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# A classification framework for HVDC-based transmission grid architectures

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## SUMMARY

Along with the extensive plans for integration of renewable energies (RE), the role of HVDC systems in electrical power systems will increase. Planning and operating HVDC links as individual and supplementary systems for a single purpose might not be efficient anymore. Rather, a coordinated planning, operation, control, and protection of AC/DC systems – including multi-terminal DC (MTDC) networks – may be beneficial. To ease coordination between the different aspects, this paper introduces a new classification method for AC/DC grid architectures on a system-wide level: Both the DC-side topology and the AC-side embedment are considered in a matrix format – in which four HVDC topologies (DC1 to DC4) and four AC embedment scenarios (AC1 to AC4) are compared. This way, any AC/DC system architecture can be categorised into exactly one element of a matrix structure. Using this classification method, the paper elaborates on how a broader group of AC/DC networks (e.g. every system architecture that falls into category DCx-ACy) can be linked to a set of required HVDC technologies, controls, and protections, as well as to a set of expected system functionalities and performance. As a result, system planning could make use of the categories as "building blocks" associated with a certain prospective behaviour, while requirements (e.g. for dynamic studies) at the early stages of the HVDC control and protection design can be formulated for a broader range of architectures. A comprehensive overview of differences between AC/DC network categories – including examples for both system planning and dynamic studies applications – is provided. Further, existing HVDC test systems as well as recently planned real HVDC applications will be categorised using the matrix.

**KEYWORDS**
AC/DC grids, Classification, Control, HVDC, Multi-terminal, Protection, System planning

## 1. INTRODUCTION

Around the globe, the desire to achieve climate neutrality is leading to drastic changes in electrical power systems. Among others, the European Commission and the UK Government have defined ambitious targets for the large-scale integration of renewable energies into the power system until 2050 [1] [2]. These challenges include managing power flow, ensuring system stability, and maintaining reliability and resilience during various disturbances, such as internal short-circuit faults, or external factors like severe weather conditions. To address these challenges and maintain or even enhance power system reliability and resilience, HVDC systems based on Voltage Source Converters (VSCs) are considered a key technology. Currently, individual VSC-HVDC systems are designed as a turn-key solution by a single entity, and serve a clearly defined purpose which can be either a) connecting remote offshore wind farms, b) interconnecting asynchronous grid areas, or c) enabling actively controlled onshore bulk power transmission. Once this paradigm changes towards expandable multi-terminal HVDC networks or a large number of electrically close HVDC links embedded into the same AC grid, planning and operating these systems individually may not be efficient anymore. Rather, a change in the role of HVDC transmission also necessitates a shift towards a holistic planning and operation of combined AC/DC systems, requiring interfaces between the different phases of system design. For example, studies performed with a variety of (state-of-the-art or new) tools for static, dynamic, and transient domains must be coordinated. The variety of potential architectures of AC/DC transmission grids brings diverse expectations, functionalities, and design possibilities. Thus, a systematic classification to arrange activities across the abovementioned study domains – and at different points in time from long-term planning, via the design phase, to commissioning and operation – is considered beneficial. This classification will enhance information exchange, and can help to define standard test systems or to standardise specifications across study domains. Although several categorisations for HVDC-based systems exist, these are focusing primarily on either the DC or the AC aspects; however, a comprehensive approach that considers both sides is essential.

This paper focuses on categorising extended AC/DC transmission grid architectures based on DC-side topology and AC-side embedment in a 4x4 matrix format. The matrix classification is presented in Section 2, and aims to facilitate information exchange among various stakeholders (e.g., parties in industry, public entities, research institutions), and to provide an interface between AC/DC system planning, HVDC control and protection design, and AC/DC system operation. In Section 3, aspects of operation, control, and protection are linked to the matrix category: Transmission system planners could make use of the categories as “building blocks” associated with specific behaviours, while for HVDC control and protection developers, requirements (e.g., for dynamic studies) at the early stages of the HVDC control and protection design can be formulated for a broader range of architectures. Moreover, with regard to operating AC/DC grids, the classification can also describe the expected changes when a given system is transformed from one category to another due to scheduled switching actions or fault events (Section 4). Section 5 applies the classification framework to both a) existing, generic AC/DC test networks and b) planned real-life HVDC projects, before 6 concludes the paper and provides an outlook for further usage of the classification approach.

## 2. AC/DC SYSTEM CLASSIFICATION FRAMEWORK

This section presents the classification framework for hybrid AC/DC systems. This approach builds on an AC/DC system classification developed within the HVDC-WISE project [3], and defines an HVDC-based transmission grid architecture through the combination of several elements:

a) the purpose of the HVDC network(s),
**b) the AC-side embedment level of the HVDC network(s),**
**c) the DC-side topology and configuration,**
d) the technological components and their electrical design, and
e) the operational algorithms, control systems, and protection concepts.

In the following, the classification matrix concentrates on aspects (b) and (c) of the architecture definition. For the matrix combinations of (b) and (c), the required technological components (d), and the required operation, control, and protection approaches (e), can be derived and clustered to finally fulfil the intended purpose (a). For example, both the desired control functionalities and the protection requirements might significantly differ between an HVDC system connecting two asynchronous AC grids and a fully embedded HVDC system – regardless of its exact technological components or its size.

## 2.1. Classification methodology

To classify aspects (b) and (c), a 4x4 style matrix for DC and AC grids is chosen as a comprehensive framework for analysing various topologies. It provides a means of grouping and examining a wide variety of HVDC systems and/or AC/DC grid areas based on their pre-contingency connection topologies. In particular, four DC topologies and four AC embedment scenarios are identified, which aim to cover the majority of possible AC/DC system setups. The four DC system topologies are divided into four categories:

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

These four types are visualised in Figure 1, where black elements indicate DC grid components and green elements represent AC grids. The diagrams are illustrative and should be interpreted for their general topologies rather than specific designs; in particular, the choice of four converter stations is an example, and the concept can be applied to any HVDC system size. The DC-side classification relates to the topology (i.e., the way AC/DC converter stations and DC switchyards are interconnected on the DC-side), and does neither specify the DC-side configuration (monopole, bipole, etc.), nor the converter technology, nor the voltage levels and line type (cable or OHL). MTDC systems – where only parallel networks based on VSC technologies are meant – are divided into radial, linear, and meshed structures, with ring topology as a subtype of meshed topologies.

Radial and linear networks are multi-terminal but non-meshed, offering only one path between any two terminals. In radial networks, converters are only connected to a single line, and the DC node (or “star point”) is a separate switching station without a converter station. In linear networks, each DC node / switching station is located at a converter station. Note that – e.g., in [4] – the term radial is often used for both “star” and “string” topologies. Here, only “star” connections are named radial, while “string” topologies are named linear topologies. In meshed networks, multiple paths are possible, as illustrated in the DC4 diagram in Figure 1.

The same DC network topology can be embedded into different AC networks, which might change – among others – its purpose, and the requirements on control and protection. As long as there are no DC-side loads, the requirements on the HVDC network are mainly defined by the AC system(s) it is connected to. Therefore, the AC systems linked to the DC systems are categorised into four types:

- **AC1**: All separate – Every DC converter station is in a separate, asynchronous AC grid, some of which may be offshore wind farms or similar.
- **AC2a**: One embedded + Wind Power Plants (WPP)/separate – At least two of the DC converter stations are in the same, synchronous AC grid and there are one or more separate, asynchronous AC grids that host other DC converter stations, some of which may be offshore wind or similar.
- **AC2b**: Multiple embedments – The DC system connects two or more separate AC grids, where each of these grids host multiple DC converter stations. For offshore, one example could be an AC connection between two offshore wind farms that each have their own HVDC converter station, e.g. on an “energy island”.
- **AC3**: Fully embedded – All converter stations of the DC system are connected to the same AC grid.

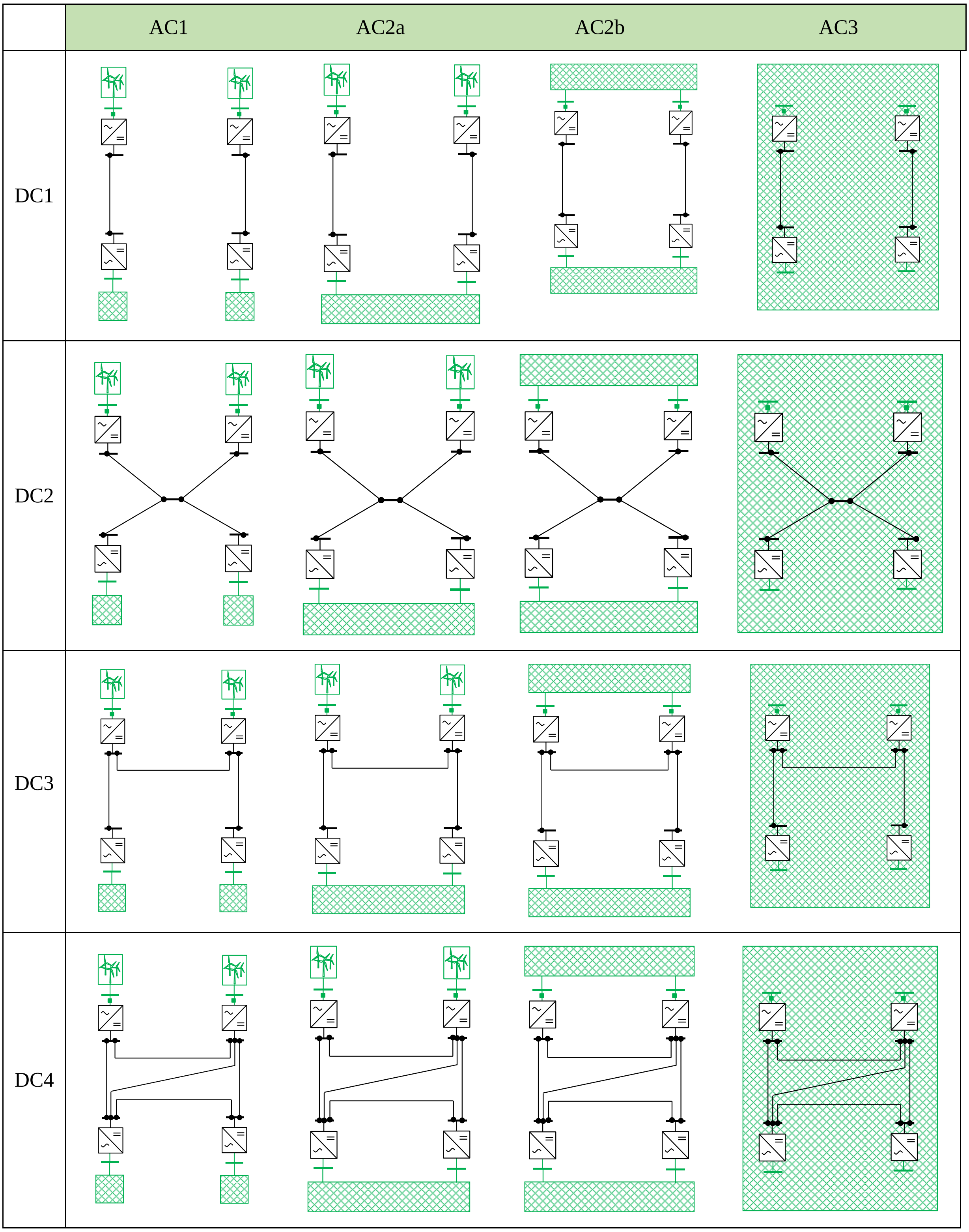


*Figure 1: Combination of AC connections for DC1-DC4 (single pole view) [3]*

In Figure 1, the different combinations of DC and AC systems are illustrated [3]. The green parts indicating wind farms or larger AC systems should be considered as interchangeable; their characteristics are not defined as part of the framework. Each generic AC grid could be of any grid strength (e.g., in terms of different fault current level, inertia, share of RE, connected loads, etc.), or could be a larger wind farm or energy island. It should be noted that all descriptions refer to the planned, normal, pre-contingency state of the respective AC/DC grid architecture. Nevertheless, a given AC/DC system (e.g. DC3-AC3) can be transferred into another classification either by scheduled actions (e.g.

for maintenance), or by specific events (e.g. by faults and subsequent protection actions to DC1-AC3, or by a system split to DC3-AC2b).

## 2.2. Limitations and possible extensions of the framework

So far, the AC/DC architecture matrix and the associated AC embedment level do not explicitly specify the characteristics of the AC network itself. This is done to keep the classification generic, and to enable a system-level definition of requirements in early design stages. However, for the effective evaluation of control performance in later stages - e.g., of grid-forming control provided by an MTDC network – requires considering scenarios with variations in system strength and inertia. While these differences are not actively covered by the framework, comparing analyses across multiple architectures can help to distinguish whether phenomena are related to AC network characteristics or to a specific HVDC-based architecture type.

Further, the framework does not differentiate whether a DC line is designed as an overhead line or as a cable. Also, the specific types of HVDC configurations – such as monopole, bipole, or mixed –remain unspecified and require a detailed examination in later project stages [3].

Both aforementioned aspects (AC grid specification and DC configuration choice) remain intentionally unspecified in the framework, but rather fall into the scope of realising a system with a given classification.  By contrast, other aspects might be able to be included into the framework by extending it. For example, it does not delve into the presence of DC/DC converters or power flow controllers, but further topological classifications (DC5-DCx) could also involve DC-DC converters (e.g. in Figure 2), hybrids of linear and radial topologies and DC side loads, as seen in CIGRE TB804 [5].

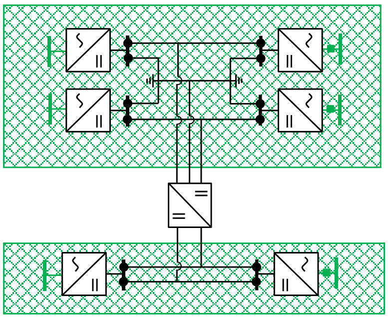


*Figure 2: Two HVDC are linked through a DC/DC converter*

With the current classification presented in this paper (based only on the connection of AC/DC converters), the system shown in Figure 2 would be classified as a 4-terminal DC2-AC2b (radial DC, multiple AC embedment). Another option could be to interpret the DC/DC converter as two AC/DC converters, such that the system can be described as two 3-terminal DC2-AC2a networks. However, the system including a DC/DC converter might have different characteristics than DC2-AC2a/b, and thus might require a separate classification. This way, the framework could also cover the integration of DC systems with varying voltage ratings and, possibly, different line configurations.

# 3. PLANNING, OPERATIONAL, AND C&P ASPECTS PER CATEGORY

In the following, the framework is used to link various system architectures with typical characteristics and requirements – in terms of system planning, system operation, control design, and protection design. This way, for an example HVDC system that is planned, certain benefits on a system-level (e.g., in normal operation, obtained in a global system study) could be associated to additional requirements for control and protection (C&P) design, and certain risks in case of faults depending on the C&P concept. To evaluate the protection and control scheme (subchapter 3.2 and 3.3), these opportunities and risks strongly depends on:

- The DC network topology (DC2-DC4) and configuration (monopole/bipole)
- The AC embedment level (e.g. wind farm as constant power infeed is connected or not)
- The HVDC protection concept (non, partially, fully selective: NS, PS, FS), see [6]

The legend for the following Table 1-Table 6 uses white to symbolise no improvement or risk, light green to indicate benefits, and dark green to represent even greater benefits. Conversely, light orange points to a vulnerability, while dark orange suggests a significantly higher level of risk.

### 3.1. System planning and system-level studies

For system planning and system operation, HVDC systems offer both opportunities and challenges. In this section, various HVDC system types as per the topology framework are assessed for their opportunities in terms of reliability and resilience (R&R) in Table 1. As visible from the table, multi-terminal systems (DC2-DC4) can improve efficiency, and enable several additional features with regard to reliability and resilience (R&R). For instance, enhanced active power transfer boosts fault resilience and renewable integration.

*Table 1: Opportunities for different topologies in terms of R&R for planning and operation, with input from [3]*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Use of grid services over multiple asynchronous areas | 🟩 | | 🟩 | | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | |
| Improve security with more than one connection between areas (synchronous / asynchronous) | | | 🟩 | | | 🟩 | 🟩 | | | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | |
| Relieve congestion on AC grid with DC power flow control | | | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 |
| Improved N-1 security | | | | | | 🟩 | 🟩 | ▩ | 🟩 | 🟩 | ▩ | ▩ | 🟩 | 🟩 | ▩ | ▩ |

As the AC embedment level increases, progressing from AC2a to AC2b, it facilitates the application of grid services over various asynchronous areas. This expansion not only allows for broader service deployment but also significantly improves security, particularly in the realm of N-1 security. This enhancement is largely due to the advanced embedment levels of AC2 and AC3. As the embedment level increases, the connection between asynchronous areas worsens, but N-1 and congestion management improve. An example of this can be seen when comparing the DC1/AC3 configuration with the DC4/AC3 setup. Despite the differences in their DC configurations, the opportunities they offer are remarkably similar. This is primarily because these opportunities are augmented by the level of AC embedment. It highlights that, when the embedment levels increase to AC2 and AC3, it upgrades existing grid services and relieve congestion. Besides, the shift from DC1 to DC4 offers distinct advantages, including a significant reduction in the number of converters. From a planning perspective, this is a crucial advantage of MTDC, as demonstrated by initiatives like Heide Hub [7].

At the same time, different AC/DC architectures introduce different risks. For example, the use of DC2-DC4 systems requires meticulous N-1 contingency planning and has a stronger interaction with the AC grid operation in case of DC faults. Table 2 introduces risks to system operation by different HVDC-based architectures via presenting examples for vulnerabilities. As DC links are expanded to MTDC configurations (DC2 to DC4), there is a noticeable rise in complexity comparable to simpler configurations as DC1. Specifically, for DC3 and DC4 systems at any embedment level (AC1 to AC3), there is a critical risk of DC circuit overloading in the event of a circuit loss in case no countermeasures are taken. Additionally, expanding the DC cable capacitance, particularly in DC2 to DC4 configurations, increases the prospective DC short circuit currents to be considered in protection design. In the event of a fault or loss, particularly those at the AC2b level, potentially shifting from a decoupled to a coupled system, multiple AC grids can be affected.

*Table 2: Risks for different topologies in terms of R&R for planning and operation, with referenced from [3]*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Faults may lead to a full loss of power transfer between asynchronous AC grids | ▓ | | ▓ | | ░ | | ▓ | | ░ | | ▓ | | ░ | | ▓ | |
| Fault may lead to a critical loss of power infeed/export in a single synchronous AC grid | | | | | | ▓ | ▓ | | | ▓ | ▓ | | | ░ | ░ | |
| Potential for AC circuit overloading for loss of DC circuit | | ░ | ░ | ▓ | | ░ | ░ | ▓ | | ░ | ░ | ▓ | | | | |
| Potential for DC circuit overloading for loss of DC circuit | | | | | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ |
| Increased complexity of control and protection solutions | | | | | ▓ | ▓ | ▓ | ▓ | ░ | ░ | ░ | ░ | ▓ | ▓ | ▓ | ▓ |

## 3.2. Control concepts

HVDC's primary role is the efficient long-distance transmission of large electrical power volumes, but it also offers various additional, control-based grid services like frequency control, AC voltage support, and grid-forming capabilities, due to the advanced control provided by VSC interfaces. In Table 3, example opportunities are identified and linked to the different categories of the AC/DC architecture classification approach.

*Table 3: Opportunities for different topologies in terms of R&R for control*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Multiple AC embedded VSCs coordinate to enable grid services such as line emulation [8] | | ▓ | ▓ | ▓ | | ░ | ░ | ░ | | ░ | ░ | ░ | | ░ | ░ | ░ |
| Grid-forming capabilities (improves system strength, provides inherent inertia etc.) [9] [10] [11] [12] | ▓ | ░ | ▓ | ░ | ▓ | ░ | ▓ | ░ | ▓ | ░ | ▓ | ░ | ▓ | ░ | ▓ | ░ |
| Black start (system restoration) | ░ | ░ | ▓ | | ░ | ░ | ▓ | | ░ | ░ | ▓ | | ░ | ░ | ▓ | |

Additional grid services, such as AC line emulation, are only possible for AC2 and AC3 embedment levels. In case of DC1 it is state-of-the-art, however for MTDC configurations, the complexity potentially increases. When it comes to grid-forming capabilities, they are especially advantageous in combinations of AC1/AC2b. These capabilities not only enhance system control but also enable black start functionalities in systems composed by converters. The significance of black start capability for system restoration is particularly notable in the integration of wind parks within AC1 and AC2a frameworks and even more important by interconnectors between two AC grids, such as AC2b scenarios. In contrast, when considering the DC1/AC1 combination, the control concepts specified in Table 3 do not offer as much advantage as they do in the higher embedment levels of AC2 or AC3 in any DC link configuration. On the other hand, configurations such as DC4/AC2, or even AC3, are able to leverage the presented opportunities more effectively. Depending on the AC/DC classification, HVDC systems also add risks to transmission system control – some of them are summarised in Table 4. HVDC converters, unlike traditional synchronous generators, do not inherently contribute beneficial behaviours to AC systems, nor do they naturally react to DC system conditions. Their behaviour is largely defined by their controls and their protective limits (e.g., lacking the inherent overload capability of synchronous generators). Fast control and protection responses in microseconds can result in abrupt transitions from normal operation to failure, often referred to as “cliff-edge” behaviour [13]. Maintaining stability in grid control and protection systems are crucial, with attention needed for AC side control interactions, weak grid issues, and DC side protection and voltage control, particularly in large MT-HVDC networks.

*Table 4: Vulnerabilities for different topologies in terms of R&R for control*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Frequency control disruption and system security issues (FRR, FCR) [14] | | | 🟧 | 🟫 | 🟧 | 🟧 | 🟫 | 🟫 | 🟧 | 🟧 | 🟫 | 🟫 | 🟧 | 🟧 | 🟫 | 🟫 |
| Potential interaction between converters electrically close on AC side | | 🟫 | 🟫 | 🟫 | | 🟧 | 🟧 | 🟧 | | 🟧 | 🟧 | 🟧 | | 🟧 | 🟧 | 🟧 |
| Oscillation risks (triggering protection, spreading oscillations across areas etc.) | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟫 | 🟫 | 🟧 | 🟧 | 🟫 | 🟫 | 🟧 | 🟧 | 🟫 | 🟫 |
| Grid-forming control interactions (synchronisation issues etc.) | | 🟧 | 🟫 | 🟫 | 🟧 | 🟫 | 🟫 | 🟫 | 🟧 | 🟫 | 🟫 | 🟫 | 🟫 | 🟫 | 🟫 | 🟫 |

In the event of potential HVDC link losses, such as faults or frequency deviation, appearances are possible across various scenarios. Despite this, there remains the possibility of grid instabilities due to control failures by grid-forming (GFM) and issues related to system synchronisation. Additionally, the closer integration of DC with AC dynamics can significantly affect HVDC controls in systems equipped with multiple grid-forming VSCs, particularly in situations where DC3 is fully embedded. When comparing these scenarios to simpler configurations like AC1/DC1, it is evident that AC2b or AC3 setups entail greater risks. These increased risks stem from the enhanced complexity due to higher levels of embedment.

## 3.3. Protection functionalities

Protection devices and strategies are essential for the secure operation of future HVDC systems, safeguarding grid assets and enabling reliable hybrid AC/DC systems. Ongoing developments in protection functions, including DC circuit breakers, fault-blocking converters, energy dissipation systems, or DC/DC converters, are of interest and will be assessed in terms of opportunities and vulnerabilities (Table 5 and Table 6). In configurations like DC1 paired with any level of AC embedment (AC1-AC3), a straightforward state-of-the-art protection design is typically suitable and effective enough. However, as the complexity of DC links grows, particularly in MTDC systems (DC2-DC4), the use of DCCBs or DC/DC converters becomes increasingly advantageous and simpler, more straightforward protection schemes might lose their efficiency. In MTDC setups, a temporary loss of the entire network during a fault is possible, and might have consequences which have been elaborated in the operational and planning (Table 1 and Table 2). Fault-blocking converters are beneficial across all embedment levels (AC1-AC3), with their positive impact becoming more noticeable as the DC link network expands into MTDC configurations (DC2-DC4).

*Table 5: Opportunities for different topologies in terms of R&R for protection*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Straightforward protection design, as can trip full network for faults. | ▒ | ▒ | ▒ | ▒ | | | | | | | | | | | | |
| Use of DC-side Protection (DCCB, DC/DC converters) | | | | | ▒ | █ | █ | █ | ▒ | █ | █ | █ | ▒ | █ | █ | █ |
| Fault-blocking converters for DC grid protection (NS/PS) | ▒ | ▒ | ▒ | ▒ | ▒ | █ | █ | █ | ▒ | █ | █ | █ | ▒ | █ | █ | █ |

With regard to risks, the efficiency of AC line protection in response to faults on the AC side can be affected in areas with a higher concentration of electrically close converters, potentially employing various control structures like GFM. This issue is particularly concerning in combinations like DC4 with AC4. In scenarios such as pole-to-pole DC faults, there is a significant risk of losing the entire DC network, including crucial grid services like grid-forming control, when DC2 to DC4 is used at higher embedment levels. Further, within MTDC systems (DC2-DC4), there exists an increased risk in case of a failure in protection devices (DCCB failure, failure of DCFRT in converter, etc.), which is affecting all levels of AC grid embedment.

Table 6 explicitly highlights the risks associated with relying on NS protection schemes for the DC grid. Protection philosophies as PS and FS could significantly lower these risks. Use of fault separation device can lower the risk in cases of a higher embedment level (AC1-AC3) and DC link (DC2 – DC4). In configurations like DC1/AC1, the risk is minimal. However, as the degree of both DC and AC complexity increases, so does the risk. This is particularly evident at the AC3 embedment level, where the protection system becomes more vulnerable and must be carefully considered. For example, the use of fault-blocking devices and the consequences of their failure can have a significant impact in scenarios involving DC2-DC4 across all embedment levels.

*Table 6: Vulnerabilities for different topologies in terms of R&R for protection*

| **DC Grid** | DC1 | | | | DC2 | | | | DC3 | | | | DC4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AC Grid** | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| Application of distance AC line protection [15] | | ▒ | ▒ | █ | | ▒ | ▒ | █ | | █ | █ | █ | | █ | █ | █ |
| Use of fault separation device like DC/DC, DCCBs (PS / FS) | | | | | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ |
| AC Circuit Breakers for DC grid protection (NS) | | | | | █ | █ | █ | █ | █ | █ | █ | █ | █ | █ | █ | █ |

## 4. COMPARISON AND EXAMPLE SCENARIOS OF AC/DC NETWORK TYPES

To compare and assess various AC/DC architectures, control strategies, and protection concepts, Key Performance Indicators (KPIs) associated test methods are required to measure reliability and resilience. This paper, along with the HVDC-WISE project, concentrates on the qualitative KPIs and test methods specific to hybrid AC/DC systems [3].

## 4.1. KPI / Metrics / Test Methods

KPIs can be either qualitative or quantitative and are defined with relation to the AC/DC matrix. The quantification of these test methods and KPIs, and the establishment of weighting mechanisms, are not yet defined and will be developed as part of the HVDC-WISE project. As one example, AC-side stability could be quantitatively evaluated using methods like as Short-circuit ratio (SCR), Angle Index (AI), and Rate of Change of Frequency (RoCoF), focusing on aspects like power transfer, transient stability, and frequency stability after disruptions.

Notably, the qualitative KPIs and tests already depend on the framework elements, differentiating them from standard categories as planning and normal operation, AC system stability, and DC system stability. Two overarching classes of KPI are distinguished in the following: Whereas KPI for AC-side contingencies aim to measure the improvement of AC system stability compared to the status quo, the KPI for DC-side contingencies assess the added risks when using HVDC networks, e.g. the response to protection system failures. For each category of the matrix, the most relevant KPI/metrics may vary: For instance, frequency stability is not a meaningful metric for designing protection in embedded systems, whereas it is significant in non-embedded systems. Further, DC stability involves dynamic response of HVDC networks to various contingencies as DC-line overload and control loss, and is thus most relevant for larger MTDC systems: For instance, DC line faults can cause power imbalances and loss of transmission capacity.

Table 7 provides an overview of the most relevant AC and DC stability test methods in case of DC faults to be evaluated and quantified within the AC/DC matrix. As a given AC/DC system can be transferred into another classification either by scheduled by specific events, all control and/or protection concepts should be able to cope with different states of the same HVDC-based system. Previous approaches often lacked a systematic framework for aligning KPIs with the specific requirements of different HVDC systems, hence which performance indicators are critical for each design. The AC/DC matrix addresses this gap by allowing a clear mapping of relevant KPIs to their corresponding HVDC system configurations, thereby enhancing the system design.

*Table 7: AC and DC stability test methods in case of DC faults with information from [3]*

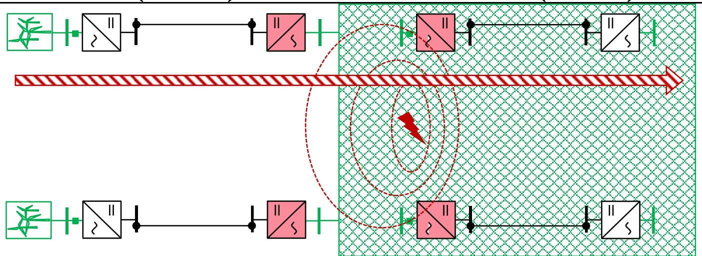
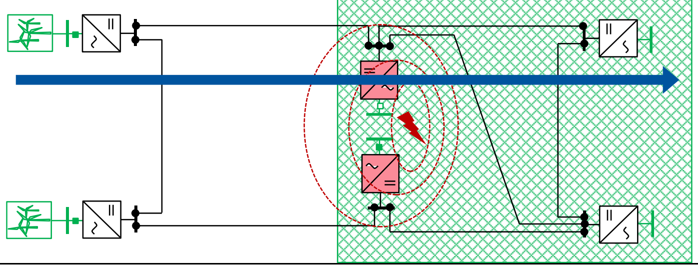
| **DC Faults** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **AC stability test methods** | | | | **DC stability test methods** | | | |
| | AC1 | AC2a | AC2b | AC3 | AC1 | AC2a | AC2b | AC3 |
| DC1 | A fault in PtP system forces a complete shutdown, requiring connected AC systems to withstand the **loss of power infeed**. These events can serve as benchmark cases for simulating or calculating KPIs in MTDC protection design. | | | Connected AC systems need to be capable of withstanding the **loss of transmission** (N-1), and the loss of grid-forming at multiple PoCs. | For monopolar systems, DC faults are leading to a shutdown. a single-pole fault in a bipolar point-to-point HVDC link can cause overload on the healthy pole, also resulting in converter overload. Current solution is the use of DC Choppers (e.g., braking resistors) | | In monopolar systems, DC faults are leading to a shutdown. Likewise, a single-pole fault in a bipolar point-to-point HVDC link can overload the healthy pole, also leading to converter overload. Current solution to change converter's setpoints and/or droop controls | |
| DC2 | Loss of power infeed | Loss of power infeed (frequency stability), loss of transmission capacity, and loss of grid-forming at multiple PoCs | | Loss of transmission capacity, and loss of grid-forming at multiple PoCs | Converter overload, DC line overload, Loss of DC voltage control. Possible solutions could be DC choppers, control systems. | | | |
| DC3 | | | | | | | | |
| DC4 | | | | | DC line overload<br>Loss of DC voltage control | | | |

## 4.2. Exemplary Representation of a Test Scenario

In this section, an example to illustrate how specific test methods are applied to assess system-level KPIs for different AC/DC architectures will be presented. This qualitative assessment uses performance indicators ranging from "--" (weak performance, high risk) to "++" (excellent performance, low risk), focusing on a scenario where two different architectures integrate offshore wind power into an onshore grid. Generally, in case of system planning, this approach allows for the estimation of risks associated with certain architectures over others without the need for detailed studies. Additionally, for control and protection developers, architectures marked with a '-' or '--' may warrant more detailed study and potential improvements. The example in Table 8 compares the KPIs performance – in particular frequency and voltage stability – of a point-to-point architecture (DC1) with a DC3/4 meshed style transfer in a grid with mixed AC2a/b and AC3 embedment. The exemplary test scenario analyses the behaviour of HVDC systems during a three-phase AC fault at connection points of point-to-point links, typical in weaker AC grid areas near the shore. Key assumptions include quick fault clearance (e.g., within 150 ms), the HVDC converters' ability to ride through AC faults with reduced power transfer, dynamic braking systems to dissipate wind power infeed, and a droop-based approach for DC voltage stabilisation and power redistribution in the "DC3/4" scenario.

For the DC1 architecture, there's a risk to frequency stability depending on the HVDC systems' power rating and wind infeed. This could lead to a complete loss if power flow from left to right, and thus a “local” RoCoF event (e.g., critical for frequency and/or angle stability) at the right end. In either way, an AC fault at one end of the HVDC system causes a large event at another end. ear the fault, four HVDC converters in DC1 help limit voltage sag and provide additional fault current, though limited by VSCs’ lower overcurrent capability. In the DC3/4 architecture, power transfer continues during the AC fault, and the event is not transferred to the system’s ends. Only in case wind power is transmitted to middle converters, it shifts to the right-end converters, still avoiding energy dissipation and RoCoF phenomena. Assuming sufficient distance between onshore converters, wind power can be transferred to the AC network during AC faults. However, grid support by HVDC converters at the fault location is less robust in "DC3/4" compared to "DC1", due to fewer converters.

*Table 8: Comparison of KPI of “Frequency” and “voltage” stability in a three-phase ac fault scenario*

| | **AC2a/b (offshore)** | **AC3 (onshore)** | **Freq** | $V_{AC}$ |
|---|---|---|---|---|
| **DC1** |  | | - | + |
| **DC3/4** |  | | ++ | - |

Currently, this is a qualitative analysis for demonstration purposes, but future work in the HVDC-WISE project will explore whether this segmented approach can be extended to larger systems quantitatively. In Table 9, a broader range of KPIs is evaluated for normal operation and DC fault scenarios in the context of DC1 and DC3/4 [3] [16]. These KPIs encompass aspects beyond the described AC fault, including operational costs, grid losses, and flexibility during normal operation, as well as frequency stability, inertia, and redundancy in the event of a DC fault.

*Table 9: KPI comparison for two example AC/DC architectures*

| | **Operation** | | | **AC fault** | | **DC Fault** | | |
|---|---|---|---|---|---|---|---|---|
| | Costs | Loss | Flex. | Freq. | $V_{AC}$ | Freq. | Inertia | Redundancy |
| **DC1** | 0 | - | - | - | + | + | + | - |
| **DC3/4** | + | ++ | + | ++ | - | - - | - | + |

## 5. CLASSIFICATION OF EXAMPLE, EXISTING OR PLANNED HVDC SYSTEMS

The authors have considered existing grids in the literature and have analysed the prevalence of the various grid topologies within the context of the AC / DC classification framework. The table illustrates that PtP configurations have been extensively discussed across all embedment levels within AC grids. In reviewing the literature, it becomes evident that there are numerous instances of existing grids operating within the AC/DC classification framework, as can be seen in Table 10. A detailed examination reveals that PtP configurations have been extensively discussed across various levels of integration within AC grids.

*Table 10: Analysis of grid topologies encountered in the literature, analysed under the classification framework*

| | AC1 | AC2 | | AC3 |
|---|---|---|---|---|
| | | AC2a | AC2b | |
| DC1: Point-to-point | 🟩 | 🟩 | 🟩 | 🟩 |
| DC2: Radial | 🟧 | ⬜ | ⬜ | ⬜ |
| DC3: Linear | 🟩 | 🟢 | 🟧 | ⬜ |
| DC4: Meshed/Grid | 🟩 | 🟢 | 🟧 | ⬜ |

| | |
|---|---|
| 🟩 | Many |
| 🟢 | Few |
| 🟧 | Rare |
| ⬜ | None |

Notably, the full embedment of point-to-point links within synchronous AC grids is not just a theoretical option, but practically foreseen, e.g. in the German HVDC corridors. Furthermore, the PROMOTioN project delves into the exploration of DC4 meshed grids, particularly in scenarios devoid of an embedment level in the AC grid (labelled as AC1) [17]. Other notable projects, such as Twenties [18], NSWPH (DC3), and the benchmark models from CIGRE TB804 [5], have successfully demonstrated AC grids with onshore embedded and offshore wind parks (classified as AC2a).

However, configurations such as AC1 with DC2 and AC2b with DC3 or DC4 are less common, with only a handful of existing examples. The absence of examples in certain configurations is indicated by grey areas in the table based on the available literature. As stated, numerous projects and test grids exist within the AC/DC matrix. However, it is evident that not all architectures have been realised so far. For instance, CIGRE TB 804 focuses on different architectures, such as those with one or multiple DC voltage levels within AC2a and AC2b [5], but these do not cover all scenarios identified by HVDC-WISE and leaving a gap for additional test models.

It also does not address AC1 and has not been evaluated for the full embedded level. While fully embedded level MTDC scenarios are not currently existing, ambitious goals set by organisations such as the European Commission for extensive renewable energy integration suggest their inevitable emergence, requiring proactive readiness. The concept of assembling larger AC/DC grids from separate 4-terminal HVDC systems, presents a structured approach to managing complex power networks. This methodology is particularly effective in dividing extensive HVDC networks, such as those with 10 terminals, into manageable subsystems. Consequently, a critical aspect of this development is the need to clearly define and classify the "architecture" of such large-scale AC networks. This involves deciding whether to use several separate HVDC networks or to integrate them into a single, expansive network.

The overall strength of the AC/DC classification framework is demonstrated by its ability to qualitatively and generically identify relevant effects within grid configurations, which can subsequently be analysed and quantified in detail. This initial identification serves as a critical first step in addressing complex grid interactions. The high-level perspective provided by the framework facilitates effective coordination across planning, operation and designing of control and protection, ensuring that these aspects are aligned to enhance the reliability and efficiency of the grid. While the framework is instrumental in highlighting general and significant effects in grid configurations, it is limited in its capacity to support detailed quantitative analysis. This limitation necessitates the use of supplementary methodologies or models to bridge the gap between the high-level insights provided by the framework and the detailed technical and operational requirements necessary for practical implementation.

### 5.1. Future HVDC-WISE Use Case: Continental Europe

The HVDC-WISE project aims to establish HVDC topologies, providing a framework for designing these topologies based on system requirements, calculated at subsequent stages. Three use cases were derived from this project, with the first focusing on the Continental European grid. Here, HVDC systems are predominantly integrated into a single synchronous zone, complementing onshore AC corridors. This scenario primarily considers Central European contexts, analysing HVDC architectures interconnected within the AC grid. Its primary objective is to investigate various designs and operational strategies for wide-area HVDC systems, particularly reinforcing a large, strongly meshed synchronous area. The Use Case explores HVDC overlay grids, considering interactions and potential risks within large AC/DC networks during failures. This exploration is not limited to systems with a few terminals. It includes diverse combinations of larger MTDC systems within and across AC2/AC3. As outlined in the introduction, the integration of these "architecture building blocks" into larger systems should follow clear and defined design guidelines. This approach ensures that results and requirements derived from smaller EMT-modelled networks are valid and transferable to larger systems. An essential aspect of this study is the interdependencies between HVDC and HVAC system architectures, especially concerning the planning and operation of hybrid AC/DC structures. For instance, DC links can be fully embedded in a single AC grid (AC3– no in-feed) or connect multiple offshore wind farms to a synchronous AC network (AC2a – multi-infeed). Additionally, the study emphasises assessing the impact of varying converter numbers in potential architectures, as this influences operational flexibility, reliability, resilience, and other key parameters like control stability, grid-forming, electrical closeness and fault current levels [3].

### 5.2. Real life applications

To demonstrate its usefulness and applicability to real life projects, the proposed methodology will be used to classify the first multiterminal DC hub project in Europe that is planned to be built in Heide by 2032 [7]. The DC Hub Heide is intended to link two planned offshore wind farms (LanWin2 and LanWin3) with two connection points to the German transmission grid (Heide West and Klein Rogahn). The offshore wind farms will be connected to a DC switching station using submarine cables via two HVDC connections, each operating at a voltage of ± 525 kV and with a nominal power of 2 GW. At the Heide Hub, one part of the electricity will be transported further via a DC link to Klein Rogan whereas the rest will be converted to AC by a converter station and distributed in the region through a substation. A visualisation of the project alongside a schematic representation is given in Figure 3 below.

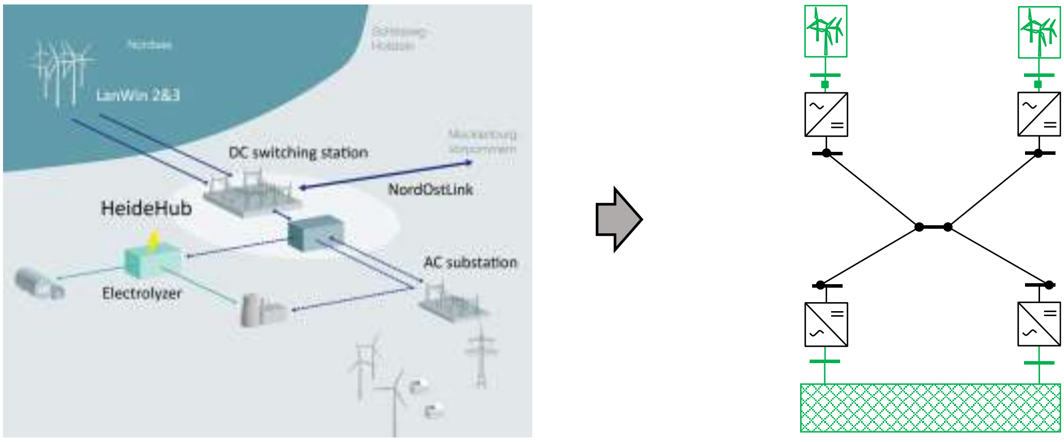


*Figure 3 : Schematic representation of DC Hub Heide*

The two converter stations in Heide West and Klein Rogahn are in the same synchronous zone whereas the two WPP are not connected on the AC side offshore. This arrangement can therefore be classified as AC2a with respect to the proposed methodology. On the other hand, all four converters are connected to each other at the DC switching station and there is no meshing on the DC side. Therefore, the DC topology of this multiterminal project can be classified as radial (DC2).

## 6. CONCLUSION AND OUTLOOK

This paper presents a comprehensive framework for classifying HVDC-based transmission grid architectures, a crucial element for electrical power systems among the global shift towards climate neutrality. An aspect of this paper is the development of a matrix-based classification system that cross-varies DC-side topology (point-to-point, radial, linear, meshed) and AC-side embedment in a 4x4 matrix, offering a systematic categorisation that aids in understanding and planning of complex AC/DC transmission grids. In terms of control and protection requirements, the analysis highlights challenges in HVDC networks, including rapid voltage sags, high fault current peaks, and the absence of a zero crossing in DC fault current. It emphasises the need for rapid and accurate fault isolation techniques in multi-terminal DC networks, underlining the evolving requirements in HVDC protection strategies. Additionally, the paper gives knowledge how control strategies and grid support can be enhanced by this framework. This framework is instrumental in identifying (KPIs) and test methods for various AC/DC architectures, thereby facilitating a comprehensive assessment of control strategies and protection concepts. Looking ahead, the paper’s classification framework sets the stage for further research and development in HVDC systems. With increasing integration of renewable sources and the shift towards more complex AC/DC systems, necessitates continuous refinement of this framework. Future studies may focus on more diverse HVDC configurations, including systems with DC-side loads and multiple DC voltage levels interconnected by DC/DC converters. Further, there remains a need for further empirical validation and refinement of the framework, especially in the context of emerging grid architectures and technological capabilities. The analysis could be pivotal in guiding the design and operation of future HVDC systems, particularly in the context of system resilience, reliability, and integration of large-scale renewable resources. The paper proposes a "Master platform" as a future solution for comprehensive power system analysis. This platform could manage various modules for input preparation and output processing, utilising detailed power system models, reliability and resilience data, and predefined HVDC architectures. It will produce detailed indicators for each architecture, including investment and operating costs, through static techno-economic analysis, adequacy, security, and resilience evaluations.

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