
| NOR-6-3 (BorWin4) [87] | North Sea-Garrel/Ost, Germany | 2028 | ±320 | 900 | VSC | Symmetrical Monopole |
| IJmuiden Ver Alpha [86] | North Sea-Borssele, Netherlands | 2029 | ±525 | 2000 | VSC | |
| IJmuiden Ver Gamma [45] | North Sea-Amaliahaven (Maasvlakte), Netherlands | 2029 | ±525 | 2000 | VSC | |

| | | | | | | |
|---|---|---|---|---|---|---|
| NOR-9-1 (BalWin1) [88] | North Sea-Unterweser, Germany | 2029 | ±525 | 2000 | VSC | |
| MOG II [89] | Belgium: offshore windfarm (Princess Elisabeth Island) to coast, to be expanded with multiterminal to UK (Nautilus) | 2029 | ±525 | | VSC | Bipole with metallic return, AC 220 kV in // with HVDC, overall 3,5 GW capacity |
| Sørlige Nordsjø II [90] | ?- Sørlige Nordsjø II | 2030 | ±320(525) | 1500 | VSC | Wind park connection. Currently planned as radial, extendibility to MT is under assessment (in which case it will be 525 kV). |
| Tyrrhenian Link [91] | Campania to Sicily & Sicily to Sardinia | 2028 | ±500 | 1000 | VSC | Two bipolar systems equipped with marine electrodes: Campania to Sicily 1000 MW (2x500 MW), Sicily to Sardinia 1000 MW (2x500 MW) |
| Adriatic Link [92] | Marche to Abruzzo | 2028 | ±500 | 1000 | VSC | Bipolar systems equipped with marine electrodes |
| Italy-Tunisia interconnection [93] | Sicily to Tunisia | 2028 | ±500 | 600 | | |
| Nederwiek 1 [94] | North Sea-Borssele, Netherlands | 2030 | ±525 | 2000 | VSC | |
| Nederwiek 2 [94] | North Sea-Amaliahaven (Maasvlakte), Netherlands | 2030 | ±525 | 2000 | VSC | |
| Nederwiek 3 [94] | North Sea-Geertruidenberg of | 2030 | ±525 | 2000 | VSC | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Moerdijk, Netherlands | | | | | |
| Doordewind 1 [94] | North Sea-Eemshaven Oude Schip, Netherlands | 2030 | ±525 | 2000 | VSC | |
| Doordewind 2 [94] | North Sea-Eemshaven, Netherlands | 2030 | ±525 | 2000 | VSC | |
| NOR-9-2 (BalWin3) [88] | North Sea-Wilhelmshaven, Germany | 2030 | ±525 | 2000 | VSC | |
| NOR-10-1 (BalWin2) [88] | North Sea-Unterweser, Germany | 2030 | ±525 | 2000 | VSC | |
| Energiø Bornholm [95] | Bornholm to Zealand (DK2) and Germany | 2030 | ±525 | 3000 | VSC | Bipole with metallic return, 2x600 MW (DK) and 2x1000 MW (DE) Bipole systems. Will be expanded in later stage |
| MOG II / Nautilus [89] | UK to Belgian offshore Princess Elisabeth Island | 2030 | ±525 | 2000 | VSC | Bipole with metallic return |
| NOR-12-1 (LanWin1) [96] | North Sea-Wehrendorf, Germany | 2031 | ±525 | 2000 | VSC | Bipole without metallic return (can be run as a Monopole) |
| DC25 [97] | Heide/West – Polsum | 2031 | | 2000 | | |
| DC 31 [97] | Heide - Klein Rogahn | 2032 | | 2000 | | |
| NOR-12-2 (LanWin2) [96] | North Sea-Heide/West, Germany | 2032 | ±525 | 2000 | VSC | |
| Energiø Nordsøen [98] | North Sea Energy Island to Denmark (DK1) and Belgium | 2032 | ±525 | 2000+2000 | VSC | Bipole with metallic return, 2x1000 MW to DK1 and 2x1000 MW to BE. Will be expanded in later stage |

| | | | | | | |
|---|---|---|---|---|---|---|
| NOR-11-1 (LanWin3) [96] | North Sea-Westerkappeln, Germany | 2033 | ±525 | 2000 | VSC | Bipole without metallic return (can be run as a Monopole) |
| NOR-11-2 (LanWin4) [96] | North Sea-Ovelgönne, Rastede, Westerstede und Wiefelstede, Germany | 2034 | ±525 | 2000 | VSC | |
| Energiø Nordsøen [98] | North Sea Energy Island to additional offshore platforms, and then to Germany | 2034 | ±525 | 2000 | VSC | Bipole with metallic return, 2x1000 MW to DE ? |
| DC34 [97] | Rastede – Bürstadt | 2035 | ±525 | 2000 | VSC | Bipole with metallic return |
| NOR-13-1 (LanWin5) [96] | North Sea-Zensenbusch, Germany | 2035 | ±525 | 2000 | VSC | |
| NOR-x-1 [99] | North Sea-Ovelgönne, Rastede, Westerstede und Wiefelstede, Germany | 2035 | ±525 | 2000 | VSC | Bipole without metallic return (can be run as a Monopole) |
| Bornholm Energy Island [32] | Bornholm to Sweden | 2035 | | ? | VSC | Expansion of the Bornholm Energy Island to Sweden, might happen |
| NOR-x-2 [99] | North Sea-Rommerskirchen, Germany | 2036 | ±525 | 2000 | VSC | |
| Energiø Nordsøen [98] | North Sea Energy Island to additional offshore platforms, and then to | 2036 | ±525 | 2000 | VSC | Bipole with metallic return, 2x1000 MW to NL ? |

| | | | | | | |
|---|---|---|---|---|---|---|
| | The Netherlands (NL) | | | | | |
| **NOR-x-3 [99]** | North Sea-Heide/West, Germany | 2037 | ±525 | 2000 | VSC | |
| **NOR-x-4 [99]** | North Sea-Oberzier, Germany | 2038 | ±525 | 2000 | VSC | |
| **Energiø Nordsøen [98]** | North Sea Energy Island to additional offshore platforms, and then to Norway | 2038 | ±525 | 2000 | VSC | Bipole with metallic return, 2x1000 MW to NO ? |
| **Energiø Nordsøen [98]** | North Sea Energy Island to the United Kingdom | 2038 | ±525 | 2000 | VSC | Bipole with metallic return, 2x1000 MW to UK ? |
| **Second interconnector Belgium – Germany [89]** | Belgium to Germany | 2038 | under study | under study | VSC | Reference is 1 GW, but higher power is under study |
| **NOR-x-5 [99]** | North Sea-Ovelgönne, Rastede, Westerstede und Wiefelstede, Germany | 2039 | ±525 | 2000 | VSC | Bipole without metallic return (can be run as a Monopole) |

## 8.2. Planned MT projects in Europe

| MT project name | Year [15] | V_nom (kV) | Power (MW) | No. terminals | Remarks | Reasoning why not further considered |
|---|---|---|---|---|---|---|
| **Shetland HVDC Connection [75]** | 2024 | ±320 | 600 | 3 (expandable to 5 terminals) | The Shetland leg will have a power rating of 600MW; the Spittal and Blackhillock converters are rated at 800MW and 1,200MW respectively. | Planning fixed / in construction |
| **UltraNet +A-Nord (mod SiWe) [23]** | 2027 | ±380 | 2000 | 3 | Full-Bridge MMC-HVDC System (active DC-side fault-ride-through), hybrid ACDC towers, mixed cable-OHL transmission, bipolar HVDC with metallic return) | Planning fixed / in construction |
| **Ijmuiden Ver [86]** | 2029 | ±525 | | | | Planned as Multi Purpose Interconnector / no meshed DC grid possible |
| **Princess Elisabeth Island [100]** | 2030 | ? | ? | ? | ? | ? |
| **Bornholm Energy Island [32]** | 2030 | ±525 | 3000 | 4 | Bipole with metallic return, 2x600 MW (DK) and 2x1000 MW (DE) Bipole systems. Will be expanded in later stage | |
| **Nautilus [89]** | 2030 | ±525 | 2000 | VSC | Bipole with metallic return | |
| **NL hub** | 2031 | ? | 2-4 GW | ? | ? | ? |
| **Heide [97]** | 2032 | ±525 | 2*2000 + 1*2000 + 1*2000 | 4 | | |
| **North Sea** | 2032 | ±525 | 2000+2000 | 4 | Bipole with metallic return, 2x1000 MW to DK1 and | |

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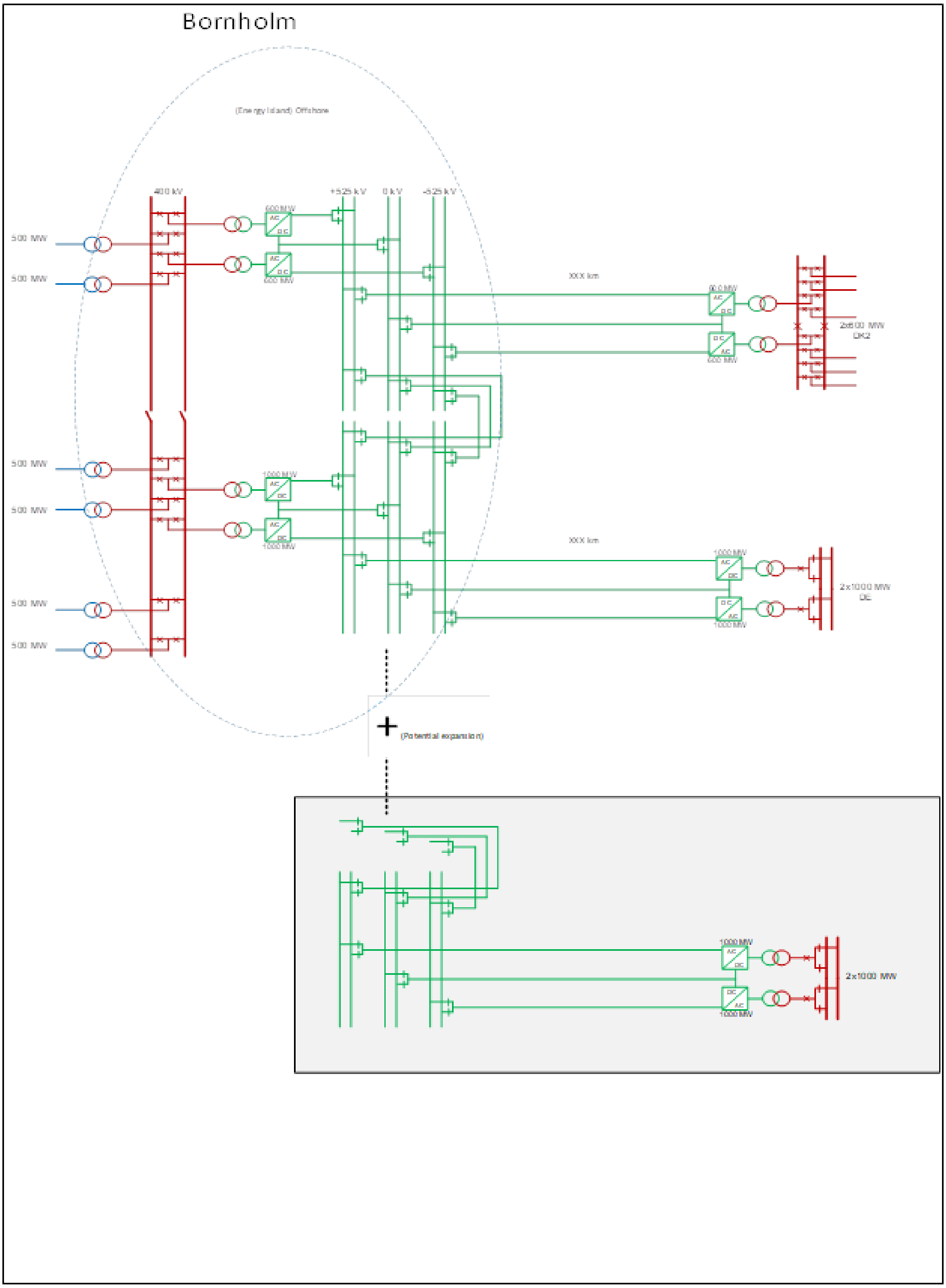
[15] commissioned

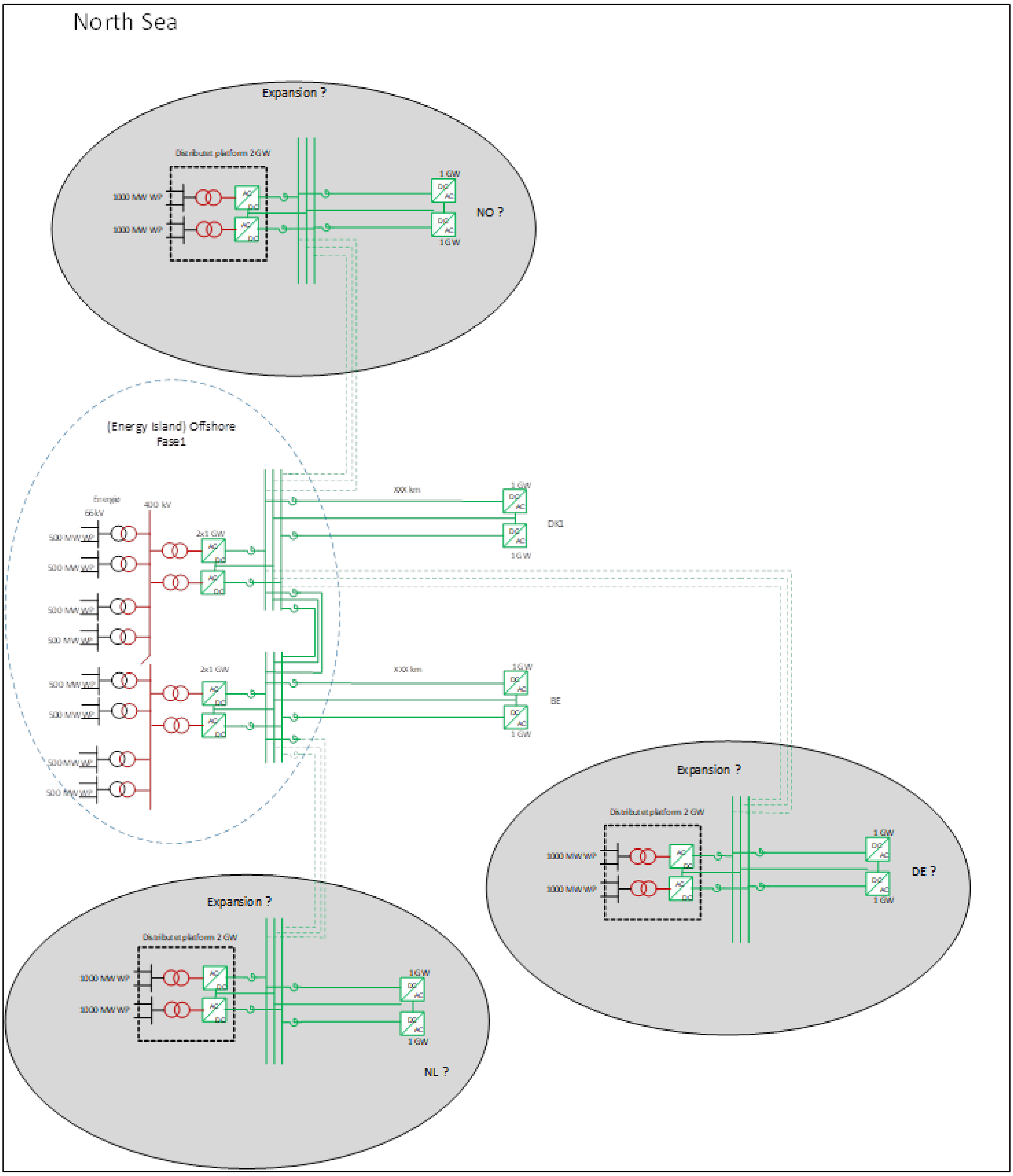
|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Energy Island [98] |  |  |  |  | 2x1000 MW to BE. Will be expanded in later stage |  |
| Pöschendorf [101] | 2032 | ±525 | 2000 | 4 |  |  |
| North Sea Energy Island [98] | 2034 | ±525 | 2000 | additional 2 | Bipole with metallic return, 2x1000 MW to DE ? | Follow up project |
| North-West hub [99] | 2035 | ±525 | 2*2000 + 1*2000 + 1*2000 |  |  |  |
| Bornholm Energy Island [32] | 2035 |  | ? | 6 | Expansion of the Bornholm Energy Island to Sweden, might happen | Follow up project |
| North Sea Energy Island [33] | 2036 | ±525 | 2000 | additional 2 | Bipole with metallic return, 2x1000 MW to NL? | Follow up project |
| Heide [97] | 2037 | ±525 | 2000 | additional 2 |  | Follow up project |
| North Sea Energy Island [33] | 2038 | ±525 | 2000 | additional 2 | Bipole with metallic return, 2x1000 MW to NO? | Follow up project |
| North Sea Energy Island [33] | 2038 | ±525 | 2000 | additional 2 | Bipole with metallic return, 2x1000 MW to UK? | Follow up project |
| Rastede [97] | 2039 | ±525 | 2000 |  | Bipole without metallic return (can be run as a Monopole) | Follow up project |

## 8.3. Short list of potential candidate projects

### 8.3.1. Bornholm Energy Island



### 8.3.2. North Sea Energy Island



## 8.4. Minimum set of functional requirements to be addressed in the functional specification

According to CLC TS 50654-2: 2020, HVDC Grid Systems and connected Converter Stations – Guideline and Parameter Lists for Functional Specifications

### 8.4.1. General structure

The proposed minimum set of requirements is split into three groups:

- AC and HVDC System network diagram and associated descriptions
- Parameters developing a first main circuit design concept
- Operational conditions and requirements

These groups are further detailed in the next sections of the paper.

### 8.4.2. AC and HVDC System network diagram and associated descriptions

To explain the AC and HVDC Grid structure a network diagram shall be specified showing the grid topology including the installations and their connections. This diagram and associated descriptions shall contain information such as:

- Arrangement of AC/DC converter stations
- Arrangement of DC switching stations
- Topology of HVDC Grid and HVDC stations according to the CLC TS 50654 nomenclature ( [11], Table 1)
- DC transmission lines (overhead line, cable or combinations thereof)
- AC networks showing the connection of each AC/DC converter station to the synchronous areas/islanded AC networks with the following additional information and descriptions:
    - Thevenin Equivalent representing the range of Short Circuit current levels
    - Connection to synchronous zones and if connected commonly to a zone, specify a typical impedance between the stations
    - AC voltage profile ( [11], Figure 3) and requirements for fault restoration ( [11], Table 7)
    - Strategies for coordinating the DC power flows during AC system faults and AC system fault recovery ( [11], Table 10)
- DC earthing conditions at each HVDC station ( [11] Tables 3, 17)
- Fault separation concepts ( [11], Clause 7)
- Energy absorbers, e.g. dynamic braking devices typically used for absorbing energy from wind farms or HV pole re-balancing after pole-to-earth DC faults ( [11], Table 43)

### 8.4.3. Parameters developing a first main circuit design concept

The following parameters are meant to develop a first main circuit design concept:

- Typical data of DC transmission lines (overhead line, cable) ( [11], Table 3)
- Typical main circuit parameters (active and reactive power ( [11], Table 2), nominal DC voltage, maximum steady state DC operating voltage and DC voltage band, ( [11], Figure 4, Tables 19-22)
- typical return path parameters ( [11], Table 18)

### 8.4.4. Operational conditions and requirements

The following operational conditions and requirements are important:

- Operating requirements for the individual HVDC stations (connection modes ( [11], Tables 44, 55, 59), DC-Voltage vs. Power characteristics ( [11], Table 53)
- Energization and shut down requirements for individual parts of the system ( [11], Table 47, 50)
- Protection zones ( [11], Tables 39, 40)
- DC system restoration and reconfiguration requirements ( [11], Tables 37, 38, 45, 49, 50)

## 8.5. Grid codes

**Dutch grid code**

The Dutch transmission system consists of the voltage levels:

- 110 kV;
- 150 kV;
- 220 kV; and
- 380 kV.

110 kV and 150 kV are considered as similar and the same codes apply to both.

220 kV and 380 kV are considered as similar and the same codes apply to both, but these codes are different from the ones applicable for 110 kV and 150 kV.

For the 220 kV and the 380 kV the following apply:

- The system shall be n-1 compliant including the transformers from 220 kV or 380 kV to 110 kV or 150 kV (no allowed loss);

Then there are exceptions for specific transformers directly from 220 kV or 380 kV to voltage levels lower than 110 kV as follows:

- Allowed loss of permanent transmitted power due to trip of transformer is 100 MW for max 10 minutes in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power due to trip of transformer is 100 MW for max 6 hours in case the transmitted power regards demand;

- Allowed loss of temporary transmitted power due to trip busbar (at <110 kV side of transformer) is according to figure 1 in case the transmitted power regards demand;
- Allowed loss of permanent transmitted power due to trip of transformer is 200 MW for max 2 weeks in case the transmitted power regards generation;
- Allowed loss of permanent transmitted power due to trip busbar (at <110 kV side of transformer) is 1500 MW for max 6 hours in case the transmitted power regards generation;
- Allowed loss of temporary transmitted power due to trip of transformer is 200 MW for max 2 weeks in case the transmitted power regards generation;
- Allowed loss of temporary transmitted power due to trip busbar (at <110 kV side of transformer) is 1500 MW for max 6 hours in case the transmitted power regards generation;

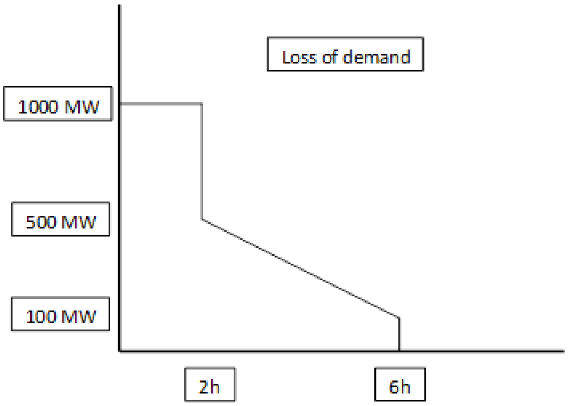


**Figure 1**

### Now for 110 kV and 150 kV systems

For transformers transforming directly from 110 kV or 150 kV to < 110 kV:

- Allowed loss of permanent transmitted power due to trip of transformer is 100 MW for max 10 minutes in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power due to trip of transformer is 100 MW for max 6 hours in case the transmitted power regards demand;
- Allowed loss of permanent transmitted power due to trip of transformer is 200 MW for max 2 weeks in case the transmitted power regards generation;
- Allowed loss of temporary transmitted power due to trip of transformer is 200 MW for max 2 weeks in case the transmitted power regards generation;

For 110 kV or 150 kV circuits:

- Allowed loss of permanent transmitted power due to trip of circuit is 100 MW for max 10 minutes in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power due to trip of circuit is 100 MW for max 6 hours in case the transmitted power regards demand;
- Allowed loss of permanent transmitted power due to trip of circuit is 500 MW for max 2 weeks in case the transmitted power regards generation;

- Allowed loss of temporary transmitted power due to trip of circuit is 500 MW for max 2 weeks in case the transmitted power regards generation;

For 110 kV or 150 kV busbars:

- Allowed loss of permanent transmitted power due to trip busbar is according to figure 2 in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power due to trip busbar is according to figure 1 in case the transmitted power regards demand;
- Allowed loss of permanent transmitted power due to trip busbar is 1500 MW for max 6 hours in case the transmitted power regards generation;
- Allowed loss of temporary transmitted power due to trip busbar is 1500 MW for max 6 hours in case the transmitted power regards generation;

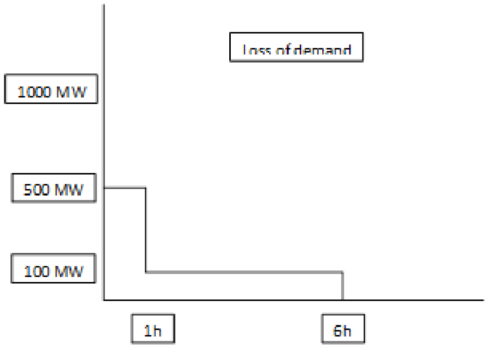


Figure 2

For 110 kV or 150 kV closed switchgears during repair, modification or replacement:

- Allowed loss of temporary transmitted power is 100 MW for max 48 hours in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power is 500 MW for max 48 hours in case the transmitted power regards generation;

For 110 kV or 150 kV gas insulated cables or oil insulated cables during repair, modification or replacement:

- Allowed loss of temporary transmitted power is 100 MW for max 1 week in case the transmitted power regards demand;
- Allowed loss of temporary transmitted power is 500 MW for max 1 week in case the transmitted power regards generation;

## 8.6. Project Aquila

### 8.6.1. Testing requirements

For Project Aquila - the following stages of de-risking are being undertaken:

- Stage 0 – define the requirements and expectations of the MTMV system- this is achieved by:
  - Constructing in Real-time, a non-vendor specific model of the DC network, and associated controls and protection sufficiently comprehensive in detail, and extent that a vendor replica control/ protection can be substituted for that model.
  - Constructing the related DC network and AC network interfaces in real time simulation and additionally the MTMV control across the convertors.
  - Defining within the context of a vendor- agnostic "test-bench" the conditions of stability and acceptable conditions for operation across the range of operating scenarios and following and across disturbance events (N-1)
  - Identifying the for the non-vendor specific controls the relevant MTMV control flexibilities and specifications to ensure stability and satisfy the range of operation conditions. These are tested by quantifying droop responses from the control in response to DC system perturbance, both 0Hz and across a small-signal spectrum quantified by the extent to which distortion may be measured and observed within the given DC system. This is conducted across the range of operating points of the convertors' operation, and to respect AC facing operation needs at that time.
- Stage 1 - defining the tests to be undertaken and the necessary conditions of performance - these being separated into:
  - Single terminal conditions of performance and test for each interface for each vendor convertor across its operating points and control priorities and related behaviour characterisation. Included at this and subsequent stage are step tests, operational conditions, energisation conditions, and transient N-1 events introduced and verified in Real Time EMT simulation.
  - Point to Point operation demonstrating the MTMV application to the 2 terminal performance results in performance analogous to single vendor performance from MTMV control.
  - Multi- terminal operation of the vendor point to point with non-vendor specific models of the residual terminals, first in a 3-terminal then a 4-terminal basis, with further testing of future stages.
  - The above is repeated across each vendor solution. At each stage the MTMV control is "trained" to capture the effect of the vendors IP within the convertor control and protection and specify across these and the other terminals to provide an envelope of 0HZ and small signal emission permissible in operation and across disturbance whilst maintaining overall DC network stability. These conditions of operation are then tested in time-domain simulation and against a range of standard step and injection tests.
  - Following the above, multiple vendors having been acceptably tested within the above environments will then be combined.
  - Finally in addition to the Centre- modelled MTMV control, physical controllers delivering the same functions will be tested further in robustness (for example communications failure/ delay).
  - Stage 1 is initially hosting "virtual replicas" based predominantly on the RTDS Giga Transistor on a Chip (GTSOC) allowing early vendor design code of the intended +/-525kV Bipole solutions at the detailed design and prior tendering stages of the projects. Stage 1 completes across 2023/24.

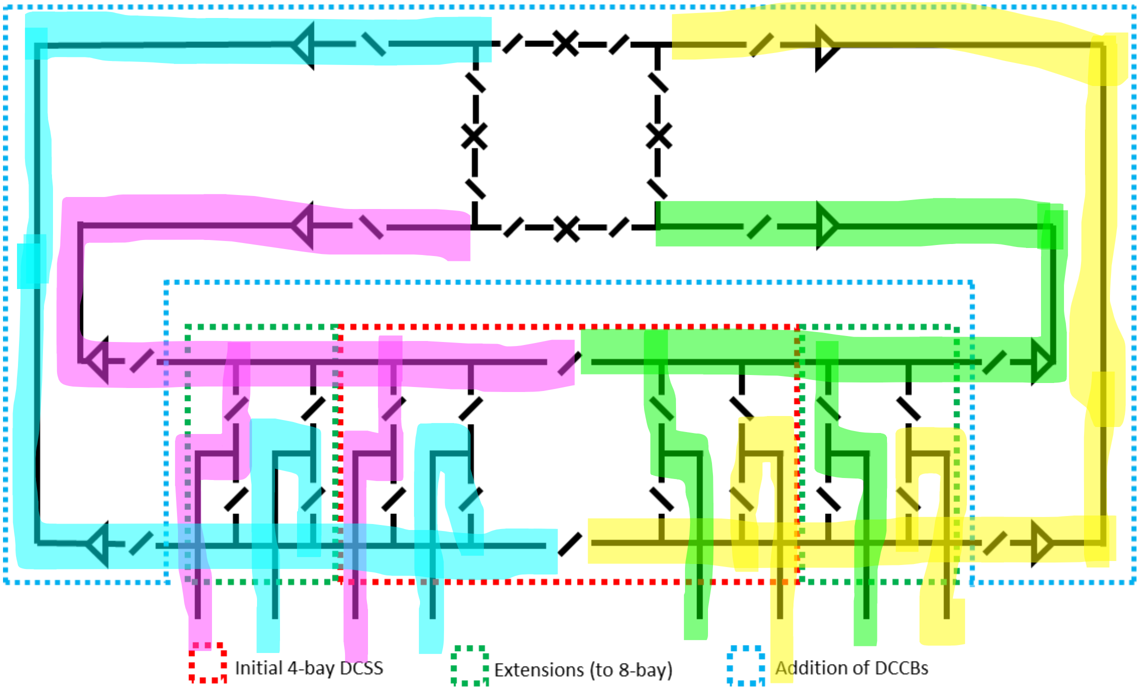
further repetition of these tests at later project developments including project specific design tuning (Stage 2), and project specific replica control testing Stage 3 will follow as the projects progress towards 2030 delivery. An important capability of the GTSOC is the ability for it to operate alongside finalised replica control of elements of the network delivering ahead of others, allowing the performance of the network to be tracked across the delivery of the projects, initially via a baseline non-vendor specific model; then incorporating early design code within GTSOC from each vendor; then more project finalised code resulting from each detailed design phase, combined with other GTSOC data; then a combination of GTSOC and replica; then finally an all replica environment.

- Ahead of the MTMV demonstration on the real system, the switching enabling of the MTMV control, this operation will be subject to "dry run" testing. Following the control switch on, operation shall be reviewed against intended and simulated behaviour with the ability to quickly revert via DCSS operation to single vendor point to point HVDC routes should any concern be identified for further test, simulation and potential update.
- The Project Aquila design includes certain notable control objectives included within the developed MTMV control design-
    - A "full Bipole" arrangement between Peterhead converters and the DC switching stations.
    - Full Bipole connections to future offshore wind connection points.
    - Rigid Bipole interfacing to TSO convertors in England/ Scotland, with the DCSS providing control to maximise availability of the rigid and residual pole connections following N-1 scenarios.
- The MTMV design approach has been taken to enable any vendor to implement the control without a requirement to "open up" open loop or inner loop control. The control focuses on characterising the effect of the convertor and establishing necessary and sufficient conditions for multi-terminal operation across the range of operating and fault scenarios.

In parallel to control development, the principles underpinning control formulation and the control itself have been filed for associated patents to preserve the available "space" for MTMV solutions to be delivered using this approach.

## 8.6.2. Protection approach

Project Aquila – illustrative topology following future expansion, considered under Network-DC innovation project at present.



**Key**

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**4 Protection Zones- either available for a selective strategy, or cleared via a non- selective strategy (all DCCB act, then selectively reclose)**

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AC/DC | Alternating Current / Direct Current (Conversion) |
| ACER | Agency For the Cooperation of Energy Regulators |
| CB | Circuit Breaker |
| CBA | Cost-Benefit Analysis |
| CENELEC | European Committee for Electrotechnical Standardization |
| C&P | Control And Protection |
| DCCB | Direct Current Circuit Breaker |
| DC-FSD | Direct Current – Fault Separation Device |
| FST | Factory System Test |
| EC | The European Commission |
| EMT | Electromagnetic Transients |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| GFC | Grid Forming Converters |
| HIL | Hardware-in-the-loop |
| HVDC | High-Voltage Direct Current |
| MMC | Modular Multilevel Converter |
| MT | Multi-terminal |
| MV | Multi-Vendor |
| MTMV | Multi-Terminal Multi-Vendor |
| OEMs | Original Equipment Manufacturer |
| OWF | Offshore Wind Farm |
| P2P | Point-to-Point |
| PEIDs | Power Electronic Interfaced Devices |
| PCI | Project of Common Interest |
| PoC | Point of Coupling |
| REPowerEU | affordable, secure and sustainable energy for Europe |

| | |
|---|---|
| RTS | Real Time Simulations |
| RTDS | Real Time Digital Simulator |
| TSO | Transmission System Operator |
| TYNDP | Ten-Year Network Development Plan |
| VSC | Voltage-Sourced Converter |

# TERMS AND DEFINITIONS

**Multiple AC grids**

Two asynchronous AC grids; AC grids are onshore and exclude additional offshore AC grids within the wind power plants.

**AC/DC converter unit**

Indivisible operative unit comprising all equipment between the PoC-AC and the PoC-DC, essentially one or more converters, together with converter transformers, control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion.

**AC/DC converter station**

Part of an HVDC system which consists of one or more AC/DC converter units including DC switchgear, if any, DC fault current controlling devices, if any, installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment.

**DC-FSD**

A DC-FSD is a device able to separate a faulty protection zone and a healthy protection zone, allowing the healthy protection zone to not be de-energized. The feature can be provided by a DCCB but also by some topologies of DC/DC converters.

**DC switching unit**

Indivisible operative unit comprising all equipment between the DC busbars and the terminals (HV poles and neutral, if any) of one point of connection on the DC side, comprising, if any, one or more switches, control, monitoring, protective, measuring equipment and auxiliaries.

**DC switching station**

Part of an HVDC Grid System which consists of one or more DC switches, but no AC/DC or DC/DC converter units, installed in a single location together with buildings, reactors, filters, control, monitoring, protective, measuring and auxiliary equipment, if any.

**HVDC Grid System**

High voltage direct current transmission network connecting more than two AC/DC converter stations transferring energy in the form of high-voltage direct current including related transmission lines, switching stations, DC/DC converter stations, if any, as well as other equipment and sub-systems needed for operation.

**Functional requirements**

A functional requirement is understood as a requirement to serve the AC and DC system needs. There may be requirements which are more relevant to serve the system needs.

**Functional specifications**

A functional specification is seen as a precise description for an item/solution.  It details out the functioning of that item based on functional requirements.

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