READY4DC

Deliverable D3.1: 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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EXECUTIVE SUMMARY

This paper outlines the joint perspectives of stakeholders across industry, research and academia on the criteria for the selection, the demonstration proposal as well as the functional specification process to achieve multi-terminal, multi-vendor (MTMV) interoperability.

Achieving selection criteria for the first MTMV demonstrator two concepts are considered available within the framework of this project. For both concepts the planned MT projects are collected. The first concept then 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 thoughtfully procedure.

After having defined the selection criteria the aim is to indicate a demonstration proposal. Though this can be done straightforward, the lack of TSOs providing possible MTMV projects leads to the fact of having only three proposed projects, namely: Bornholm Energy Island, North Sea Energy Island, 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.

The initial approach to obtain functional specification for MTMV is based on generic use cases a.) Multi-in-feed HVDC system with single AC grid b.) Multi-in-feed 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.

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.

1. INTRODUCTION AND STRUCTURE OF THE DELIVERABLE

The climate neutrality is a crucial task, so many countries are trying to achieve these goals by possibly using electricity from renewable energy sources and, naturally, the offshore renewable energy strategy in Europe. In this respect, offshore wind farm operators clearly need an interoperable HVDC system. 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.

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

The European Commission (EC) has announced a joint EU Action for more affordable, secure & sustainable energy (REPowerEU), which proposed a massive speed-up and scale-up in renewable energy in power generation for meeting the climate targets at affordable price on one hand, and for accelerating the EU phasing out of Russian fossil fuels on the other hand [3].

The REPowerEU proposal will become a driving force for European Energy Infrastructure change by among other proposals addressing [4]:

- Improving gas & electricity interconnections – completion of critical links, full synchronization of power grids etc.
- 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
    - 45% of the energy generation capacity with renewables by 2030 (up from 40% envisaged under Fit for 55)
- A Hydrogen Accelerator for infrastructure, storage facilities & ports

The REPowerEU proposal will accelerate the energy transition [3]. The expected RES capacity will grow from current 511 GW to 1236 GW by 2030. This includes not only development of wind energy, but also extensive increase of solar capacity to 600 GW by 2030.

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.

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

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, 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 [5]:

- **Definition of roles, responsibilities and methods needed within the interoperability process (Objective 3 in** [5]**)**
  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** [5]**)**
  The paper will provide in the final white paper 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 [6] 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 5.1. 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) [13], and Caithness-Moray-Shetland[5] [8] 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 [7] and PROMOTION [8]

[3] like INELFE (Spain-France) [9], different BorWin projects [10] [11] [12] (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

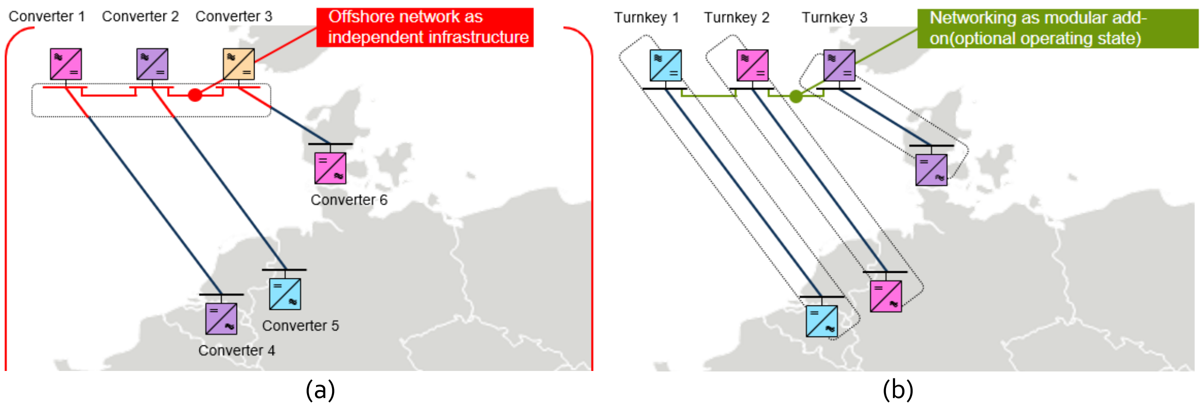
required to ensure interoperability and stability. The specific range of requirements will depend on the project itself and whether it includes all of these components.

In 2018, the Best Paths R&D project [9] 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 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 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



(a) (b)

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 0). 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 4.3. 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 4.4.

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.

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. 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.

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 incorporates 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. This also represents a shift in responsibility from the traditional turnkey vendors to the asset owner, and thus a consequent build 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 PtP 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 the stakeholders to design a first demonstrator being adjustable with regards to new arrangements. This will most likely include adjustments of parameters in the control and protection system of the first demonstrator.

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 is the CENELEC (CLC/TS 50654-1, -2) standard [2] [10]. 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 [11]. 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*
- **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*

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 1 and 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 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 [12, p. 38]; [13]; [14]		≤2000MW [12, p. 38]		≤2000MW [12, 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; 500MW 2h; 100MW 6h
Norway	1400MW	1400MW	1400MW	1400MW	1400MW
Poland	1100MW [15]	1100MW [15]	1100MW [15]	1100MW [15]	
UK[8]	1800MW		1800MW		1400MW
Ireland	500MW	500MW	500MW	500MW	

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[6] Includes MT-systems

[7] See explanation in section 5.5.1

[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)

Table 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 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: 1.05 – 1.0875 p.u.: 60 min N: 1.05 – 1.1 p.u.: 60 min	CE/N: 47.0 – 47.5 Hz: ≥60 sec 47.5 – 48.5 Hz: ≥90 min 48.5 – 49.0 Hz: ≥90 min 51.0 – 51.5 Hz: ≥90 min 51.5 – 52.0 Hz: ≥60 min
Germany	2000 MW [16] 4000 MW per route (cable trench) [16]	390 kV – 420 kV (n-0) 380 kV – 420 kV (n-1) > 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		For HVDC connected to 400 kV grid: 0,85 pu – 1,05 pu - no limited 1,05 pu – 1,10 pu – 60 min For HVDC connected to 400 kV grid: 0,85 pu – 1,118 pu – no limited 1,118 pu – 1,15 pu – 60 min	For HVDC: 47,0 Hz – 47,5 Hz: 60 s 47,5 Hz – 52 Hz: no limited
UK[9]	2000MW, up to 2030		49.5 Hz – 50.5 Hz
Ireland	500MW	370 – 410 kV (n-0) 210 – 240 kV (n-1)	49.0 - 51.0 Hz

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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

DESIGN IMPACT: DC FAULT PROTECTION

If the power ratings of the planned MTMV system exceeds the ratings defined in Table 1 and 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.

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] [16]. 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 [17] 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 5.1 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 [18] 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.

FUNCTIONAL REQUIREMENT: FULFILMENT OF TRANSMISSION REQUEST

DESIGN IMPACT: DC VOLTAGE OPTIONS

With MMC technology the DC voltage range can be selected arbitrarily. Cigré TB684 [19] 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, four voltage levels in the 320-525 kV range are identified as follows:

- ± 320kV
- ± 380kV

- ± 400kV
- ± 525kV

While ± 320kV is currently used for symmetrical monopole operation, ± 380kV appears for special applications [20]. The Nemo Link between Belgium and the UK is the only European HVDC connection at ± 400 kV. Future DC projects, according to Appendix 5.1, 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.

DESIGN IMPACT: SELECTION OF ACTIVE POWER PER CONVERTER STATION

Current developments for DC projects according to Appendix 5.1 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 [22] [23] [24]. Higher active power rating is currently not considered as the cable ratings are based on a 2 kA limit. 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.

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 5.1. 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 [24] [25].

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] [26]. 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 [27]. 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. 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 aspects. 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 [6].

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.

4.3 Selection of potential candidate projects

Based upon the selection criteria defined in chapter 0, 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 5.1 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 0. 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 three proposed projects, namely:

- Bornholm Energy Island [28]
- North Sea Energy Island [29]
- 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 [30] a topological drawing was provided and can be found in Appendix 5.3.1. 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 [29]. A topological drawing of North Sea Energy Island can be found in Appendix 5.3.2. 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.

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 windparks, 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

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.

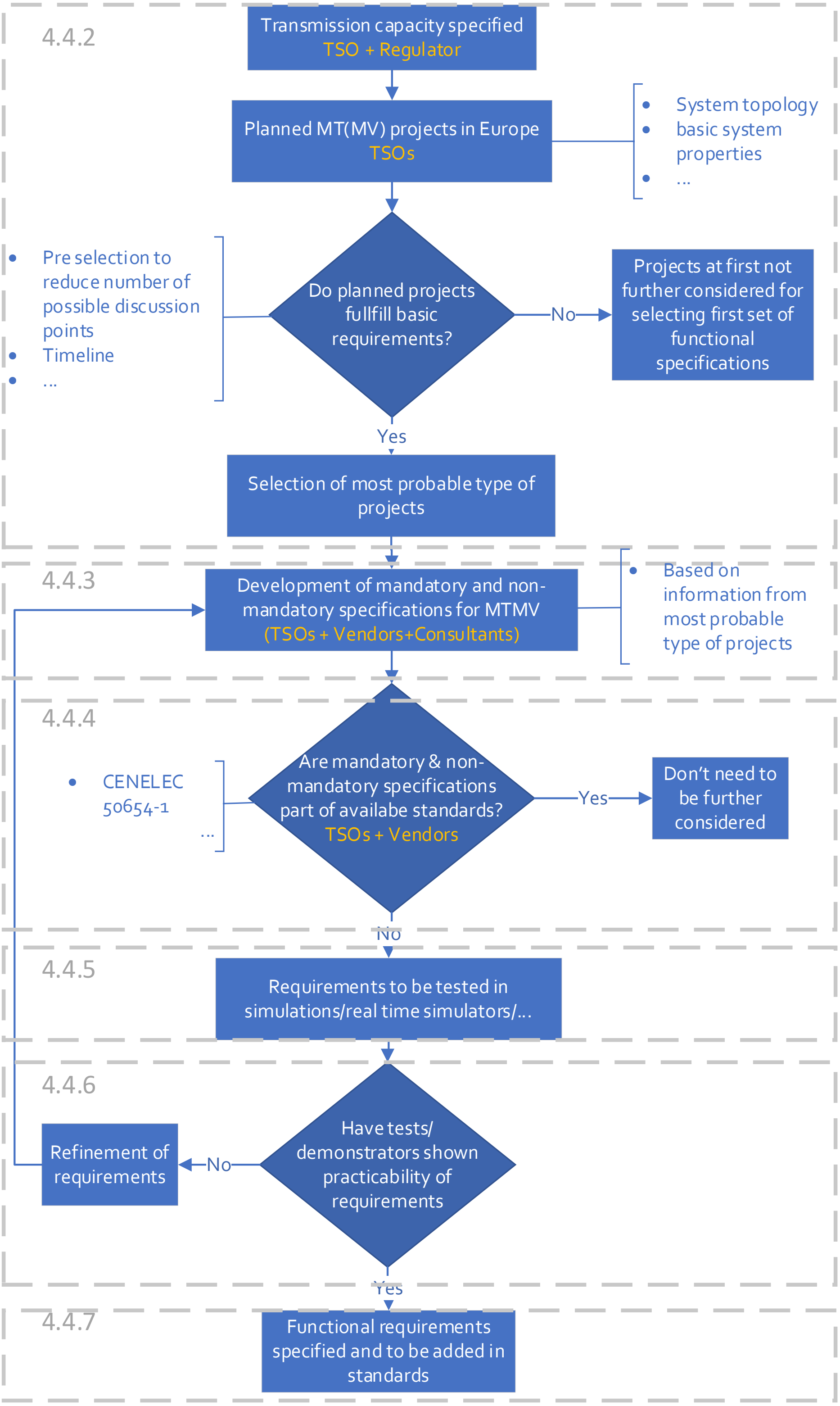
Subsequently, the process structure concludes out of the discussions in this working group. The approach is to first select the most probable MTMV types of projects currently planned in the European transmission grid and derive upon their detailed functional requirements necessary & beneficial (must-have 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 sections 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 integrate the identified gaps into future standards of MTMV network codes.

The procedure shown in Figure 2 summarizes the identification of the functional requirements for MTMV grids.

FIGURE 2

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 [31]. 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 [31], describes guidelines for the commissioning of high voltage direct current (HVDC) converter stations and associated transmission systems [32]. 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 [33]. Recently, the China GB/T 40865-2021 standard has specified the terminology for HVDC transmission based on voltage source converters (VSC-HVDC) [33]. 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 [34], [35], [36], 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 [14] 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 [36] [37]. 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 [36] [37]. 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 [39] [40]. 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* [41] 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 4.3 and according to the procedure of Figure 2, 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 Figures 3 - 6. 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 4.3). 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 4.3, is applied in Figures 7 and 8.

- **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 Fig. 3a) and Eurobar, an initiative of eight European TSOs [42], a meshed HVDC offshore grid project [17] (see Fig. 3b).

FIGURE 3

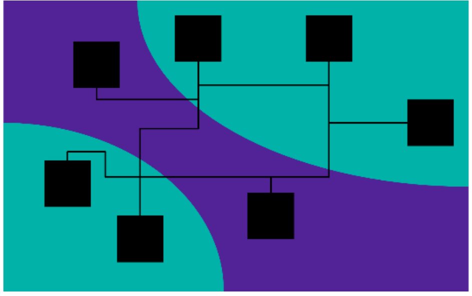
Multi-in-feed HVDC system with single AC grid, (a) energy island and (b) Euro Bar or Meshed


(a) (b)

- **Multi-infeed HVDC system with multiple AC grids**: In this HVDC system typology as shown in Fig 4, 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 [43].

FIGURE 4

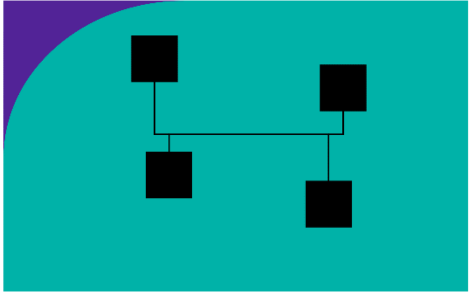
Multi-infeed HVDC system with multiple AC grids



- **No-infeed HVDC system with single AC grid**: The other HVDC system typology, as shown in Fig. 5, 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 5

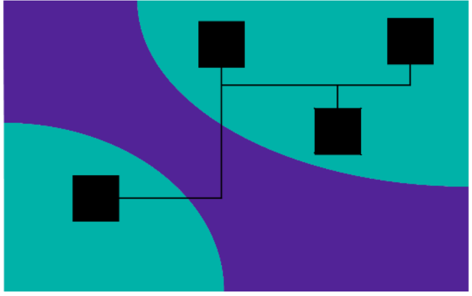
No-infeed HVDC system with single AC grid



- **No-infeed HVDC system with multiple AC grids**: Finally, another HVDC system (see Fig. 6) 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 6

No-infeed HVDC system with multiple AC grids



Based on the planed MT projects in Appendix 5.2, the system layout of a first use-case should be based on a multi-infeed HVDC system, as shown in Figure 7. 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 8. 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 7

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

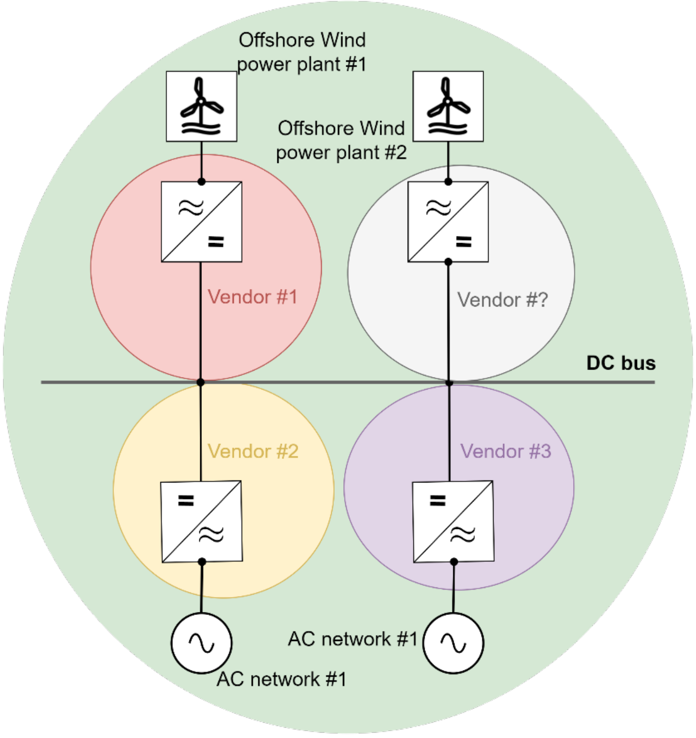
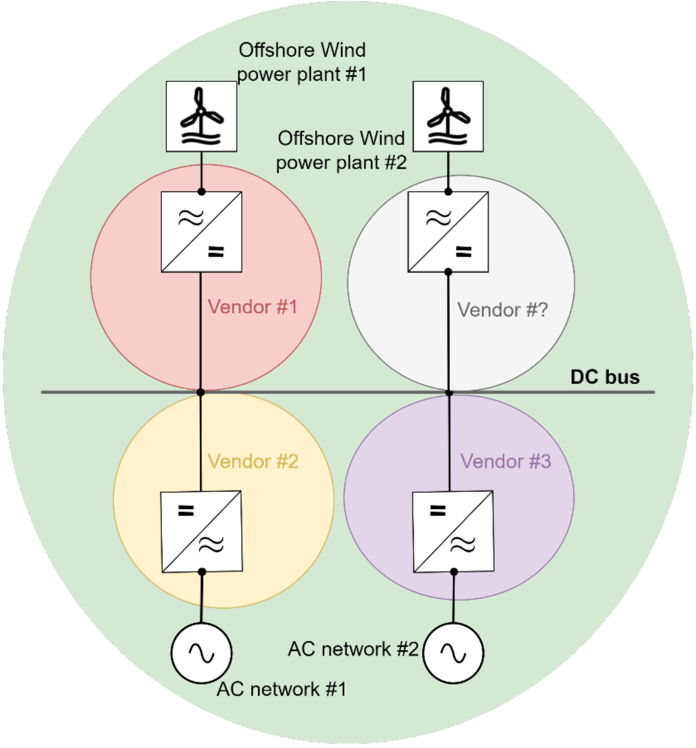


FIGURE 8

Multi-infeed HVDC system with two asynchronous AC grids



4.4.3 Development of mandatory & non-mandatory specifications for MTMV

After having identified the most probable type of projects, like it has been exemplarily done in Figure 7 and 8, 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 5.4. 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 7 and 8 to propose a first 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 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 3 may forthcoming be translated to functional specifications. Afterwards the developed functional specifications are to be compared to existence in available standards.

TABLE 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. 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	

4.4.4 Gap analysis to available standards

The existing CENELEC standard [2] [10] and IEC TS 63291 [37] [38] 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 this 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 [5] 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 FAT 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 MT-MV 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.

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 [44]. 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. APPENDIX

5.1 Planned DC projects in Europe

DC Project Name	**Location**	**Year** [10]	**Nominal Voltage (kV)**	**Power (MW)**	**Converter Type**	Remarks
Caithness Moray HVDC Link [45]	Kergord, Spittal,Black hillock, Scotland	2019	±320	800 / 1200	VSC	Symmetrical monopole
SavoiePiedmont, Italy-France [46]	Piossasco, Italy-f Grande Ile, France	2021	±320	2x600	VSC	
IFA2 [47]	Tourbe, France - Daedalus,England	2021	±320	1000	VSC	Symmetrical monopole
North Sea Link (NSL) [48]	Blyth, Great Britain - Kvilldal, Norway	2021	±525	1400	VSC	Bipole without metallic return (can be run as a monopole)
NordLink [49]	Ertsmyra, Norway and Wilster, Schleswig-Holstein, Germany.	2021	±525	1400	VSC	The system is designed to operate in the following modes: o Bipolar mode o Monopolar metallic return mode o Reduced DC voltage operation o STATCOM mode o Black Start / Islanded mode
Neuconnect [50]	GB-DE Interconnector	2022				HVDC Interconnector
NOR-3-3 (DolWin 6) [51]	North Sea-Emden/East, Germany	2023	±320	900	VSC	

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[10] commissionned

Dogger Bank A [52]	North Sea - Teesside and Creyke Beck, UK	2023	±320	1200	VSC	Symmetrical monopole
Viking Link [53]	DK to GB	2023	525	1400	VSC	TYNDP22 Reference Grid (RegIP-2022-NS.pdf page 14)
DKE, DE Westcoast [54]	TenneT-DE to Energienet DK	2023				
NOR-1-1 (DolWin5) [55]	North Sea-Emden/East, Germany	2024	±320	900	VSC	
Shetland HVDC Connection [56]	Upper Kergord -UK – near Staxigoe, UK	2024	±320	600	VSC	Symmetrical monopole (multi-terminal)
Greenlink [57]	Irish sea, Ireland to Wales	2024	320	500	VSC	Monopole
Sofia [58]	North Sea - Lazenby, England	2025	±320	1400	VSC	
NOR-7-1 (BorWin5) [59]	North Sea-Garrel/Ost, Germany	2025	±320	900	VSC	
Celtic Link [60]	Ireland - France	2025	± 320 kV	700	VSC	
Dogger Bank B [52]	North Sea - Teesside and Creyke Beck, UK	2025	±320	1200	VSC	Symmetrical monopole
North South Interconnector [61]	IE to Northern Ireland	2025	400	900		AC or DC ? connects SONI and Eirgrid by overheadlines
Dogger Bank C [52]	North Sea - Teesside and Creyke Beck, UK	2026	±320	1200	VSC	Symmetrical monopole
OST-1-4 [62]	Baltic Sea - Brünzow /	2026		300		AC Technology not an HVDC Project

	Kemnitz / Lubmin					
Ultranet [20]	Osterrath to Philippsburg	2026	380	2000	VSC	Fullbridge Convertes, Rigid Bipol
NOR-7-2 (BorWin6) [63]	North Sea-Büttel, Germany	2027	±320	980	VSC	
SuedLink DC3 [64]	Brunsbüttel - Großgartach, Germany	2027	±525	2000	VSC	
SuedLink DC4 [64]	Wilster - Bergrheinfeld, Germany	2027	±525	2000	VSC	
North connect [65]	Norway to Great Britain	2027		1400		
Biscay Gulf [66]	Atlantic Ocean - Cubnezais (France) and Gatika (Spain)	2027	320-500kV	2000	VSC	Double symetrical monopole ? Not multi-terminal, 400km
IJmuiden Ver Beta [67]	North Sea-Amaliahaven (Maasvlakte), Netherlands	2028	±525	2000	VSC	
NOR-3-2 (DolWin4) [68]	North Sea-Hanekenfähr, Germany	2028	±320	900	VSC	Symmetrical monopole
NOR-6-3 (BorWin4) [68]	North Sea-Garrel/Ost, Germany	2028	±320	900	VSC	Symmetrical monopole
IJmuiden Ver Alpha [67]	North Sea-Borssele, Netherlands	2029	±525	2000	VSC	
IJmuiden Ver Gamma [43]	North Sea-Amaliahaven (Maasvlakte), Netherlands	2029	±525	2000	VSC	

NOR-9-1 (BalWin1) [69]	North Sea-Unterweser, Germany	2029	±525	2000	VSC	
MOG II [70]	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 [71]	?- 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 [72]	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)
Nederwiek 1 [73]	North Sea-Borssele, Netherlands	2030	±525	2000	VSC	
Nederwiek 2 [73]	North Sea-Amaliahaven (Maasvlakte), Netherlands	2030	±525	2000	VSC	
Nederwiek 3 [73]	North Sea-Geertruidenberg of Moerdijk, Netherlands	2030	±525	2000	VSC	
Doordewind 1 [73]	North Sea-Eemshaven Oude Schip, Netherlands	2030	±525	2000	VSC	

Doordewind 2 [73]	North Sea-Eemshaven, Netherlands	2030	±525	2000	VSC	
NOR-9-2 (BalWin3) [69]	North Sea-Wilhelmshaven, Germany	2030	±525	2000	VSC	
NOR-10-1 (BalWin2) [69]	North Sea-Unterweser, Germany	2030	±525	2000	VSC	
Energiø Bornholm [74]	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 [70]	UK to Belgian offshore Princess Elisabeth Island	2030	±525	2000	VSC	Bipole with metallic return
NOR-12-1 (LanWin1) [75]	North Sea-Wehrendorf, Germany	2031	±525	2000	VSC	Bipole without metallic return (can be run as a monopole)
DC25 [76]	Heide/West – Polsum	2031		2000		
DC 31 [76]	Heide - Klein Rogahn	2032		2000		
NOR-12-2 (LanWin2) [75]	North Sea-Heide/West, Germany	2032	±525	2000	VSC	
Energiø Nordsøen [77]	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) [75]	North Sea-Westerkappeln, Germany	2033	±525	2000	VSC	Bipole without metallic return (can be run as a monopole)
NOR-11-2 (LanWin4) [75]	North Sea-Ovelgönne, Rastede, Westerstede	2034	±525	2000	VSC	

	und Wiefelstede, Germany					
Energiø Nordsøen [77]	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 [76]	Rastede – Bürstadt	2035	±525	2000	VSC	Bipole with metallic return
NOR-13-1 (LanWin5) [75]	North Sea-Zensenbusch, Germany	2035	±525	2000	VSC	
NOR-x-1 [78]	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 [28]	Bornholm to Sweden	2035		?	VSC	Expansion of the Bornholm Energy Island to Sweden, might happen
NOR-x-2 [78]	North Sea-Rommerskirchen, Germany	2036	±525	2000	VSC	
Energiø Nordsøen [77]	North Sea Energy Island to additional offshore platforms, and then to The Netherlands (NL)	2036	±525	2000	VSC	Bipole with metallic return, 2x1000 MW to NL ?
NOR-x-3 [78]	North Sea-Heide/West, Germany	2037	±525	2000	VSC	

NOR-x-4 [78]	North Sea-Oberzier, Germany	2038	±525	2000	VSC	
Energiø Nordsøen [77]	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 [77]	North Sea Energy Island to the United Kingdom	2038	±525	2000	VSC	Bipole with metallic return, 2x1000 MW to UK ?
Second interconnector Belgium – Germany [70]	Belgium to Germany	2038	under study	under study	VSC	Reference is 1 GW, but higher power is under study
NOR-x-5 [78]	North Sea-Ovelgönne, Rastede, Westerstede und Wiefelstede, Germany	2039	±525	2000	VSC	Bipole without metallic return (can be run as a monopole)

5.2 Planned MT projects in Europe

MT project name	Year [11]	V_nom (kV)	Power (MW)	No. terminals	Remarks	Reasoning why not further considered
Shetland HVDC Connection [56]	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) [20]	2027	±380 (mod. SiWe)	2000	3 (mod SiWe)	Full-Bridge MMC-HVDC System (active DC-side fault-ride-through), hybrid ACDC towers, mixed cable-OHL transmission, bipolar HVDC with metallic return) (mod SiWe)	Planning fixed / in construction
Ijmuiden Ver [67]	2029	±525				Planned as Multi Purpose Interconnetor / no meshed DC grid possible
Princess Elisabeth Island [79]	2030	?	?	?	?	?
Bornholm Energy Island [28]	2030	±525	3000	4	Bipole with metallic return, 2x600 MW (DK) and 2x1000 MW (DE) bipole systems. Will be expanded in later stage	
Nautilus [70]	2030	±525	2000	VSC	Bipole with metallic return	
NL hub	2031	?	2-4 GW	?	?	?
Heide [76]	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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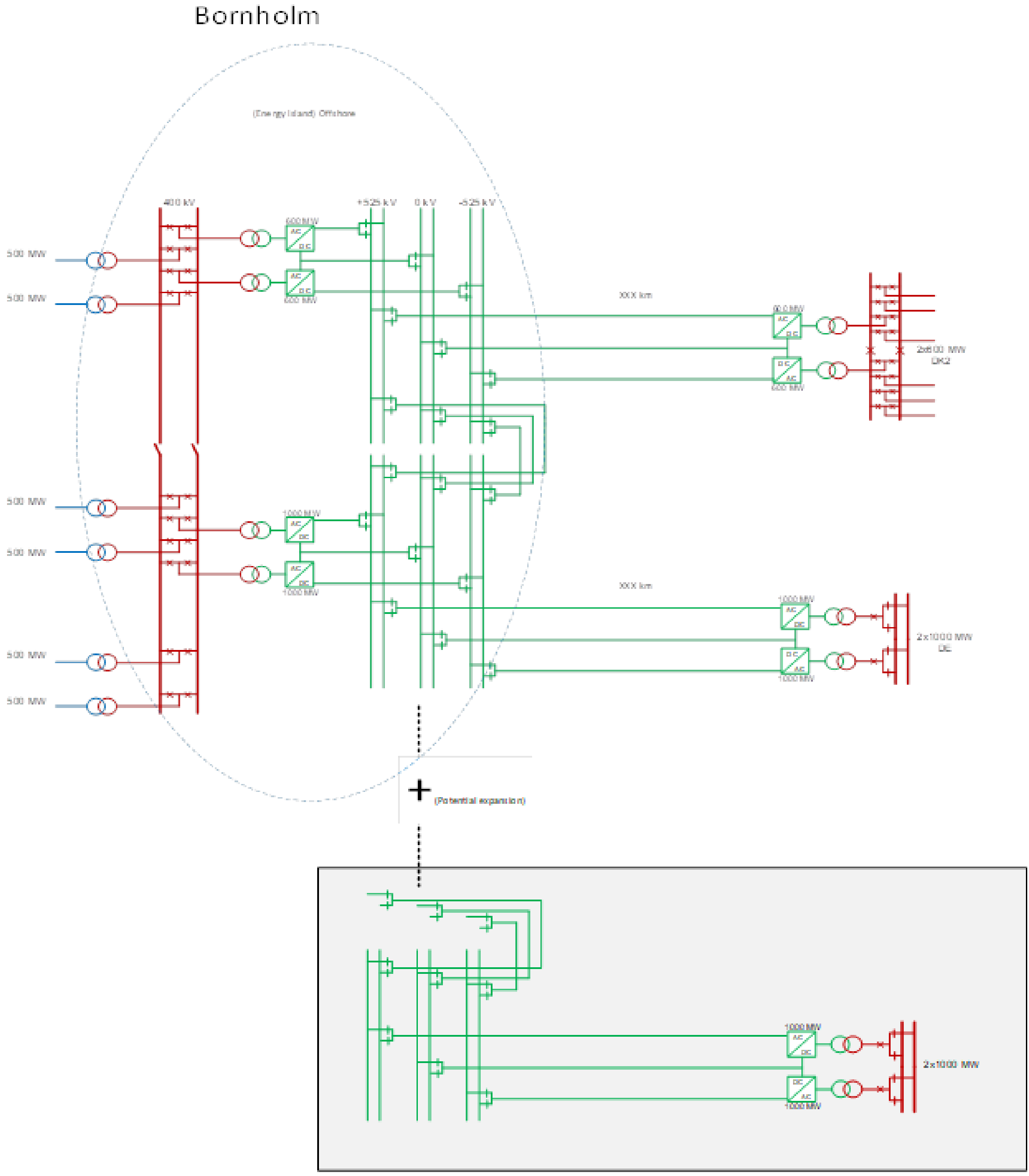
[11] commissionned

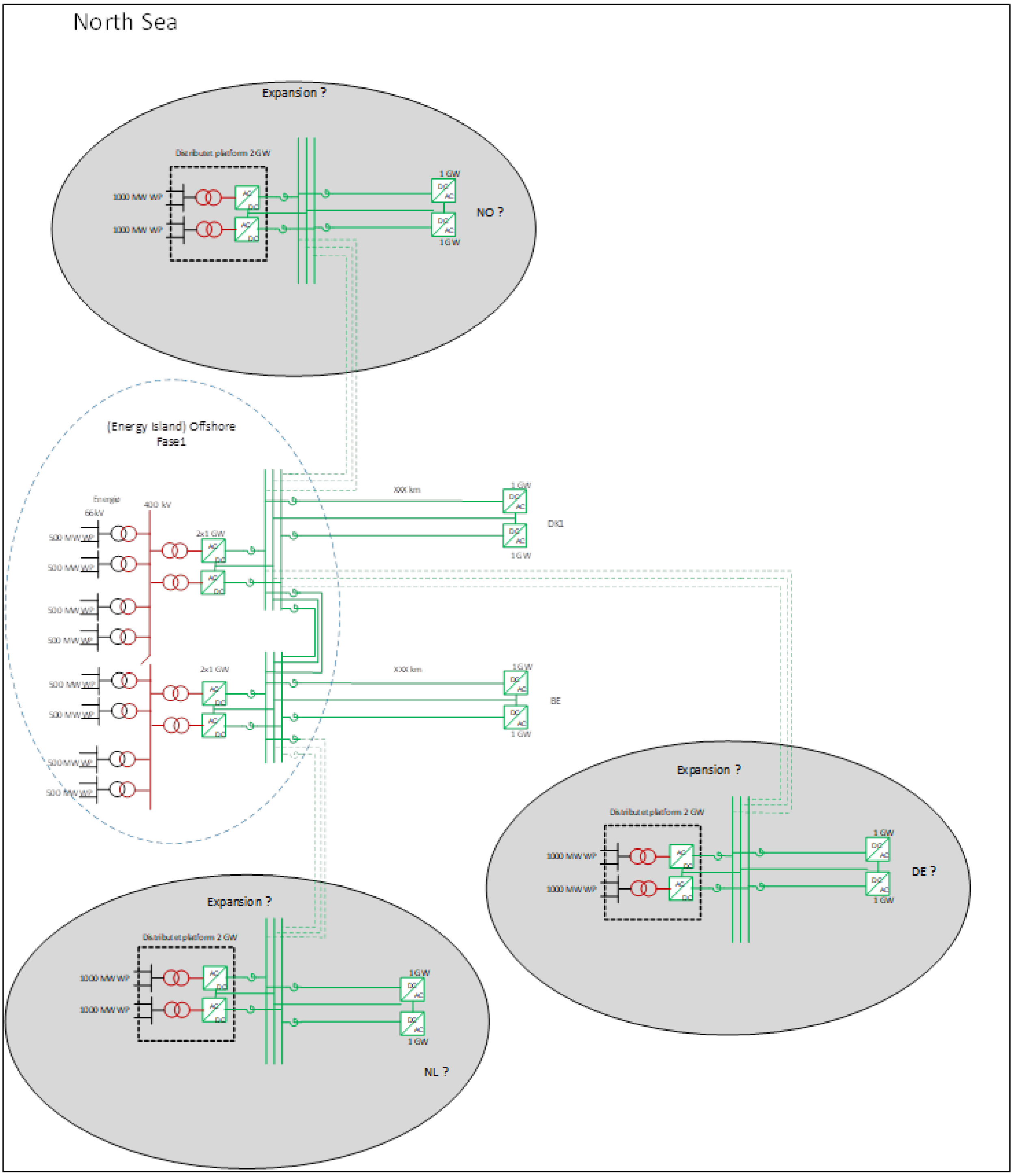
Energy Island [77]					2x1000 MW to BE. Will be expanded in later stage	
North Sea Energy Island [77]	2034	±525	2000	additional 2	Bipole with metallic return, 2x1000 MW to DE ?	Follow up project
North-West hub [78]	2035	±525	2*2000 + 1*2000 + 1*2000			
Bornholm Energy Island [28]	2035		?	6	Expansion of the Bornholm Energy Island to Sweden, might happen	Follow up project
North Sea Energy Island [29]	2036	±525	2000	additional 2	Bipole with metallic return, 2x1000 MW to NL ?	Follow up project
Heide [76]	2037	±525	2000	additional 2		Follow up project
North Sea Energy Island [29]	2038	±525	2000	additional 2	Bipole with metallic return, 2x1000 MW to NO ?	Follow up project
North Sea Energy Island [29]	2038	±525	2000	additional 2	Bipole with metallic return, 2x1000 MW to UK ?	Follow up project
Rastede [76]	2039	±525	2000		Bipole without metallic return (can be run as a monopole)	Follow up project

5.3 Short list of potential candidate projects

5.3.1 Bornholm Energy Island



5.3.2 North Sea Energy Island



5.4 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

5.4.1 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.

5.4.2 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 ([10], 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 ([10], Figure 3) and requirements for fault restoration ([10], Table 7)
  - Strategies for coordinating the DC power flows during AC system faults and AC system fault recovery ([10], Table 10)
- DC earthing conditions at each HVDC station ([10] Tables 3, 17)
- Fault separation concepts ([10], 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 ([10], Table 43)

5.4.3 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) ([10], Table 3)
- Typical main circuit parameters (active and reactive power ([10], Table 2), nominal DC voltage, maximum steady state DC operating voltage and DC voltage band, ([10], Figure 4, Tables 19-22)
- typical return path parameters ([10], Table 18)

5.4.4 Operational conditions and requirements

The following operational conditions and requirements are important:

- Operating requirements for the individual HVDC stations (connection modes ([10], Tables 44, 55, 59), DC-Voltage vs. Power characteristics ([10], Table 53)
- Energization and shut down requirements for individual parts of the system ([10], Table 47, 50)
- Protection zones ([10], Tables 39, 40)
- DC system restoration and reconfiguration requirements ([10], Tables 37, 38, 45, 49, 50)

5.5 Grid codes

5.5.1 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;

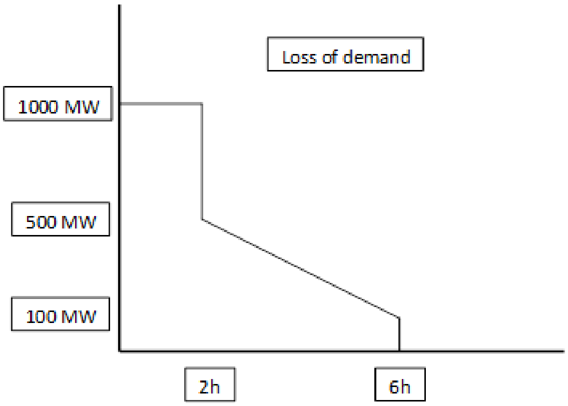


Figure 1

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;

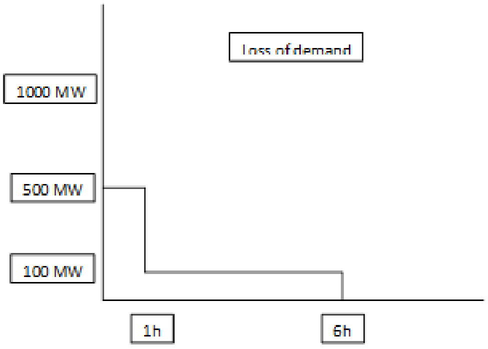


Figure 2

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;

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
FATs	Factory Acceptance Tests
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
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.

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