Design and planning approach for HVDC systems in large scale transmission systems

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Abstract: High-voltage direct current (HVDC) transmission systems are progressively being integrated into the grid expansion efforts of European transmission system operators. Whereas today, most systems are planned individually, the potential integration of more and larger HVDC systems into the existing AC transmission grid requires a thorough consideration of the potential interactions between the two technologies during the planning phase, and a clear assessment of benefits and risks. This paper presents a design and planning approach for HVDC systems that enables a systematic analysis of different architectural components and their impact on the AC transmission grid. In particular, various combinations of HVDC topologies and integration levels are clustered to architectural building blocks. This approach enables a systematic investigation of different HVDC-based architectures, e.g. for static studies in the context of load flow and redispatch calculations. The inclusion of design principles ensures that considerations such as constraints resulting from the control and protection concepts or insulation coordination can be incorporated without a need for a detailed dynamic study at the time of system planning.

Keywords: HVDC systems, network expansion planning, AC/DC transmission, reliability, resilience

1 Background and Objectives

The EU's goal is to be climate-neutral by 2050. This requires the increasing integration of renewable energy plants (RE) into the electricity system [1]. For the integration of power from remote RE sources into the transmission grid, but also for a more flexible power flow control within the transmission grid, high-voltage direct current systems (HVDC systems) are an increasingly used solution. So far, mainly point-to-point (P2P) HVDC systems have been used for this purpose, with several projects already under construction or even in operation. In recent years, a further development from individual P2P HVDC systems towards multi-terminal HVDC systems (MTDC systems) has been discussed, and more precise plans have been made for the upcoming decade [2-6]. One example of this is the Heide Hub project, which links two offshore grid connections with the NordOst link to form an MTDC system [3]. With increasing penetration of the meshed AC transmission grid with the new planned DC connections, changes are not only expected on the DC side: For both P2P systems or MTDC systems, the interactions between the AC transmission grid and the DC overlay grid may increase, such that a separate planning and operation approach might not be suitable anymore. As a constraint on system planning and operation, it is particularly important that reliability and resilience are maintained in the future. Reliability is a measure of the ability of a power system to deliver electricity to all points of consumption and receive electricity from all points of supply within accepted standards and in the amount desired and includes both adequacy and security. [7] Resilience describes the ability to limit the extent, severity, and duration of system degradation following an extreme event. [8]

In future AC/DC transmission systems, both reliability and resilience (R&R) are likely to not only depend on the feed-in and load situation as well as (n-1) outages in the AC grid, but also – and increasingly – on the HVDC system architectures that are used. In this paper, the architecture of an HVDC system is defined as the combination of a) the purpose of the HVDC system b) the configuration and topology of the HVDC system, c) the degree to which it is embedded in the AC grid, and d) the control and protection (C&P) concepts that are applied. No standard for HVDC architectures has yet been established, as DC technology is relatively new compared to AC technology for use in the transmission grid. [9] Depending on the project, the purpose, and the area of application of the HVDC system, the aforementioned aspects that define an HVDC architecture are therefore varied. However, there are no standards for this yet. Each HVDC system is a separate project, more or less independent from other HVDC projects. “Candidates” are proposed for planning and then tested in grid calculations. [10] In the course of this, R&R indicators are determined. In addition, the complexity increases when more and more MTDC systems and P2P connections are connected electrically close to each other in the AC grid. So far there are no academic approaches that highlight the R&R benefits and risks of specific HVDC architectures - mainly because different projects are difficult to compare and because most are P2P only.

Moreover, C&P solutions are only developed once the system topology and configuration is fixed. Nevertheless, the C&P concept can have an impact on R&R. However, this has so far been difficult to take into account in a static planning study. C&P challenges and technological development needs – at least in parts – relate strongly to some of the architecture aspects e.g., MTDC protection vs. P2P protection. If it is possible to identify sensible “groupings”, known as building blocks, these potential C&P issues could be considered at an earlier stage of planning. This would therefore be possible at least at a higher level as part of a needs and risk assessment, not as a final control and protection concept. This makes it possible to map restrictions from C&P, dynamic investigations or isolation coordination on the basis of various design rules, which are presented in more detail below, without having to carry out detailed C&P studies at the planning stage, for example.

This paper presents a design and planning approach that allows to systematically evaluate different options for HVDC architectures in terms of reliability and resilience. In particular, the different aspects of HVDC architectures are grouped in architectural building blocks in the context of this work. As those architectural building blocks are not used in grid planning as carried out by the transmission system operators today, the presented method is intended as a new academic approach that represents to support and enhance the existing planning approaches of the transmission system operators.

As a test scenario for the approach, the same (n-0) transportation task for the AC grid is assumed for all HVDC architectures, and is used to define the ratings between all relevant points of the transmission grid. Through the application of the systematic planning approach, different HVDC-based architectures can be created to solve the same transportation task.

Design rules can be formulated to constrain the variety of architectures, and/or to link them to technological limits/assumptions. The effects that occur when the HVDC architecture is varied can be attributed solely to the architecture properties themselves - e.g., the use of multiple point-to-point links, two smaller MTDC networks, or a large MTDC network. This allows to evaluate different HVDC overlay architectures within a comparable framework. Examples of investigations that can be carried out on the designed AC/DC transmission grid are static redispatch calculations as well as dynamic RMS and EMT simulations.

The focus of this paper is on the presentation of the approach itself – i.e., the architectural building blocks and possible variations of these – and not yet on its simulation-based application. Questions that can subsequently be answered by varying the architectural building blocks are for example:

- How does a changed HVDC architecture affect the load flows and possible congestions in the AC grid?
- Can the redispatch volume be reduced or the RE integration increased by certain HVDC architectures?
- How does the flexibility available in congestion management change due to the HVDC converters in an MTDC system compared to several P2P connections?

Section 2 of the paper presents the concept of architectural building blocks. To this purpose, a distinction is first made from the grid planning process at the transmission system operators. Subsequently, HVDC topologies and embedding levels are presented. A combination of these is then referred to as an architectural building block, which is used as part of the approach presented to carry out system studies as part of grid planning. Based on this, the methodological procedure of the approach is presented in section 3. Section 0 summarizes the findings and provides an outlook on the further procedure for the design and planning of an HVDC system.

2 Architectural building blocks for HVDC systems

2.1 Network expansion planning at the transmission system operator

Transmission system operators distinguish between national and international grid expansion planning. In national grid expansion planning, each TSO is responsible for the implementation of grid expansion projects in its control area. National grid planning is explained using the example of Germany, but may vary slightly between European TSOs. In Germany, grid planning is carried out as part of the “electricity grid development plan”, which is published jointly by all four German TSOs. Both grid expansion projects within and across control areas within Germany are proposed. These must then be approved by the Federal Network Agency. [10] European grid expansion planning is carried out as part of the Ten Year Network Development Plan (TYNDP). Interconnectors and storage projects are identified in a system need study. The proposed projects are then evaluated in a cost-benefit analysis. [11]

Cost-benefit analyses are likewise carried out as part of the German grid development plan. These are based on load flow and outage calculations and a previously determined feed-in and load situation. If there is a violation of the grid assessment criteria (in particular the (n-1) criterion) in the starting grid, an additional transmission requirement between a starting and an end node is determined. However, no MTDC systems are considered in the first planning step. This only arises through mandatory testing of a transmission path bundling. Thus, in particular, no variation of an HVDC architecture is made in the planning process. Once the additional transmission requirements have been determined, the system stability and transient stability will be assessed. Possible restrictions resulting from this are not yet taken into account in the first step of the planning process. [7,11]

The design and planning approach presented here allows restrictions that arise in the downstream planning stages (C&P, stability studies) to be taken into account at an early stage. In addition, by varying the HVDC architecture, a comparison between an MTDC system and several P2P connections is possible. The input data for this approach is assumed to be a sufficiently developed AC transmission grid, which is not varied further. This allows to answer the specific questions mentioned above, which describe the effects of the HVDC system architecture on the (AC) transmission grid and its reliability and resilience.

2.2 Topologies and embedment level for HVDC systems

Topologies for HVDC systems distinguish between point-to-point connections and multiterminal HVDC systems. HVDC systems that are located between two interconnection points in one or more AC grids are referred to as P2P connections. A schematic P2P connection is shown in Figure 2-1.

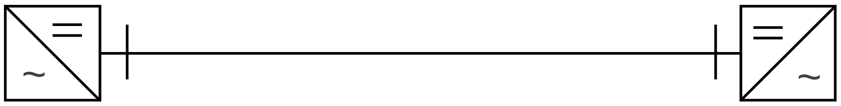

Figure 2-1: Schematic representation of a point-to-point HVDC system

Multiterminal systems are HVDC systems that are located between more than two connection points in one or more AC grids. Within MTDC systems, a distinction is made between linear, radial and meshed MTDC topologies. These are shown schematically in Figure 2-2, where a number of three terminals is used as an example. In addition, a degree of embedding in the AC grid can be specified for each HVDC system, irrespective of the topology. This is shown schematically in Figure 2-3 using a P2P HVDC system as an example. The HVDC system is fully embedded when both converters are in the same AC grid. The HVDC system can also be used to connect offshore wind farms to an AC grid. Furthermore, the coupling of two asynchronous areas is possible. In MTDC systems, mixed forms of these three degrees of embedding presented here can occur due to the increasing number of converters.

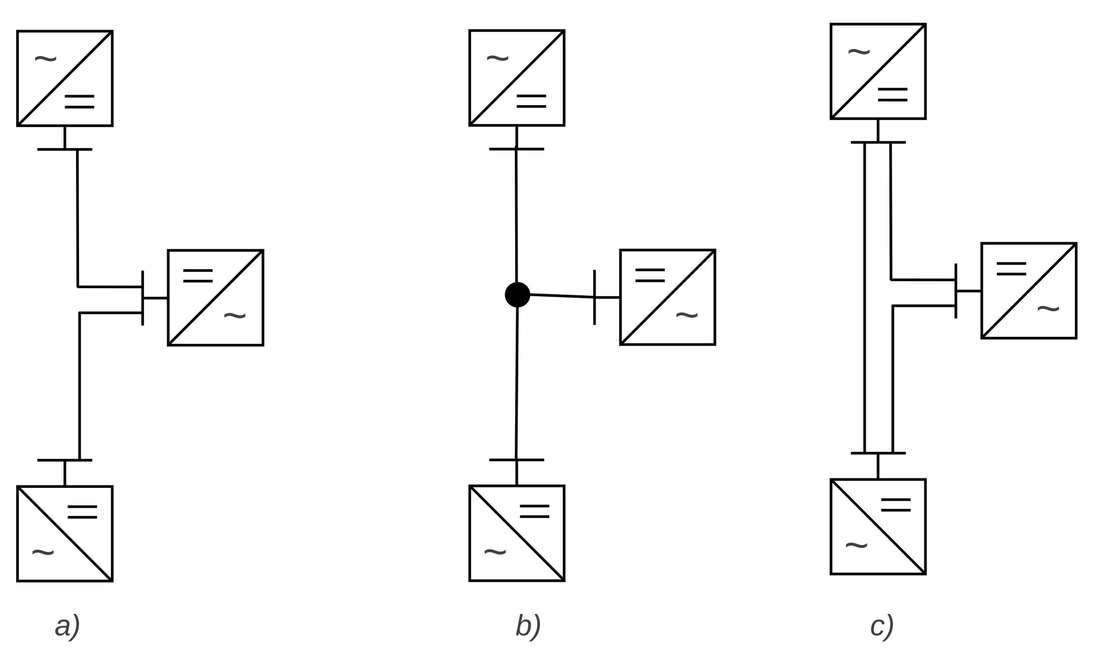

Figure 2-2: Schematic representation of a multiterminal HVDC system a) linear b) radial c) meshed [12]

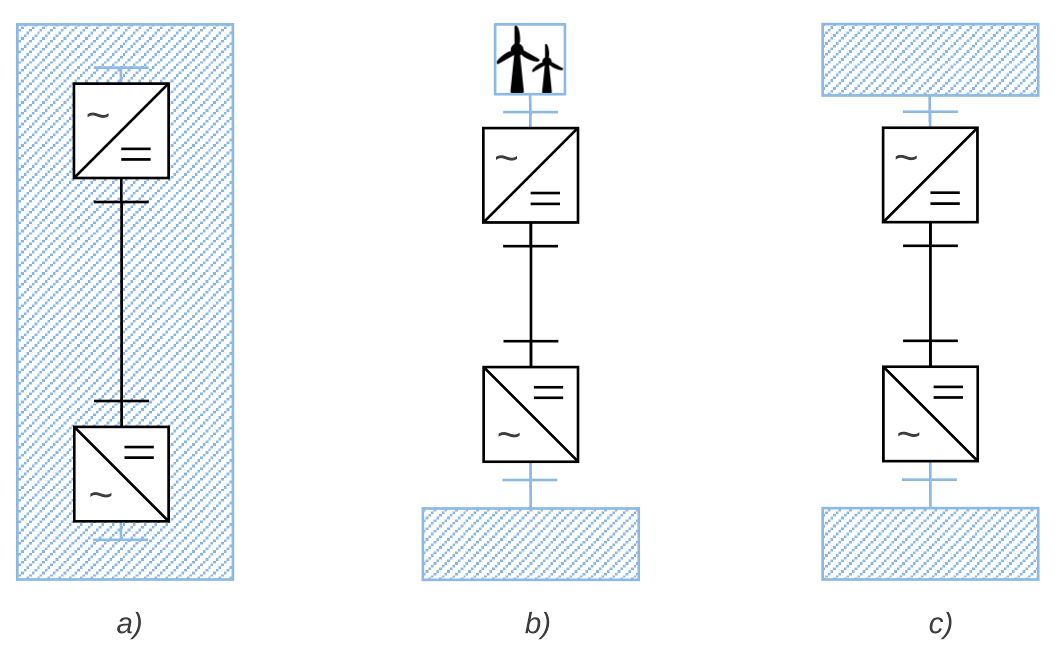

Figure 2-3: Schematic representation of degrees of embedding of an HVDC system in the AC grid a) fully embedded b) Offshore wind farm connected to AC grid via HVDC system c) two embedded systems

2.3 Definition of architectural building blocks for HVDC systems

The architecture of an HVDC system includes the purpose, the configuration and topology of the HVDC system, the degree of embedding in the AC grid as well as control and protection. The topology and embedment level are particularly relevant for the design and planning of HVDC systems. Since their definition is already sufficiently complex in the context of network expansion planning, the approach presented enables the variation of these two aspects of an

HVDC architecture to be systematically investigated. The different variations of these two aspects are summarized in architectural building blocks. For all architectural aspects that have no influence on the results of a system study, this work either defines a standard that may not be varied for further investigations, or introduces a design rule that takes into account the restrictions, e.g., from C&P. The defined standards and delimitations are explained below.

The configuration of an HVDC system can be either a monopole or a bipole. In the (n-1) fault case, the remaining transmission power of an HVDC link varies depending on the configuration. A bipole can be reconfigured in the (n-1) fault case after the fault and then continue to operate as an asymmetrical monopole with half the remaining transmission capacity. With monopole configurations, no transport capacity remains in the (n-1) fault case.

Whether cables or overhead lines are used to transmit the power in the HVDC system is not relevant for static calculations. In Germany, priority is given to underground cables for the construction of HVDC systems. For these reasons, no variation of cable and overhead line is made in this design and planning approach. In addition, a uniform rating of $2\ GW$ is assumed for all converters and cables in a system.

The architectural building blocks that vary in this work are those defining the HVDC system within a specific area of interest and are relevant for static system studies. The focus is therefore particularly on the combination of the topology with the degree of embedding. In Figure 2-4 a variation of the HVDC architecture created via the combination of different architectural building blocks is shown, whose main task is to integrate the generated energy from offshore wind farms into the onshore transmission grid. The purpose, which is also part of the HVDC architecture, is therefore retained in all three variants.

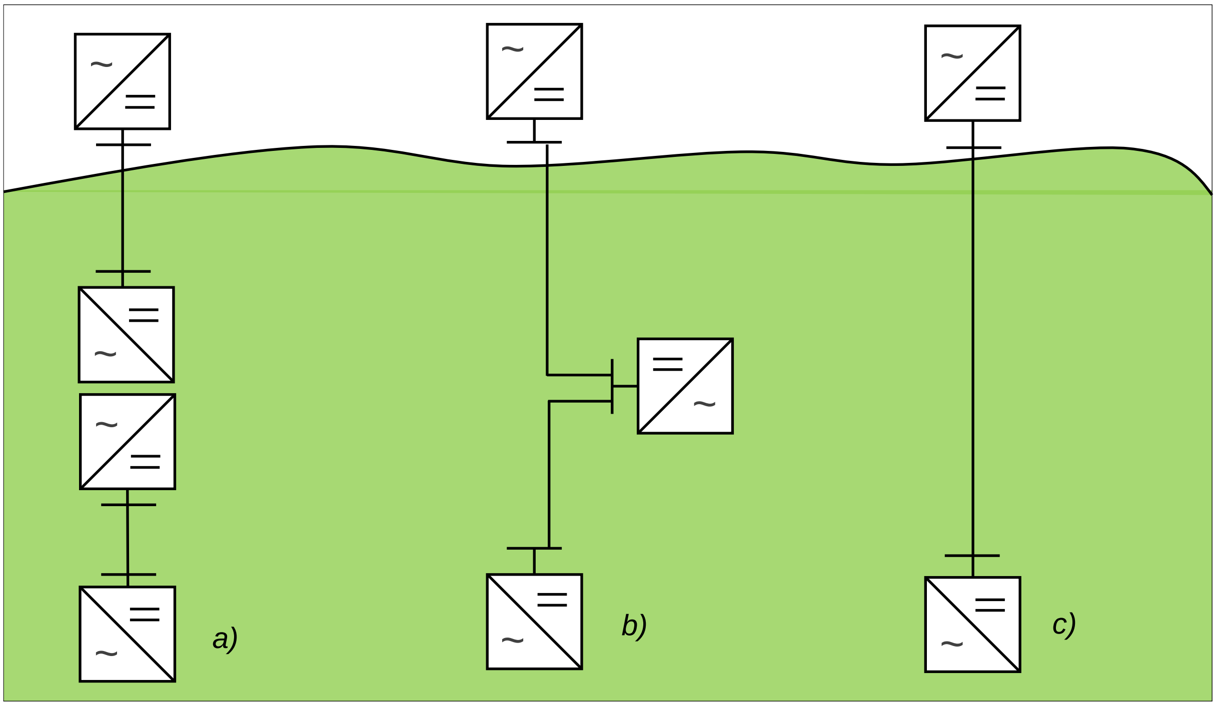

Figure 2-4: Architectural building block with a) two P2P links b) one MTDC system c) one P2P link

Variant a) shows two P2P links. The upper link transports the power generated offshore to land and is fed into the AC grid close to the coast. The lower P2P link is used to transport the power further, for example to load centers that are not located near the coast. Variant b) fulfills the same transport task, except that a linear MTDC system is used instead of two separate P2P links. This means that a converter can be spared. Variant c) is a single P2P link. In this case, the power generated offshore is transported directly to the load center and no further power can be fed in or withdrawn. The approach presented can be used to investigate how useful the respective HVDC architecture is for the transmission grid. Do variants a) and b) offer more flexibility in congestion management than variant c)? Is this flexibility needed at all if the energy generated is demanded in the load centers and not near the coast? Will congestion occur between the AC nodes where the two coastal converters in variant a) are close to each other because the AC grid is only used for short transit between the two P2P connections? Does variant b) offer less flexibility in the choice of operating points of the converters in congestion management, as the entire MTDC system must be balanced, which can be more restrictive than with P2P links?

3 Methodical approach

The presented method for the design and planning of HVDC systems consists of four steps. First, areas of interest are identified that are of interest for the planning of HVDC systems and should be considered in more detail. Then, architectural building blocks are integrated into the transmission grid at the areas of interest. When combining those building blocks to architectures, defined design rules must be respected. Based on this, variations of the architectural building blocks and resulting HVDC architectures or AC/DC grid architectures can be made. The individual steps are described in more detail below.

3.1 Identification of areas of interest

The grid area under consideration comprises the European interconnected grid of the UCTE. In order to identify areas of interest, load flow calculations are carried out in the existing transmission grid, which is assumed to be fixed – i.e., all additional lines that are added are HVDC lines. This part of the transmission grid includes the $220\ kV$ and $380\ kV$ level as well as existing HVDC links, which are assumed to be part of the scenario framework. Since most of the onshore HVDC systems planned for the future and all offshore HVDC systems in Europe are planned as bipoles, only bipoles are assumed for the configuration of the newly planned HVDC systems in this approach. Existing HVDC systems, which are assumed to be already in place and unchangeable in the course of this approach, are modeled according to their existing configuration. The converter rating is assumed to be $2\ GW$ and thus $1\ GW$ per converter of the bipole. A uniform voltage level of $\pm\ 525\ kV$ is assumed for the HVDC systems. Like the power class of $2\ GW$, this voltage level has become the standard for HVDC systems currently in planning. A variation of the voltage level mainly has an effect on the insulation coordination, which will not be considered in this paper. For all existing HVDC links that do not comply with the previously defined $2\ GW$ and $\pm\ 525\ kV$ bipole standard, it is assumed that these cannot be extended to MTDC systems. The basis for the load flow calculation is a given dispatch of the power plants and other feeders, which is determined in an electricity market simulation based on a given scenario. Areas of interest can be, for example, load centers, highly meshed AC regions or regions with existing or planned HVDC systems.

3.2 Integration of architectural building blocks into the transmission grid

The next step is to integrate the architectural building blocks presented in section 2.3 into the grid where areas of interest were previously identified. Expandable HVDC systems are those that have a nominal voltage of $\pm 525\ kV$, a bipole configuration and a converter rating of $2\ GW$. In addition, new HVDC systems or individual converters can be added in the areas of interest. Figure 3-1 shows a possible integration of architectural building blocks in exemplary areas of interest.

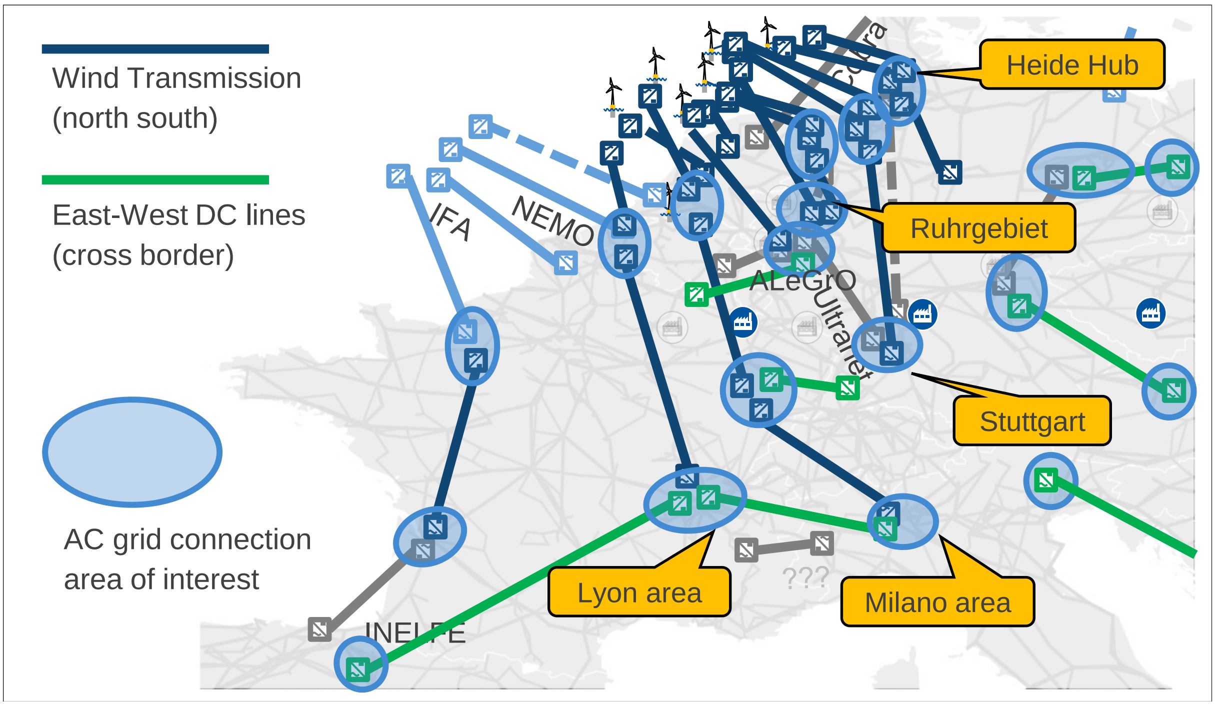

Figure 3-1: Exemplary areas of interest and application of architectural building blocks

Figure 3-1 shows the underlying AC transmission grid in light gray. Existing HVDC systems that are considered part of the scenario framework are also shown in gray. An example of this is the ALeGrO P2P link between Belgium and Germany. In this presentation, all HVDC systems are initially assumed to be P2P connections. A combination of several P2P links to form a MTDC system is made as part of the variation of the architectural building blocks. The HVDC systems in light blue represent a connection to the asynchronous UK system. The HVDC systems in dark blue are designed to transport the energy generated offshore to the load centers. It is therefore mainly a north-south transportation task. The green HVDC systems are used for east-west transportation (or vice versa) and they often cross bidding zones. The areas of interest are marked in the blue circles. They are located in regions where several converters are close to each other. Examples of this are the Ruhr region as an area of interest in which the AC network is particularly meshed. The Stuttgart area is a load center within Germany and can therefore be an area of interest. The region around Heide Hub may also be an area of interest, as several HVDC systems are being planned there. Within the areas of interest, the variations a) to c) presented in Figure 2-4 can then be carried out. It is therefore possible that there are not three converters within the area Lyon as in Figure 3-1, but for example only one or two as part of an MTDC system or even no converter, but only one DC busbar.

3.3 Variations of architectural building blocks

The variations made for the architectural building blocks focus on the topology and the embedment level of the HVDC system. They therefore allow a systematic investigation of different HVDC architectures within the scope of a planning task. The variation is carried out within an area of interests similar to the variation presented Figure 2-4. A distinction is made between areas of interest with large load or generation and areas with little or no load or generation. Figure 3-2 shows possible variations of the architectural building blocks in areas with large load or generation. These areas should be designed with a load in between 1 p.u. and 2p.u. of a single converter rating. If an area has a larger peak load or infeed imbalance, it might be split into two areas. In special cases, this is not limited to three terminals.

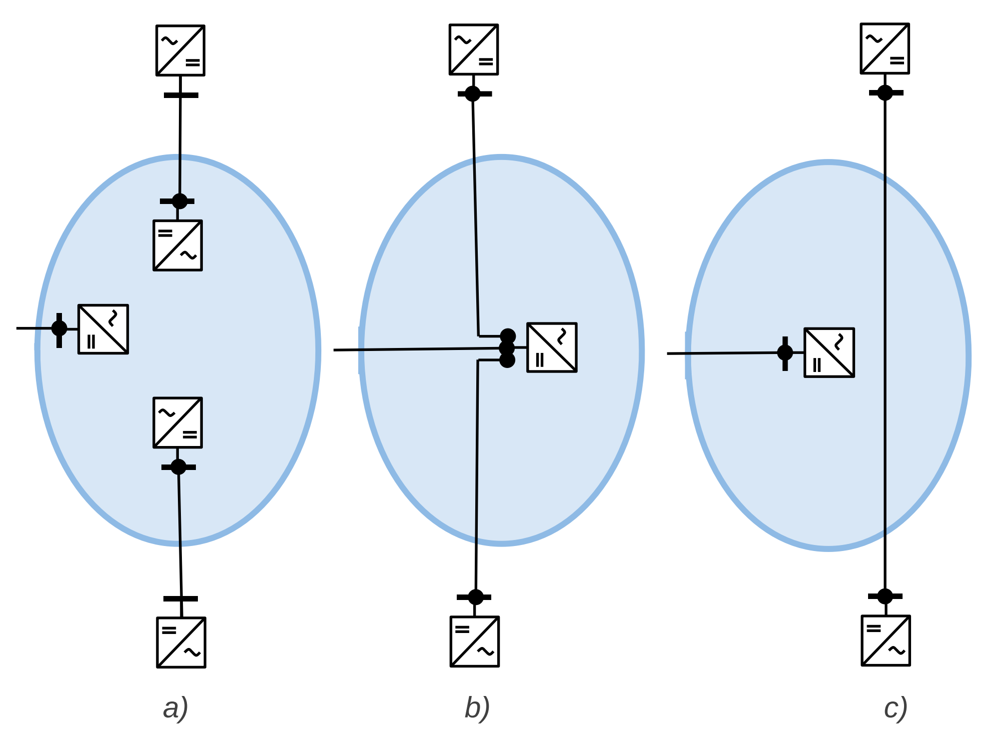

Figure 3-2: Variation of architectural building blocks with areas with large load or generation

Variant a) shows an area of interest in which three converters of P2P connections are located. In variant b), the topology is combined into an MTDC system and there is only one converter in the area of interest. In variant c), one converter ends in the area of interest and another P2P connection is routed through the area. As described in section 2.3, this results in various load flow situations in the AC grid and HVDC systems can be used in congestion management. This can therefore be investigated as part of static system studies in grid planning.

Figure 3-3 shows the possible variations for areas of interest with little or no load or generation. Offshore coastal regions are an example of this. In variant a), two P2P connections intersect in the area of interest. In variant b), there is a DC busbar at the previous crossing point, creating a radial MTDC system with four terminals. Variant c) shows the topology of two P2P connections, one of which ends in the area of interest. In variants a) and b), no power can therefore be fed into or withdrawn from the DC system within the area of interest. This is possible in variant c). Whether this HVDC architecture is advantageous in a region with little generation or load can be determined using the static load flow and redispatch calculations. Power is exchanged between the two P2P connections via the underlying AC grid.

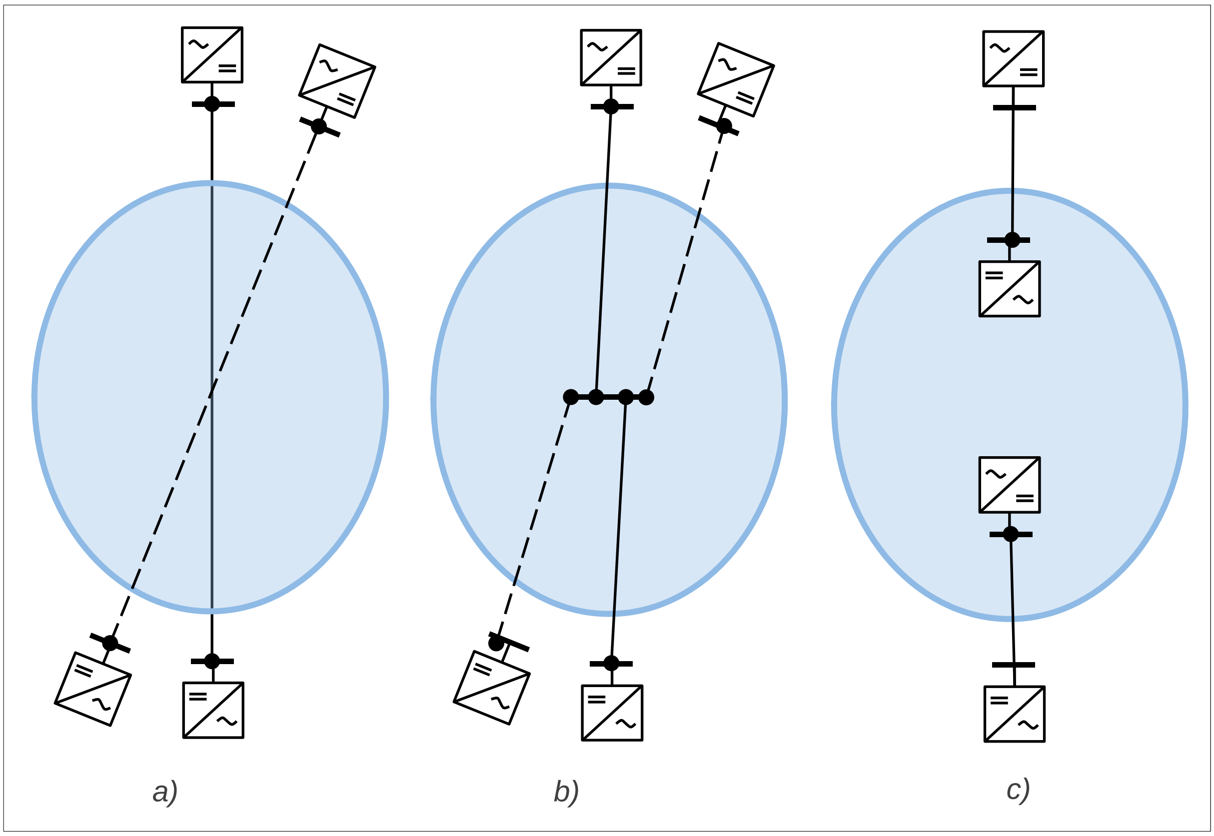

Figure 3-3: Variation of architectural building blocks with areas with no or little load or generation

3.4 Design rules

By specifying design rules, restrictions resulting from C&P, insulation coordination or dynamic investigations can already be taken into account in the static planning considerations in a simplified manner. These aspects are not initially relevant in the planning of HVDC systems and are specified in subsequent stages. However, they can have a restrictive effect on the choice of HVDC architecture. These design rules must be respected when integrating the architectural building blocks. In this paper, these rules are divided into fixed and variable design rules. A fixed design rule is that all areas of interest must be connected. However, there does not have to be a single HVDC grid that connects all areas of interest. For offshore converters in MTDC grids, the requirement is that no more than three connections may be made to the converter due to reasons of space on the offshore converter platform.

Variable design rules can be used to create different architecture options and match them with certain scenarios of available technologies or design choices made in the future. These could for example be:

- The maximum number of converters in an MTDC system should not exceed a certain number e.g., four, if no DC circuit breakers are planned to be installed within the systems. This ensures to limit the maximum loss of power infeed / loss of power transmission to a certain size.

- No meshing of HVDC systems, for example to reduce the number of DCCBs required, and to reduce complexity in load flow control.
- The maximum length between two converters in an MTDC system should not exceed a certain length e.g., 2000 km. This limits maximum voltage shift on the metallic return conductor (DMR). To allow larger connected networks, the technology ofDC/DC converters might be needed.
- The number of converters that are electrically close (i.e., in the same area of interest) should be limited to a certain number e.g., two or three. This would be a restriction in case AC side control interactions are observed and it is decided to avoid those by architecture design.
- As for offshore, the number of maximum connections per DC switching station could also be limited onshore due to space restrictions.

4 Conclusion and Outlook

The design and planning approach for HVDC systems presented in this paper enables a systematic investigation of different architectural building blocks and their impact on the AC transmission grid. In the course of the architectural building blocks, different combinations of HVDC topologies and embedment levels are investigated. This makes it possible to answer static questions in the context of load flow and redispatch calculations. By considering design rules, restrictions resulting from the C&P concept, insulation coordination or dynamic investigations are also taken into account in the planning in a simplified manner. These restrictions are not yet taken into account at such early planning stages in conventional network planning. In subsequent work, the design and planning presented here will be applied to a continental European transmission grid in order to investigate the influence of different HVDC architectures on the static evaluation parameters.

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