Pan-European interoperable AC-DC HYbrid electricity NETworks

D2.1: Description of boundary conditions, overall requirements of hybrid AC-DC grids and operation modes of the demo sites

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List of acronyms and abbreviations

Abbreviation	Description
AC	Alternate Current
ACER	Agency for the Cooperation of Energy Regulators
A-DFs	Asynchronously connected Demand Facilities
A-ESMs	Asynchronously connected Electricity Storage Modules
A-PPMs	Asynchronously connected systems and Power Park Modules
A-PtG-Us	Asynchronously connected Power-to-Gas demand Units
CDSs	Closed Distribution Systems
DC	Direct Current
DCCB	DC Circuit Breaker
DMR	Dedicated Metallic Return
EDS	Energy Dissipation Systems
eDSO	European Distribution System Operators
ENTSO-e	European Network of Transmission System Operators for Electricity
EV	Electric Vehicle
FCB	Fault-Blocking Converter
FS	Fully Selective (Protection)
FSM	frequency sensitive mode
GA	Grant Agreement
HRES	Hybrid renewable energy systems (HRES)
HVDC	High Voltage DC grids
HT	Hybrid Transformers
HYNET	Pan-European interoperable AC-DC **HY**brid electricity **NET**works
ILC	Interlinking Converter
LCC	Line Commutated Converter
LED	Light Emitting Diode
LFSM-O	Limited Frequency Sensitive Mode — Over frequency
LFSM-U	limited frequency sensitive mode — underfrequency
LVDC	Low voltage DC grids
LTTRs	Long-Term Transmission Rights

MMC	Modular Multilevel Converter
MTDC	Multi-Terminal Direct Current
MVDC	Medium voltage DC grids
NC-CACM	Network Code on Capacity Allocation & Congestion Management
NC CS	Network Code on Cybersecurity
NC DC	Network Code on Demand Connection
NC DR	Network Code on Demand Response
NC EB	Network Code on Electricity Balancing
NC ER	Network Code on Electricity emergency and Restoration
NC FCA	Network Code on Forward Capacity Allocation
NC RfG	Network Code on Regulations for Generators
NC SO	Network Code on System Operations
NEMO	Nominated Electricity Market Operator,
NRAs	National Regulatory Authorities
NS	Non-Selective (Protection)
OHL	Overhead lines
PS	Partially Selective (Protection)
R&R	Reliability and Resilience
SSEN	Scottish and Southern Electricity Networks
SST	Solid state transformer
UHVDC	Ultra-High Voltage Direct Current
VSC	Voltage Source Converter
WP	Work Package
DSO	Distribution system operator

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Executive summary

Deliverable D2.1 “Description of boundary conditions, overall requirements of hybrid AC/ DC grids and operation modes of the demo-sites” is the first technical deliverable of WP2 of the HYNET project. It provides a comprehensive analysis of the state of the art and current industry-scale pilot solutions for hybrid AC/DC grids related to all voltage levels. The deliverable analyses in depth the boundary conditions, the overall requirements, and operation modes of hybrid AC/DC grids, and maps these challenges and requirements with the four demonstration sites within the project. It also addresses key technical, regulatory, and operational aspects in an integrated manner, which is essential for the successful deployment and integration of hybrid AC/DC grids into modern power systems.

The work is structured into six main sections. The first section introduces the overall project and maps the HYNET expected outputs with the scope and objectives of this deliverable. The second section offers an overview of hybrid AC/DC grids, introducing key technologies such as power electronics converters, protection systems, and grid topologies, while also reviewing existing deployments and research projects to identify trends in DC technology adoption. The third section defines the technical boundaries, including voltage and frequency coordination, converter constraints, protection challenges, and interoperability, alongside an analysis of regulatory boundaries such as ENTSO-E and eDSO network codes and grid connection standards.

The fourth section examines the challenges and requirements for hybrid AC/DC grids, covering stability management in power electronics-dominated systems, adequacy, security, and reliability considerations, as well as technical challenges related to DC grid maturity and fine mesh network planning. The fifth section introduces the scope and the operation modes of the four demo-sites of the HYNET project, providing brief descriptions of each demo-site, the tools and methodologies applied, and a mapping of requirements to address key deployment challenges.

Key conclusions highlight that hybrid AC/DC grids require advanced converter technologies, coordinated protection schemes, and harmonized regulatory frameworks for seamless integration. Stability and reliability remain critical challenges, necessitating real-time monitoring and adaptive control strategies. The demo-sites ambitions such as to validate interoperability, scalability, and performance under different operational modes are fully aligned with the identified challenges and requirements. Further standardization needs and compliance with grid codes are also emphasized as essential for large-scale adoption.

The purpose of this deliverable is to serve as a reference document for the upcoming developments in WP3, WP4 and WP5 and it could also serve for other stakeholders, including grid operators, regulators, and technology providers outside the HYNET consortium. By consolidating these findings, the deliverable may also support policy and standardization efforts, contributing to the advancement of hybrid AC/DC grid technologies and facilitating their transition from research to real-world application.

1. Introduction

The efficient planning, operation, and control of DC and hybrid AC/DC grids present significant challenges that are critical to the evolution of modern power systems. In other words, the required transition from AC legacy grids at all voltage levels to more complex grid architectures, such as hybrid AC/DC grids, necessitates a thorough understanding of both current and emerging obstacles to ensure seamless integration and management of AC and DC components.

Integration obstacles in hybrid grids are multifaceted, encompassing technical, operational, and regulatory challenges. Identifying these barriers is essential for developing strategies that facilitate the harmonious coexistence of AC and DC elements within the grid infrastructure. This involves not only addressing apparent issues but also anticipating potential future challenges that may arise as the grid evolves. By doing so, power system stakeholders can proactively implement solutions that enhance grid stability and efficiency. Within this Deliverable (D2.1) a detailed analysis of integration obstacles and their related boundary conditions are examined as part of Chapter 2 – *Overview of hybrid AC/DC grids* and Chapter 3 – *Boundary conditions for hybrid AC/DC grids*.

Multi-vendor environments add another layer of complexity to grid management. Thus, establishing basic functional requirements and specifications for multi-vendor systems is crucial to ensure interoperability and maintain high performance standards. These specifications help create a unified framework that allows different vendors' technologies to work together seamlessly, thereby optimizing grid operations and reducing the risk of compatibility issues. These multi-vendor environments and the interoperability aspects are addressed in this deliverable as part of Chapter 4 – *Challenges and requirements for hybrid AC/DC grids*.

Further, all the insights gained from this comprehensive analysis provides the pathways for enhancing the performance, reliability, and overall effectiveness of DC and hybrid AC/DC grids. In HYNET, and specifically as part of the scope of this deliverable, the mapping between the HYNET demonstrations and the identified challenges are summarized in Chapter 5 – *HYNET demonstrations for addressing hybrid AC/DC grid challenges*. By leveraging these findings, other stakeholders, outside the consortium, could also use this report to develop optimized planning and operational strategies which might pave the way for a more resilient and efficient power systems. This, in turn, supports the broader goals of sustainability and energy security in the face of evolving energy demands, one of the strategic objectives of the project.

1.1 Mapping HYNET Outputs

The purpose of this section is to map HYNET Grant Agreement (GA) commitments, both within the formal Deliverable and Task description, against the project’s respective outputs and work performed.

Table 1: Adherence to HYNET GA Deliverable & Tasks Descriptions

HYNET GA Component Title	HYNET GA Component Outline	Respective Document Chapter(s)	Justification
DELIVERABLE			
D2.1 Description of boundary conditions, overall requirements of hybrid AC/ DC grids and operation modes of the demo-sites’			
TASKS			

Task 2.1: Analysis of challenges for efficient planning, operation and control of hybrid AC/ DC grids	- *Examination of the complexities in planning, operating, and controlling DC and hybrid AC/DC grids, based on updated ENTSO-e and eDSO whitepapers, and Network codes.*	*Chapters 3, Section 3.1.2 (Work Packages Description), WP2, Task 2.1.*	*Chapter 2. Overview of Hybrid AC/DC grids*
	- *Identification and understanding of both apparent and potential obstacles in integrating and managing AC and DC components within grid infrastructure.*		*Chapter 3. Boundary conditions for hybrid AC/DC grids and Chapter 4. Challenges and Requirements for hybrid AC/DC grids*
	- *Provision of basic functional requirements and specifications for multi-vendor environments to ensure interoperability and efficiency.*		*Chapter 5. HYNET demonstrations for addressing hybrid AC/DC grid challenges/ Mapping requirements with challenges*
	- *Contribution of valuable insights to improve the performance, reliability, and overall effectiveness of DC and hybrid AC/DC grids, leading to optimized planning and operational strategies.*		*Chapter 5. HYNET demonstrations for addressing hybrid AC/DC grid challenges/ Tools to be demonstrated in the demo*

1.2 Scope and Objectives

The scope of the deliverable D2.1 (Description of boundary conditions, overall requirements of hybrid AC/ DC grids and operation modes of the demo-sites) is to conduct a comprehensive examination of the challenges associated with the efficient planning, operation, and control of DC and hybrid AC/DC grids, drawing from updated ENTSO-e and eDSO whitepapers, network codes, and other relevant sources. It aims to identify and understand both apparent and potential obstacles in the integration and management of AC and DC components within the grid infrastructure. As part of this first technical deliverable, a detailed analysis of key technologies, components, and existing deployments of hybrid AC/DC grids, along with the technical and regulatory boundary conditions that govern their operation is provided. Specific technical constraints such as voltage and frequency coordination, converter technology, protection and fault management, and grid topologies are also analysed. Additionally, D2.1 addresses regulatory frameworks, including ENTSO-e and eDSO network codes, and grid connection requirements. Following the broader landscape of hybrid AC/DC grids, a detailed analysis related to the challenges associated with stability management, adequacy, security, and reliability in power electronics-dominated systems is also conducted considering the state-of-the-art solutions and other relevant requirements for modern hybrid AC/DC grids. Finally, within the scope of this deliverable is the introduction into the technical challenges related to hybrid DC grid maturity, their sizing and planning of fine mesh networks in direct relation with the proposed HYNET solutions. Thus, the demonstration pilots in France, Norway, Montenegro, and Cyprus are summarized, considering the practical tools and strategies which HYNET will be developing for addressing the identified challenges. The findings from this analysis will be input for the development stage WPs (WP3, WP4 and WP5).

1.3 Structure of the deliverable

This report is composed of six chapters, starting with the Introduction where the main scope and objectives of the deliverables are highlighted within the broader scope of the HYNET project. Chapter 2 provides the background on the key technologies and existing deployments of hybrid AC/DC grids. Chapter 3 goes deeper into the analysis of the technological and regulatory boundary conditions for hybrid AC/DC grids. Chapter 4 discusses the challenges and requirements for stable, adequate, secure and reliable hybrid AC/DC grids. Chapter 5 maps the HYNET pilot’s challenges and requirements to the broader landscape described in the previous chapters and highlights the technologies and tools to be demonstrated in each of the pilots. Chapter 6 concludes this report.

2. Overview of Hybrid AC/DC Grids

2.1 Introduction of Hybrid AC/DC Grids

The technological evolution of power grids, from centralized to decentralized paradigms, has been driven by the extensive integration of hybrid renewable energy technologies (e.g., wind, solar), energy storage systems (e.g., batteries), and the widespread availability of advanced power electronic devices. These developments have fundamentally changed how power is generated, transmitted, and distributed, highlighting the need for more flexible and efficient power grid network [1] . Early power grid development primarily relied on small, isolated direct current (DC) systems, which were uneconomical for long-distance transmission due to significant power losses. The evolution toward multi-phase alternating current (AC) systems proved both technically viable and economically efficient, as AC allowed easier voltage conversion and level adjustments through transformers [2] . However, recent advancements in DC technologies, ranging from thyristor-based converters to multi-level converter-based high-voltage direct current (HVDC) systems for hybrid renewable energy systems (HRES), have transformed interest in transitioning future disruptive power grids toward hybrid AC/DC grid configuration [3] . Conclusively, hybrid AC/DC grids provide a pivotal solution for integrating traditional AC networks with DC subsystems that support substantial HRES in parallel, as shown in Fig. 1. Furthermore, substantial advancements in the control and stability of HVDC systems both in conventional point-to-point links [4] and multi-terminal networks [5] , have further emphasized the necessity of hybrid AC/DC grids. The interconnection of various voltage source converter-based HVDC systems is depicted in Fig. 2, enabling efficient long-distance transmission and interconnection of asynchronous AC grids. Such an integrated system utilizes power electronic converters to manage energy exchange among them, while each side of the grid has its own generators, storage, and loads [6] . Moreover, advanced coordinated control systems are used to regulate power flow in hybrid grids, while reducing conversion losses and improving overall system efficiency by 5–7% [7] .

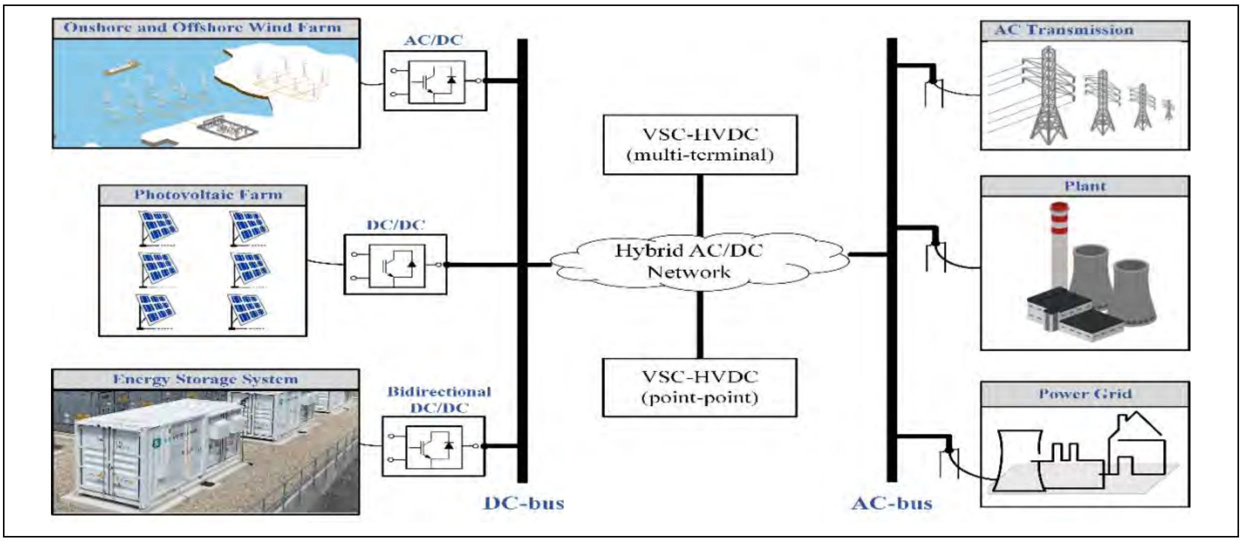

Figure 1: Hybrid AC/DC grid network with various renewables and HVDC systems

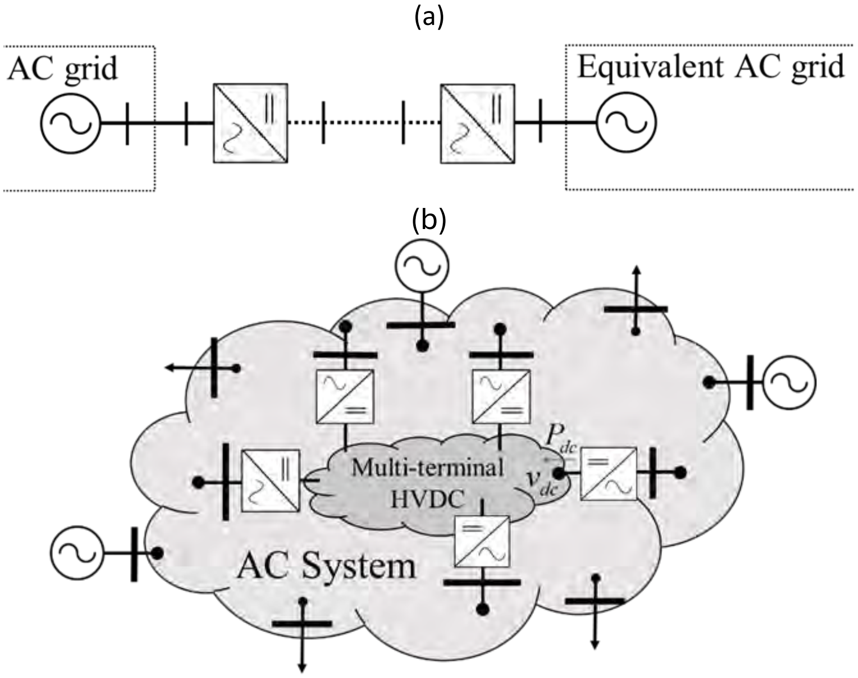

Figure 2: HVDC transmission system-based Voltage Source Converter (VSC). In (a), point-point VSC-HVDC system is presented, while (b) presents multi-terminal use of HVDC (MTDC)

Unlike traditional AC grids, which rely solely on transformers and switchgear, hybrid grids offer substantial benefits by integrating bidirectional converters to bridge the AC and DC sections. The key benefits include:

1. **Centralizes power conversion:** Hybrid grids reduce the need for individual inverters or rectifiers at each device by centralizing power conversion, thereby improving efficiency and lowering costs [8] .
2. **Reduced DC-AC conversion stages**: By minimizing the number of DC-AC conversion stages across various voltage levels, especially in low and medium-voltage DC transmission systems, hybrid grids help reduce converter losses, eliminate the need for extensive harmonic filtering, and lower overall system costs, all while maintaining compatibility with existing AC infrastructure.
3. **System flexibility and resilience:** Hybrid grid architecture enables operators to reroute power during peak demand or faults, enhancing operational adaptability.
4. **Intentional Islanding and Reliability:** In the event of grid failure, hybrid grids can isolate affected sections and continue operating with local generation, ensuring uninterrupted power supply to both AC and DC loads [9] .

Considering these benefits, hybrid microgrids are emerging as a key solution for future smart energy systems, enabling distributed resource integration while ensuring reliability and power quality. Their adaptability and resilience make them vital to next-generation grid infrastructure.

In a hybrid AC/DC grid, few power network sections operate at the fundamental AC frequency (50 or 60 Hz), while the remaining network operate on DC (0 Hz), with bidirectional rectifiers/inverters regulating energy flow and maintaining stability by controlling parameters like AC frequency and voltage, as well as DC link voltages. Typically, AC sources and loads connect to an AC bus, while DC sources (e.g., PV panels, fuel cells) and DC loads (e.g., LED lighting, servers, EV chargers) connect to a DC bus, enabling coordinated operation across the grid [10] . Hybrid AC/DC grids span multiple voltage levels: low-voltage DC (LVDC) systems (~380-400 V) for buildings and data centres, medium-voltage

DC (MVDC) systems (±10 kV - 35 kV) for campus grids and industrial facilities, and high-voltage DC (HVDC) links (e.g., ±320 kV or ±500 kV) for bulk power transfer and interconnecting regional AC grids [11] . Typically, power converters manage power exchange, allowing seamless integration of AC and DC elements into a unified grid. The following are in detailed comparison of hybrid grids with traditional AC grid and DC grid.

In comparison with the traditional AC grid, hybrid AC/DC grids can: (i) allow direct connection of DC-based devices (e.g., solar panels, batteries, EV chargers) to the DC bus, reducing conversion losses, (ii) improve efficiency by minimizing the need for multiple AC-DC conversions, thereby enhancing overall system performance, especially during periods of high renewable energy generation, (iii) enhance flexibility by better accommodating diverse energy sources and consumption patterns, (iv) employ sophisticated control strategies to manage power flow between AC and DC subsystems, ensuring stability and optimal performance, and (v) facilitate efficient integration of HRES with the DC network, reducing reliance on AC infrastructure.

In comparison with the traditional DC grid, hybrid AC/DC grids can: (i) enable power exchange between AC and DC systems through interlink power converters, allowing bidirectional energy flow and improved load balancing, (ii) utilize solid-state transformers and DC-DC converters to simplify voltage transformation processes, enhancing system reliability and reducing infrastructure complexity, (iii) enhance coordinated protection and fault management schemes to address both AC and DC grid faults, thereby improving system resilience and fault tolerance, (iv) optimize energy storage utilization by connecting storage systems directly to the DC bus, reducing losses associated with multiple power conversions, and (v) offer scalability to accommodate future technological advancements and increasing energy demands, ensuring long-term viability and adaptability.

2.2 Key technologies and components

The widespread adoption of hybrid AC/DC transmission and distribution grids, driven by their efficiency, flexibility, and resilience, relies on the following key technologies and components to enable seamless integration and coordinated operation between AC and DC subsystems.

- **Interconnecting power converters:** Enables bidirectional energy flow between low and high voltage AC and DC networks (mainly through voltage source converters for fast and controllable power flow), minimizing conversion losses and supporting HRES integration. Additionally, grid-forming converters provide voltage and frequency reference to enhance the hybrid grids stability. Specifically, grid forming strategy based on bidirectional virtual inertia support and dual-port grid-forming converter, as presented in [12] and [13] , respectively, to address the weak grid conditions, which simultaneously manage AC and DC voltages to improve system resilience.
- **DC/DC Converters:** Facilitate efficient voltage level conversion between different DC sub-networks (including LVDC, MVDC and HVDC), enhancing modularity and enabling the seamless integration of diverse DC-based generation sources and loads within hybrid AC/DC systems.
- **Solid state transformers (SSTs):** Medium-frequency power electronics replace conventional transformers to offer voltage regulation, reactive power compensation, and direct integration with energy storage systems for better power flow control and HRES integration.
- **Hybrid Transformers (HTs):** Combine conventional transformer elements with power electronics to enable voltage regulation and reactive power compensation.

The aforementioned components are common to both hybrid AC/DC transmission and distribution grids. The following subsections present the key technologies and components specific to hybrid AC/DC transmission and distribution systems, respectively.

2.2.1 Hybrid AC/DC transmission grids

Hybrid AC/DC transmission grids enable long-distance, high-capacity power transfer for integrating large-scale renewable integration (e.g., offshore wind) and interconnection of asynchronous grids across regions or countries. Key design considerations include: (i) high operational voltages (hundreds of kilovolts to over a megavolt) to reduce losses, (ii) optimized use of existing AC infrastructure for DC transmission, and (iii) advanced protection systems to manage faults and maintain grid stability across interconnected grids. Some key technologies and components of hybrid AC/DC transmission grid include:

- **High-Voltage Direct Current (HVDC) Systems**: Use Line-Commutated Converters (LCC) or Voltage-Source Converters (VSC) for efficient long-distance power transmission.
- **Overhead Lines and Submarine Cables**: Handle high voltages (e.g., ±320 kV to ±800 kV) for efficient long distance power transfer.
- **Advanced Control Systems**: Manage power flow, voltage stability, and fault detection across the transmission network.
- **Protection Systems:** The integration of robust protection schemes in hybrid AC/DC transmission grids is essential to ensure overall system stability, reliability, and safety. Inadequate or inaccurate protection during grid faults can result in several critical issues: (i) damage to key grid components such as transformers, converters, circuit breakers, and connected loads; (ii) severe grid instability due to delayed or incorrect fault isolation; (iii) uncontrolled bidirectional power flow, leading to overloading and potential failure of transformers, power converters, and other grid infrastructure; and (iv) increased risks of non-compliance with regulatory and safety standards, jeopardizing the secure operation of the power system [14] . The existing protection solutions for hybrid AC/DC transmission grids primarily fall into two categories. AC protection systems, such as circuit breakers, fuses, and relays, are adapted to monitor and isolate faults in the AC network, while DC protection schemes rely on specialized HVDC circuit breakers and fault-blocking converters to interrupt current in the absence of natural zero-crossings. However, relying solely on AC protection systems presents significant limitations when dealing with DC-side faults, such as cable insulation failures, short circuits, converter overheating or damage, uncontrolled fault propagation into the AC grid through interlinking converters, and the misdetection of low fault currents [14] . Conversely, a standalone DC protection approach can leave AC-side disturbances (e.g., line-to-ground or overcurrent faults) undetected, risking damage to transformers, switchgear, and generators; can suffer from miscoordination or false trips; and may cause grid synchronization loss and blackouts due to its inability to respond to rapidly changing operating conditions [15] . Limited research on hybrid AC/DC transmission grid protection mainly emphasis on (i) high-speed, differential protection-based on multi-sample differential scheme [16] , unified impedance-based relating protection [17] , and integration of hybrid components protection devices (e.g., combines mechanical and solid-state technologies) [18] , to allow for fast and reliable fault interruption, but challenges remain in coordinating protection schemes and ensuring fast fault detection and isolation to ensure selectivity and minimize the impact of faults on the overall grid. Despite the effectiveness of the aforementioned techniques for fault protection in hybrid transmission grid, there remains a critical need for adaptive protection algorithms that can respond dynamically to varying grid conditions and evolving fault scenarios. Additionally, the integration of advanced communication systems is essential for real-time coordination and decision-making across AC and

DC subsystems, while the deployment of high-speed DC circuit breakers is necessary to ensure rapid fault isolation, minimize damage, and enhance overall system reliability and resilience.

- **Cables:** Hybrid AC/DC transmission grids utilize both HVDC and HVAC cables, each with distinct voltage and current characteristics, to enable long-distance power transmission with minimal losses. These cables are often installed within a shared infrastructure corridor to reduce space requirements and enhance cost-effectiveness. Depending on geographic and environmental factors, installations may be overhead lines (OHL), underground or submarine [19] . Key factors in cable selection mainly include voltage rating, insulation type and material (e.g., cross-linked polyethylene, mass-impregnated non-draining paper), thermal performance, current-carrying capacity, and the ability to maintain performance and safety in mixed AC/DC environments. Generally, AC cables are commonly used for local grids and shorter transmission lines on the AC side. However, phenomena such as skin and proximity effects result in uneven current distribution and increased losses. In contrast, HVDC cables are preferred for bulk power transfer over longer distances, which must withstand continuous dielectric stress and higher thermal loads due to unidirectional current without natural zero-crossings [20] . Additionally, space charge accumulation in DC insulation can accelerate aging and lead to premature failure. Existing research primarily focuses on improving cable materials, insulation techniques, and thermal management. However, several challenges remain, particularly in optimizing cable designs and enhancing thermal and electrical performance of cables. Therefore, the development of advanced materials with higher thermal conductivity (e.g., superconducting DC cables – see SCARLET project listed in Section 2.3.2), improved insulation resilience, and optimized cable designs is essential to enhance long-term reliability and facilitate the broader deployment of hybrid AC/DC transmission systems.

2.2.2 Hybrid AC/DC distribution grids

In contrast to hybrid AC/DC transmission grids, hybrid AC/DC distribution systems focus on local or regional power distribution, aiming to efficiently integrate HRES and electric vehicles. Additionally, both AC and DC loads can be intrinsically supported, thus enhancing overall system flexibility and efficiency. Key design considerations include: (i) lower operational voltage levels (typically 400 V to 33 kV) suitable for residential and commercial applications, (ii) application-specific flexible topologies (e.g., AC-coupled, DC-coupled, or AC-DC coupled systems), and (iii) integration with existing AC distribution networks to incorporate DC technologies without extensive infrastructure overhauls. Key technologies and components include:

- **Protection Systems:** The development of reliable protection schemes for hybrid AC/DC distribution grids remains a significant challenge, particularly with the widespread integration of distributed generators based on power electronic inverters. The widespread integration of inverter-interfaced sources introduces several critical protection challenges, including: (i) limited fault current contribution due to the inherent current-limiting behaviour of interfacing converters, which impairs conventional fault detection methods [22] , (ii) the inability of traditional protection schemes, such as overcurrent and rate-of-change relays, to detect and discriminate low-magnitude faults, especially in DC systems where distinctive fault signatures (e.g., natural current zero-crossings) are absent [23] , (iii) difficulties in achieving accurate selectivity and coordination among multiple distributed converters and bidirectional power flows [24] , (iv) complexities arising from bidirectional power transfer across interlinking converters, which complicate fault directionality and the definition of protection zone boundaries [25] , and (v) the need for ultrafast fault isolation mechanisms capable of withstanding medium-voltage DC conditions to prevent the formation of sustained and destructive arcs [26] .

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Limited research has addressed these challenges [22] - [28] . For instance, fault detection techniques using negative-sequence resistance-based [27] , and data-driven-based [28] schemes have been proposed to identify faults even with low current magnitudes. While effectiveness in accurate fault detection, these methods often require detailed system models, high-speed processing, and may struggle with unseen scenarios, thus traditional relays remain in use for industrial applications. Additionally, adaptive overcurrent, communication-based, and hybrid protection schemes have been developed to address challenges in fault selectivity and coordination. Multi-terminal coordination strategies aim to ensure selective protection across distributed converters and interlinking lines [29] . Hybrid methods, such as those combining line differential and distance protection, extend across AC/DC interfaces for improved fault discrimination [25] -[26] . Other hybrid schemes incorporate DC bus-voltage monitoring to detect fault direction, enabling accurate and rapid isolation in systems with bidirectional power transfer. In addition to distributed generators, the interconnection of microgrids with different characteristics further increases protection challenges, as microgrids can respond differently under fault conditions. The key protection components in the protection of hybrid AC/DC distribution include overcurrent protection, current differential protection, unbalanced current protection (including both positive and negative-pole currents), and local backup protection to prevent false tripping. Although extensive research has been conducted on the protection of AC microgrids [30] and DC microgrids [31] , limited research has been carried out on hybrid AC/DC microgrid protection. Still, there is a need for accurate fault detection and identification schemes to enhance the protection speed of DC lines and ensure selectivity.

- **Cabling and Conductors:** Hybrid AC/DC distribution grids require a sophisticated cabling infrastructure to accommodate both AC and DC transmission. The primary challenge lies in managing the differing characteristics of AC and DC systems, such as their distinct insulation, thermal, and electromagnetic requirements. For instance, DC cables generally have lower insulation needs due to the absence of reactive power, allowing for more compact designs. However, they are subjected to continuous dielectric stress, which leads to space charge accumulation and accelerated insulation aging. In contrast, AC cables must be designed to handle reactive power, necessitating larger conductors and thicker insulation to mitigate losses caused by phenomena like the skin and proximity effects. These effects can result in uneven current distribution, increased losses, and reduced efficiency [32] . Consequently, in hybrid distribution grids, thermal management becomes a significant concern, as DC cables tend to operate under higher continuous thermal loads. Moreover, electromagnetic interference between AC and DC cables, along with inductive coupling, can cause crosstalk and signal distortion, further complicating system design. The lack of standardized, hybrid-compatible cables also limits integration and compromises the long-term reliability of hybrid grid systems [32] . To address these challenges, current research primarily focuses on enhancing cable materials, insulation techniques, and thermal management strategies. Nevertheless, significant work remains to optimize cable designs capable of supporting both AC and DC transmission while minimizing losses, ensuring thermal stability, and maintaining high reliability. Additionally, effective protection strategies are essential to prevent the propagation of DC faults, which are more difficult to detect and isolate than AC faults.

2.3 Review of existing deployments and projects

This section highlights real-world examples like multi-terminal including offshore wind integration, urban DC networks, and industrial applications and also analyses relevant research projects.

2.3.1 Trends of DC technology

HVDC grids

Decarbonisation and large shares of variable renewables are pushing grids to adopt HVDC. By moving bulk power efficiently across long distances, bridging asynchronous AC areas and exporting offshore wind, HVDC has become a key enabler of tomorrow’s network. As HVDC systems become more prevalent and powerful, understanding the trends in their deployment, and the various architectures and designs being implemented is crucial for effective grid planning and operation. Factors such as system performance, interoperability, cost-effectiveness, and the ability to support stable grid operation are key considerations in the design and implementation of these complex systems.

The information presented is largely based on analyses conducted within the HVDC-WISE[1] project, particularly the survey of HVDC projects found in *Section 4.2 of Deliverable D2.1* from the same project [34] . This work extends and updates that survey to enable a more refined analysis of emerging trends.

Trends in HVDC System Deployments

The deployment of HVDC technology is accelerating globally, characterized by several distinct trends identified through surveys of existing and planned projects:

- **Increasing Capacity:** Globally, HVDC systems are being designed for progressively higher power transfer ratings to manage bulk power transmission and integrate large renewable generation hubs (see Figure 5). LCC systems have achieved ratings as high as 12 GW (Changji-Guquan UHVDC[2]). Concurrently, VSC technology has also seen significant capacity growth, with operational projects like the Zhangbei DC Grid[3] in China reaching 4.5 GW. While these examples showcase the upper limits of current technology, many new VSC projects, particularly in Europe, are standardizing around 2 GW per bipole or converter station [34] , [36] . This specific capacity target in Europe is influenced by factors such as offshore wind farm scaling, AC grid operational constraints like infeed loss limits, and strategic procurement initiatives aiming for component standardization (as seen with TenneT 2GW project [36]). This contrasts with the pursuit of even higher capacity single VSC links in other regions driven by different system needs and planning philosophies.

- **Higher Voltages:** The pursuit of efficiency, especially for long-distance transmission, continues to push HVDC operating voltages higher. LCC technology has reached operational levels of ±1100 kV (Changji-Guquan UHVDC). VSC systems are also advancing, with the Wu Dong De project in China operating at ±800 kV, and other projects globally planned at similar or increasing voltage levels (Champa-Kurukshetra HVDC). Within Europe and increasingly influencing global projects due to technology development and supply chain focus, ±320 kV and particularly ±525 kV are emerging as common voltage standards for new VSC deployments [34] , [36] . The ±525 kV level, for instance, is becoming a focal point for cable and system development, often aligning with 2 GW power ratings to create a standardized modular approach, as adopted by system operators like TenneT and Scottish and Southern Electricity Networks (SSEN) [36] [37] . This standardization facilitates large-scale procurement and deployment, though the ultimate choice of voltage level globally will continue to be

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[1] https://hvdc-wise.eu/

[2] https://www.hitachienergy.com/news-and-events/customer-success-stories/changji-guquan-uhvdc-link

[3] https://www.hitachienergy.com/news-and-events/customer-success-stories/zhangbei

influenced by specific project economics, technological readiness for the required power capacity, and regional grid integration strategies.

- **Longer Distances:** HVDC is increasingly used for very long transmission corridors, including intercontinental links planned over thousands of kilometres, see Figure 3. For example, the AAPowerLink project between Singapore and North Australia is supposed to reach 5000 km. Nonetheless, a significant portion of planned projects involves lengths under 750 km.
- **Technology Shift:** VSC technology, particularly Modular Multilevel Converter (MMC), is now the dominant choice for new HVDC projects, especially for offshore wind connections and multi-terminal systems. This shift is driven by VSC's superior controllability, including independent active/reactive power control, black start capability, and suitability for connection to weaker AC networks. Furthermore, this technological evolution is closely linked with the increasing adoption of extruded cable systems (like those using Cross-Linked Polyethylene (XLPE) insulation) for HVDC transmission. These cables offer advantages in manufacturing, installation, and environmental considerations, particularly for underground and subsea applications, and are becoming standard for high-power, long-distance VSC-HVDC projects, including those at voltage levels like ±525 kV.
- **Rise of Multi-Terminal Systems:** There is a growing trend towards MTDC systems, moving beyond simple point-to-point links. Radial, linear, and meshed configurations are increasingly planned (constituting 9% of planned projects versus 5% of existing ones), enabling more integrated offshore grids and flexible onshore network reinforcement.
- **Dominant Purposes:** The primary applications driving HVDC deployment remain large-scale energy trading (interconnectors) and the grid connection of major renewable energy zones, particularly offshore wind farms.

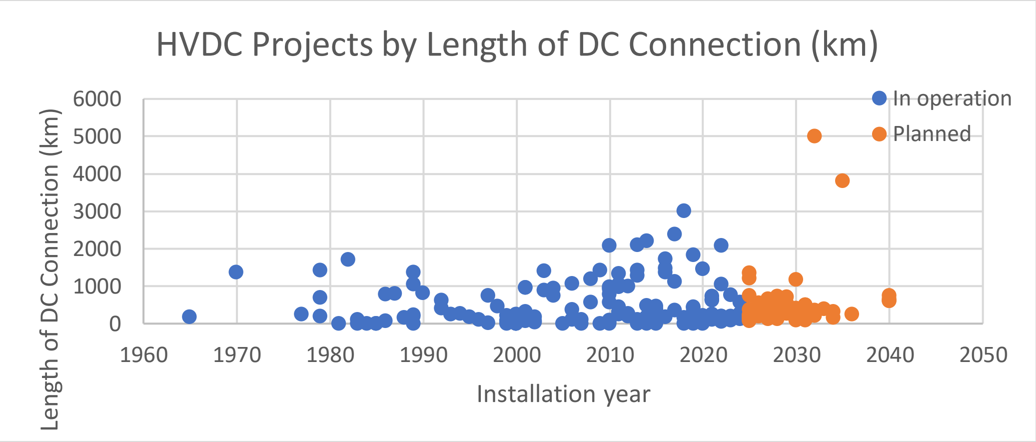

Figure 3 HVDC Project by DC Connection Length

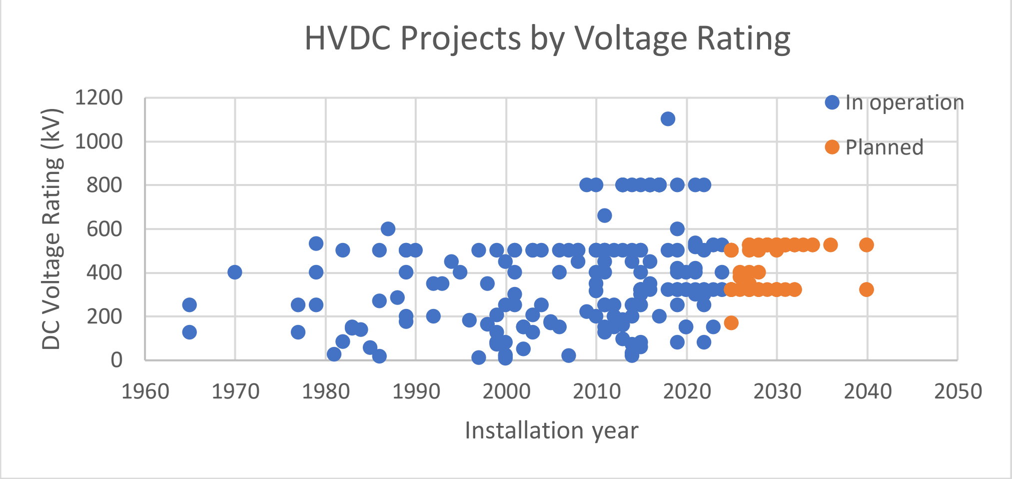

Figure 4 HVDC Project by Voltage Rating

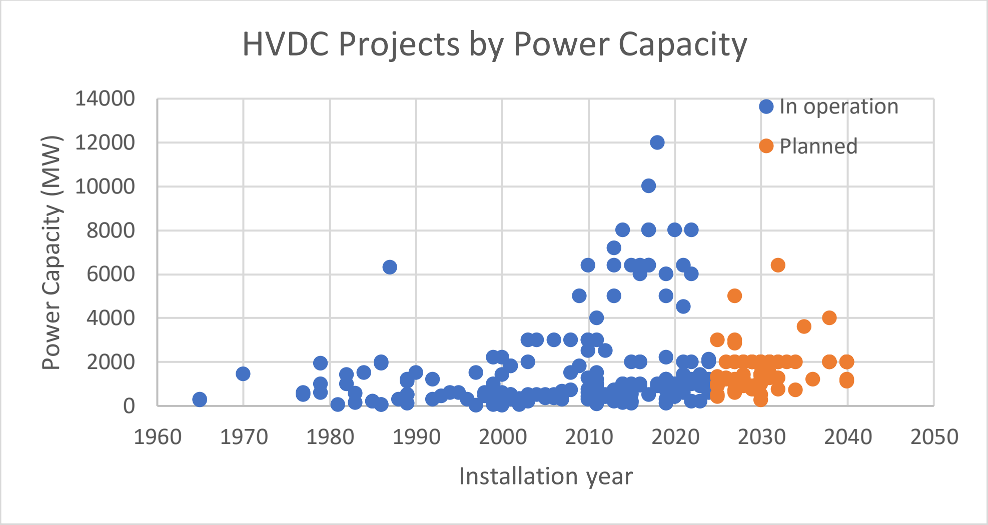

Figure 5 HVDC Project by Power Capacity

HVDC Architectures and Common Designs

The configuration of an HVDC system, encompassing both its internal DC topology and its connection points within the wider AC network, fundamentally influences its operational characteristics and integration potential.

A useful **topology framework**, defined in HVDC-WISE D2.1, classifies HVDC systems based on:

- **DC Network Topology:** Ranging from simple **DC1** (Point-to-Point) links to multi-terminal **DC2** (Radial), **DC3** (Linear), and **DC4** (Meshed) networks. Meshed networks offer multiple power flow paths, enhancing flexibility and potentially redundancy.
- **AC Network Connection:** Categorized by how terminals connect to AC systems: **AC1** (all terminals in separate, asynchronous AC grids), **AC2** (terminals connecting one or two synchronous AC grids alongside separate asynchronous connections like offshore wind), and **AC3** (all terminals connecting within the same synchronous AC grid).

Emerging Common Designs: Common design choices are solidifying for HVDC projects, especially in Europe, influenced by both technical and strategic factors:

- **Converter Technology:** VSC-MMC is standard. While half-bridge submodules are common for efficiency, full-bridge variants offer inherent DC fault-blocking, beneficial for overhead line applications and managing DC fault currents without necessitating DC circuit breakers [37] .

- **Connection Configuration:** Bipoles with a Dedicated Metallic Return (DMR) conductor is increasingly favoured. This configuration enhances availability during faults and helps manage DC stray currents [34] .

- **Voltage and Power Ratings:** In Europe, ±525 kV and 2 GW per bipole are becoming prominent, partly driven by standardized procurement for offshore wind integration and AC grid infeed limits. However, global HVDC ratings vary, with some VSC projects achieving higher capacities and voltages based on different regional needs and technological applications.

These common designs provide a degree of standardization but must be adapted based on specific project requirements and the evolving capabilities of the technology.

System Integration Aspects and Considerations

Integrating large HVDC systems effectively requires careful consideration of their impact on the overall power system operation and planning.

- **Multi-terminal Systems:** While demanding complex control and protection, especially multi-vendor, MTDC systems offer enhanced flexibility and transfer options, with growing deployment experience demonstrating their value.

- **Higher Capacity Links:** Allow efficient bulk power transfer but increase the magnitude of contingencies (N-1 loss) that the AC system must withstand, impacting reserve requirements and potentially AC network stability.

- **Higher Voltages:** Improve transmission efficiency but necessitate careful insulation coordination and management of the higher energy stored in cables during fault conditions.

Different AC/DC topologies present trade-offs: Meshed (DC4) and linear (DC3) offer more redundancy than radial (DC2) or point-to-point (DC1). Embedded connections (AC2, AC3) provide direct AC grid support (stability, congestion relief). However, greater interconnection increases disturbance propagation risks, needing robust coordination and protection.

Reliability and Resilience (R&R) Aspects: Large-scale HVDC integration brings R&R benefits and challenges. While link failures are significant contingencies, and control/cyber risks exist, VSC-HVDC's controllability enhances R&R. Advanced protection (e.g., selective fault clearing) and meshed topologies improve fault containment, acting as a "firewall"; indeed, HVDC links have demonstrated this capability by helping prevent cascading failures in major system disturbances (e.g., North America 2003[38] , Europe 2006 [39]). Balancing cost, complexity, and R&R remains key [40] .

Role of Control & Protection:

- **Control Systems:** The advanced controllability of VSC-HVDC is a major asset. Functions like frequency control, AC voltage support (reactive power), power oscillation damping, AC line emulation, grid-forming control, and black start capability allow HVDC systems to actively contribute to grid stability and operational flexibility. Effective implementation requires careful tuning, coordination (especially in multi-terminal systems), sufficient headroom, reliable communications, and robust cyber security measures [37] , [41] .

- **Protection Systems:** Robust protection is essential for isolating faults rapidly and minimizing system impact. While simple AC breakers can protect basic HVDC links (Non-Selective), MTDC and meshed grids benefit from faster, more selective DC-side protection using technologies like DC Circuit Breakers (DCCBs) or Fault-Blocking Converters (FBCs) to limit fault propagation. The choice between Non-Selective (NS), Partially Selective (PS), and Fully Selective (FS) protection involves trade-offs between cost, complexity, and performance. DC/DC converters and Energy Dissipation Systems (EDS) also play roles in protection and operational stability [42] [43] .

HVDC technology is integral to the ongoing development of power transmission systems globally, facilitating the integration of renewable energy and enhancing grid connectivity [44] . Current trends indicate a move towards higher-capacity, higher-voltage VSC-based systems, frequently employing bipole configurations and increasingly forming multi-terminal and meshed networks. While common designs offer some standardization, the complexity of these systems demands careful consideration of system integration aspects, including impacts on AC grid operation, topology choices, control system capabilities, and protection strategies. Successfully navigating the expansion of hybrid AC/DC grids requires continued technological advancement, robust planning methodologies, and effective coordination to ensure future power systems are efficient, flexible, and reliable.

MVDC grids

Though the rationale of the DC technology in High Voltage (Lower losses in long distance transmission) and Low Voltage applications (DC featured equipment: Computer, Battery, Building, Industry applications such as Electrolysis, EV, Aircraft, etc.) is straightforward, the benefits (considering the Pros and Cons) of DC technology in Medium Voltage applications are still questionable. Economics are driven by multiple and complex parameters that would require more granularity analysis before we could sort out the key performance indicators.

However, we found out some industry pilot projects where the MVDC solution is moving the needles from an attractive solution for AC-DC Hybrid electricity Networks to a cost benefit one. This is the case of DSO coupling application.

Angle-DC

The paper [132] provides an insight of the Europe’s first MVDC link reported as part of Scottish Power Energy Networks’ Angle-DC project between 2016 and 2020. The objective is underlined below: “*ANGLE-DC is an innovative project which aims to demonstrate a smart and flexible method for reinforcing distribution networks by converting Alternating Current (AC) assets for Direct Current (DC) operation. ANGLE-DC will adapt existing power electronic technologies to build a medium voltage DC (MVDC) link which could be an effective solution to facilitate the integration of renewable resources and accommodate future demand growth. ANGLE-DC aims to build the confidence in deploying MVDC technologies by other UK Distribution Network Operators (DNOs) and also trigger the medium voltage DC supply chain*” [131].

The application is a conversion of an existing 33kV AC double circuit to a bipolar +/- 27kV DC circuit. Angle-DC showcases an optimized path (from the risks standpoint) where the combination of innovation spirit and power conversion experience is the key success factor. A much more secured solution could have been a downgrade of well-known HVDC solution. But it would jeopardize the economics of the project. The technology proposed in Angle-DC is a good fit to deliver a best value solution for future dissemination.

See below the network schematics [131]:

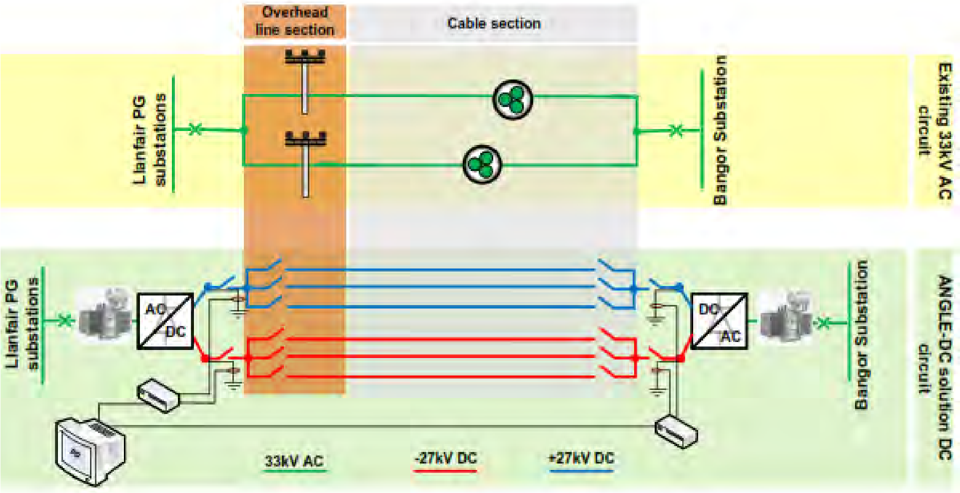

Figure 6: Schematic of the Angle-DC network

See below also the converter Single Line Diagram (SLD) [130]:

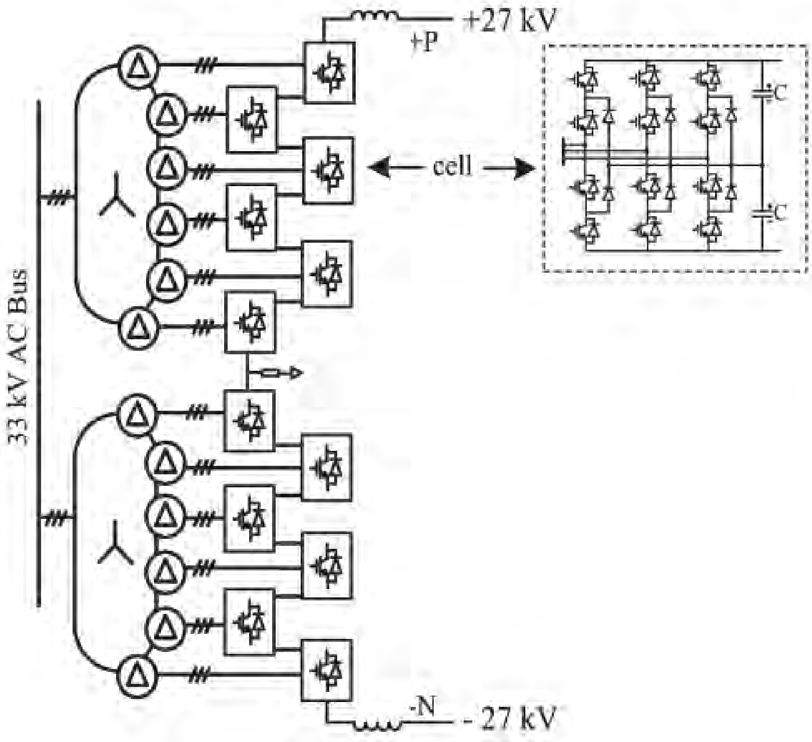

Figure 7: Single line diagram of the converter of the Angle-DC network

Power converters

MMC is a common topology converter for HVDC transmission to withstand high voltages.
The topology of the solution is an MMC like where the usual cell (Full/Half H bridge) is replaced by a full fledge 3L (3 Levels) NPC (Neutral Point Clamped) Inverter.

Twelve off-the-shelf (3 kV, 6 MVA rated) power converters are processing the AC/DC and DC/AC electric conversion. We can notice 3L NPC inverters is an existing AC reliable product using industry well known IGBT (Insulated Gate Bipolar Transistor) components.

Transformers

The star/delta six secondary windings AC transformer is a common industry equipment enhanced by a couple of additional design rules to mitigate the electromagnetic cross-couplings of the multiple windings. Cables are kept unchanged.

Controls

In high power applications a number (N =12) of AC/DC converters can be effectively paralleled and coupled to AC grid via a multi-winding transformer. Coordinated control of 12 converters at each station (current control + dc bus voltage control, current sharing control and voltage balancing) is a typical approach in this design. Further, unexpected interactions have been found in a particular transformer design which has produced high cross coupling of the control loops leading to instabilities if conventional control strategies are used. Hence, a multivariable control approach to stabilize control of dc bus voltage and balancing control loops were implemented.

Lessons learned

The power electronics solution is a combination of industry reliable and well proven technology bricks. Angle-DC showcases incumbent AC electric components could be a good option for DC transmission/distribution projects - provided sizing rules related to DC Physics are correctly implemented. The technical risks (Hardware) of such shift could be mitigated by means of more complex real time control algorithm (Software). As outcome the benefits are striking. Angle-DC pilot showcases how the DC technology could bring additional capacity and value to incumbent AC electric facilities [131] (see Figure 8).

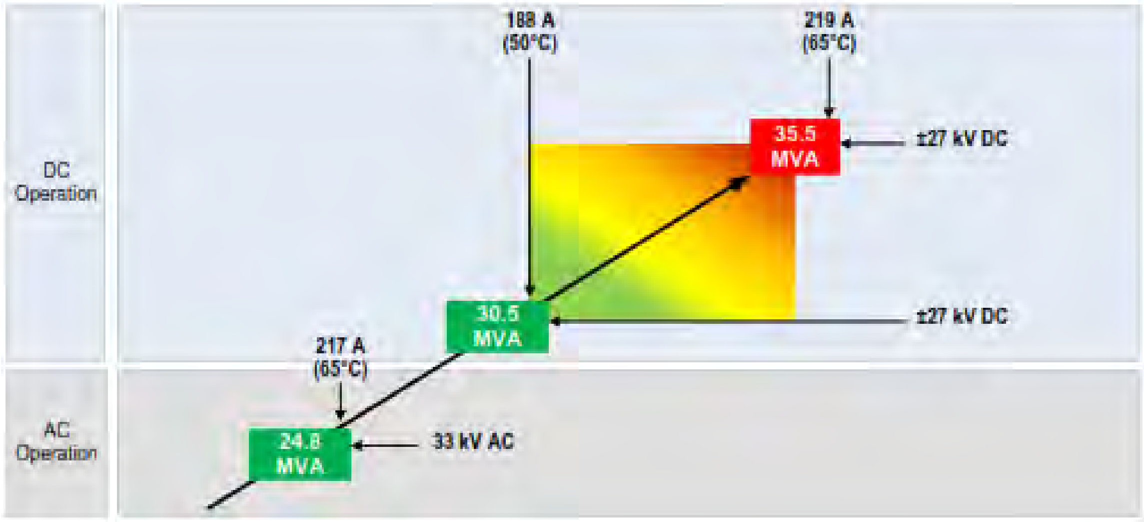

Figure 8: Power transmission increase when shifting from AC to DC technology [131]

A deeper techno-economic oriented analysis considering multiple criteria (ROI, Reliability/Redundancy, Cell technology, ROI, TCO) done by Gyan & Al [130] shows up the rated Voltage and current of the link (regardless of the cable) are two important parameters of the economics of the full solution. As we already suspected customization of the DC solution vs power ratings (applications) is paramount to optimize the economics of the solution. The authors of the study did not mention any specifics of the control though we do believe it is an additional challenge to design a real time calculator and algorithm that keep on control the voltage/current levels and balances of each cell regardless of the zero-sequence current circulating in this complex architecture. We do believe in such kind of project the skills and the know-how of the engineering teams are also paramount to secure the success of the project.

OPHELIA

The paper [132] resents a linear PV power plant based on MVDC collection network realized under the OPHELIA project. The project develops a linear PV power plant of approx. 1 km long and 5 m wide at 1 MWp. The electrical architecture is based on a ±5 kV MVDC collection network. The construction and testing phases are scheduled to take place between 2025 and 2028. The project will also develop the required technologies for long linear PV power plants at 20 MW and above.

The PV requires large areas (approximately 1 ha/MWp) while the available lands are limited. Long linear photovoltaic power plants provide a response to land scarcity, as they help optimize the use of long, narrow land surfaces and structures that have already been designated for other uses (dikes, spaces alongside railways, roads, cycle paths, etc.), leaving natural spaces as they are. The wedges of land in question retain their original use while electricity production becomes a complementary activity. France’s development potential is estimated at approximately 35 GWp.

The linear PV power plants would be only a few meters large but could reach the length of many kilometres and the power up to a few tens of megawatts (roughly 1 MWp/km). The distance between the PV power plant and the available AC grid substation may be up to tens of kilometres. The length of the linear PV power plant and the distance to the AC grid substation present some challenges for the medium voltage AC collection network. A novel network architecture based on medium voltage DC (MVDC) is investigated in OPHELIA project. It is an interesting candidate to reduce power losses, voltage drops, and carbon footprint of linear PV power plants.

Architecture

The electrical architecture of the demonstrator is based on a ±5 kV MVDC collection network (Figure 9). There is one DC-AC converter station and 3 DC-DC converter stations. The connections between converter stations are realised with a radial MVDC network. The target architecture for approx. 20 MW power plants is planned at ±10 kV or higher.

The symmetric monopole line configuration is proposed with a high impedance earthing system localised at the DC-AC converter station. The symmetric monopole allows to minimize the equipment dielectric stress in normal conditions (compared to asymmetric monopole) and to minimize the pole-ground fault current.

Funded by
the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

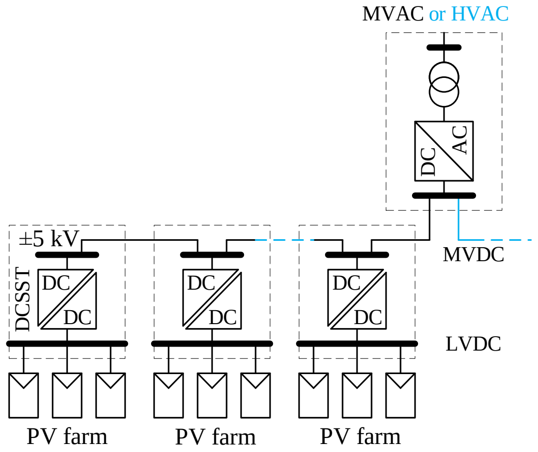

Figure 9: MVDC electrical architecture of the linear PV power plant implemented in the OPHELIA 1 MW demonstrator (black) and planned for multi-megawatt projects (blue).

Control

The MVDC collection network for a PV power plant, like any DC network, requires some controls for the proper operation. The simplest control scheme involves the MVDC network voltage control by the DC-AC converter. The DC-AC converter also controls the reactive power at the connection to the AC grid (there is only one converter to control the reactive power). DC-DC converters ensure the maximum power point tracking (MPPT) of PV strings, and they limit the active power if requested by the utility grid operator. A central controller is implemented managing start/stop sequences and converter setpoints. Network reconfiguration is done thanks to disconnectors located at all nodes.

Protection

The OPHELIA demonstrator uses an unidirectional DC-AC converter which ensures nearly zero short circuit power in the MVDC network, so no DC protection device is required. The target architecture may require a DC circuit breaker and/or DC fuses.

An insulation monitoring device is required for detecting pole-ground faults in MVDC network with high impedance earthing system. The operation of the MVDC network with a single ground fault is possible to maximize the collection network availability.

Surge arresters are recommended for protecting the power converters and other equipment against overvoltage due to lightning impulse, switching or faults.

DC-AC converter

A modular multilevel converter (MMC) seems the best candidate for the target architecture, considering the network voltage and power ratings as well as the DC fault response. The MMC is nowadays the most common and industrially feasible converter topology above ±10 kV (20 kV). The MMC using half-bridge submodules can handle DC faults thanks to bypass thyristor while using relatively cheap flat pack IGBT power modules. The expected efficiency of MMC is 99% or higher.

A transformer is required in the DC-AC converter station. It provides the galvanic separation between AC and DC circuits, and it adjusts the voltage between the MVDC network and the AC grid. It also has a role in converter harmonics filtering and fault current limitation (limited role in case of MMC, compared to 2 and 3-level topologies).

DC-DC converter

The DC-DC converter topologies suitable for PV power plants based on MVDC collection network were reviewed in [133] . The galvanic separation between LV and MV circuits is mandatory. The isolated DC-DC converters (also called DC solid state transformers) provide inherent fault current limitation or blocking, and they can be either bidirectional or unidirectional. Unidirectional step-up DC-DC converter at 250 kW was selected for the PV power plant. The converter power at 250 kW allows to optimize the length of the low voltage PV cables (thus the power losses) and the number of DC-DC converter stations.

The topology selected for OPHELIA project is based on multiple boost MPPT converters and a single isolated phase-shifted full bridge (PSFB) converter. This topology ensures high efficiency over the entire operating range (power and voltage variations), and it is robust to DC faults. The expected efficiency of the PSFB converter is approx. 99% (98.5% for the entire converter, including MPPT). The very high efficiency of DC-DC converters overpasses the efficiency of the state-of-the-art conversion chain composed of PV inverter and step-up transformer. This is possible thanks to zero voltage switching (ZVS) of PSFB topology, silicon carbide (SiC) power semiconductor devices and medium frequency transformer (MFT). The MFT not only allows to reach very high efficiency but also allows to reduce the weight and size, as well as the use of raw materials.

Other MVDC projects

The synthesis of some MVDC projects around the world is presented in the table below.

Table 2: List of MV projects around the world

Projects	Applications	Voltage	Status
Angle-DC	Utility grid	±27 kV	Completed
Jiangdong MVDC	Utility grid	±10 kV	Completed
Flexible DC Power Distribution	Utility grid	±10 kV	Unknown
Guizhou University Demonstration	Utility grid	±10 kV	Completed
Suzhou Industrial Park Pilot Project	Utility grid	±20 kV	Completed
Wenchang project	Utility grid	±10~±15 kV	Completed
KEPCO MVDC station project	PV farm	±35 kV	Unknown
OPHELIA	PV farm	±5 kV	Ongoing
Shanghai Nanhui VSC DC Project	Onshore wind farm	±30 kV	Completed
SCARLET	Offshore wind farm	±50 kV	Ongoing
Anhui Lu'an Jinzhai DC distribution	RES+BESS	1.5 kV	Completed
ABB Lithium-ion BESS	BESS	11 kV	Completed
MVDC Project of Beijing	RES+BESS	±10 kV	Completed
E-FAN X flight	Aircraft	3 kV	Cancelled
NASA N3-X	Aircraft	±5 kV	Ongoing
Tangjia Bay MVDC distribution	Utility grid	±10 kV	Completed

LVDC grids

The increasing integration of renewable energy sources (RES), the proliferation of DC-based loads (e.g., electric vehicles, LED lighting, and consumer electronics), and the global push for energy efficiency have fuelled a renewed interest in Low Voltage Direct Current (LVDC) systems. LVDC microgrids, particularly, have emerged as an efficient alternative to traditional AC systems for distributed generation and localized energy consumption. These systems are especially well-suited for applications where generation and load are both naturally DC, reducing the need for conversion and associated losses.

A notable real-world implementation of an LVDC system is a pioneering research site in Finland [45] , aiming to demonstrate how LVDC can be integrated within a utility-operated network, replacing conventional medium-voltage (MV) and 400 V low-voltage AC lines, particularly in rural sites with long distances. The Finnish LVDC system encompasses a bipolar 750 V unearthed DC network. This configuration significantly enhances transmission capacity and improves voltage quality control at the customer level via Customer-End Inverters (CEIs). One of the project's key innovations is the transition from a half-controlled thyristor bridge rectifier to a commercial PWM rectifier, which facilitates bidirectional power flow and integration with future battery energy storage systems. This research site is not only a functional distribution network but also a test platform equipped with remote supervision, web-based monitoring, and high-resolution data acquisition.

In[46] it is presented the design, implementation, and operation of a hybrid AC/DC microgrid located at CEDER-CIEMAT in Spain. This microgrid serves as a real-life demonstration site within the European TIGON project, funded by the Horizon 2020 program. The aim is to showcase the technical and operational potential of DC grids. Under the scope of this project, it is recognized the primary motivations for using DC grids is the increase in energy efficiency, being highlighted that by avoiding multiple AC/DC conversions—common in traditional AC systems integrating renewables and batteries—significant energy losses can be reduced. The TIGON microgrid is a hybrid AC/DC system, which brings challenges in coordinating power flow between the two domains. Interoperability is key to ensure smooth operation across both AC and DC sections. The microgrid operates at two DC voltage levels: Medium Voltage DC (MVDC) for wide power distribution, and Low Voltage DC (LVDC) for local connections. The CE.D.E.R. microgrid introduces MVDC network, established using a solid-state transformer (SST) that converts energy from the existing AC medium voltage network. This MVDC grid is connected to a lead-acid battery bank and feeds into a low voltage DC (LVDC) grid through DC/DC converters. The LVDC network integrates renewable generation sources such as photovoltaic panels and small wind turbines, along with lithium iron phosphate (LFP) batteries for additional storage capacity.

The core goal of the project is to ensure that the developed solutions are modular and replicable. The system is designed to be adaptable for other contexts, such as rural electrification, smart urban grids, or island systems. This makes the TIGON microgrid a testbed for wider adoption of DC technologies in the energy transition.

In the residential and commercial sector, projects in countries such as the USA, Japan, Germany, and China have demonstrated the viability of LVDC networks in homes and office buildings [47] . Examples include the University of California prototype house and NTT buildings in Japan, which utilize 380 V DC for PV integration and battery storage. Similarly, the Fraunhofer IISB building in Germany uses a hybrid AC/DC architecture integrating solar, batteries, and EVs.

For rural electrification, LVDC has proven especially promising. Projects like the Ruksibhanjyang village in Nepal and several installations in India and Tunisia use off-grid LVDC systems powered by solar PV and batteries to bring electricity to remote areas. On Flinders Island in Australia, a hybrid off-grid LVDC system integrates renewables for community-scale energy independence.

In the industrial and institutional domains, data centres such as IBM's LVDC facility in Sweden benefit from the efficiency and reliability of DC systems. Educational institutions like the Illinois Institute of Technology also operate smart LVDC testbeds to support microgrid research and innovation.

These LVDC microgrids are deployed with a diverse set of technical and socio-economic objectives. These include improving energy efficiency by reducing conversion losses, enabling seamless integration of DC renewable sources and loads, enhancing energy access in off-grid and underserved communities, and increasing system reliability and resilience. Additional goals involve supporting energy autonomy at the community and building levels and reducing greenhouse gas emissions through local clean energy utilization.

LVDC systems have delivered significant achievements in both technical performance and socio-economic impact. From an efficiency standpoint, energy savings ranging from 10 to 30 percent have been reported, primarily due to the avoidance of multiple AC/DC and DC/AC conversions. LVDC distribution lines have been shown to carry between 2.2 and 3.9 times more power than their AC counterparts, allowing for thinner and less expensive conductors.

LVDC microgrids demonstrate high modularity and scalability. They can operate in grid-connected, islanded, or partially connected modes, offering flexibility in control and adaptability to diverse user needs. Economically, commercial projects have demonstrated favourable return on investment periods, such as seven years for certain commercial buildings. In rural settings, LVDC systems provide a cost-effective approach to electrification, especially when paired with energy-efficient DC appliances.

Standardization efforts are underway. According to CurrentOS foundation[48] preferred voltage levels for LVDC systems are converging around 48 V, 350V and 700 V for high power applications. Bus and ring topologies are the most common due to their simplicity and reliability. Technological advancements in DC circuit breakers, grounding methods, and protection systems have further supported the growth and safety of these networks.

The current landscape of LVDC projects and research indicates that these systems are both technically and economically viable. They offer superior efficiency, integration capabilities for renewables and storage, and flexibility in configuration. LVDC networks are especially suitable for applications where both generation and consumption are DC, such as solar-powered homes, data centres, and EV charging systems.

Off-grid LVDC systems represent a transformative solution for remote and underserved regions, facilitating clean and reliable energy access. Despite these advantages, several challenges remain. These include the lack of harmonized standards, higher upfront costs, and limited awareness among planners and stakeholders.

2.3.2 Relevant research projects

Table 3 List of EU funded research projects for HV/MV/LV DC grids

Projects	Applications	Voltage	Status
HYPERRIDE	DC grid protection	MV	Completed

TIGON	DC-based hybrid grids	MV	Ongoing
READY4DC	Interoperability in multi-terminal multi-vendor HVDC	HV	Completed
SCAARLET	Superconducting cables for MVDC	MV	Ongoing
HVDC-WISE	Resilience of the grid	HV	Ongoing
SiC4GRID	RES integration	HV/MV	Ongoing
NEWGEN	RES integration	HV	Ongoing
AdvanSiC	Cost-effective power electronics	MV	Ongoing
FOR2ENSICS	Energy storage and RES integration	MV	Ongoing
InterOPERA	Interoperability of multi-vendor HVDC grids	HV	Ongoing
SHIFT2DC	DC technology for MV/LV loads	MV/LV	Ongoing
MISSION	SF6 switchgear for MVDC grids	MV	Ongoing

1. Hyperride[4]

HYPERRIDE THE FUTURE OF POWER DISTRIBUTION	***Hybrid Provision of Energy based on Reliability and Resiliency by Integration of DC Equipment***

From 8/2020 to 31/3/2025

The HYPERRIDE project aims to enhance energy distribution efficiency and resilience by implementing **DC and hybrid AC/DC grids**.

Key objectives include:

- Technological advancements in DC **grid components:**
  Key technologies for
  - **DC grid protection (MVDC circuit breakers)** and
  - **grid automation (MVDC sensors, DC measurement unit)** will be developed further, and
  - **automation algorithms** will be created, validated in a test platform and transferred towards demonstration.
  - This also involves concepts and solutions for **cyber security** and **fault detection**.
- Development of **grid guidelines**

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[4] https://hyperride.eu/

- Resilience enhancement through **fault mitigation** and **cybersecurity solutions**, and **renewable energy integration**.
- Demonstrations in in three countries (Aachen - Germany, Lausanne - Switzerland and Terni - Italy) validate the technologies, with outcomes including
    - **improved grid reliability**,
    - **increased renewable energy** penetration, and
    - **development of business models** for new products/services.

Key exploitable results and sub-key exploitable results achieved to date

- Development of **MVDC circuit breakers and sensors** for grid automation and protection.
- Adaptation of **sizing tools for DC grids** to facilitate grid planning. Creation of **automation algorithms** for efficient grid operation.
- Demonstration of **field-ready devices** in demo sites. **Evaluation of integration potential** of renewables and assessment of benefits.
- **Creation of business models** for products, services, and applications.
- Development of an **open ICT platform** for interoperability.
- **Establishment of a data repository** for reliability information.
- Demonstration **of fault management** and **cybersecurity** solutions.
- Compilation of **recommendations for standardization and regulation bodies.**

2. TIGON[5]

TIGON	***Towards Intelligent DC-based hybrid Grids Optimizing the network performance***

From 9/2020 to 8/2025

DC grids are being more appealing the last years due to, the high proliferation of RES and also the increased DC loads. TIGON project focuses on a smooth deployment and integration of **intelligent DC-based grid architectures** within the current energy system, while providing ancillary services to the main network.

TIGON proposes a **four-level approach aiming at improving (1) Reliability, (2) Resilience (3) Performance, and (4) Cost Efficiency** of hybrid grids through the development of an innovative portfolio of power electronic solutions and software systems and tools focused on the efficient monitoring, control and management of DC grids.

A **modular concept of DC-based grid** topology is proposed consisting of a **MVDC line** connecting the main grid with the LV hybrid grid. grid. Under this concept, TIGON demonstrators will integrate more efficiently distributed RES, energy storage and a variety of loads including EVs.

TIGON’s innovations include:

- the Solid-State Transformer (SST),
- the integration of novel typologies of high efficiency (SiC WBG) DC/DC converters. These converters will make possible
- the direct connection of the MV network to
    - novel topologies of PV plants (French demo-site) and
    - battery storage systems (Spanish demo-site).

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[5] https://tigon-project.eu/

- DC Protection schemes will be complemented by the implementation of a WAMPAC system and TIGON will make use of the results obtained and the characteristics of the solutions and grids under analysis for the development of a DSS.
- Smart EMS able to control in a centralized manner the hybrid micro-grid.
- Cybersecurity Defence System.

3. READY4DC[6]

READY4DC	***Getting ready for multi-vendor and multi-terminal DC technology***

From 01/04/2022 to 31/10/2023

READY4DC aims to face the **challenges in interoperability** (when we consider networks with multi-vendors) that come with DC grid technology. READY4DC will create the right conditions to establish a community of experts that will discuss all the implications of the offshore wind farms both from **a technical and a legal perspective**. Thanks to the work of a set of working groups with open participation, that will develop **targeted white papers** consolidating the perspectives and views of all relevant sectors on the various technical, long-term planning and legal aspects. The results will target both the offshore and onshore use cases, overall, the application of **power electronics-driven grids** at every voltage level and will set the stepping stone towards a futuristic **grid infrastructure with DC grids playing a central role** at every voltage level.

READY4DC focuses on the growing role of **multiterminal multi-vendor (MTMV) HVDC** solutions within the current AC transmission networks both onshore and offshore. This project aims at 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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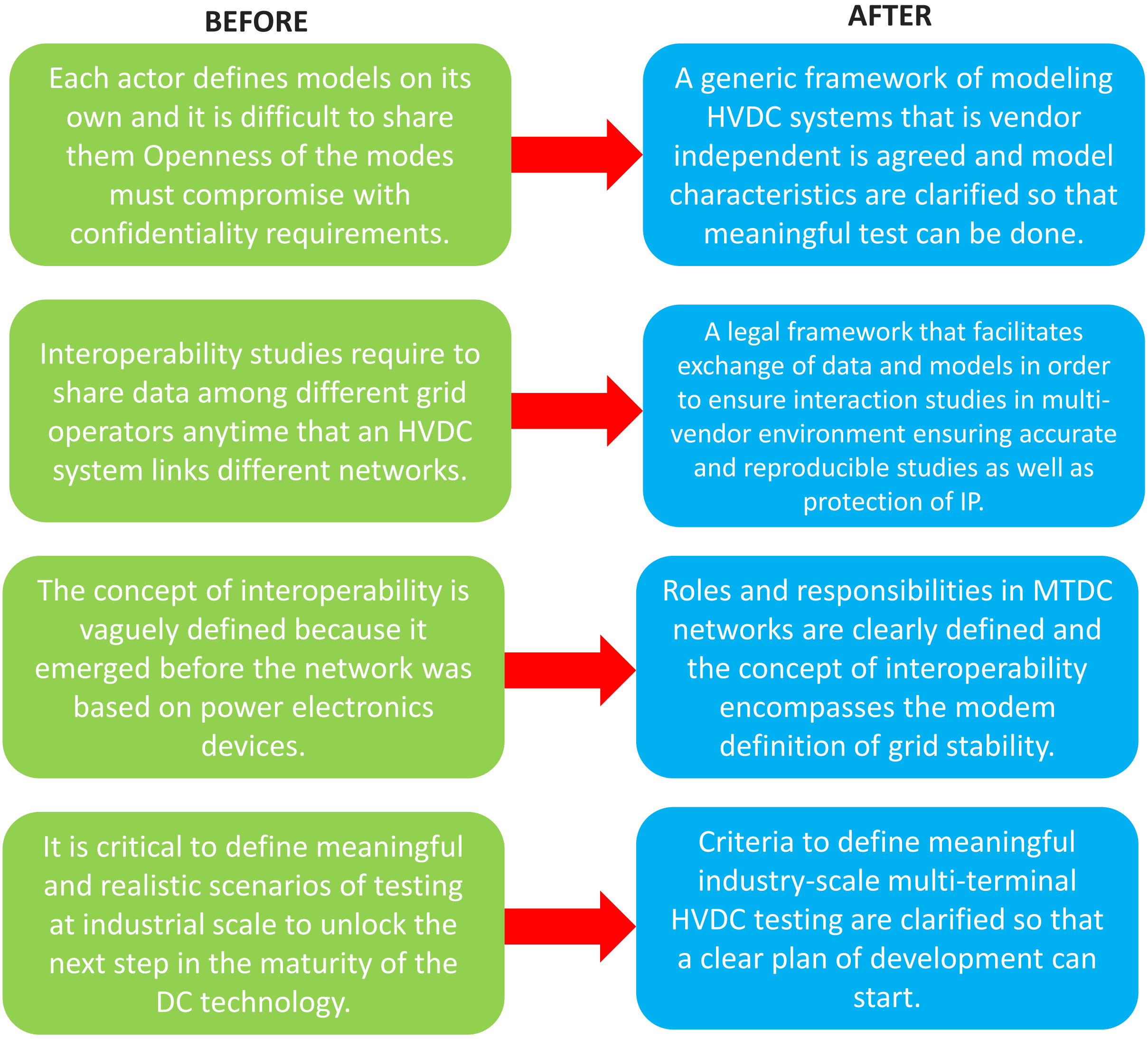
[6] https://ready4dc.eu/



BEFORE	AFTER
Each actor defines models on its own and it is difficult to share them Openness of the modes must compromise with confidentiality requirements.	A generic framework of modeling HVDC systems that is vendor independent is agreed and model characteristics are clarified so that meaningful test can be done.
Interoperability studies require to share data among different grid operators anytime that an HVDC system links different networks.	A legal framework that facilitates exchange of data and models in order to ensure interaction studies in multi-vendor environment ensuring accurate and reproducible studies as well as protection of IP.
The concept of interoperability is vaguely defined because it emerged before the network was based on power electronics devices.	Roles and responsibilities in MTDC networks are clearly defined and the concept of interoperability encompasses the modem definition of grid stability.
It is critical to define meaningful and realistic scenarios of testing at industrial scale to unlock the next step in the maturity of the DC technology.	Criteria to define meaningful industry-scale multi-terminal HVDC testing are clarified so that a clear plan of development can start.

Figure 10: READY4DC Framework for model sharing platforms

4. SCARLET[7]

SCARLET	***Superconducting cables for sustainable energy transition***

From 9/2022 to 2/2027

SCARLET focuses on developing **superconducting cables** for high-power transmission from remote renewable energy sites to existing grids at low cost, utilizing HTS and MgB2 materials. Operating under **DC conditions at medium voltages**, these cables **eliminate the need for costly converter** stations, leading to significant cost reductions. SCARLET aims to industrialize these cables for **multi-kilometre lengths** and demonstrate their **effectiveness**.

Onshore HTS cables offer a **compact design**, preserving the environment and minimizing land use. Offshore HTS cables **reduce costs** and eliminate the need for large converter stations. MgB2 cables, paired with liquid hydrogen transport, **introduce a dual-energy approach**. Both **HTS** and **MgB2 MVDC** cables will be developed and tested, along with fault current limiters, aiming to reduce LCOE for

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[7] https://scarlet-project.eu/

offshore windfarms by 30%, lower total costs by 15%, enable simultaneous transfer of 0.5 GW H2 and 1 GW electric energy with cables of 90 GW transmission capacity.

Expected key exploitable results of the project:

- Onshore MV HTS cable connection of renewable production and interconnection.
- Export MV HTS cable for offshore wind farms.
- MV HTS cable for offshore applications (offshore generation export, interconnector, hybrid solutions).
- Cryogenic systems for MgB2 cables.
- Cryogenic cooler for reliquefication of LH2 storage.
- Cryogenic cooler systems for MV HTS cables and SFCL.
- MgB2 cables for combined electricity transmission and LH2 transport systems.
- Flexible cryogenic transfer line for LH2.
- Electromagnetic transient (EMT) simulation models Electrical system methodology and techno-economic models.
- FCL module demonstrator.
- Current leads from ambient to 2 K on high voltage.
- Health and safety analysis for operation of a superconducting cable system in LH2.

5. HVDC-WISE[8]

HVDC-WISE	***HVDC-based grid architectures for reliable and resilient WIdeSprEad hybrid AC/DC transmission systems***

From 10/2022 to 3/2026

The European Commission considers **that massive offshore wind power** is needed by 2050 and **HVDC grid technologies** are a key enabler in fulfilling Europe’s low-carbon energy ambition. **HVDC** grid is has many advantages over HVAC on **power transfer over long distances**.

The **HVDC-WISE project** will propose a number of reliable and resilient HVDC grid configurations that will lay the groundwork for a future integrated EU-GB transmission system.

Aligned with European objectives HVDC-WISE aims to **optimize energy resource utilization**, promote the **transition to renewable sources**, improve **system efficiency**, and ensure equitable and inclusive **access to energy**.

HVDC-WISE addresses the challenge of **modernizing electrical grids** by leveraging **HVDC technology** for enhanced **resilience and reliability**. Key components like **HVDC systems** and **advanced control algorithms** contribute to achieving project goals by enhancing grid resilience and reliability.

Expected key exploitable results of the project:

- Development of **reliability-&-resilience-oriented planning toolset**.
- **Library of standardized models of HVDC** technologies.
- Proposition and **assessment of HVDC-based grid architecture** concepts.
- Identification, modelling, and **assessment of emerging technologies for HVDC-based grid architectures**.

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[8] https://hvdc-wise.eu/

- **Validation** of resilience-oriented **planning toolset** and **HVDC-based grid architecture concepts in industrially relevant environment**: **Realistic use cases** representing different regions of Europe, each with specific challenges.

Specific achievements of the project:

- The project will test its approaches on a specific **GB replica of the third Eastern HVDC reinforcement** between Scotland and England.
- Within this solution, together with potential island connections and **an embedded HVDC connection transmitting the power along GBs’ eastern coastline, access of up to 5.2 GW of renewable energy could be enabled**.
- More **demonstration cases** based in continental Europe will be **created and tested** using advanced simulation modelling.
- **Market simulations** will be performed to derive time series of dispatches of generation, flexible demand, and interconnector transfers.
- **Dynamic assessments** will be conducted to test firewall capabilities and the benefits of differently configured HVDC systems.
- Lessons will be drawn on **which parameters significantly impact the obtained grid configurations** as well as how regulatory frameworks impact the integration of renewable energies.

6. SiC4GRID[9]

SiC GRiD	***Next Generation Modular SiC-Based Advanced Power Electronics Converters for Enhanced Renewables Integration into the Grid***

From 10/2022 to 3/2026

The overall concept of SiC4GRID is to **develop a fully integrated technological and digital SiC-based converter** with higher energy-efficiency, enhanced cost reduction and improved eco-design. SiC4GRID innovations will foster the **commercialisation of SiC semiconductors** and increase the overall efficiency and grid integration of renewable energy systems.

The main objective of SiC4GRID is to develop innovative eco-designed energy-efficient **SiC-based semiconductors that are 30% cheaper, 15% smaller, and have a lifespan of 30+ years**. SiC4GRID aims at validating its solutions for both onshore and offshore **HVDC/MVDC converter applications**.

The project aims to **optimize the semiconductors** based on physical and digital approach for industrial applications and reduce the environmental impact by **reducing CO2 emissions** and the **use of resources** by **50%** and 3**0%** respectively.

The project is driven by innovations in hardware, software, and IoT, and its ultimate goal is to **bring European leadership to the forefront of converter technology** providers for the integration of renewable energies into the energy grid.

Main Objectives:

- Develop cost-effective innovative **3.3kV SiC-based power modules**

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[9] https://sic4grid.eu/

- Develop reliable **digital tools for SiC-based converter** modelling and prediction optimization
- **Integrate the SiC-based converter** with tailored IoT architecture for **HVDC-MVDC** applications
- **Validate SiC4GRID’s technologies** through 3 use cases of WBG SiC-based switching semiconductor converter
- Improve the **environmental and techno-economic viability** of the WBG SiC-based converters

Expected Impacts:

- **Production, test and validation of WBG-based switching semiconductors** such as Silicon Carbide (SiC) for **HVDC – MVDC converter applications** in converter stations
- **Reduced size of components** and equipment for offshore / onshore applications
- **Reduced cost of WBG-based semiconductors** such as Silicon Carbide (SiC)

7. NEWGEN[10]

NEWGEN	***New generation of HVDC insulation materials, cables and systems***

From 10/2022 to 9/2026

NEWGEN contributes to the European Green Deal **by enabling the long-distance transmission** of electricity **from renewable energy sources** with **minimal losses** and increased reliability.

The project also supports the **digitalisation** of the energy system by developing online **monitoring and modelling tools for HVDC cable systems**.

The project also considers the **sustainability and circular economy** aspects of the new materials and technologies, as well as the social and economic impacts of the **HVDC cable systems**.

Main challenges:

- **space charge accumulation** and **ageing** phenomena in **HVDC cable** insulation;
- **defect detection** and pre-fault monitoring of **HVDC cable** systems;
- life and reliability **estimation and optimization of HVDC cable** systems under various working stresses; and
- firewall **capability and resilience** of **HVDC cable links** in **hybrid AC/DC** transmission grids.

Main innovations:

- molecularly defined and sustainable **space charge mitigating additives for PP- and XLPE-based HVDC cable** insulation matrices;
- new **HVDC cable extrusion equipment** and process solutions for thermoplastic insulations;
- a **novel leakage current measurement technique** and an online global **monitoring system for HVDC cable** systems; and
- a comprehensive **life and reliability model for HVDC cable**.

8. AdvanSiC[11]

AdvanSiC	***Advances in Cost-Effective HV SiC Power Devices***

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[10] https://www.newgen-project.eu/

[11] https://advansic-euproject.eu/

	for Europe's Medium Voltage Grids

From 1/2023 to 12/2025

The AdvanSiC project focuses on developing **cost-effective High-Voltage (HV) Silicon Carbide (SiC) MOSFET semiconductors for Medium Voltage (MV)** grids. The aim is to minimize **HV SiC device cost** by advancing novel design structures and process optimization. Beyond this, AdvanSiC shall assure an **immune and reliable environment** to handle SiC fast transients, as well as **optimize passives and cooling system** to provide cost reduction not only at device level but also at system level. The project aims to demonstrate **cost savings, reliability improvements, and system-level benefits** of HV SiC devices in **wind and solar power converters**, and **DC circuit breakers**.

The project aims to:

- Reduce the overall cost of epitaxy.
- Design a 3.3 kV SiC MOSFET chip with high performance and reduced costs.
- Optimize the development process of HV power modules.
- Ensure a reduced size, immune, and reliable HV SiC-based power stack.
- Demonstrate the benefits of HV SiC MOSFETs in full-scale laboratory prototypes.
- Quantify the techno-economic benefits of HV SiC MOSFETs in grid applications.

Expected key exploitable results of the project

- Cost-effective HV SiC MOSFET semiconductors optimized for MV grids.
- Improved system reliability for handling SiC fast transients.
- Enhanced passive components and cooling systems for increased efficiency and performance.
- Techno-economic benefits demonstrating cost savings and performance advantages.
- Market growth opportunities in the SiC semiconductor industry.

9. FOR2ENSICS[12]

	Future Oriented Renewable and Reliable Energy SIC Solutions

From 1/2023 to 12/2026

The project will develop **innovative energy storage solutions**, integrate renewable energy sources, and enhance grid flexibility. It will **integrate renewable energy sources** into the grid by developing efficient **DC/DC converters** for low to medium voltage. Key objectives include **designing converters using silicon carbide (SiC)** based ultra-high voltage switching devices and **implementing low-cost production** processes. Methodology involves **theoretical design**, **SiC device fabrication**, and **converter testing**. SiC devices offer higher efficiency and reliability compared to traditional silicon-based converters.

The project's uniqueness relies on developing innovative **SiC-based converters** that enable seamless integration of renewable energy sources into the grid.

Key exploitable results and sub-key exploitable results **achieved to date**:

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[12] https://for2ensics.imb-cnm.csic.es/

- Development of **ultra-high voltage SiC-based switching devices for MVDC and DC/DC** applications.
- Progress made in the production processes for **efficient, low-cost, compact DC/DC converters for LV (<1500V) to MV (>10kV)**.
- Preliminary **testing and validation of commercial DC/DC converter** prototype underway.
- Exploration of **cost reduction strategies** and **environmental impact** mitigation in fabrication processes.
- Ongoing **research on increased efficiency, lower volume, reduced weight, longer product lifetime** of power electronics systems ongoing.
- Investigation into **novel system topologies** and applications **leveraging UHV SiC** devices in progress.
- Initial studies on **higher reliability due to reduced number of components** and easier cooling for power cycling conditions underway.

10. InterOPERA[13]

Inter OPERA	***Enabling Interoperability of multi-vendor HVDC grids***

From 1/2023 to 4/2027

InterOPERA aims to enable **interoperability of multi-vendor HVDC grids** for offshore wind integration. It focuses on **standardizing HVDC systems**, facilitating collaboration among industry leaders, and providing policy recommendations. Ensuring that HVDC systems, HVDC transmission systems or HVDC **components from different suppliers can work together** – making them “interoperable”- is a top priority to accelerate Europe’s energy transition.

Key objectives include defining **demonstrator case studies**, de-risking **interoperability issues**, and establishing **modular approaches to HVDC projects**. Measurable outcomes include **detailed functional specifications**, **simulation platforms**, and **cooperation** agreements, leading to cost-effective solutions and wider adoption of HVDC technology. Its approach differs by **coordinating diverse industry** stakeholders, fostering **collaboration among HVDC vendors**, **TSOs**, and wind turbine **developers** accelerating the development of a sustainable European HVDC grid.

Key components like **HVDC systems, protection, and network management tools** contribute to achieving seamless **integration, scalability, and grid resilience**.
Technological impacts:

- Development and dissemination of new interoperability standards.
- Advancement of grid-forming capabilities for HVDC systems.
- Integration of distributed energy resources into the grid.

Key exploitable results and sub-key exploitable results achieved to date

- Development of standardized functional specifications for multi-vendor HVDC grids
- Establishment of standardized models and simulation platforms for interoperable HVDC systems
- Initiation of cooperation agreements facilitating multi-vendor collaboration
- Early-stage progress on interoperability assessment tools for HVDC grid development
- Preliminary guidance for offshore network planning

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[13] https://interopera.eu/

- Initial development of operational and strategic tools for multi-terminal HVDC grid deployment

11. SHIFT2DC[14]

Shift2DC	***SHIFT to Direct Current***

From 12/2023 to 12/2026

SHIFT2DC aims to design, simulate, and implement MV and LV DC solutions across Europe.
The project **evaluates technical feasibility, cost-effectiveness, and environmental impact** in data centres, buildings, industries, and ports.
It will also assess **consumer attitudes towards DC solutions** and develop tools to encourage their **adoption**. Despite Direct Current's benefits, including savings on materials and improved system controllability, technical, regulatory, and **standardization challenges** hinder its widespread adoption. Addressing these, particularly the need for **advanced control algorithms, protection designs, and simulation tools**, is critical for DC's future.

SHIFT2DC innovates DC grid technology, focusing on low-voltage areas. It aims to harmonize **converter controls, enhance fault protection, and utilize durable insulation materials** to ensure stable DC operation. The project will develop **open-source design** tools, living labs for real-time **testing**, sustainable DC **cabling**, and **control algorithms** for efficient DC integration. It will also propose **new DC/DC converter technologies** for renewables and storage, **design power flow control for DC and hybrid grids**, and perform environmental and **feasibility studies**. Solutions will be tested in **key sectors and across European demonstrators**, with **regulatory** insight and **standardization** efforts integral to its strategy.

Table 4 Expected key exploitable results of the project Shift2DC

• Pre-qualification of DC solution procedure. • Participation in Grid and system services. • Energy hubs Management. • Sustainable and smart DC Cable. • Micro Solar DC Systems and Partial Power Processing. • Smart PDU High Density V2X DC stations. • LVAC-LVDC Interlink converter /Static protection System. • LVDC measurement device and DC connector. • Fast-response control technologies.	• Multisocket-Smart Power Distribution Unit. • Passive cooling system. • Sharing Voltage control approach. • EMS tool for AC/DC Hybrid Systems. • DC Solutions Design tool. • DC Solutions simulation tool. • DC Protection & Stability Assessment tool. • DC Challenges and opportunities. • DC simulation tools and algorithms. • LV living lab for testing solutions. • Industrial DC grid demonstrator. • DC data centre demonstration. • Data Exploitation.

12. MISSION[15]

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[14] https://cordis.europa.eu/project/id/101136131

[15] https://cordis.europa.eu/project/id/101135484

MISSION	***eMISsion-free HV and MV transmission switchgear for AC and DC***

From 1/2024 to 12/2026

The **SF6** filling the MVAC and HVAC switchgear is the world's most potent GHG.

The objective of MISSION project is to **develop and demonstrate three SF6-free products** as key-levers for climate neutral power transmission based on the requirements defined by TSOs, filling critical gaps in future **hybrid ACDC grids.**

- **SF6-free HVAC circuit breaker** will be developed and type tested by Siemens Energy and installed and demonstrated by Statnett in Norway and RTE in France reaching TRL 8,
- **SF6-free HVDC GIS** will be developed and type tested by Siemens Energy in Germany reaching TRL 8,
- **MVDC circuit breaker** will be developed and tested in relevant environment by G&W reaching TRL 6.
- In addition, MISSION will **determine technical properties of different SF6-alternatives** for application in AC and DC switchgear for high and medium voltage operation.

MISSION will provide full LCA of the new technologies, not only to include the **impact from SF6 reductions**, but also take into account the **positive and negative consequences of raw materials** and the use of the switchgear from cradle to grave.

MISSION's vacuum circuit breaker will contribute to the **replacement of existing SF6-based** switchgear and avoid new installations. MISSION will deliver a **compact, reliable, and cost-effective MVDC breaker** design for these applications. Its configuration **permits its integration in medium voltage DC grids**. With the **HVDC GIS developed in MISSION**, the footprint of the offshore platforms for collecting and exporting energy from offshore wind can be significantly reduced compared to conventional air-insulated switchgear. This adds to the already significant GHG reductions from the SF6-free GIS itself.

Expected key exploitable results of the project

- 42 kV AC air-insulated live-tank vacuum circuit breaker.
- 55 kV HVDC gas-insulated switchgear.
- 12 kV MVDC air insulated circuit breaker.

3. Boundary Conditions for Hybrid AC/DC Grids

3.1 Definition of Boundary Conditions

Boundary conditions in hybrid AC/DC grids refer to the fundamental limits and non-negotiable constraints dictated by the nature of AC and DC systems and by external requirements. A key example is the need for frequency synchronization in AC networks – **all interconnected AC systems must maintain a common nominal frequency (50 or 60 Hz), whereas DC networks have no frequency** at all. This inherent difference means that when AC and DC networks are coupled, the DC side does not inherently share a frequency and must interface through converters that impose and regulate an AC frequency on the DC link to maintain synchronization with the AC grid. Additionally, AC and DC differ in reactive power behaviour: **AC grids continuously manage reactive power flow and voltage through synchronous machines or compensators, while DC grids have no reactive power circulation by nature**. Hybrid AC/DC systems must accommodate this by ensuring the AC side meets reactive power needs and by using power-electronic converters to manage voltage conversion and support, effectively bridging the gap between AC and DC operational parameters [49] [50] .

Another intrinsic boundary condition is the **disparity in fault characteristics between AC and DC** systems. AC faults benefit from natural current zero-crossings every half-cycle, which help conventional AC circuit breakers interrupt fault currents; in contrast, DC faults lack any zero-crossing point, causing fault currents to rise rapidly and making interruption far more challenging. As a result, traditional AC protection devices cannot be directly applied on DC lines, and specialized DC circuit breakers or fault-clearing strategies are required to handle DC faults. **Grounding practices** also differ – DC systems often use different grounding/reference schemes, and the absence of zero-crossing combined with those differences poses protection coordination issues in a hybrid grid. Furthermore, hybrid grids tend to have lower overall inertia because power-electronic converters decouple generator rotating mass from the system; high renewable penetration and DC links yield a low-inertia environment where frequency is less damp and can deviate more quickly during disturbances. All these factors – from frequency synchronization and reactive power support to fault clearing and inertia – act as fixed boundary conditions that TSOs and DSOs must account for to ensure stable hybrid AC/DC grid operation. They define the operational limits within which the hybrid system must be designed and controlled [51]

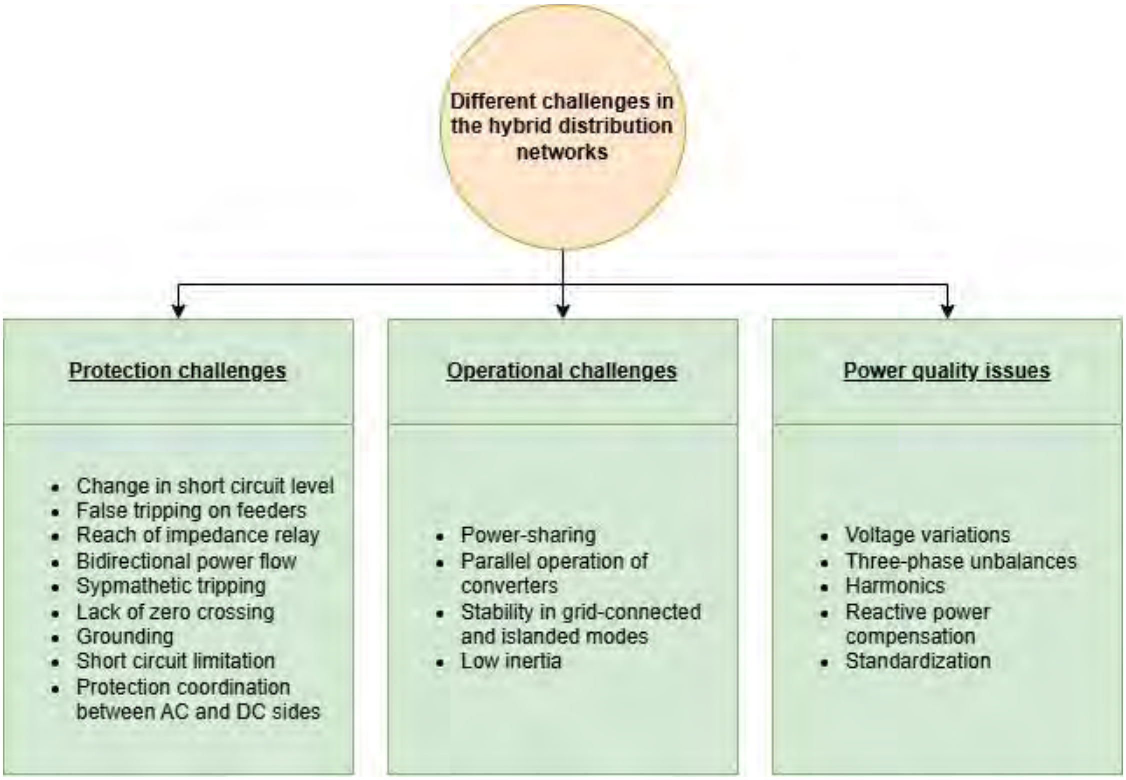

Figure 11: Challenges in hybrid AC/DC distribution networks[49]

3.2 Technical boundaries

3.2.1 Voltage and Frequency Coordination:

In a hybrid AC/DC grid, maintaining consistent voltage levels and frequency across the AC and DC domains is a critical technical boundary. The AC sub-grid must uphold its nominal frequency while the DC sub-grid maintains its voltage within design limits; when they are interconnected through converters, any power imbalance will affect both AC frequency and DC voltage. The interlinking converter (ILC) serves as the bridge between AC and DC sections, actively modulating power flow to keep the AC-side frequency and DC-side voltage stable and within acceptable deviations. Effective control strategies are required to coordinate this behaviour: for instance, droop control methods are extended such that a DC link voltage droop is used to stabilize the DC grid while allowing the DC system to participate in regulating the AC grid frequency via ILC. This ensures that when the AC system frequency tends to drift (due to load changes or generation fluctuations), the ILC can transfer appropriate power from or to the DC side to counteract the deviation, and vice versa for DC voltage fluctuations. Coordinating frequency and voltage in this manner is fundamentally more complex than managing either an isolated AC or an isolated DC system, because control actions on one side inherently impact the other. Hybrid AC/DC operation therefore demands robust control algorithms to tie the two subsystems together without compromising stability [50] , [52] , [53] [50] .

Researchers have identified that careful hierarchical control is needed to manage AC/DC coordination under different operating conditions. In normal grid-connected mode, the large conventional AC grid helps hold frequency steady, but in islanded or weak-grid scenarios the hybrid system’s converters must assume grid-forming responsibilities to maintain stable AC frequency and DC voltage simultaneously. In fact, surveys highlight that ensuring stability in both operating modes and properly sharing power between AC and DC subsystems are among the main challenges for control design in hybrid microgrids. Advanced control schemes (primary droop control with secondary frequency/voltage restoration, adaptive and neural-network-based controllers, etc.) have been proposed to handle this coordination in real time. Without proper coordination, issues such as frequency deviations or DC voltage oscillations can arise when the two subsystems exchange power. Thus, voltage and frequency coordination remain a central challenge in hybrid AC/DC grids, and numerous studies in recent years have been devoted to control strategies that ensure a seamless interaction between the AC frequency regulation and DC voltage control mechanisms [49] .

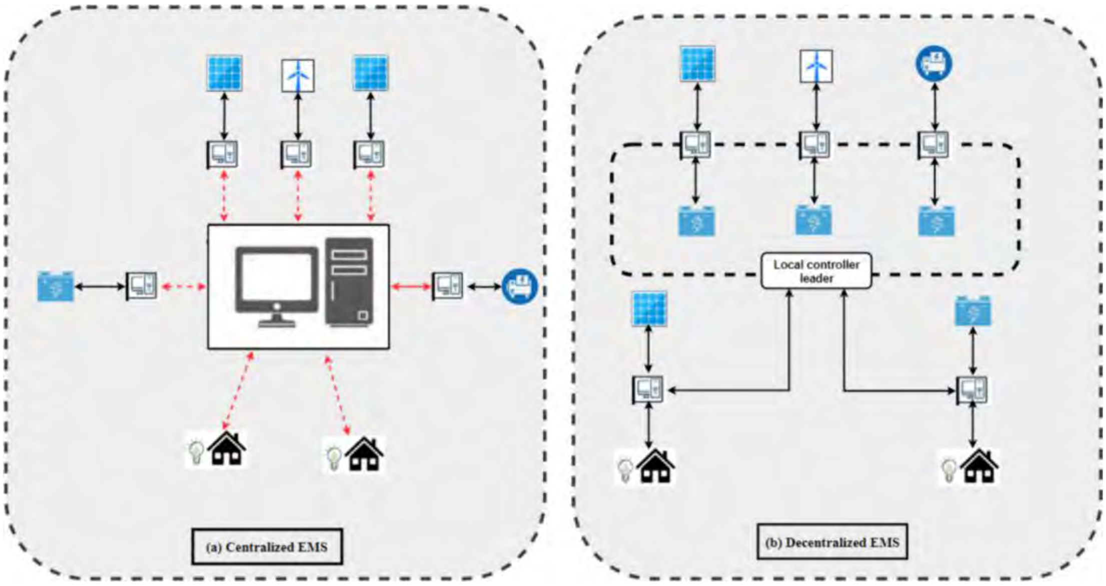

Figure 12: Typical structure for centralized and decentralized control strategy[49]

3.2.2 Converter Technology Constraints

Power converter technology forms the backbone of AC/DC interfaces in a hybrid grid, but it comes with inherent constraints that define technical boundaries for the system. Every AC/DC or DC/DC conversion stage introduces losses; even state-of-the-art voltage source converters (VSCs) and modular multilevel converters (MMCs) incur conversion inefficiencies on the order of a few percent, so multiple conversion stages can significantly reduce overall efficiency. For this reason, hybrid network designs aim to minimize the number of interface conversions – interlinking converters are kept to as few stages as necessary to connect AC and DC subsystems, balancing functional needs with efficiency and cost considerations. Indeed, limiting the count of conversion steps (for example, using a single multi-port converter to tie together multiple AC and DC links) can save on capital cost and avoid unnecessary energy losses. Nonetheless, the converters that remain in the system must handle the full power exchange between sub-grids; they have finite current-carrying capacity and switching speed and are typically rated for a maximum fault current and overload duration. This imposes limits on the hybrid grid’s ability to ride through disturbances or transfer large surges of power, compared to a purely AC grid with many spinning generators that have inherent overload and inertia capabilities [49] .

A critical constraint of converter-based grids is their limited contribution to short-circuit current and system inertia. Unlike synchronous generators which naturally provide substantial fault current and inertial response, power-electronic converters are usually current-limited and cannot supply large surge currents, which complicates protection schemes and fault recovery. During a short-circuit, a converter will rapidly cut its output to protect its semiconductors, so the grid sees much lower fault current levels – this requires more sensitive or communications-assisted protection to detect and isolate faults in hybrid grids. Similarly, converter-interfaced sources do not inherently provide inertia;

without special controls, they don’t resist frequency changes the way synchronous machines do, leading to a low short-circuit strength and low inertia in systems dominated by power converters. To mitigate this, grid-forming converter control strategies (virtual inertia, synchronverter algorithms, etc.) are being developed so that converters can emulate inertial response and support frequency stability. However, implementing such features is non-trivial – it is constrained by converter hardware limits and requires careful coordination among devices, especially if they are from different vendors with different control dynamics [49] .

Converters also introduce power-quality and control dynamics issues that define operational boundaries. High frequency switching in VSCs/MMCs generates harmonics (e.g. at multiples of the fundamental frequency) which can distort voltages and currents if not filtered, so hybrid grids must include filtering and abiding by harmonic standards to maintain power quality. Additionally, the fast control loops of converters can interact with one another or with the rest of the network; adverse control interactions (for instance, between the controllers of two different converters) may lead to instability or oscillations if not properly mitigated. Ensuring stable operation with many converters often requires careful tuning and sometimes standardization of control interfaces and communication protocols between devices. Furthermore, the cost and complexity of converter stations mean that practical deployments must balance performance with economic feasibility. All these constraints – limited fault current contribution, lack of innate inertia, harmonic emissions, strict control coordination requirements, and cost/efficiency trade-offs – must be recognized when planning and operating hybrid AC/DC grids. They effectively cap the performance envelope of the network’s interface technology and must be addressed through advanced converter designs and control schemes in any robust hybrid grid architecture [54]].

3.2.3 Protection and Fault Management constraints

Protection and fault management in hybrid AC/DC grids is considerably more complex than in traditional AC networks, due to the different fault behaviours in AC vs. DC systems and their tight coupling via converters. As noted, DC networks lack a natural current zero which makes interrupting DC faults difficult. When a short-circuit occurs on a DC link, currents can rise extremely quickly and will not self-extinguish, demanding very fast detection and the use of specialized DC circuit breakers or fault current limiters to isolate the fault. Meanwhile, a fault in one subsystem (AC or DC) can have repercussions in the other: for example, a DC pole-to-pole fault might suddenly draw power from the AC side through the converters, or an AC fault on a grid-forming converter could cause a DC voltage collapse if the converter unbalances. This interdependency means protective relays and breakers must be coordinated across AC and DC portions of the network to prevent a fault on one side from propagating into the other. Indeed, a newly recognized cascading fault phenomenon in hybrid grids involves a disturbance sequentially propagating between the AC and DC sub-grids, severely threatening overall system stability if not quickly controlled. This risk underscores the need for fast and discriminating protection schemes tailored to hybrid environments [55] .

Conventional protection strategies must therefore be rethought for hybrid AC/DC applications. AC protection techniques (like time-delayed overcurrent or distance relays) may not operate well in a hybrid context because the presence of power converters’ limit’s fault currents and alters the fault signatures seen on AC lines. On the DC side, high-speed communication and differential sensing are often required, since local measurements alone (e.g. overcurrent magnitude) may not reliably distinguish faults given the limited fault currents and the need to trip almost instantaneously. Moreover, grounding practices differ between AC and DC sections; for instance, ungrounded or differently grounded DC systems do not provide a return path like AC systems do, and the lack of a natural zero-cross means detecting and clearing ground/pole faults on DC requires novel criteria and device capabilities. Recent literature surveys indicate that while protection solutions for pure AC or pure DC microgrids are well studied, integrated protection for hybrid AC/DC grids remains an open challenge with relatively few comprehensive solutions demonstrated so far. Researchers are exploring approaches such as coordinated AC/DC differential protection, adaptive relay settings, and communication-assisted schemes to ensure faults are cleared selectively without sacrificing one subsystem’s security for the other. Ensuring a fast and selective fault response is essential to prevent wide-area disturbances in hybrid grids but achieving this is constrained by current technology – for example, the limited availability of ultra-fast DC circuit breakers and the lack of widely adopted standards for DC protection – which is a major ongoing area of development [49]].

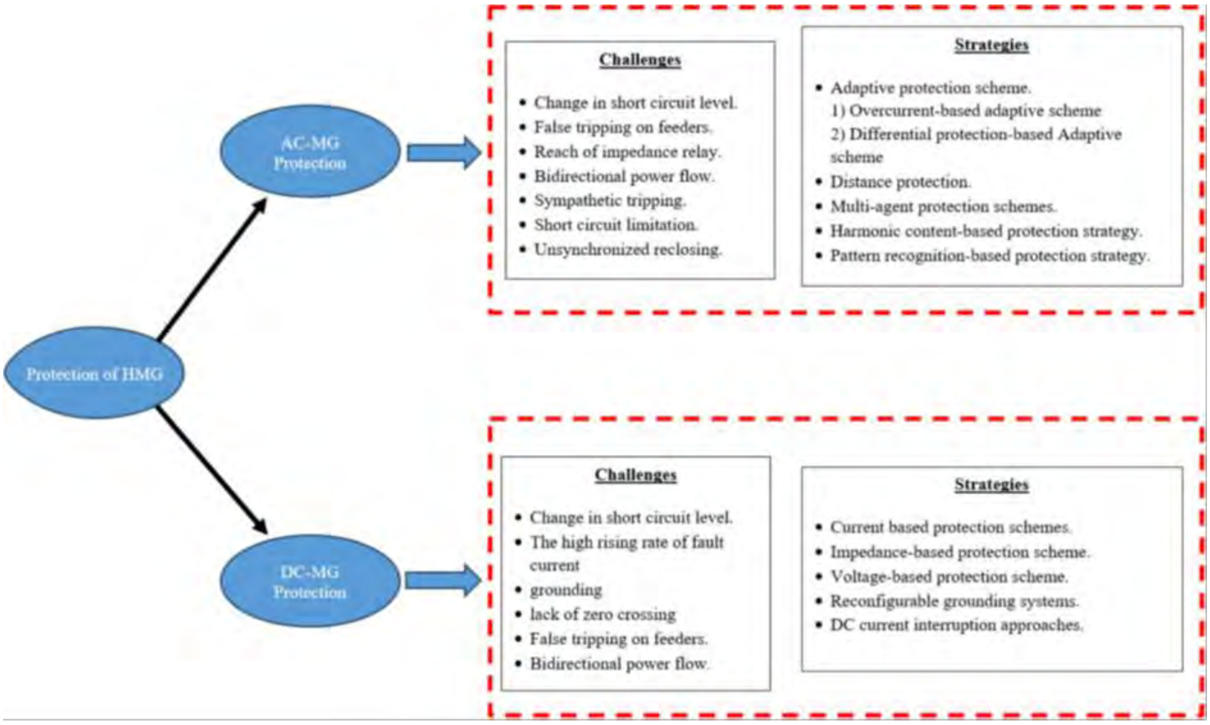

Figure 13: Most common protection challenges and proposed strategies for both AC microgrid and DC microgrid [49]

3.2.4 Grid Topology and Interoperability

Hybrid AC/DC grids also face challenges related to topology design and multi-vendor interoperability. There is a wide variety of possible architectures – for example, AC and DC networks can be AC-coupled, DC-coupled, or fully AC–DC coupled in various configurations – and ensuring that components from different manufacturers work seamlessly across these configurations is non-trivial. Unlike the AC grid, which benefits from decades of standardization, DC grid technology (especially at the distribution level and in multi-terminal systems) is still evolving without universally adopted standards for equipment, control, and protection. This lack of unified standards means that converters, switchgear, and control/protection devices from different vendors may not inherently communicate or coordinate well in a hybrid setup. Interoperability issues have already been observed in emerging multi-terminal HVDC systems, where each vendor’s converter stations might use proprietary control and protection schemes; integrating them requires careful interface design and often custom engineering solutions. As a result, a harmonized approach to interfaces and communication protocols is being actively pursued to enable multi-vendor, multi-terminal hybrid grids to operate reliably as cohesive systems. Industry and research collaborations emphasize developing standard interface specifications and testing procedures to ensure that equipment from different manufacturers can interoperate in the same AC/DC network [49] [54]].

Additionally, the introduction of HVDC links and DC sub-networks into a predominantly AC grid changes the system dynamics and planning considerations. DC systems can respond to and propagate disturbances much faster than AC systems due to the lack of inertia and the direct control of power electronic converters – this can introduce new transient phenomena and stability concerns that must be studied in network planning and operation. For instance, a meshed HVDC overlay grid can greatly enhance controllability and reduce transmission losses, but its fast-acting dynamics mean that traditional AC stability analysis methods must be extended (often using detailed nonlinear electromagnetic transient simulations) to ensure stable interaction between the AC and DC parts. Ensuring stability also involves managing interactions between multiple converters: without coordination, different converters (potentially from different vendors) might have adverse control interactions under various operating conditions, leading to oscillations or performance degradation. To tackle these issues, system operators are adopting extensive multi-domain simulation studies and hardware-in-the-loop testing to predict and mitigate interaction problems, and working groups are developing interoperability guidelines for multi-vendor AC/DC systems. Overall, achieving a truly “plug-and-play” hybrid AC/DC grid – where any compliant device or subnetwork can be integrated seamlessly – remains a future goal. It will require convergence toward common standards and practices, as well as improved tools for joint AC/DC grid analysis and control, to handle the complexity of multi-vendor, multi-topology hybrid networks [54] [56] [57]].

3.3 Regulatory boundaries

3.3.1 ENTSO-E and eDSO Network Codes & Guidelines

Capacity Allocation & Congestion Management Network Code

COMMISSION REGULATION (EU) 2015/1222 of July 2015[16] establishes a **Network Code on Capacity Allocation & Congestion Management** (**NC-CACM**). NC-CACM provides binding rules for the **implementation and operation** of EU-wide single market coupling in **the day-ahead** and **intraday** timeframes. Specifically, NC-CACM establishes EU-wide rules for managing **electricity transmission capacity and congestion** to enhance operational security, **market efficiency** and **cross-border trade**, ensuring optimal use of the transmission infrastructure. This Regulation shall apply to all **TSOs**, Nominated Electricity Market Operators (**NEMOs**), **regulatory authorities** and the European Agency for the Cooperation of Energy Regulators (**ACER)**.

The NC-CACM sets the requirements and specifications for

- **market coupling** (including **day-ahead** and **intraday market coupling** to optimize cross-border electricity trading);
- **calculation and allocation** of cross-zonal capacity (using **flow-based capacity calculation methodology** or fallback procedures);
- **management of residual congestions:** physical congestion, which were not prevented by capacity calculation and allocation, need to be managed by coordinated TSOs’ actions (e.g. countertrading or re-dispatching;
- **regional coordinated capacity calculation;**
- **TSOs, NEMOs** and **National regulatory authorities.**

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[16] https://eur-lex.europa.eu/eli/reg/2015/1222/oj/eng

The Regulation fosters **integrated EU energy markets**, reduces price disparities, and supports renewable energy integration. NC CACM is the cornerstone of a European single market for electricity.

Electricity Balancing Network Code

COMMISSION REGULATION (EU) 2017/2195 of 23 November 2017[17] establishes a **Network Code on Electricity Balancing (NC-EB).** The Electricity Balancing Regulation establishes harmonized rules on electricity balancing markets for procuring, activating and exchanging of the balancing services.

It applies to **TSOs**, **National Regulatory Authorities** (**NRAs**) and **ACER,** providing **binding requirements** and **regulating their activities** in order to implement and ensure proper functioning of the integrated electricity market in the balancing timeframe.

NC EB includes rules for:

- **Market-Based Balancing** of **Service Providers** and **Responsible Parties**: the terms and conditions related to **competitive** procurement of balancing energy with **fair, transparent and non-discriminatory** rules for all actors involved.
- **TSO Responsibilities** and **settlement** between **TSOs**: It ensures that all the exchanges between TSOs are settled with common rules, guaranteeing a fair and non-discriminatory approach, and ensuring **system stability**.
- Harmonisation of **imbalance settlement**: The imbalance settlement is a national mechanism, and its harmonisation at European level provides a consistent application of the rules across member states. NC EB implements a single pricing mechanism to ensure cost-reflective imbalance charges for market participants.
- Exchange of **balancing capacity and cross-zonal capacity allocation**: these rules enable TSOs to jointly procure and use balancing capacity and benefiting from economic reserve providing resources outside their area.
- **European platforms for the exchange of balancing energy**: the integration of balancing energy markets is facilitated by European platforms that apply common merit order list to ensure cost-efficient activation of balancing energy bids across Europe.

TSOs and NRAs must adapt their frameworks to comply, with oversight by **ACER.**

ACER Recommendation DR NC No 01/2025 Annex 2a [18] introduces changes in the NC EB (including **aggregation models** and **financial transfer and compensation**) in view of a publication of a **Network Code on Demand Response (NC DR)**.

Forward Capacity Allocation Network Code

COMMISSION REGULATION (EU) 2016/1719 of 26 September 2016[19] establishes a **Network Code** on **Forward Capacity Allocation** (**NC FCA**). The NC FCA provides rules on cross-zonal capacity calculation and allocation in the forward timeframe. The NC FCA’s regulations are **obligatory for TSOs, NRAs and ACER** in order for the proper functioning of the European electricity markets in the forward timeframe and regulate the relevant activities.

The **NC FCA** describes the:

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[17] https://eur-lex.europa.eu/eli/reg/2017/2195/oj/eng

[18] https://www.acer.europa.eu/news/new-network-code-demand-response-will-further-advance-energy-transition

[19] https://eur-lex.europa.eu/eli/reg/2016/1719/oj/eng

- **Forward calculation of capacities between bidding zones** for the year- and month-ahead market time frames, so that reliable and transparent information to market participants is ensured. Thus, TSOs provide the optimal amount of **long-term cross-zonal capacities** for allocation of long-term transmission rights (LTTRs).
- **Forward allocation of cross-zonal capacities**: By allocating LTTRs and using harmonised allocation rules across Europe, market participants can be provided with equal access to long-term markets.
- **Establishment of a Single Allocation Platform**, developed by all European TSOs to facilitate the allocation of LTTRs to market participants, applying the harmonised allocation rules while reducing barriers for all European market participants.

NC FCA applies to **all transmission systems** and interconnections in the Union, except the transmission systems on islands which are not connected with other transmission systems via interconnectors.

Network Code on Cybersecurity

COMMISSION DELEGATED REGULATION (EU) 2024/1366 of 11 March 2024 [20] establishes a **Network Code on Cybersecurity (NC CS)**. It establishes a comprehensive framework to enhance the cybersecurity of cross-border electricity flows in the EU. It applies to **TSOs, DSOs** and other relevant entities involved in the electricity market.

Among the main provisions, NC CS:

- Encourages **collaboration between TSOs, DSOs, and cybersecurity agencies** to strengthen defences.
- Provides a **governance model** and objectives for the development and review of terms and conditions, methodologies, and plans.
- Describes the types of **cybersecurity risk assessments**: Union-wide, regional and Member State-level, as well as a comprehensive cross-border **risk assessment report**. Competent authorities must monitor and report on significant cybersecurity incidents to national and EU authorities, ensure rapid response.
- Sets rules on **cybersecurity risk management** by the high-impact and critical-impact entities, to identify, assess, and mitigate risks to the electricity grid and contains provisions **on cybersecurity crisis management**.

- Includes a **common electricity cybersecurity framework** with minimum and advanced cybersecurity controls, covering supply chain security and a cybersecurity management system, along with provisions on its verification.
- Presents rules for **detecting cyber-attacks** and for managing and sharing information related to cyber-attacks, threats, and unpatched actively exploited vulnerabilities.

- Provides the principles for protecting **confidential information.**
- Foresees **cybersecurity exercises** at the entity, Member State, regional, and cross-regional level.

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[20] https://eur-lex.europa.eu/eli/reg_del/2024/1366/oj/eng

Demand Connection Network Code

COMMISSION REGULATION (EU) 2016/1388 [21] establishes a Network Code on Demand Connection (NC DC). The NC DC is motivated by the goal of a fully functioning and interconnected internal energy market, crucial to maintaining the security of energy supply, increasing competitiveness and ensuring that all consumers can purchase energy at affordable prices.

This Regulation is aimed to apply to **new** (not existing) **transmission-connected demand facilities**, new **transmission-connected distribution facilities**, new **distribution systems (including closed distribution systems - CDSs)** and new **demand units** used by a demand facility or a CDS to provide demand response services to relevant system operators and relevant TSOs (for the **demand units**, see below for proposed changes brought by ACER Recommendation DR NC No 01/2025 Annex 4a).[22]

System operators have the power to **deny the connection** of new transmission-connected demand facilities, transmission-connected distribution facilities, or distribution systems, which do not comply with the requirements set out in the Regulation.

The NC DC defines requirements regarding:

- the **connection of transmission-connected demand facilities, transmission-connected distribution facilities and distribution systems**, including
  - **frequency** requirements (e.g. minimum time periods of connection to the grid under specific frequencies ranges) and
  - **voltage** requirements (e.g. minimum time periods of connection to the grid under specific voltage ranges)
  - **short-circuit** requirements (including information demanded by the relevant TSO concerning SC current values and planned events)
  - **reactive power** requirements demanded from the transmission-connected demand facilities and transmission-connected distribution systems, so that they maintain their steady-state operation at their connection point within a reactive power range. The TSO is also in power to actively control the exchange of reactive power at the connection point for the benefit of the entire system.
  - **protection** requirements, which may be needed such as external and internal short circuit, over- and under-voltage at the connection point to the transmission system, over- and under-frequency, demand circuit protection, unit transformer protection, back-up against protection and switchgear malfunction.
  - **control** requirements for system security to cover isolated (network) operation, damping of oscillations, disturbances to the transmission network, automatic switching to emergency.
  - supply and restoration to normal topology, automatic circuit-breaker re-closure (on 1-phase faults).
  - **information exchange.**
  - **demand disconnection** (including low frequency demand disconnection capabilities and requirements) and **reconnection.**
  - **power quality** (in terms of distortion and fluctuation)
  - **simulation models** (including the TSO’s entitlement in requiring simulation models or equivalent information showing the behaviour of the transmission-connected demand facility, or the transmission-connected distribution system in steady and dynamic states).

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[21] https://eur-lex.europa.eu/eli/reg/2016/1388/oj/eng

[22] https://www.acer.europa.eu/news/new-network-code-demand-response-will-further-advance-energy-transition

- the **connection of demand units used by a demand facility or a closed distribution system to provide demand response services to system operators** (see below for proposed changes brought by ACER Recommendation DR NC No 01/2025 Annex 4a), including active and reactive power control, voltage levels specifications, RoCoF specifications, provisions for demand units with demand response frequency control, and provisions for demand units with demand response very fast active power control.
- the **operational notification procedure** comprising Energisation, Interim, Final and (where applicable) Limited operational notification, (EON, ION, FON and LON respectively) for
    - new transmission-connected demand facilities, new transmission-connected distribution facilities and each new transmission-connected distribution systems, and
    - demand units used by a demand facility or a closed distribution system (connected at below 1000V or above 1000V)

- **compliance testing** and **simulation,** the TSO’s rights and entitlements over the compliance procedures and the **monitoring** equipment and organizing involved.
- **cost benefit analysis** and
- the specifications for granting **derogations** from one or more provisions of this **regulation.**
-

ACER Recommendation DR NC No 01/2025 Annex 4a introduces changes in the NC DC in view of a publication of a **Network Code on Demand Response (NC DR)**. NC DC is proposed to be changed by deleting the **Demand response** requirements and all related Chapters and Articles from it and introducing new chapters to include **V1G electric vehicles** equipment, **Power to Gas demand** units and **heat pumps**. The **Recommendation** introduces criteria for **significant modernization** of transmission-connected demand facilities, transmission-connected distribution facilities, distribution systems and demand units used to provide demand response services following TSOs’ proposals and regulatory approval. The **Recommendation** also introduces amendments to the **requirements for transmission-connected demand facilities** and **distribution systems**.

Requirements for Generators Network Code

COMMISSION REGULATION (EU) 2016/631 of 14 April 2016[23] establishes a Network Code defining the requirements for grid connection of generators (hereinafter referred to as **Network Code** on **Regulations for Generators** - **NC RfG**). It lays down the requirements for grid connection of **synchronous power-generating modules**, **power park modules** and **offshore power park** modules, to the interconnected system. As a result, it serves to **level the playing field in the internal electricity market**, fortify system **security** by including renewables, and ease electricity trade across the EU. It also lays down relevant obligations so that system operators utilize power generation resources **fairly and transparently**, ensuring equal access for all within the Union.

This Regulation is aimed at applying to **new** (not existing) generating facilities (except for specific cases of type C or type D power-generating modules). Power-generating module types (A, B, C and D) are also defined in the NC RfG. The Regulation’s applicability to **power-generating modules**, **pump-storage power-generating modules**, combined **heat and power facilities**, and **industrial** sites is also described.

As defined in other NCs, the relevant System operator has the power to **deny the connection** of a power-generating module which does not comply with the requirements set out in this Regulation.

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[23] https://eur-lex.europa.eu/eli/reg/2016/631/oj/eng

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NC RfG describes requirements for:

- **type A, type B**, **type C** and **type D** power-generating modules with regard to
    - **frequency** ranges (and minimum time period for operation)
    - **RoCoF** withstand capability
    - the limited frequency sensitive mode — over frequency (**LFSM-O**) (type A)
    - **constant output capability** (maintained at its target active power value regardless of changes in frequency)
    - admissible **active power reduction** from maximum output
    - the power-generating module being equipped with a **logic interface** (input port) in order to **cease active power output** within five seconds following an instruction being received at the input port. (type A and B)

- **type B**, **type C** and **type D** power-generating modules with regard to
    - **frequency stability** (type B, type C)
    - **robustness** (with regard to fault-ride-through capability of power-generating modules, and fault-ride-through capabilities in case of asymmetrical faults shall be specified by each TSO)
    - **system restoration**
    - **system management requirements** (including control schemes and settings, electrical protection schemes and settings, protection and control devices organizing and information exchange)

- **type C** and **type D** power-generating modules with regard to
    - **LFSM-O,** limited frequency sensitive mode — underfrequency **LFSM-U**, frequency sensitive mode (**FSM**), frequency restoration control and underfrequency
    - **voltage stability** (type C shall be capable of automatic disconnection) (type D: voltage ranges and time periods)
    - **system restoration** (black start, island operation, quick re-synchronisation capability)
    - **instrumentation**
    - **simulation models**
    - installation of **devices for system operation** and devices for system security
    - minimum and maximum limits **on rates of change of active power output** (ramping limits) in both an up and down direction of change of active power output for a power-generating module
    - **earthing arrangements**

- **type B synchronous power-generating modules** and **power park modules**
- **type C synchronous power-generating modules** and **power park modules** (including a **U-Q/P max-profile** within the boundaries of which the synchronous power-generating module shall be capable of providing reactive power at its maximum capacity)
- **type D synchronous power-generating modules** and **power park modules**
- **offshore AC-connected power park modules:**
    - **Frequency stability**
    - **Voltage stability**
    - **Robustness**
    - **System restoration**
    - **General system management requirements**

- the **operational notification** and procedure for the **connection of new** power-generating modules (The operational notification procedure for connection of each new type D power-generating module shall comprise an EON, ION, FON and LON (See above “High Voltage Direct Current Connections” for definitions)**.**
- **Cost-benefit analysis**
- requirements for **Compliance** including the relevant system’s operator degree of participation and tasks, **common provisions** for compliance **testing** and **simulation**, for
    - type B synchronous power-generating modules and power park modules
    - type C synchronous power-generating modules and power park modules
    - type D synchronous power-generating modules and power park modules
    - **offshore power park modules**
- the specifications for granting **derogations** from one or more provisions of this **regulation.**

Emergency and Restoration Network Code

COMMISSION REGULATION (EU) 2017/2196 of 24 November 2017 [24] establishes a Network Code defining the requirements for Electricity emergency and Restoration (hereinafter referred to as **Network Code** on **Electricity emergency and Restoration** - **NC ER**).

Even though **each TSO is responsible** for maintaining operational security in its control area, the **secure** and efficient operation of the Union's electricity system **is a task shared between all the Union TSOs** since all national systems are, to a certain extent, interconnected and a fault in one control area could affect other areas. The efficient operation of the Union's electricity system also requires **close collaboration and coordination between stakeholders**.

The NC ER fixes the **processes that the TSOs** must follow when they face an incident on their grid, so that the highest standards and practice in dealing with emergency situations will thus apply in all Europe. These include **safeguarding operational security**, **preventing the propagation or deterioration** of an incident to avoid a widespread **disturbance** and the **blackout** state as well to allow for the **efficient and rapid restoration** of the electricity system from the emergency or blackout states.

The NC ER lays down the requirements on a) the **management by TSOs** of the emergency, blackout and restoration states, b) the **coordination of system operation** across the Union in the emergency, blackout and restoration states, c) the **simulations and tests** to guarantee a reliable, efficient and fast restoration, d) the **tools and facilities** needed to guarantee a reliable, efficient and fast restoration.

The NC ER applies to **existing and new: power generating modules** type C and D (and type A and B where applicable) (See NC RfG), transmission-connected **demand facilities**, transmission connected **CDSs**, **HVDC systems** and direct current-connected **power park modules** and **providers of re-dispatching** of power generating modules and **energy storage** units.

NC ER sets the requirements for

- the **system defence plan that must be designed by each TSO**, including
    - **activation** conditions,
    - **technical** and **organisational** measures implemented, such as **automatic under-frequency** and **over-frequency** control scheme, **automatic scheme against voltage** collapse, **frequency**

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[24] https://eur-lex.europa.eu/eli/reg/2017/2196/oj/eng

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    and **voltage deviation** management procedures, **power flow** management procedure, assistance for **active power procedure** and **manual demand disconnection** procedure.
    The scheme for the **automatic control of under-frequency** of the system defence plan shall include a scheme for the **automatic low frequency demand disconnection** and the settings of the **limited frequency sensitive mode-underfrequency** in the TSO load frequency control (LFC) area. The scheme for **automatic over-frequency control** of the system defence plan shall lead to an automatic decrease of the total active power injected in each LFC area.
  - **Inter-TSO assistance** and coordination in emergency state
- the **restoration plan that must be designed by each TSO**, including
  - **activation** conditions,
  - **technical and organisational measures** implemented such as:
    - **re-energisation procedure**, including managing **voltage and frequency deviations** due to re-energisation, monitoring and managing **island operation** and **resynchronising island operation** areas.
    - **frequency management procedure** (including the appointment of a **frequency leader** frequency management **after frequency deviation,** frequency management after **synchronous area split**)
    - **resynchronisation procedure** (including the appointment of a **resynchronisation leader, the resynchronisation strategy**
- **market interactions**, including
  - the entitlement of TSO to **suspension market activities** (and to establish **an active power set-point** at which each Significant Grid User (SGU) shall operate, in case of suspension of market activities)
  - the launch of **the communication procedure** (in case of suspension of market activities)
  - the **rules for suspension and restoration** of market activities that the TSOs must develop.
- **information exchange and communication, tools and facilities** (including the TSOs’ entitlement to **gather information** from DSOs and SGUs and the information that the TSO shall **provide** in case of emergency, describing the respective **communication systems, tools and facilities**)
- **compliance** and **review**, including compliance testing of
  - **power generating module** capabilities,
  - **demand facilities** providing demand side response,
  - **HVDC** capabilities,
  - **low frequency demand disconnection relays**,
  - **communication** systems,
  - **tools** and **facilities**
  - the **system defence** and **restoration plan** (and periodic review)

System Operations Network Code

COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 [25] establishes a Network Code defining the requirements for electricity transmission system operation (hereinafter referred to as **Network Code** on **System Operations** - **NC SO**).

This Regulation lays down detailed guidelines on:

- requirements and principles concerning **operational security**.

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[25] https://eur-lex.europa.eu/eli/reg/2017/1485/oj/eng

- rules and responsibilities for the coordination and **data exchange** between TSOs, between TSOs and DSOs, and between TSOs or DSOs and SGUs, in operational planning and in close to real-time operation.
- rules for **training** and certification of system operator employees.
- requirements on **outage** coordination.
- requirements for **scheduling between** the TSOs' **control** areas.
- rules aiming at the establishment of **a Union framework** for load-frequency control and reserves.

This Regulation applies to existing and new:

- **power generating modules** that are, or would be, classified as type B, C and D.
- transmission-connected **demand facilities.**
- transmission-connected **CDSs.**
- **demand facilities, CDSs systems and third parties if** they provide demand response directly to the TSO.
- **providers of re-dispatching** of power generating modules or demand facilities by means of aggregation and providers of active power reserve.
- **HVDC** systems.

This Regulation analyses:

- **system states** including the
    - classification of **system states** (Normal, Alert, Emergency, Blackout, Restoration state)
    - specifications for **monitoring and determination** of system states by TSOs
- **remedial** actions including:
    - **design, preparation and activation** of remedial actions by the TSO (such as modification of the duration of a **planned outage**, actively impact **power flows**, **control voltage and manage reactive power**, re-calculate day-ahead and **intraday cross-zonal** capacities, **redispatch transmission** or distribution-connected system users, **countertrade** between two or more bidding zones, adjust **active power flows** through **HVDC** systems, activate **frequency deviation** management procedures, **curtails**, manually controlled **load-shedding**).
    - specification of **operational security limits.**
- **short-circuit current** management (including TSO’s rights and obligations on setting short circuit values, perform calculations and make evaluations).
- **power flow** management (including TSO’s obligations to maintain power flows within the **operational security limits**).
- **contingency analysis** and **handling.**
- **protection** (including **dynamic stability** monitoring, assessment and management).
- **data exchange** including organisation, roles, responsibilities and quality of data exchange between TSOs and
    - TSOs
    - DSOs within the TSO's control area
    - owners of interconnectors or other lines and power generating modules connected to the transmission system
    - DSOs and distribution-connected power generating modules
    - DSOs concerning significant power generating modules
    - transmission-connected demand facilities
    - distribution-connected demand facilities or third parties participating in demand response
- **compliance requirements** (including roles, responsibilities and operational testing).

- **training** (including training program, conditions, coordinators and trainers, employees’ certification).
- **operational planning** (including Year-ahead, week-ahead and day-ahead time frames and intraday common grid models.)
- **operational security analysis** (including Year-ahead, week-ahead, day-ahead, intraday and close to real-time operational security analysis).
- **operational security analysis in operational planning.**
- **outage coordination** by TSOs in order to in order to monitor the **availability status of the relevant assets** and **coordinate** the availability plans to ensure the operational security of the transmission system.
- **development and update of availability plans of relevant assets.**
- **forecast for control area adequacy analysis.**
- **ancillary services** (including **reactive power ancillary services**).
- **Scheduling.**
- **load-frequency control** and **reserves.**
- **frequency quality** (including **frequency containment** and **restoration**).
- **operation of load-frequency control.**
- **time control process** of frequency to the nominal value.

ACER Recommendation DR NC No 01/2025 Annex 3a introduces changes in the NC SO in view of a publication of a **NC DR**. NC SO expanding the requirements and rights concerning TSOs to **DSOs** and **CDSOs** where they are applicable.

3.3.2 Grid Connection Requirements and standards

High Voltage Direct Current Network Code

COMMISSION REGULATION (EU) 2016/1447 [26] establishes a Network Code defining the requirements for grid connection of *high voltage direct current systems and direct current-connected power park modules* (hereinafter referred to as **Network Code** on **High Voltage Direct Current Connections** - **NC HVDC**).

By finalizing the NC HVDC as soon as possible, the goal is to create a fully operational and **interconnected internal energy market**, unlocking key benefits such secure, increased market **competitiveness**, and accessible energy **prices** for all consumers.

The NC HVDC also ensures the integration of **renewable electricity sources** and facilitates **Union-wide trade** in electricity.

The regulation lays down the obligations for ensuring that **system operators make appropriate** use of HVDC systems and DC-connected power park modules (See also on Draft NC HVDC below for more) capabilities in a transparent and non-discriminatory manner to provide **a level playing field** throughout the Union. It also elaborates on the **power system planning** and **operational security** of the EU power systems. Th NC HVDC sets the stage for the connection of HVDC systems or DC-connected power park modules (See also on Draft NC HVDC below for more) in future meshed networks.

Applying on HVDC systems with a below 110 kV connection point (unless the relevant TSO demonstrates a cross-border impact), the NC HVDC analyses:

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[26] https://eur-lex.europa.eu/eli/reg/2016/1447/oj/eng

- HVDC system **robustness** requirements.
- **frequency-related topics** (frequency values and rates of change under which HVDC systems must stay connected, frequency control performance, frequency stability requirements for DC power park modules (See also on Draft NC HVDC below for more)).
- the **active power controllability, control range** and **ramping rates** requirements (establishing the TSOs’ authority on specifying the relevant parameters).
- the **reactive power capability requirements** (set in coordination with the relevant TSO) of HVDC systems, at the connection points in the context of varying voltage (The proposal for those requirements must include a U-Q/P_{max} – profile), and the **reactive power control mode** that an HVDC converter station shall be capable of operating in (at least one of (a) voltage control mode; (b) reactive power control mode; (c) power factor control mode, as specified by the relevant system operator and the relevant TSO).
- the **short circuit behaviour** of HVDC systems during **faults.**
- the **power quality** of HVDC systems, in terms of acceptable distortion or fluctuation (in accordance with the relevant TSO).
- the **fault ride through capability** of HVDC systems (specified by the relevant TSO).
- requirements for **Energisation and synchronisation** of HVDC converter stations.
- the **interaction** between HVDC systems or other plants and equipment (establishing the relevant TSO’s entitlement in **requesting specific studies** exhibiting that no adverse interaction will occur).
- the **power oscillation damping capability** (specified under the approval of the relevant TSO) and the **sub-synchronous torsional interaction damping capability** of HVDC systems (the relevant TSO is entitled to ask for and assess SSTI studies and demand mitigation actions if deemed necessary).
- requirements for **protection** devices and settings and **black start** requirements.
- requirements for **remote-end HVDC converter stations.**
- **information** exchange and coordination (specifies measured parameters, fault recording and monitoring aspects and simulation models).
- the **operational notification procedure for connection** of
    - new HVDC systems
    - new DC-connected power park modules (See also on Draft NC HVDC below for more)

  comprising Energisation, Interim, Final and (where applicable) Limited operational notification, (EON, ION, FON and LON respectively).
- the **cost benefit analysis** on existing HVDC systems or DC-connected power park modules to demonstrate that the benefits exceed the costs. (See also on Draft NC HVDC below for more).
- the **compliance** requirements of HVDC systems and DC-connected power park modules (See also on Draft NC HVDC below for more) regarding the performance **testing** and **simulations** aimed at aim at demonstrating that the requirements of this Regulation have been complied with. (Including the System Operator’s involvement and participation on the HVDC system owner’s compliance tests and simulations, as well as the operator’s entitlement to carry out their own).
- the specifications for granting **derogations** from one or more provisions of this **regulation.**

A **Draft Amendment Proposal** (hereinafter **Draft NC HVDC**)[27], has been given to public consultation by ACER. Its motivations are to safeguard **future system needs** while ensuring that the **rules** are well defined, to cover **the isolated offshore AC networks** (AC hubs) which are expected to grow in the near

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[27] https://www.acer.europa.eu/public-consultation/pc2024e05-public-consultation-amendments-electricity-grid-connection-network-code

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future, to maintain a sound and cost-effective design and operation in **meshed offshore HVDC systems**, and to ensure consistency with ACER recommendation for NCs RfG 2.0/DC 2.0.

The Draft NC HVDC except for HVDC systems and power park modules **(A-PPMs)** (See also Figure 1 below)**,** expands its applicability to asynchronously connected demand facilities **(A-DFs),** asynchronously connected power-to-gas demand units **(A-PtG-Us)** and asynchronously connected electricity storage modules **(A-ESMs)** (See also Figure 2 below). This is being done both on a holistic level and on a paragraph-to-paragraph level. The Draft NC HVDC (as well as the NC HVDC) **does not apply to existing** A-PPMs, A-DFs, A-PtG-Us, and A-ESMs unless specific prerequisites exist.

The Draft NC HVDC is proposed to apply **only on the AC side of HVDC systems**, and, additionally on **connecting isolated AC networks**, too. **Frequency stability, reactive power and voltage requirements** are added to cover isolated AC networks (E.g. in Article 48 and 49).

The Draft NC HVDC departs from the **Synthetic Inertia** term to the more inclusive **Grid Forming** capability of the systems at their connection points, describing the latter in more detail (E.g. A proposed Article 40b on Grid Forming, demands synthetic inertia capability from A-PPMs and A-ESMs). Detail is also given to the **frequency stability**, **reactive power and voltage requirements** of A-PPMs, A-DFs, A-PtG-Us and A-ESMs. (E.g. A specific LSFM-UC (limited frequency sensitive mode — underfrequency consumption) curve is given for a power-to-gas demand unit (PtG-U). Moreover, a new Article (40a) is proposed on the **Fault-ride-through capability of power-to-gas demand units**).

On the simulation model requirements, the Draft NC HVDC presents the **TSO’s rights on model requirements** and provides minimum characteristics for RMS, EMT simulations. (Moreover, if needed, the TSO can ask for the frequency dependent impedance model of the HVDC converter station at the AC side.)

The Draft NC HVDC extends the requirements on the **operational notification procedure for connection** (EON, ION, FON and LON), on the **cost benefit analysis,** on **compliance testing and simulations** (in order to demonstrate compliance with the NC HVDC) to include A-DFs, A-PtG-Us and A-ESMs. It also contains more details in the amendments. (E.g. on rated voltages, voltage ranges and fault-ride-through capability time parameters).

In the Draft NC HVDC, ACER, in cooperation with ENTSO for Electricity is set in charge of the implementation of this Regulation and responsible for making the **compliance tests and process to be performed, publicly available**.[28]

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[28] https://eepublicdownloads.entsoe.eu/clean-documents/Network%20codes%20documents/NC%20HVDC/140430-NC%20HVDC%20Frequently%20Asked%20Questions.pdf

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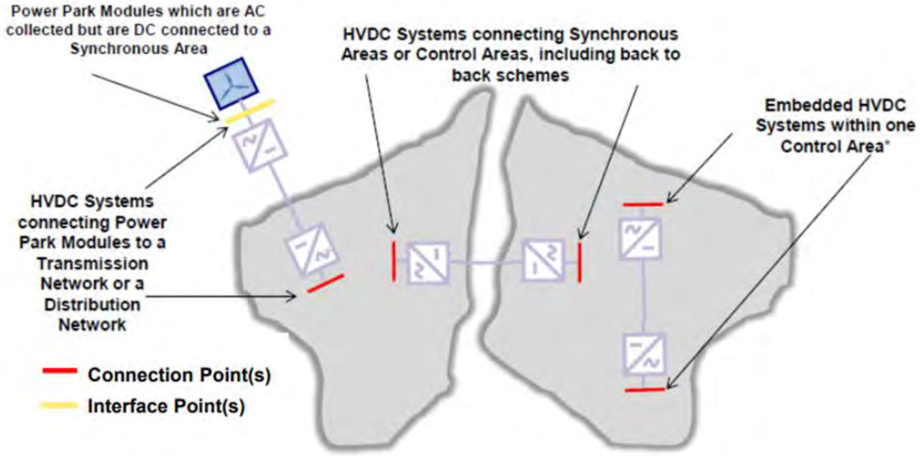

Figure 14 Scope of NC HVDC 1.0 and the Connection Points and Interface Points at which the requirements apply.

Figure 15 Explanation of NC HVDC 2.0 applicability and the relation to the definitions of the connection point and the interface point. (Source: Expert Group on Connection Requirements for Offshore Systems – Phase II (Proposal for the NC HVDC amendment), 10.11.20.

4. Challenges and Requirements for Hybrid AC/DC Grids

4.1 Stability Management in Power Electronics-Dominated Systems

4.1.1 *Challenge*

European renewable energy targets aimed at reducing the dependence on fossil fuels and mitigating the greenhouse effect have led to the replacement of conventional synchronous generators with renewable energy sources (RES) connected to the grid through power electronic devices. However, these devices, known as inverters, do not replicate the dynamic behaviour of conventional synchronous generators in terms of fault response and system stability. For example, regarding system stability, renewable energy resources interfaced via power electronic (PE) present the disadvantage of not contributing to the inertia system. This makes the power system more sensitive to frequency variations and reduces its ability to damp frequency oscillations. Therefore, control strategies should be implemented into the RES inverters to ensure stable system operation.

Among the different solutions that can be implemented to improve the frequency stability in power electronic dominated systems, the following section focuses on the ones related to power-sharing, loss of damping rate and the absence of inertia.

4.1.2 *State-of-the-art solutions*

The control techniques used by RES inverters can be classified into two categories: Grid Following (GFL) and Grid Forming (GFM) control. Grid Following control regulates the active and reactive power using a phase locked loop (PLL) to synchronize with the grid. By contrast, Grid Forming control allows the regulation of the frequency and voltage at the converter’s output. Furthermore, GFM offers black start capabilities, supports islanded operation and contributes to system inertia, enhancing the stability of the power system [58] . Then, this type of converter architecture is the most appropriate to use in power systems with high penetration levels of renewable energy to improve the stability and reliability of the grid. Following, control strategies that can be implemented in grid forming control are described.

4.1.2.1 Real-time droop control and adaptive control techniques to manage power-sharing between AC and DC grids.

Droop control is one of the most widely used control strategies in power systems for managing distributed generation and converter-based resources. It is a decentralized mechanism that typically consists of two main components: the active power droop controller and the reactive power droop controller. The active power droop controller manages the active power output of converters operating in parallel, ensuring proportional load sharing based on their power ratings. Meanwhile, the reactive power droop control regulates the voltage level to fulfil the reactive power setpoint, maintaining voltage stability across the system .

The conventional droop control determines the voltage and frequency references (V_{ref} and f_{ref}, respectively) by evaluating the active (P) and reactive (Q) power measured at the Point of Common Coupling (PCC), as detailed in equations (1) and (2). Figure 16 illustrates the linear relationship between the frequency and active power, as well as between voltage and the reactive power. The figure also indicates the frequency droop coefficient (m) and the voltage droop coefficient (n).

$$f_{ref} = f_{rated} - m(P - P_{rated}) \tag{1}$$
$$V_{ref} = V_{rated} - n(Q - Q_{rated}) \tag{2}$$

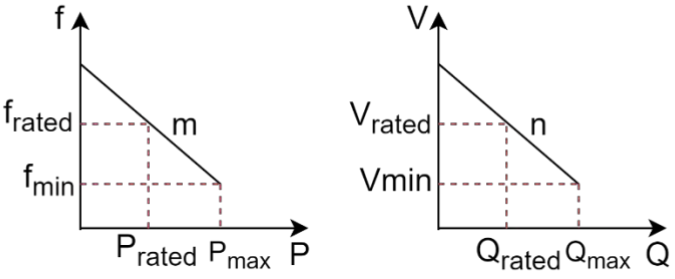

Figure 16. Static droop control characteristic.

Conventional droop controls offer advantages such as simplicity and reliability. However, it also presents several limitations, including slow dynamic response, sensitivity to the line impedance and imprecise power sharing [60] . To overcome these limitations, several droop methods such adaptive and robust droop control[61] techniques are proposed and described in the literature.

Adaptive droop control [62] [63] [64] enhances conventional droop methods by dynamically adjusting control coefficients in response to real-time operating conditions, allowing for improved voltage regulation and power sharing among distributed generators. When deviations in power occur, the controller modifies the voltage amplitude, accordingly, maintaining system balance and stability. indicates that adaptive control such as derivative-term-based techniques, optimization algorithms or theoretic approaches can be used to further improve transient performance. As it is indicated in , derivative-term-based techniques are often incorporated to suppress power oscillations and minimize circulating currents between converters. Optimization algorithms such as genetic algorithms and particle swarm optimization are used to fine-tune adaptive droop parameters, enhancing the power sharing and stability of the system. Finally, theory-based approaches, such as bifurcation theory and Kuramoto oscillator models, provide structured, analytical methods to derive adaptive droop coefficients. Although these strategies significantly improve power-sharing accuracy and resilience, they also introduce greater complexity and require careful tuning of parameters to ensure effective real-world implementation.

4.1.2.2 Synthetic inertia

One strategy to mitigate the frequency instabilities caused by the lack of inertia response from the renewable resources (RES) connected to the electric grid through power electronic converters is to provide Virtual or Synthetic Inertia to the system via these power electronic devices . The main objective of **Virtual Inertia control is to emulate the inertial response of the conventional synchronous generation (SG) by using an inverter and/or an energy storage system (ESS) equipped with an appropriate control algorithm**. This virtual control allows the power converter to dynamically adjust its active power output according to the rate of change of grid frequency (ROCOF), thereby contributing to frequency stabilization. Additional power should be supplied by the converter during the time interval between the occurrence of power imbalance and the activation of the primary frequency control, i.e., before the governor response takes effect (typically within 10s).

In systems without energy storage, the renewable generator must operate below the maximum power point (MPP) to provide virtual inertia, which compromises frequency regulation and introduces weather-dependency in the solution.

There are several strategies to model Virtual Inertia in power converters. [58] classifies the different strategies proposed in the literature as:

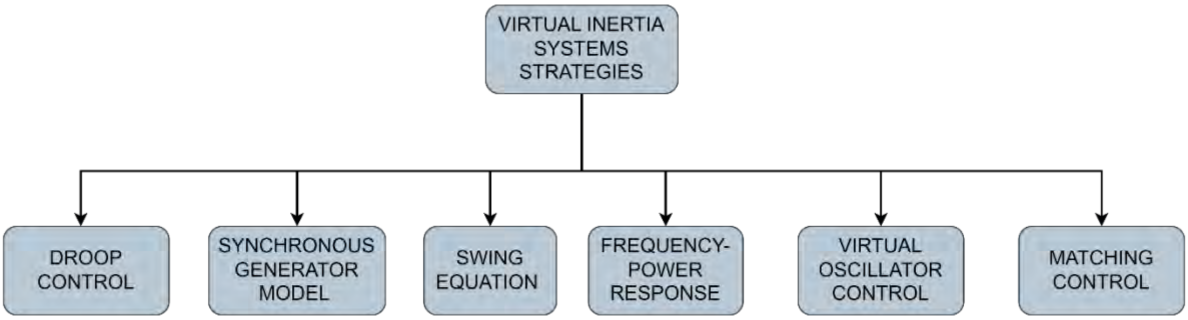

Figure 17. General classification of virtual inertia strategies.

Following, a few characteristics of these control strategies used to generate virtual inertia are listed:

- Droop control strategy: The control strategy uses a conventional droop controller along with low-pass filters to simulate the virtual inertia of the system.
- Synchronous generator model: A representative example of this type of topology is the *Synchronverter*. The Synchronverter is an inverter designed to emulate the dynamic behaviour of a conventional synchronous generator. The synchronverter can regulate both the voltage and frequency of the electric grid, and it consists of two fundamental components: the power stage and the control unit. Four primary blocks define the control unit: one for managing active and reactive power based on droop control, another for calculating power, a virtual impedance block and a current controller [70] . The details of the underlying control theory can be found in [71] . The synchronverter can be designed to operate in a self-synchronized mode, i.e., without relying on a phase-locked loop (PLL), which reduces system complexity and enhances overall performance [72] .
- Based on Swing equation: A representative example of this type of topology is *the Ise Lab's topology*. This technique emulates inertial response by evaluating the power-frequency swing equation at every control cycle [69] .
- Frequency-Power response: A representative example of this type of topology is the *Virtual Synchronous Generator* (VSG) [68] [72] [73] , which emulates the inertial behaviour of conventional synchronous machines by simulating the exchange of kinetic energy during power imbalances. In addition to providing frequency regulation, the VSG also enables dynamic frequency control, achieved through a control strategy that relies on the rate of change of the measured frequency [69] . The control structure is relatively simple and consists of two main loops: an outer power loop and an inner current/voltage loop. The outer power loop is responsible for replicating the mechanical performance of a synchronous generator, while the inner loop emulates its electromagnetic behaviour [68] . One of the disadvantages of this method is the sensibility to the noise that makes unstable the operation.
- Virtual Oscillator Control (VOC). This control strategy emulates the dynamics of nonlinear limit-cycle oscillators, such as Van der Pol, Dead Zone Oscillators or Andronov-Hopf oscillators, to achieve robust synchronization with the electric grid [67] [74] . It operates without the need for direct communication links, and its time-domain implementation enables fast frequency response, significantly enhancing performance compared to conventional droop control [75] .
- Matching Control. This method is focused on the relationship between the DC side and AC side of a power inverter. By measuring DC bus voltage at the inverter's DC side, this method assesses frequency stability on the AC side and facilitates active power control [76] .

Another approach to improving system stability is the online estimation of inertia under normal operating conditions. The literature identifies two main methods to estimate inertia in real time: probing signals-based methods and ambient measurements-based methods. The probing signals-based methods estimate the inertia by injecting small signal perturbations into the power system and analysing the frequency response during the disturbance. In contrast, the ambient measurements-based method uses the data provided by phasor measurement units (PMUs) to estimate the inertia. These methods typically employ state estimation techniques such as Least Square Method, N4SID or ARMAX (autoregressive moving average exogenous input) to perform this task. Once the inertia value is known, several corrective actions can be taken such as informing the control centre about the current grid conditions, enabling operators to anticipate potential contingencies, or adjusting the setpoints of FACTS devices to enhance system stability.

4.1.2.3 Advanced damping techniques to mitigate oscillations between AC and DC networks

Conventional synchronous generators damp low-frequency oscillations through the use of a control loop called Power System Stabilisers (PSS) that acts through the generator excitation system. The transition from conventional synchronous generators to renewable energy sources interfaced with the grid via power inverters has created the need for FACTS and renewable power plants to actively contribute to oscillation damping within the power system.

The Power oscillation damping (POD) control is designed to provide damping characteristics similar to those offered by the PSS in conventional synchronous generators. This type of control can be implemented in FACTS devices or in the Power Plant Controller (PPC) of a renewable power plant and applies uniform damping setting across all inverters within the plant. It receives input signals related to existing oscillation in the power system, including active power, voltage and frequency.

There are different POD control approaches that can be used to damp power system oscillations. One such strategy focuses on mitigating these oscillations by injecting both active and reactive power . In this approach, the POD-P and POD-Q modulation controls are integrated into the active and reactive power control loops of the PPC. These controls generate additional reference signals to the active and reactive power controllers (dP_POD and dQ_POD), respectively. This strategy offers the advantage of enhancing system stability margins, however the interaction between active and reactive control loops can have a negative impact on the overall damping performance .

Figure 18 illustrates a general diagram of the POD-P model implemented within the active power control loop of the PPC.

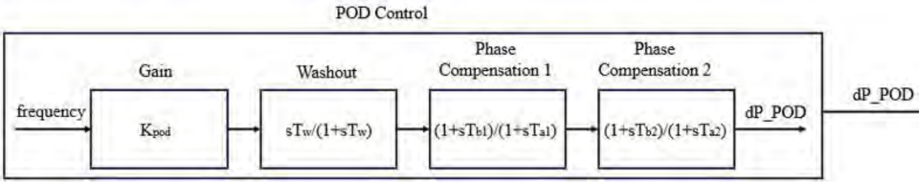

Figure 18. POD-P model diagram [80] .

Conventional local controllers are limited by the lack of visibility of the electric grid. The growing deployment of Phasor Measurement Units (PMUs) in the electric grid has improved real-time observability, enabling more effective detection and analysis of inter-area oscillations across the grid. In this context, wide area damping control systems (WADCs) offer great potential. A key factor to consider when using a WADCs is the time-delay associated with the wide-area measurements, as it can lead to systems instability [82] . As an example, [83] presents a WAC system that, using wide area measurements, improves the robustness of the grid through the integration of local controllers for

RES units and conventional generators. In addition, [84] details the design, implementation and commissioning of a WADC system in the China Southern Grid, which operates by modulating HVDC links and generator exciters. Field tests conclude that the coordination between WADC and HVDC systems can enhance damping ratios and increase power transfer capacity.

4.1.3 Relevant requirements for modern hybrid AC/DC grids

Next table shows the key requirements that should be met for the operation of modern hybrid AC/DC grids:

Table 5: Key technical requirements for modern hybrid AC/DC grids

ID	Focus Area	Requirement
R1.1	A1: Control methods for Power Electronics Converters	Deployment of adaptive control techniques to provide power-sharing between converters.
R1.2		Deployment of advanced control techniques to maintain voltage and frequency stability in the electric grid.
R1.3		Deployment of advanced control techniques that allows black start functionality and inertia emulation.
R2.1	A2: Damping oscillations	Implementation of wide-area control systems that make easier the detection and analysis of inter-area oscillations across the grid.
R3.1	A3: Communication and Data Management	Implementation of a communication network to ensure that the PMU client can access grid status information in a fast and secure manner.
R4.1	A4: Cybersecurity	Stablish cybersecurity protocols to prevent unauthorized personnel from accessing or modifying the information provided by the PMUs, in order to avoid compromising the inertia estimation process and, consequently, the stability of the system.

4.2 Adequacy, Security, and Reliability of Hybrid AC/DC Networks

Hybrid AC/DC networks combine the benefits of traditional AC grids with the advantages of DC grids, optimizing energy flow for modern and renewable energy applications. They can offer increased efficiency, greater compatibility with renewable energy sources (RES), and enhanced operational flexibility for loads. However, the hybrid nature of these systems introduces specific challenges in terms of adequacy, security, and reliability that need to be effectively addressed to ensure stable, efficient, and resilient grid operation. Below is a detailed analysis of these challenges and potential solutions.

4.2.1 Adequacy

Adequacy in modern power systems refers to the ability to provide sufficient generation capacity, energy storage, and supporting infrastructure to reliably meet electricity demand under a wide range of operating conditions [88] .

Ensuring adequacy in hybrid AC/DC grids, particularly those with high penetration of renewable energy sources (RES), presents a series of interconnected challenges. One of the primary concerns is the intermittency of RES, such as wind and solar power. These sources exhibit significant variability and unpredictability, often resulting in mismatches between electricity supply and demand. Managing this variability requires advanced grid management techniques capable of maintaining system balance in real time. In addition to generation-side variability, demand-side uncertainties—particularly those introduced by the widespread adoption of electric vehicles (EVs) and industrial direct current (DC) loads like electric arc furnaces and data centres—further strain grid adequacy. The stochastic nature of EV charging patterns and abrupt fluctuations in industrial DC loads complicate forecasting and demand management efforts.

Moreover, the system’s flexibility is constrained by the limitations of power electronic converters, such as Voltage Source Converters (VSCs). These devices, while essential for interfacing RES and DC loads with the grid, have limited overload capacity, reducing the system’s ability to handle sudden power surges and limiting its scalability in high-demand scenarios. Lastly, the complexity of planning hybrid AC/DC systems poses a substantial challenge. Determining the appropriate design and sizing of components like converters and energy storage systems involves careful trade-offs between cost, performance, and reliability. These decisions must also account for the uncertainties associated with renewable generation and evolving demand profiles.

To address the multifaceted challenges of ensuring adequacy in modern hybrid AC/DC power systems, a range of innovative solutions are being developed and deployed. These approaches aim to enhance grid flexibility, optimize resource utilization, and improve system resilience against variability in both supply and demand. One key solution lies in the deployment of Hybrid Energy Storage Systems (HESS). By combining technologies that serve different temporal needs—such as long-duration storage like batteries with fast-responding systems such as supercapacitors and flywheels—HESS can effectively buffer the variability of renewable energy sources (RES) and absorb demand spikes, such as those caused by electric vehicle (EV) charging. This hybrid approach helps to smooth out fluctuations and maintain power quality and stability across the grid.

Another crucial measure is the implementation of Demand-Side Management (DSM). Leveraging tools like dynamic pricing, smart contracts, and real-time consumption feedback, DSM encourages the flexible shifting of loads—particularly those from EVs and other controllable devices—to align with periods of high renewable generation. This not only alleviates stress on the grid during peak times but also improves overall energy efficiency and reduces curtailment of renewables. The complexity of hybrid system planning calls for Multi-Objective Planning Tools. Here, artificial intelligence (AI) and machine learning (ML) play a transformative role. These technologies enable planners to navigate trade-offs between multiple objectives—such as minimizing operational costs, reducing carbon emissions, and enhancing reliability—while also accounting for the stochastic nature of RES and load variability. Finally, Advanced Forecasting techniques, powered by data-driven ML models, significantly enhance the accuracy of predictions for both renewable generation and load profiles. Improved forecasting enables more effective generation dispatch, supports better reserve management, and minimizes the dependency on fossil-fuel-based backup generation, thereby promoting a cleaner and more reliable energy mix.

4.2.2 Security

Security in modern power systems encompasses the protection of the grid from both physical disruptions—such as short circuit faults and equipment's technical failures—and emerging cyber threats, including data breaches and false data injection attacks. As hybrid AC/DC architectures become more prevalent and renewable integration deepens, ensuring security has become increasingly complex and critical [89] [90] [91] .

One of the foremost challenges lies in DC fault propagation. Unlike AC faults, DC faults, such as pole-to-ground faults, escalate faster than AC faults due to the nature of DC current, potentially damaging critical equipment like converters before conventional protection systems can react. Equally concerning are cyber-physical vulnerabilities. The growing reliance on digital communication and control introduces risks such as communication delays, cyberattacks, and compromised protection coordination. For instance, false data injection attacks can mislead control systems, potentially trigger incorrect protective actions or mask real threats, thereby increasing the likelihood of cascading failures or widespread instability [92] .

Another challenge stems from low inertia in converter-dominated grids. With fewer synchronous generators in operation—due to the increased share of inverter-based resources—there is significantly less rotational inertia available. This makes the system more vulnerable to rapid frequency fluctuations during disturbances, requiring advanced control strategies and fast-acting frequency response mechanisms to maintain stability. Additionally, there is a notable protection mismatch between AC and DC systems. Traditional protection schemes, such as AC relays, are often not suitable for detecting and isolating DC faults. This creates challenges in designing a unified and effective protection strategy that can handle the distinct behaviours of AC and DC components within the same grid architecture.

To address the above-mentioned security challenges facing hybrid power systems, several advanced technological solutions are being developed and implemented, targeting both physical and cyber vulnerabilities. A critical advancement is the deployment of hybrid DC circuit breakers, particularly for HVDC systems. These fast-acting devices can interrupt DC faults in less than 5 milliseconds, effectively isolating faulted segments before damage propagates to vulnerable components such as converters. Their rapid response enhances system resilience and significantly mitigates the risks associated with DC fault propagation [93] [94] . On the cyber front, cyber-secure communication architectures are vital. The implementation of encrypted protocols, such as IEC 61850 with GOOSE (Generic Object-Oriented Substation Events) messaging, strengthens the reliability and security of protection signal exchange. Furthermore, leveraging blockchain technology for decentralized peer-to-peer energy transactions offers a tamper-resistant layer, ensuring data integrity and preventing unauthorized control actions within the hybrid grid infrastructure.

To overcome the challenges of low inertia in inverter-dominated networks, virtual inertia emulation has emerged as a promising solution. Through control algorithms like Virtual Synchronous Machine (VSM), power electronic converters can mimic the inertial response of traditional synchronous generators. When integrated with fast-response energy storage systems such as batteries or supercapacitors, these converters help stabilize frequency during disturbances, effectively bridging the gap created by the loss of mechanical inertia. Additionally, adaptive protection schemes powered by artificial intelligence are reshaping fault detection and response. These schemes dynamically tune protection settings based on real-time grid conditions—such as fluctuations in renewable output, load variability, or evolving fault characteristics. This adaptability enhances coordination and sensitivity in both AC and DC domains, ensuring reliable operation under diverse and rapidly changing system conditions.

4.2.3 Reliability

Reliability in the context of hybrid AC/DC power systems refers to the ability of the grid to maintain continuous and stable operation, even under abnormal or faulty conditions, without causing significant disruptions to end users. As power systems evolve to incorporate higher levels of renewable generation and power electronics, ensuring reliability becomes increasingly complex [95] [88] , [95] .

One of the most pressing challenges is the risk of cascading failures, particularly in systems where DC subsystems—such as HVDC converters—play a central role in interconnecting major grid regions.

Outages in these components can trigger widespread disturbances in adjacent AC networks, especially when those systems are heavily dependent on power injections through HVDC links or have high penetration of inverter-based resources (IBRs). These failures can quickly escalate, leading to instability in voltage and frequency, and in extreme cases, cascading blackouts.

Another concern is component degradation due to the operational demands placed on power electronic devices. Frequent switching operations contribute to accelerated aging and reduced lifespan of components. Over time, this degradation increases the likelihood of component failure and raises maintenance requirements and operational costs. Redundancy gaps further exacerbate reliability risks. A lack of sufficient backup infrastructure—such as redundant transmission lines or spare converter stations—limits the system’s ability to withstand individual component failures (i.e., N-1 contingencies). This makes the grid more vulnerable to disruptions and reduces its capacity to recover quickly following faults. Moreover, harmonic distortion introduced by power electronic interfaces poses a challenge to the reliable operation of AC subsystems. These harmonics can interfere with the stable operation of AC subsystems and reduce the efficiency of grid power transmission.

To address the reliability challenges inherent in hybrid AC/DC power systems, several innovative and proactive solutions have been proposed to enhance the grid's ability to operate continuously and withstand disturbances. One of the foremost strategies is the **mitigation of cascading failures through the use of real-time digital simulators (RTDS) and electromagnetic transient analysis software such as PSCAD**. These platforms enable detailed modelling of hybrid AC/DC grid behaviour under faulted conditions, allowing operators to identify vulnerable components and validate fault isolation schemes. By simulating various contingency scenarios, such tools support the development of robust protection and control strategies that can contain disturbances before they propagate.

Predictive maintenance is another crucial approach. By integrating Internet of Things (IoT) sensors with digital twin technologies, utilities can continuously monitor the operational health of critical components like power converters. These systems can detect anomalies and degradation trends in real time, enabling predictive diagnostics and maintenance scheduling. Such foresight not only reduces the risk of unexpected failures but also extends asset life and reduces operational costs.

To bolster system resilience under single contingencies, N-1 redundancy is essential. This involves incorporating redundant infrastructure such as DC lines and parallel converter configurations, particularly using fault-resilient technologies like Modular Multilevel Converters (MMCs). These redundant pathways ensure that power flow can be maintained even if a primary component fails, thereby enhancing the grid’s fault tolerance. In addition, active harmonic filtering plays a vital role in ensuring reliable grid operation, especially at the AC/DC interface where power electronics introduce significant harmonic content. Advanced filters based on power electronic devices can dynamically compensate for these distortions, thereby preserving power quality, protecting sensitive equipment, and maintaining overall grid performance.

4.2.4 Relevant requirements for modern hybrid AC/DC grids

To ensure stable, secure, and efficient performance, hybrid AC/DC grids must meet specific adequacy, security, and reliability requirements. Defining these needs is critical for guiding future planning, design, and control strategies.

Table 6 Requirements for modern hybrid AC/DC grids for adequacy, security and reliability

ID	**Focus Area**	**Requirement**
R5.1	A5: Adequacy	Deploy hybrid energy storage systems (HESS) that integrate both long-duration storage (e.g., lithium-ion or flow batteries) and short-duration high-power devices (e.g., supercapacitors or flywheels) to buffer renewable energy source (RES) variability and high-power demand spikes from electric vehicles (EVs). This layered storage architecture ensures both energy adequacy and fast dynamic response.
R5.2		Implement AI-driven demand-side management (DSM) frameworks capable of forecasting and dynamically shifting flexible loads, such as EV charging and HVAC systems. This enables the grid to proactively balance supply and demand, especially under high-RES penetration, and enhances operational efficiency and economic dispatch.
R6.1	A6: Security	Mandate the integration of hybrid DC circuit breakers capable of ultra-fast fault isolation (e.g. in less than 5 milliseconds) [96] [97] . These fast-acting devices are essential for preventing fault propagation and protecting sensitive power electronic equipment, particularly in meshed or multi-terminal DC grids.
R6.2		Deploy grid-forming converters (GFCs) equipped with Virtual Synchronous Machine (VSM) control algorithms to emulate the inertial response of synchronous generators. These converters enhance frequency stability in low-inertia, RES-dominated environments, and ensure grid resilience during disturbances and black-start conditions.
R7.1	A7: Reliability	Ensure N-1 redundancy in critical DC/AC components such as transmission corridors, converter stations, particularly in DC segments and interconnections. This redundancy is vital for maintaining system operability during single-contingency failures and supports uninterrupted power delivery in hybrid grid architectures.
R7.2		Adopt predictive maintenance frameworks utilizing digital twin models and real-time monitoring through IoT sensors. These systems provide early warnings of asset degradation, enabling condition-based maintenance strategies that enhance reliability, minimize downtime, and extend the lifespan of high-value infrastructure components.

4.3 Technical challenges associated with hybrid DC grid maturity

Hybrid DC grid maturity refers to the developmental stage at which hybrid DC grids (those that integrate both DC and AC systems) are in terms of their operational capabilities, reliability, technical standards, and integration with existing power systems. Hybrid DC grid maturity reflects a grid that is technically advanced, operationally efficient, and economically viable. It also ensures that the system is resilient, able to manage complexities like intermittent renewables, and well-prepared for integration into the broader energy ecosystem. A mature hybrid DC grid represents a well-established and optimized integration of AC and DC components that work seamlessly to deliver reliable, sustainable, and cost-effective power—efficiently incorporating renewable energy, energy storage, and other distributed energy resources (DERs) to meet modern energy demands. Table 7 outlines key aspects of hybrid DC grid maturity.

Table 7: Key enablers and characteristics of hybrid DC grid maturity

Category	Maturity

Technological Readiness [98] [99]	Advanced Control Systems: Sophisticated control algorithms for coordination between AC and DC components, ensuring reliable grid operations under various conditions (grid-connected and islanded modes).
	Power Flow Management: Advanced tools and optimization techniques to ensure efficient energy transmission between AC and DC subsystems while maintaining voltage and frequency stability.
Operational Efficiency [100] [101] [102]	Power Sharing: Efficient power-sharing mechanisms, such as droop control, to balance power between AC and DC subsystems, ensuring that power is distributed based on the availability of renewable resources, demand, and energy storage.
	Stability and Resilience: Ability to maintain stable operation with intermittent renewable energy sources and fast, reliable protection mechanisms to handle disturbances or faults.
Infrastructure Integration [103]	Interoperability with AC Grids: Smooth integration with existing AC networks, enabling seamless transitions between grid-connected and islanded modes without significant disturbances.
	Compatibility with Energy Storage and Renewables: Integration with diverse renewable energy sources and energy storage technologies to optimize real-time system stability and efficiency.
Standardization and Regulation [103]	Development of Standards: Adoption of standardized protocols for voltage levels, protection mechanisms, and operational procedures to improve system coordination and ensure reliability.
	Regulatory Support: Evolving regulatory frameworks to support hybrid DC grids’ widespread adoption while ensuring compliance with grid codes and technical standards.
Cybersecurity and Protection [103] [104] [106] [107] [108]	Advanced Protection Systems: Development of advanced protection strategies to manage both AC and DC faults, including solutions for bidirectional current flows and rapid fault isolation.
	Cybersecurity Measures: Robust cybersecurity systems to protect against attacks, ensuring the grid's resilience amidst increasing digital integration.
Economic and Environmental Viability [109]	Cost-Effectiveness: Balancing the costs of infrastructure, energy storage, control systems, and maintenance while maximizing efficiency and reducing operational costs.
	Sustainability: Optimized energy use, including maximizing the incorporation of renewable energy sources and minimizing losses, making the grid more sustainable.

4.3.1 *Challenge*

The challenges in achieving hybrid DC grid maturity are diverse and multifaceted, touching upon technical, operational, regulatory, and economic aspects. These challenges must be addressed to ensure the successful integration of hybrid AC/DC grids into the existing energy infrastructure. Some of the key challenges include:

1. Technical Challenges

One of the primary technical challenges lies in the **integration of AC and DC systems**, as these two infrastructures possess inherently different electrical characteristics. Coordinating their operation within a unified hybrid grid demands advanced control strategies to manage power sharing, voltage regulation, and dynamic stability. Another critical challenge is **power flow management**, particularly given the increasing penetration of intermittent renewable energy sources such as solar and wind [110] . Balancing the fluctuating input from these sources across interconnected AC and DC networks requires efficient real-time coordination to prevent instability and ensure overall system reliability and resilience. Fault detection and isolation in DC systems presents additional complexity. Fault currents in DC systems behave differently from those in AC systems, making it difficult to implement traditional protection schemes. DC fault currents rise quickly and have no natural zero crossing, making fault isolation challenging and increasing the risk of converter damage. Moreover, **bidirectional current flow in DC microgrids—especially those with meshed or ring configurations—further complicates protection strategies**. Traditional protection schemes are often unfit for handling reverse current directions, necessitating the development of advanced, communication-assisted methods to detect and isolate faults promptly and accurately. Additionally, the absence of natural inertia in converter-dominated DC grids, especially those reliant on renewables, poses challenges for frequency regulation. In both grid-connected and islanded modes, the lack of rotational inertia makes these systems more vulnerable to disturbances. Although virtual inertia emulation is being explored, fully replicating the stabilizing effects of conventional synchronous machines remains an ongoing area of research and development.

2. Control and Stability Issues

Control and stability represent critical dimensions in the operation of hybrid AC/DC grids, introducing a range of challenges that stem from their inherent structural and operational complexity. One of the foremost issues is the complexity of control required to manage these systems. Given the need to coordinate multiple subsystems—AC and DC networks, distributed energy resources, and energy storage—control architectures must be advanced, typically hierarchical, and highly adaptive. These systems are expected to respond dynamically to changing grid conditions, ensuring stable operation under both steady-state and transient scenarios. Another major challenge is the seamless transition between grid-connected and islanded modes. This process involves maintaining voltage and frequency stability during mode shifts, which is particularly difficult when renewable energy sources contribute significant variability. Effective transition control must be capable of managing abrupt changes in power flow and system topology without introducing service disruptions or compromising system integrity. Developing robust and responsive control strategies for this purpose remains a key requirement in the advancement of hybrid grid technologies.

3. Economic and Financial Challenges

Economic and financial considerations play a crucial role in the development and deployment of hybrid AC/DC grids, presenting a set of challenges that can hinder widespread adoption. One of the most prominent issues is the high initial capital cost. Establishing hybrid grid infrastructure—including converters, energy storage systems, and advanced control platforms—requires substantial upfront investment. This financial barrier can be especially limiting in regions with constrained budgets or competing infrastructure priorities. Another significant challenge lies in economic dispatch and market integration. For hybrid DC grids to function efficiently, they must optimize power generation and consumption while coordinating diverse energy sources, including renewables and conventional generators. Furthermore, integrating these hybrid systems into established electricity markets demands sophisticated scheduling and dispatch mechanisms that account for the operational intricacies of both AC and DC networks.

Moreover, the cost of protection and control systems adds another layer of economic burden. Unlike traditional grids, hybrid AC/DC systems require fast, intelligent, and highly reliable protection and control architectures tailored to their unique behaviour. The design and deployment of such systems involve considerable expense, making cost-effective innovation in this area essential for the economic viability of hybrid grid solutions.

4. Regulatory and Standardization Challenges

Regulatory and standardization issues represent a critical hurdle in advancing the maturity and deployment of hybrid AC/DC grids. A primary concern is the lack of standardized regulations, which poses a substantial barrier to interoperability and scalability. Unlike traditional AC systems, hybrid grids require new standards for voltage levels, protection mechanisms, communication protocols, and interconnection practices between AC and DC components. The absence of such standards can hinder the widespread adoption of hybrid AC/DC grids. Compounding this issue is the complex regulatory environment in which hybrid grids operate. These systems intersect multiple domains—AC and DC infrastructure, renewable energy integration, and energy storage technologies—each governed by distinct regulatory frameworks. Navigating this complex regulatory landscape and ensuring compliance with multiple standards is a significant challenge for grid operators. Furthermore, grid codes need to be updated or developed to accommodate the unique characteristics of hybrid AC/DC grids. This includes defining operational guidelines, fault detection and isolation protocols, and integration procedures for renewable energy sources and energy storage systems.

5. Cybersecurity and Communication

Cybersecurity and communication introduce additional challenges in the deployment and operation of hybrid AC/DC grids due to their reliance on digital infrastructure for control, monitoring, and coordination. One of the primary concerns is their vulnerability to cyber-attacks. As these grids increasingly depend on digital communication for real-time operations, they become potential targets for threats such as data breaches, false data injection, and denial-of-service attacks. Such cyber intrusions can compromise operational security, disrupt power flows, and even lead to large-scale grid instability. To mitigate these risks, it is essential to implement robust cybersecurity frameworks that include encryption, intrusion detection systems (IDS), secure authentication protocols, and resilience-enhancing network architectures. In parallel, communication and data management represent another layer of complexity. Hybrid AC/DC systems rely on high-speed, reliable communication to synchronize diverse control systems, coordinate protection schemes, and manage power flows across AC and DC subsystems. Any delay or failure in communication can compromise system stability or delay critical protection responses. Furthermore, the vast amount of real-time data generated by these systems requires efficient and scalable data management solutions. Addressing these challenges calls for investment in secure and low-latency communication networks, advanced data analytics platforms, and resilient control architectures capable of handling high-throughput information streams in a secure and coordinated manner.

6. Protection and Fault Management

Protection and fault management pose fundamental challenges to the reliable operation of hybrid AC/DC grids due to the inherent differences in fault behaviour between AC and DC systems. A key issue is the development of hybrid fault protection schemes capable of accurately detecting and isolating both AC and DC faults. Unlike AC faults, DC fault currents rise rapidly and lack natural zero crossings, making traditional AC protection mechanisms ineffective. This necessitates the design of new protection algorithms and devices that can address the unique dynamics of each domain while coordinating their operation to avoid false trips or missed fault detections. The risk of cascading failures is particularly pronounced in hybrid systems, not only due to failure propagation across interconnected AC and DC networks, but also because of outages in critical interconnecting components, such as DC links or power converters. A failure in one of these elements can disrupt the power exchange between subsystems, destabilize voltage and frequency profiles, and trigger a sequence of failures throughout the grid. This interdependency requires carefully coordinated protection strategies capable of isolating faults swiftly while maintaining overall system stability. In addition, enhancing system resilience remains a priority. Hybrid AC/DC grids must be equipped with fast-acting protection and recovery mechanisms to handle operational disturbances and external hazards such as extreme weather or cyber intrusions. This includes the ability to quickly isolate affected sections, restore normal operation, and maintain stability in the presence of renewable energy fluctuations or equipment failures. Developing such resilient protection architectures is essential for ensuring the security and continuity of supply in future power systems.

7. Energy Storage and Renewable Integration

Energy Storage and Renewable Integration present other challenges in the operation of hybrid AC/DC grids. While Energy Storage Systems (ESS) play a vital role in enhancing grid stability and flexibility, their integration poses complexities related to optimal sizing, strategic placement, and real-time management. ESS must reliably support the grid during periods of low renewable generation and handle charge-discharge cycles in a way that maintains system efficiency and prolongs asset lifespan. Simultaneously, the inherent variability and intermittency of renewable energy sources like solar and wind complicate grid balancing. Accurate forecasting and responsive control strategies are essential to manage these fluctuations, ensuring a seamless match between energy supply and dynamic demand across both AC and DC subsystems.

4.3.2 State-of-the-art solutions

The state-of-the-art solutions for addressing the challenges of Hybrid AC/DC grids are advanced and multifaceted, involving innovations in control systems, protection strategies, grid integration, and technological advancements in power electronics and energy storage. These solutions aim to enhance the reliability, stability, and efficiency of hybrid grids while addressing the specific challenges of integrating AC and DC systems. Advances in power electronics, control systems, protection strategies, and data management are central to the development of reliable, efficient, and resilient hybrid grids. The continued evolution of these solutions, in conjunction with advancements in cybersecurity, regulatory frameworks, and market integration, will be essential for achieving the maturity of hybrid AC/DC grids. Some of the most notable solutions are outlined below:

1. Advanced Control and Stability Solutions

Hierarchical control systems (illustrated in Figure 19 and Figure 20) enable structured coordination across multiple control layers, which is essential for operating modern hybrid AC/DC grids [111] [112] [113] . These systems typically include a high-level supervisory layer responsible for system-wide optimization and decision-making, and a low-level layer focused on the real-time management of power electronic converters. This layered architecture allows for efficient power sharing, enhanced grid stability, and seamless transitions between grid-connected and islanded modes. Control strategies within this hierarchy can be categorized as centralized, decentralized, or distributed. Centralized control, conceptually illustrated in Figure 21, offers global optimization but may face challenges related to communication delays and vulnerability to single points of failure. In contrast, decentralized control, conceptually illustrated in Figure 22, allows for fast, local responses using locally available data, though it may lack holistic coordination. Distributed control, conceptually illustrated in Figure 23, presents a hybrid solution, where local controllers share information and collaborate to achieve system-wide objectives, offering both scalability and robustness. An advanced example of hierarchical implementation is Model Predictive Control (MPC). MPC facilitates real-time, predictive adjustments of power converter behaviour by forecasting future grid states and dynamically optimizing control actions. This approach is particularly effective in managing the variability of renewable energy sources, ensuring stable operation, minimizing losses, and maintaining optimal power flow across the hybrid network [114] [115] [116] .

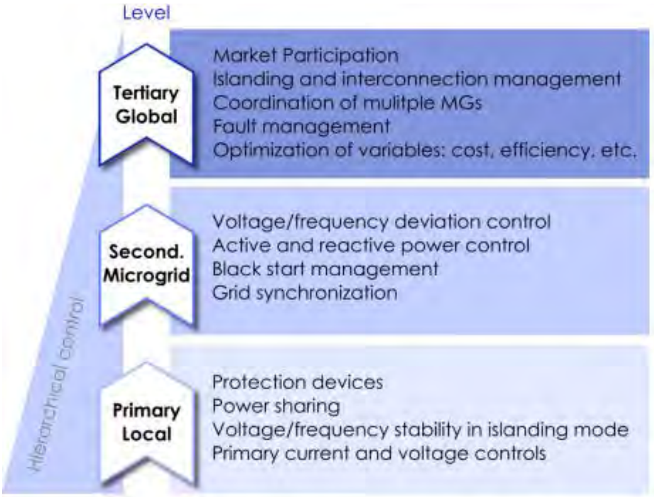

Figure 19: Main functions of control levels of a hierarchical control architecture [117] .

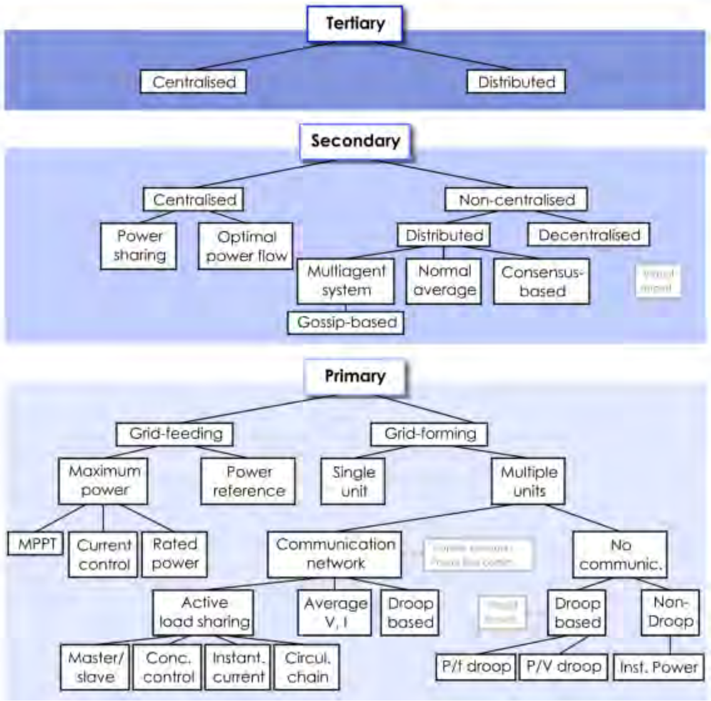

Figure 20: Classification of different types of microgrid control strategies based on the hierarchical architecture [117] .

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HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

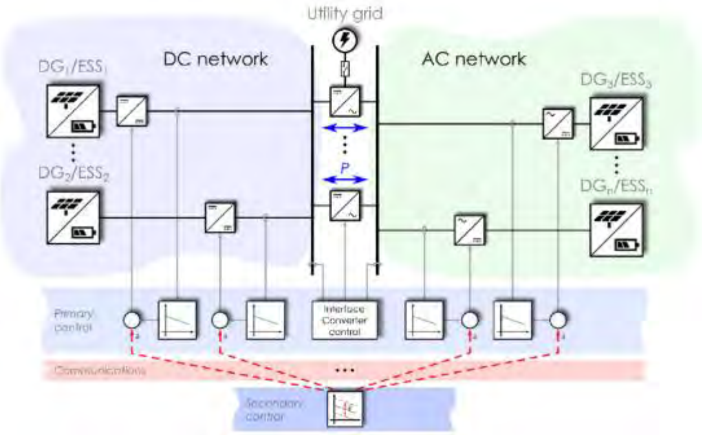

Figure 21: Concept of the centralized secondary control [117] .

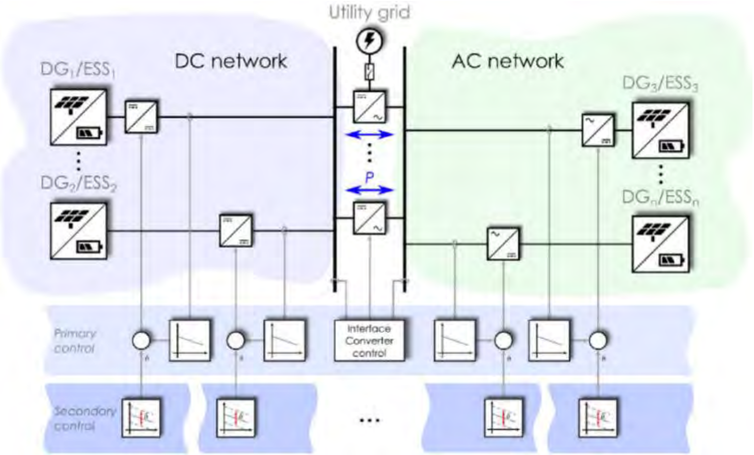

Figure 22: Concept of the decentralized secondary control [117] .

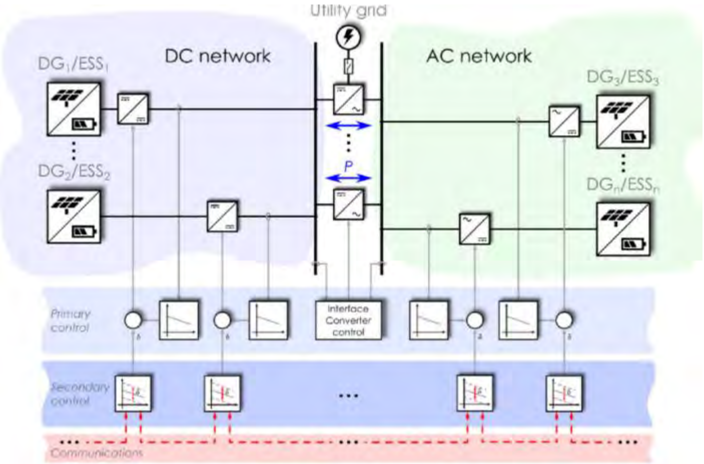

Figure 23: Concept of the distributed secondary control strategy [117] .

Moreover, hybrid AC/DC grids, especially those powered by renewable sources, face a significant challenge due to the absence of natural inertia, a feature typically provided by traditional synchronous machines in AC systems. To address this, advanced control strategies, such as virtual inertia, are being implemented. This is achieved by using energy storage systems (ESS) or power converters to dynamically respond to frequency fluctuations and stabilize the grid. One key example of this approach is the use of Virtual Synchronous Machines (VSMs) in DC grids. VSMs emulate the behaviour of synchronous generators, providing frequency regulation in a similar way to AC grids. This not only enhances grid stability but also ensures reliable operation despite the intermittent nature of renewable energy sources [118] [119] [120] [121] .

2. Protection and Fault Management Solutions

In hybrid AC/DC grids, traditional protection schemes designed for AC systems are not effective due to the absence of zero-crossing points in DC fault currents. New protection schemes are being developed using communication-based protection that leverages real-time data from grid sensors to detect faults more accurately and isolate them quickly. One example of this is adaptive protection schemes, which use synchronized measurements, such as those provided by Phasor Measurement Units (PMUs), to detect and isolate faults in hybrid AC/DC grids more rapidly. These schemes can dynamically adjust protection parameters based on real-time grid conditions, improving the speed and accuracy of fault management.

In hybrid AC/DC grids, traditional protection schemes designed for AC systems are ineffective due to the absence of zero-crossing points in DC fault currents. As a result, new protection solutions are being developed, which rely on communication-based protection. These systems use real-time data from grid sensors to detect faults more accurately and enable quick isolation, ensuring greater reliability and safety for the grid. One example of this is adaptive protection schemes, which use synchronized measurements, such as those provided by Phasor Measurement Units (PMUs), to detect and isolate faults in hybrid AC/DC grids more rapidly. These schemes can dynamically adjust protection parameters based on real-time grid conditions, improving the speed and accuracy of fault management [122] .

Additionally, hybrid fault management techniques are being developed to handle both AC and DC fault conditions effectively. These techniques incorporate fault current limiters (FCLs) and solid-state circuit breakers that can operate in milliseconds, preventing significant damage to equipment and minimizing the risk of cascading failures. A notable example is hybrid circuit breakers, which combine mechanical and solid-state components to interrupt fault currents in both AC and DC networks, offering fast fault isolation without causing system instability [6] .

3. Power Electronics and Energy Conversion

Power converters are central to the operation of hybrid AC/DC grids, enabling the conversion between AC and DC and controlling power flow. The development of high-efficiency, high-power density converters has been a significant advancement. These converters reduce losses, increase system efficiency, and support flexible power flow management. For instance, multilevel converters such as Modular Multilevel Converters (MMC) and Cascaded H-Bridge Converters (CHB) are commonly used in HVDC (High Voltage DC) systems. These converters offer improved efficiency and flexibility, making them ideal for hybrid grid applications. Furthermore, advanced DC-DC converters are key to integrating energy storage systems (ESS) into hybrid grids. These converters enable efficient bidirectional power flow and dynamic voltage regulation, supporting energy storage to provide stability and backup during periods of high renewable energy variability. Bidirectional DC-DC converters, in particular, allow for quick charging and discharging, helping to balance power supply and demand effectively [6] .

4. Energy Storage Integration

The integration of hybrid energy storage systems combining both batteries and supercapacitors is a state-of-the-art solution for providing grid stability. These systems offer both long-term energy storage (for periods of low renewable generation) and short-term high-power support (for rapid frequency regulation and smoothing renewable generation). Li-ion batteries paired with supercapacitors or flywheels are being deployed in hybrid grids to provide fast response times for frequency regulation and longer-term energy storage to manage renewable energy variability. Optimization algorithms are being developed to manage energy storage and its interaction with power converters. These algorithms help determine when to charge and discharge energy storage systems, optimizing grid performance and minimizing operational costs. Optimization-based dispatch algorithms are employed to control the storage and release of energy in hybrid grids, ensuring that energy storage systems are used effectively to balance supply and demand [6] .

5. Renewable Energy Integration

Advanced forecasting tools enable predicting renewable generation from sources such as solar and wind. These tools use machine learning algorithms to predict generation patterns based on weather data and historical trends, improving grid operations by reducing uncertainty in power generation. Moreover, advanced power flow optimization techniques can be used to integrate large amounts of renewable energy into hybrid AC/DC grids. These techniques include distributed optimization and coordinate control strategies that ensure efficient power flow management between renewable energy sources, storage systems, and the grid. Decentralized optimization algorithms, such as consensus-based algorithms, are used in hybrid grids to coordinate the operation of distributed renewable generators, ensuring that energy is dispatched efficiently across the grid [123] [124] .

4.3.3 Relevant requirements for modern hybrid AC/DC grids

The requirements for modern hybrid AC/DC grids are diverse and comprehensive, addressing challenges in power flow management, stability, fault protection, renewable energy integration, and cybersecurity. Meeting these requirements is essential to ensure that hybrid grids can efficiently and reliably operate, offering benefits such as enhanced grid stability, better integration of renewable energy, and improved system flexibility. As technology continues to evolve, these requirements will need to adapt to meet the growing demands of modern power systems. Table 8 outlines the key requirements that must be met for the successful deployment and operation of modern hybrid AC/DC grids:

Table 8 Key technical requirements for modern hybrid AC/DC grids

ID	Focus Area	Requirement
R8.1	A8: Power Flow Management and Coordination	Efficient, real-time power flow management through advanced control algorithms (e.g., Model Predictive Control (MPC), Distributed Energy Resource (DER) management) to balance AC and DC power exchanges.
R9.1	A9: Grid Stability and Reliability	Deployment of advanced control systems (e.g., virtual inertia, frequency control through storage systems) to ensure both frequency and voltage stability in the grid.
R9.2		Black start solutions for hybrid AC/DC systems, leveraging energy storage or other distributed generation resources.
R10.1	A10: Protection and Fault Management	Development and deployment of hybrid protection schemes that can respond rapidly to AC and DC faults, ensuring minimal disruption and damage to the system.
R10.2		Real-time fault detection and rapid isolation protocols, integrating smart grid technologies and communication-based protection.
R11.1	A11: Integration of Renewable Energy Sources	Advanced forecasting, real-time power flow management, and integration strategies for renewable generation. The grid should be capable of balancing intermittent renewable power with flexible energy storage and backup generation.
R11.2		Efficient and scalable energy storage (e.g. batteries, supercapacitors, and flywheels) integration that supports fast frequency regulation, voltage control,

ID	Focus Area	Requirement
		and peak load management (by storing excess renewable energy and providing backup power during periods of low generation or high demand).
R12.1	A12: Power Electronics and Converter Technology	Deployment of high-efficiency, high-power-density converters that minimize energy losses, support high-voltage operations, and provide flexible control of power flow between AC and DC systems (such as voltage source converters (VSCs) and Modular Multilevel Converters (MMC).
R12.2		Power converters that allow bi-directional energy flow with high efficiency and fast response times to ensure the stability and reliability of the hybrid grid.

4.4 Sizing and planning of fine mesh hybrid networks

This section discusses the key technical challenges of optimal AC/DC integration, surveys state-of-the-art solutions (from advanced planning tools to real-world projects by industry leaders), and derives requirements to guide modern hybrid grid design and demo implementations.

4.4.1 *Challenge*

Designing an optimal hybrid AC/DC system requires careful consideration of interoperability, control, protection, and scalability across multiple voltage levels. Major challenges include:

- **Interoperability and multi-vendor integration:** Ensuring equipment from different vendors (converters, control systems, protection devices) operates seamlessly is non-trivial. A lack of standardized interfaces and grid codes for hybrid AC/DC systems hinders interoperability. For instance, multi-terminal DC systems at medium- and low-voltage levels currently lack common standards, making cross-border or multi-vendor integration difficult [127] . Furthermore, hybrid systems often require co-simulation platforms to test interaction between equipment types, yet these simulation frameworks still lack universally accepted data models for DC components. This lack of interoperability increases both the engineering effort and the risk of failure during integration.
- **Control complexity and stability:** AC and DC systems have fundamentally different dynamic behaviours. In traditional AC systems, frequency serves as the global indicator of power balance and inertia plays a key role in damping oscillations. In contrast, DC systems rely on tightly regulated voltage control without frequency, and power electronic converters introduce little or no inertia into the grid. As converters replace synchronous machines, power systems are increasingly prone to small-signal and transient instabilities. This is especially critical in hybrid systems, where AC and DC controls must interact—often without a common frequency reference. If not properly coordinated, converter control loops can enter into harmful interactions, causing instability or suboptimal performance. Grid-forming converters are emerging as a solution, yet they bring new complexities in tuning and interoperability. One of the most critical challenges in hybrid AC/DC networks is the **coordination of control strategies across AC and DC domains** [6] . AC networks rely on synchronized voltage and frequency signals, while DC systems operate independently of frequency, requiring different control objectives. The **interlinking converters** must manage power flow bidirectionally, ensure voltage regulation, and maintain stable operation in both grid-connected and islanded modes. Uncoordinated operation of those may lead to power quality degradation, instability, and circulating currents between subsystems.
- **Protection and fault coordination:** One of the most challenging issues in implementing a hybrid network is the development of a reliable protection scheme. Integrating distributed generation, particularly those based on inverters, introduces additional protection challenges due to the limited current contribution caused by interfacing converters. Additionally, the interconnection of microgrids with different characteristics complicates the protection system since both MG sides

behave differently during fault conditions. DC faults propagate rapidly and lack the natural zero-crossing present in AC systems, making traditional overcurrent or impedance-based protection schemes ineffective. Research has proposed several advanced techniques—such as travelling wave detection, voltage derivative analysis, and wavelet transform-based relays—to improve fault detection and selectivity. However, protection coordination between AC and DC zones is still an open challenge, especially in meshed or interconnected networks, where bidirectional fault paths must be considered.

- **Scalability and modularity:** As hybrid systems grow, challenges emerge in network planning, reconfigurability, and topological scalability. AC–DC coupled topologies may suffer from complex fault paths, multiple conversion stages, and unstable power flows if not properly managed. Studies show that system expansion planning must include converter placement, line conversion decisions, and modular expansion capacity to maintain reliability and cost-effectiveness

4.4.2 State-of-the-art solutions

Despite the existing challenges, recent innovations in planning methodologies, power electronics, and pilot projects are paving the way for robust mesh hybrid networks. Key state-of-the-art solutions include advanced design tools, optimized converter deployment strategies, modular hardware architectures, and practical demonstrations of meshed AC/ DC systems

- **Smart planning tools**: Modern planning of AC/DC networks leverages powerful software and simulation tools to handle the added complexity. **Digital twin** technology is increasingly used to create a real-time virtual model of the grid, enabling scenario testing and optimization before physical deployment. For instance, digital twin frameworks for DC microgrids have been developed to provide real-time monitoring and predictive control, using modular forecasting to maintain stability under dynamic conditions [128] . Such virtual replicas combined with AI-driven analytics allow engineers to anticipate issues (like thermal overloads or voltage instability) and evaluate control strategies in a risk-free environment. In parallel, **AI and advanced optimization algorithms** assist in network planning. Sophisticated techniques (e.g. mixed-integer linear programming or evolutionary algorithms) can determine where to best integrate DC links or converters in an AC grid [129] . A planning model for hybrid AC/DC microgrids is presented in [130] , which determines the optimal allocation of DC feeders. The objective of the model is to minimize overall investment and operation costs, including investments in DER, converters, distribution lines, and microgrid operation, while ensuring the reliable operation of DC feeders. The problem is formulated as a mixed integer second-order cone programming (MISOCP) or mixed integer linear programming (MILP) problem, allowing for efficient optimization of the placement of DC feeders. This optimization aims to supply DC loads economically and securely within the hybrid AC/DC microgrid. In [131] , a planning model is presented that proposes a flexible investment strategy to address long-term development uncertainties. This strategy involves dynamic investment decisions that can be adjusted over time to account for new information as it becomes available.
- **Converter and Power Electronic Device Placement:** Research efforts (and some utilities) use optimal power flow and sensitivity analysis to pinpoint high-impact nodes for converter placement. Converters can act as flexible coupling points – for instance, an HVDC back-to-back at a network interface can control power flows between regions or limit fault propagation. Planners evaluate metrics like reduced line overloads, improved voltage profiles, and short-circuit level reduction when testing various converter locations. Multi-objective algorithms now consider technical gains and cost, finding a Pareto-optimal set of converter additions [129] . This **smart**

placement ensures each added AC/DC converter yields maximal network support (e.g. mitigating a specific congestion or providing path-diversity for RES). At the transmission level, planners identify congested corridors where converting AC lines to HVDC or adding parallel HVDC links yields significant gains. A notable example is Germany’s UltraNet project, where one circuit of a 380 kV AC double-circuit line is converted to 380 kV DC. This conversion will enable ~2 GW of wind power transfer from north to south over the same right-of-way[29]. By reusing existing towers and routes, hybrid AC/DC corridors like UltraNet significantly increase capacity without new lines, offering a smart placement of HVDC where AC was bottlenecked. Another example is the UK’s Angle-DC project, which converted a 33 kV AC feeder to 27 kV DC to link two distribution networks. The result was a ~23% increase in transfer capacity under existing thermal limits, showcasing how inserting a medium-voltage DC link can relieve stress on rural distribution systems. It is state-of-practice to co-locate power electronics with RES plants or microgrids that inherently produce or use DC. For example, linking a large solar farm via an MVDC connection directly into a DC collector grid can avoid unnecessary AC/DC conversions. In microgrids, the placement of converters at points of common coupling to the main grid or between AC and DC sub-networks is optimized to allow **quasi-independent** operation. The EU project TIGON[30] is demonstrating this by building hybrid AC/DC microgrids where solid-state transformers (SSTs) and DC/DC converters are placed at the interface of local PV, battery, and AC utility supply

- **Ensure for scalability and modular expansion of HVDC/MVDC/LVDC systems without major overhauls, support meshed DC networks:**
  - **Modular Multilevel Converters (MMC):** MMC VSC technology is now the industry standard for HVDC and MVDC, providing a flexible building block that can scale in voltage and power by stacking submodules. VSC-based HVDC allows independent control of active and reactive power and even black-start capability for islands. Today’s MMC stations (by ABB, Siemens, GE, etc.) are designed to be modular – multi-gigawatt HVDC converter stations can be built as a series of identical racks or cubes, simplifying scaling and maintenance. This modularity extends downwards: medium-voltage DC links often employ modular converters or even **multi-port converters** that can interface several feeders.
  - **Solid-State Transformers and DC/DC Converters:** At distribution and microgrid scale, solid-state transformers (SSTs) and high-power DC/DC converters provide the backbone for AC/DC coupling. SSTs are power electronic transformers that directly convert between MVAC, MVDC, and LVDC, offering a compact and controllable interface. Likewise, DC/DC converters (often based on modular multilevel or resonant designs) allow interconnection of different DC voltage levels (HVDC to MVDC, MVDC to LVDC), forming multi-level DC networks.
  - **Meshed Topologies and DC Switchgear:** To support fine-mesh networks, power equipment has evolved to handle multi-node configurations. On the DC side, **fast HVDC circuit breakers** (using hybrid semiconductor designs) have been prototyped by ABB, Mitsubishi and others, and were successfully tested in projects like PROMOTioN[31]. These breakers, along with DC disconnectors and protection IEDs, allow for sectionalizing a DC grid much like AC substations do in AC grids. Gas-insulated switchgear (GIS) for HVDC is also being developed and long-duration tested, making it feasible to have compact DC hubs and switchyards. Commercial

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[29] https://new.abb.com/news/detail/11828/convert-from-ac-to-hvdc-for-higher-power-transmission#:~:text=A%20further%20conversion%20example%20is,be%20increased%20by%2035%20percent

[30] https://www.efacec.com/wp-content/uploads/2025/01/Ficha_Projeto_TIGON.pdf#:~:text=The%20EU%20project%20TIGON%20will,in%20the%20residential%20and%20urban.

[31] https://www.hvdccentre.com/innovation-projects/promotion-testing-the-feasibility-of-meshed-dc-grids-protection/#:~:text=PROMOTioN%20is%20focused%20on%20the,delivered%20within%2016%20work%20packages.

vendors are now offering *“DC grid”* packages: ABB (Hitachi Energy) has delivered a four-terminal ±500 kV VSC-HVDC system in China’s Zhangbei project[32], which came with the necessary modular converters and DC grid control to operate as a ring network.

4.4.3 Relevant requirements for modern hybrid AC/DC grids

Following the above-mentioned state-of-the-art, we outline a set of key technical requirements for future hybrid AC/DC grids. These requirements are grouped in focus area serving as guidelines to ensure scalability, modularity, protection, control, and interoperability in mesh topologies:

Table 9 Key requirements for modern hybrid AC/DC grids considering scalability, modularity, protection, control, and interoperability

ID	Focus Area	Requirement
R13.1	A13: Control & stability	Intelinking converters must support coordinated control across AC and DC subsystems for bidirectional power flow, voltage regulation, and seamless model transitions.
R14.1	A14: Protection & fault management	Develop protection schemes capable of detecting and isolating DC faults and coordinated AC/DC protection strategies to ensure selective, reliable fault isolation in hybrid scenarios.
R15.1	A15: Scalability & planning	Planning tools must support scalable hybrid AC/DC topologies using long-term multi-energy optimization framework, while enabling reconfigurability and support future-proof designs through scalable converter placements and flexible planning methodologies.
R16.1	A16: Communication & interoperability	Ensure real-time, low-latency communication between controllers using standardized protocols, while guaranteeing interoperability across multi-vendor converter systems via harmonized control and communication standards.
R17.1	A17: RES & energy management	Conduct studies including scenarios covering multi-energy system operational cases, use advanced optimization algorithms for hybrid energy dispatch under nonlinear constraints including predictive dispatch and scheduling capabilities for RES and storage integration.

4.5 Summarized requirements for hybrid AC/DC grids

In the above sections, the requirements corresponding to each identified challenge were defined and analysed in detail, based on state-of-the-art solutions that are either applied in real-life demonstrations or proposed in the literature. As expected, the four main challenge categories namely: (1) Stability Management in Power Electronics-Dominated Systems, (2) Adequacy, Security, and Reliability of Hybrid AC/DC Networks, (3) Hybrid DC Grid Maturity, and (4) Sizing and Planning of Fine

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[32] https://www.nsenergybusiness.com/projects/zhangbei-vsc-hvdc-power-transmission-roject/#:~:text=The%20Zhangbei%20high,a%20rated%20voltage%20of%20%C2%B1500kV.

Mesh Hybrid Networks, include overlapping requirements and focus areas. In this section, a summary of the challenges categories along with the corresponding requirements identified in the previous analysis is provided in Table 10.

Table 10: Summarized challenges and requirements

ID	**Category**	**Requirement**
R1.1, R1.2, R1.3, R8.1, R9.1, R13.1	**C1: Advanced Control and Stability**	Deployment of adaptive and advanced control techniques (e.g., MPC, DER management) to provide power-sharing, ensure voltage/frequency stability, enable black start and inertia emulation, and coordinate bidirectional power flow in hybrid AC/DC systems.
R2.1	**C2: Oscillation Damping**	Wide-area control systems for detection and analysis of inter-area oscillations across the grid.
R3.1, R16.1	**C3: Communication and Interoperability**	Implementation of real-time, low-latency communication networks using standardized protocols to support secure PMU access and interoperability across multi-vendor converter systems.
R4.1	**C4: Cybersecurity**	Implementation of cybersecurity protocols to protect data integrity and prevent unauthorized access or manipulation of grid information, particularly for PMU-based applications.
R5.1, R11.2	**C5: Hybrid Energy Storage Systems (HESS)**	Integration of layered storage systems combining long-duration and high-power devices to manage RES variability, frequency regulation, and peak load demands.
R5.2, R17.1	**C6: Energy and Demand Management**	AI-driven DSM frameworks and predictive dispatch/scheduling for flexible loads and RES/storage integration under multi-energy scenarios.
R6.1, R14.1, R10.1, R10.2	**C7: Protection and Fault Management**	Development of hybrid AC/DC protection schemes including fast-acting DC breakers, real-time detection/isolation protocols, and coordinated fault management strategies.
R6.2, R9.2	**C8: Grid Resilience and Black Start**	Use of grid-forming converters with VSM and distributed resources to enhance frequency stability, support black start, and ensure grid resilience.
R7.1, R7.2	**C9: Reliability and Maintenance**	Ensure N-1 redundancy in critical components and apply predictive maintenance via digital twins and IoT-based monitoring for reliability and asset lifespan extension.
R12.1, R12.2	**C10: Power Electronics and Converters**	Use of high-efficiency, high-power-density converters (e.g., VSCs, MMCs) with bi-directional energy flow and fast response for AC/DC interfacing.

R11.1	**C11: RES Integration**	Real-time integration and balancing strategies for intermittent RES, supported by forecasting, flexible storage, and backup generation.
R15.1	**C12: Scalability and Planning**	Planning tools for scalable hybrid topologies using optimization frameworks, enabling reconfigurability and future-proof converter placements.

5. HYNET demonstrations for addressing hybrid AC/DC grid challenges

HYNET will advance the state-of-the-art solutions and address the identified challenges through four complementary demo-sites located in four different European countries (France, Norway, Montenegro and Cyprus). In the following, each demo is briefly described along with the proposed HYNET solutions and tools to be developed and tested in each demo site. Further details with respect to mapping requirements of the tools with the identified challenges in the previous sections of this document are also listed.

5.1 Demonstration in France

5.1.1 Short description of the demo 1a

Demonstration 1a, led by EDF within the HYNET project, addresses frequency stability challenges in weak and isolated grids, using Guadeloupe’s power system as a primary case study. Islanded grids like Guadeloupe’s face significant frequency deviations due to high penetration of variable RES, such as solar PV and wind, coupled with low system inertia and the absence of interconnections with larger networks. These conditions lead to frequent instability and challenges in maintaining grid resilience. To mitigate these issues, the TSO is installing a synchronous compensator at EDF SEI’s TAC Jarry Sud plant in collaboration with GE Vernova. Additionally, innovative solutions like BESS with grid-forming capabilities and potential HVDC interconnections are being explored to enhance frequency stability and grid reliability.

The demonstration evaluates the performance of traditional synchronous compensators against advanced inverter-based resources, such as BESS with grid-forming control, through offline simulations and PHIL testing on EDF’s microgrid. By leveraging real operational data from Guadeloupe, the study assesses these solutions under realistic conditions, focusing on their ability to regulate frequency, support inertia, and improve grid resilience.

KPIs include average frequency, RoCoF, maximum frequency deviation (NADIR), and recovery time. The results will provide actionable insights for grid operators and solution providers, offering scalable strategies for managing frequency stability in islanded or weakly interconnected grids globally.

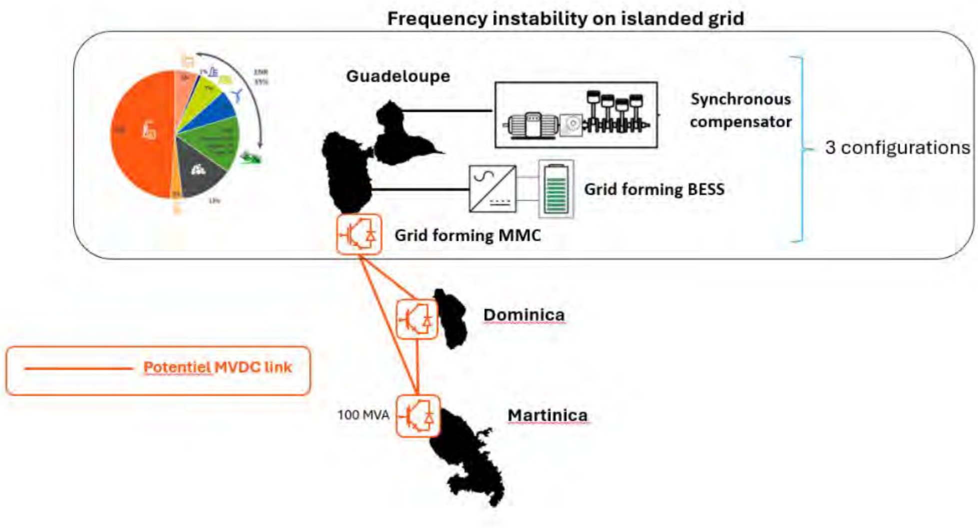
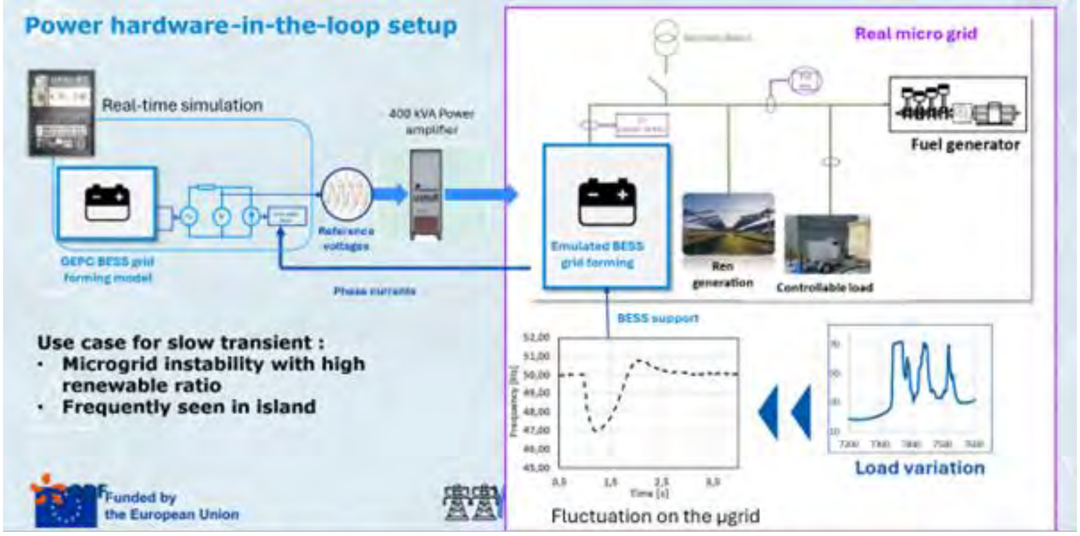


Figure 24 – Guadeloupe grid


Power hardware-in-the-loop setup

Use case for slow transient :
- Microgrid instability with high renewable ratio
- Frequently seen in island

Figure 25 – PHIL configuration for grid forming BESS testing at EDF facilities

5.1.2 Tools to be demonstrated in the demo 1a

Two tools developed within the HYNET framework—Tool #5 and Tool #8—will be implemented and validated in this demonstration to address frequency stability in Guadeloupe’s weak grid. These tools target dynamic simulation and advanced grid-forming control, respectively, and will be tested in two phases: offline simulations and real-world validation through PHIL testing and field demonstrations.

Tool #5: Dynamic Simulation

Tool #5, developed by **INESC TEC**, is a computational simulation suite designed for steady-state analysis, real-time dynamic studies, and transient simulations of hybrid AC/DC medium-voltage and low-voltage distribution grids. It supports both interconnected and autonomous/islanded operation modes, making it ideal for modelling Guadeloupe’s isolated grid. In this demonstration, Tool #5 will simulate the Guadeloupe power system using real field data to compare the effectiveness of a synchronous compensator against a BESS with grid-forming capabilities.

The tool will assess frequency ride-through events, inertia support, and renewable energy integration under various operating conditions and grid configurations. For instance, it will model frequency events caused by generation loss or load variations, enabling grid operators to predict instabilities and design mitigation strategies during early planning stages.

The demonstration will leverage Tool #5 in two scenarios:

- **Guadeloupe 2025**: Simulating the current energy mix and inertia levels to evaluate frequency events with and without grid support strategies (e.g., synchronous compensator or BESS).
- **Guadeloupe 2033**: Based on the PPE 2033 roadmap and Zero Net Energy scenario, it will explore the impact of reduced inertia due to higher RES penetration and test combined IBR strategies.

Additionally, Tool #5’s accuracy will be validated through PHIL testing using an **EDF** microgrid, where simulated results are compared with experimental data from a real-world setup. This ensures the tool reliably predicts grid behaviour, supporting technical decision-making for integrating new controllable assets, as outlined in UC8 of the European call.

Tool #8: Grid-Forming control software

Tool #8 is a control software solution providing innovative grid support through BESS equipped with grid-forming algorithms and virtual synchronous machine strategies. Unlike traditional grid-following controls, grid-forming techniques enable BESS to actively regulate frequency and provide inertia-like support, which is increasingly critical in high-RES contexts. In this demo, Tool #8 will be tested in offline simulations (via Tool #5) and PHIL demonstrations to validate its performance in stabilizing Guadeloupe’s grid. It targets solution providers participating in tenders, where grid-forming capabilities are now prioritized over grid-following approaches.

The implementation of Tool #8 includes:

- Offline Validation: Using Tool #5’s simulations, Tool #8 will assess BESS responses to frequency deviations in the Guadeloupe 2025 and 2033 scenarios, comparing its effectiveness against the synchronous compensator.
- PHIL Testing: Integrated into an EDF microgrid via a power amplifier, Tool #8 will emulate grid-forming actions in real-time, ensuring robustness under realistic conditions.
- Field Demonstration: Following successful PHIL testing, Tool #8’s control strategies will be deployed in a real-world setting to confirm operational benefits.

Integration and Objectives

The combined use of Tool #5 and Tool #8 aims to validate their functionalities within HYNET:

- Tool #5: Enables detailed dynamic studies of hybrid AC/DC architectures, providing insights into frequency regulation and grid resilience.
- Tool #8: Delivers active frequency support via BESS, enhancing grid stability in weak systems.

Both tools address frequency control in high-RES environments, with KPIs such as RoCoF, NADIR, and recovery time used to quantify their impact. For example, RoCoF will be calculated based on ENTSO-E recommendations to ensure accurate evaluation, while NADIR will measure maximum frequency deviations during events.

By simulating and testing these tools across Guadeloupe’s real grid and **EDF’s** experimental platform, the demonstration will provide actionable results for grid operators and manufacturers like **GE**, supporting the transition to sustainable, resilient power systems in islanded and poorly interconnected regions.

5.1.3 Short description of the demo 1b

Demonstration 1b focuses on addressing contingency issues in the French distribution grid due to the mass integration of high-power electric vehicle chargers, a critical challenge for DSOs like ENEDIS. The rapid deployment of fast and ultra-fast EV charging stations introduces significant and unpredictable loads, leading to potential grid congestion, voltage fluctuations, and asset overloading in low- and medium-voltage networks. This demonstration leverages the HYNET project’s advanced simulation and control tools to evaluate strategies for mitigating these challenges, ensuring reliable grid operation while supporting the electrification of mobility.

The demo utilizes EDF’s Concept Grid experimental platform to simulate real-world distribution network conditions under various EV deployment scenarios. It explores smart charging, local flexibility (e.g., BESS and V2G), and innovative DC architectures (point-to-point and multi-terminal DC configurations) to enhance grid reliability and efficiency. By modelling these scenarios, the demonstration aims to identify cost-effective and scalable solutions, such as optimized grid reinforcements and protection strategies, to manage congestion without compromising system stability.

KPIs include overload incidents avoided, voltage violation rates, and system reliability indices, ensuring the grid can accommodate high EV penetration while maintaining operational security and economic viability.

5.1.4 Tools to be demonstrated in the demo 1b

Demonstration 1b integrates four tools (#1, #5, #6, and #11) developed within the project’s framework to address the challenges of mass EV integration in the French distribution grid. Each tool targets specific aspects of grid congestion, reliability, and protection, collectively enabling a comprehensive approach to managing the impacts of high-power EV chargers.

Below are a detailed description of each tool and its role in the demonstration.

Tool #1: Congestion Prediction and Management

Tool #1 is a simulation tool designed to forecast and manage congestion in distribution networks under diverse EV deployment and charging behaviour scenarios. It models real-world grid configurations, such as EDF’s Concept Grid, to predict potential congestion hotspots caused by high-power EV chargers (up to 350 kVA) and other loads. By employing optimal power flow algorithms, the tool evaluates the need for grid reinforcements or flexibility solutions, such as smart charging or demand-side management.

Key performance indicators include forecasting accuracy (average and maximum error) and average computation time, ensuring the tool provides reliable and timely insights for DSOs to plan and operate the grid effectively.

Tool #5: Power hardware-in-the-Loop Simulation

Tool #5 enables real-time simulation through PHIL testing, conducted on the real-time simulator. This tool validates dynamic grid responses under realistic conditions, focusing on the integration of high-power EV chargers and their impact on grid stability. By simulating scenarios on EDF’s microgrid, Tool #5 tests the effectiveness of grid-forming control strategies (in conjunction with Tool #8) in mitigating congestion and ensuring stable operation. It requires accurate grid data, including duration, sampling rate, and time step, to support precise modelling. The tool’s ability to replicate real-world conditions makes it critical for validating control algorithms before field deployment.

Tool #6: Reliability analysis of DC/AC Architectures

Tool #6 focuses on assessing the reliability of integrating DC architectures (point-to-point and multi-terminal configurations) into existing AC distribution grids. It evaluates how DC connections can mitigate congestion caused by EV chargers by improving power flow control and reducing conversion losses. The tool models scenarios on the Concept Grid platform, analysing reliability indices. By simulating the impact of DC architectures under various EV load profiles, Tool #6 ensures that grid reliability is maintained while accommodating high EV penetration, supporting innovative grid designs for urban and mobility-focused areas.

Tool #11: Protection strategy for hybrid AC/DC Grids

Tool #11 addresses the protection challenges of complex hybrid AC/DC grid configurations integrating high-power EV chargers. It defines tailored protection strategies to ensure system security under new operational conditions, such as those introduced by DC architectures and V2G integration. The tool evaluates fault detection time (in milliseconds), protection selectivity (percentage of faults correctly isolated), coordination accuracy across AC/DC devices, and the number of false trips during normal operation. By simulating protection scenarios on the Concept Grid, Tool #11 ensures that the grid remains secure and resilient, even under high EV-induced stress, enabling safe and scalable electrification of transport.

Together, these tools form a cohesive framework for Demonstration 1b, combining simulation, real-time testing, reliability analysis, and protection strategy development. By addressing congestion, reliability, and security challenges, they support DSOs in achieving cost-effective and future-proof grid operations, paving the way for widespread EV adoption in France.

5.1.5 Mapping the requirements for addressing challenges

The challenges are mapped to the requirements both in chapter 4 and here to ensure robust, efficient, and resilient grid operation. This mapping aligns with the objectives of Demonstrations 1a and 1b.

Table 11 Mapping requirements to challenges for the French demo

Challenge Category	Req. ID	Requirement Summary	Mapped Tool(s)	Justification
C1: Advanced Control and stability	**R1.2**	Deploy advanced control techniques for voltage and frequency stability	**Tool #8**	Enables grid-forming converters to emulate synchronous generator behaviour, stabilizing frequency in Guadeloupe’s grid (Demo 1a).
	R1.1	Implement adaptive droop control for power-sharing.	**Tool #6**	Enhances power-sharing accuracy and mitigates oscillations in hybrid AC/DC systems, tested in Demo 1b’s MTDC configurations.
	R8.1	Deploy advanced control algorithms for real-time power flow management	**Tool #6**	Balances AC and DC power exchanges, supporting stable operation in Demo 1b’s hybrid architectures.
	R13.1	Deploy interlinking converters for bidirectional power flow and voltage regulation	**Tool #6**	Ensures stable operation and seamless AC/DC integration in grid-connected and islanded modes for Demo 1b.
C2: Oscillation Damping	**R2.1**	Implement wide-area control systems for oscillation detection	**Tool #11**	Facilitates detection and analysis of inter-area oscillations, critical for Demo 1b’s hybrid grid stability.
C3: Communication and Data Management	**R3.1**	Implement a fast and secure communication network for PMU data access	**Tools #5, #8**	Supports real-time grid status monitoring, essential for both demos’ digital control systems.
C9: Reliability and maintenance	**R7.1**	Ensure N-1 redundancy in critical components	**Tool #7**	Provides fault tolerance via redundant DC lines and converters, tested in Demo 1b’s MTDC scenarios.

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C9: Grid stability and reliability	**R9.1**	Deploy advanced control systems for frequency and voltage stability	**Tool #8**	Ensures stability via virtual inertia and frequency control, supporting Demo 1a’s resilience goals.
C7: Protection and Fault Management	**R10.1**	Develop hybrid protection schemes for rapid fault response	**Tool #11**	Ensures minimal disruption and rapid fault isolation in Demo 1b’s hybrid grids.
	R14.1	Develop DC fault detection and coordinated AC/DC protection	**Tool #11**	Supports rapid and selective fault isolation in Demo 1b’s hybrid architectures.
C12: Scalability & Planning	**R15.1**	Use scalable planning tools and modular converter designs	**Tool#7**	Supports flexible grid expansion for Demo 1b’s EV infrastructure without compromising reliability.
C3: Communication & Interoperability	**R16.1**	Implement low-latency communication and standardized protocols	**Tools#5, #8**	Ensures secure, real-time data exchange and interoperability for both demos’ digital control systems.
C6: Energy and Demand Management	**R17.1**	Conduct multi-energy scenario studies with predictive dispatch	**Tools #1, #5**	Supports optimal ESS sizing and RES forecasting in Demo 1b (Tool#1) and Demo 1a (Tool#5).

5.2 Demonstration in Norway

5.2.1 Short description of the demo

This demonstration aims to assess an HVDC interconnection project in Norway. The project would link southern Norway to a second country via an **offshore energy hub** strategically positioned between the two. This setup serves as a suitable case study for analysing HVDC interconnections and the integration of offshore renewable energy sources, such as **wind power, combined with hydrogen production**.

The goal is to demonstrate methodologies and tools for conducting different types of long-term (or real-time) analysis of new projects within AC/DC interconnected hybrid transmission systems: cost-benefit analysis, network security and reliability analysis, inertia losses evaluations. The overall analysis integrates multi-energy features, such as the interaction between electricity and hydrogen, as well as addressing congestion and grid security constraints, along with inertia losses and compensation strategies. By addressing these factors, the demonstration seeks to prove that the tool developed within HyNet suite provide valuable insights into technical feasibility, economic viability, and system stability for operators and project developers, thereby facilitating future AC/DC grid developments.

5.2.2 Tools to be demonstrated in the demo

- Tool#2: Inertia compensation scheme. The tool evaluates inertia levels in an AC system by performing real-time inertia estimation. It utilizes PMU data from various points across the electric grid to estimate the inertia in a given area and generates alarm signals to notify the system operator when a low inertia condition is detected in a specific region.

- Tool #3: Multi-energy vector integration tool. This tool is a planning and optimization software for a pan-European energy system that integrates multiple energy carriers, including hydrogen. It models the system at a zonal level, considering installed capacities, demand, and renewable energy variability. It calculates the optimal hourly system operation, costs, social welfare, congestion rents, and renewable energy integration. The tool is especially suited for evaluating different kind of projects, including for example a context of offshore energy hubs.
- Tool #10: Stochastic security analysis tool for AC/DC hybrid transmission networks. This tool is a grid security analysis tool that performs N-1 contingency analysis and stochastic Optimal Power Flow (OPF) simulations for transmission networks. It combines Monte Carlo methods with zonal-to-nodal downscaling to convert hourly system data into generation/demand timeseries suitable for grid model. The tool evaluates congestions, line overloads, and redispatch costs using input from grid topology, HVDC connections. Its reliability analysis identifies critical infrastructure vulnerabilities while optimizing remedial actions for secure grid operations.

5.2.3 Mapping the requirements for addressing challenges

Table 12 provides the mapping between the challenges related to the demo in Norway and the set of requirements identified in Section 4.

Table 12 Mapping requirements to challenges for the demo in Norway

Challenge Category	Req. ID	Requirement Summary	Mapped Tool(s)	Justification
C5: Hybrid Energy Storage Systems	**R5.1**	Hybrid energy systems	**Tool #10**	Tool#10 enables to ensure adequacy in hybrid AC/DC grids, with high penetration of RES.
C1: Advanced control and stability	**R1.2**	Advanced control for maintaining frequency and voltage stability	**Tool #2, Tool #10**	Tool#2 estimates the needs for inertia compensation. Tool#10 also performs security analysis.
C11: Integration of Renewable Energy Sources	**R11.1**	Integration strategies for renewable generation	**Tool #3, Tool #10**	Both tool#3 and tool#10 deals with integration of RES in an energy system and a network, through dispatch optimization and optimal power flows.
C12: Scalability and planning	**R15.1**	Long-term multi-energy optimization frameworks	**Tool #3, Tool #10**	The tool#3 is used in Demo#3 to conduct multi energy studies with an optimization framework. The tool supports AC/DC topologies, such as HVDC.
C6: Energy and demand management	**R17.1**	Conduct studies including scenarios covering multi-energy system operational cases and dispatch with RES	**Tool #3, Tool #10**	The tool#3 is used in Demo#3 to conduct multi energy studies. It is used to cover use cases such as offshore RES corridors. Both tool#3 and #10 deal with dispatch for RES.

5.3 Demonstration in Montenegro

5.3.1 Short description of the demo

The Montenegro electricity system supplies an area of approximately 14,000 km of the country with a number of approximately 400,000 electricity consumers and a peak load of approximately 6,010MW. The overall installed capacity of coal plants is 218MW, the Hydro generation is approximately 700MW and solar and wind generation adds for 158MW, which is expected to double in the following 5 years. The country is AC interconnected with Serbia, Albania, Kosovo, Bosnia and Hercegovina and DC interconnected with Italy, providing an excellent corridor for the integration of Western and SEE energy markets (see figure).

The demonstration in Montenegro will study the integration of renewables in the system operation in coordination with the impact of the HVDC interconnection with Italy. A detailed simulation model of the power system including generation and demand timely series at hourly resolution will be developed to perform power flow analysis both under normal and contingency scenarios (from N-1 to N-k), analysing also the impact of the HVDC link. Network adequacy and security analysis will be conducted and provide useful indicators towards network operational and planning decisions that optimize the overall costs and benefits both for consumers and producers across the region, while ensuring the reliability and resilience of the network at the same time.

5.3.2 Tools to be demonstrated in the demo

The tools that will be validated for the Montenegro demo are the following:

- The first tool will be the Tool#4, named “Techno Economic Analysis (TEA)-based adequacy and security analysis tool for optimal orchestration of hybrid AC/DC networks”. This tool will be developed by SGI and can conduct power system adequacy and security analysis integrated with DC technology of the interconnection. The adequacy and security assessment will be performed based on metrics such as available generation, served load, etc.
- The second tool will be the Tool#2, named “Inertia compensation scheme”. This tool will be developed by CIRCE, targeting to design and evaluate control actions for loss of inertia compensation in HVAC grids. Loss of inertia compensation strategies can be improved by considering real-time PMU measurements on several locations of the grid. Control actions can be activated by a wide area protection and control systems.

Preparatory activities are taking place for the organization of the demonstration in the Montenegro that will commence at M19. Technology providers CIRCE and SGI are in ongoing discussions with CGES and NKUA to define the steps, the information and the details of interest for the end users regarding the validation case in Montenegro.

5.3.3 Mapping the requirements for addressing challenges

According to the challenges and requirements defined in Section 4, the Montenegro demo along with the two tools that will be developed and demonstrated in Montenegro are expected to address the following challenges and requirements.

Table 13 Mapping requirements to challenges for the demo in Montenegro

Challenge Category	Req. ID	Requirement Summary	Mapped Tool(s)	Justification
C9: Reliability and maintenance	**R7.1**	Ensure N-1 redundancy in critical DC/AC components such as transmission corridors, converter stations, particularly in DC segments and interconnections.	**Tool#4, Tool#2**	Both tools are dealing with reliability analysis of hybrid power systems
C5. Hybrid Energy storage systems	**R5.1**	The tool will study and optimize the system's ability to meet the electric power and energy requirements of its customers within acceptable technical limits, considering scheduled and unscheduled outages of system components.	**Tool#4**	Tool#4 conducts the Technoeconomic Analysis
C8: Grid resilience and black start	**R6.2**	Study and optimize the inertia response of hybrid power systems and ensure grid resilience during disturbances and black-start conditions.	**Tool#2**	Tool#2 advances on the evaluation and minimization of inertia losses in electrical system

5.4 Demonstration in Cyprus

5.4.1 Short description of the demo

The demonstration in Cyprus focuses on the validation of advanced grid-supporting technologies in the context of a weak and islanded power system that faces increasing integration of renewable energy sources. The Cyprus power system is currently not interconnected with neighbouring countries, which presents operational challenges such as limited system inertia and vulnerability to disturbances.

To address these challenges, the demonstration integrates the future interconnection scenario via the Great Sea Interconnector (formerly EuroAsia Interconnector)—a flagship HVDC project connecting Cyprus, Greece, Crete. The project features a 1518 km long, 400 kV multi-terminal HVDC link with a transfer capacity of 2000 MW. Once implemented, this interconnection is expected to significantly enhance the resilience and operational flexibility of the Cyprus system, aligning it with the broader vision of a pan-European interconnected grid.

Within this demonstration, a digital twin of the entire Cyprus transmission system will be developed using real-time simulation environments. This twin integrates real PMU measurements from the field and includes modelling of the HVDC link to emulate the future AC-DC hybrid system realistically. The demo in Cyprus aims to validate three technological tools under TRL5 conditions:

- Tool#9 for assessing the resilience of the system against cascading weather-induced failures
- Tool#12 for quasi real-time inertia estimation using PMU data
- Tool#13 for frequency support and adaptive inertia provision via HVDC systems.

The University of Cyprus (UCY) leads the development and implementation of the digital twin and resilience tools. The Cyprus Transmission System Operator (TSOC) supports the modelling and validation using operational data, while NKUA and 3SI contribute to the emulation of the interconnected Greek system and the digital modelling of the Eastern Mediterranean region.

5.4.2 Tools to be demonstrated in the demo

Three key tools, namely Tool #9, Tool #12, and Tool #13, will be demonstrated in the Cypriot demo, each addressing a different aspect of the hybrid AC-DC grid operation, resilience, and stability. These tools will be integrated within a high-fidelity digital twin of the Cyprus transmission system and the HVDC interconnection with Greece, enabling a realistic, non-invasive testing environment.

Tool#9: Static and dynamic cascading analysis of large networks, focuses on the resilience assessment and quantification of cascading failures due to weather-induced events. This tool supports both static and dynamic analysis of the AC-DC power system using real grid data. The simulation will be conducted within DIgSILENT PowerFactory’s RMS environment, incorporating dynamic data from the Cyprus and Greece power systems, including controller models and protection relays. Various scenarios will be implemented to test the tool’s capabilities, including N-K contingencies, randomized outages using Monte Carlo methods, and weather-related event simulations that model grid component fragility. The objective is to evaluate system behaviour under compound stress events and quantify impacts in terms of lost load and the number of triggered protection devices. These results will be used to evaluate the system’s resilience and reliability, particularly with the future HVDC interconnection in place. Tool #9 directly supports Use Cases 1 and 8 of HYNET project, and its performance will be assessed based on KPIs such as the extent of demand not served and the frequency of protection trips.

Tool#12: Quasi real-time estimation of system inertia in AC/DC systems, enables quasi real-time estimation of system inertia in AC and DC systems using PMU measurements. The tool will be developed using a weighted least squares estimation approach and will be validated using real PMU data provided by the Cyprus TSO. These measurements, collected mainly from generators, will be integrated into the Cyprus digital twin model. The tool will estimate system inertia during various time windows under different operational conditions, enabling the quantification of inertia in near real-time. Its accuracy will be evaluated by comparing the estimated values with inertia figures calculated by the TSO based on the committed generation mix. This allows for a direct benchmarking of tool performance. Tool#12 contributes to Use Cases 2 and 4 of HYNET project and is expected to achieve a mean estimation error of less than 7%, ensuring its suitability for real-world deployment.

Tool#13: Provision of adaptive synthetic inertia and frequency support by HVDC, concerns the provision of adaptive synthetic inertia and frequency support using HVDC systems. This tool will demonstrate how HVDC converters, operating in grid-forming (GFM) or grid supporting modes, can provide variable and coordinated frequency support across interconnected AC systems. Within the Cyprus and Greece digital twin environment, frequency events, such as generator outages or sudden load variations, will be simulated to assess the impact of HVDC-based control on system stability. The HVDC controller developed for this purpose will use the real-time inertia estimates from Tool#12 and operate within the constraints set by the respective TSOs. The frequency response with and without Tool#13 will be compared to evaluate its impact on frequency nadir and Rate of Change of Frequency (RoCoF). The expected improvement in frequency stability is in the range of 20–30%, making this tool highly relevant for future HVDC-connected systems. Tool#13 supports Use Cases 2 and 4 and enables advanced frequency management strategies in weakly interconnected grids.

Together, these tools form a coherent demonstration package that enables the assessment of hybrid AC-DC system performance under realistic future scenarios. Their integration into the Cyprus digital twin framework ensures a robust and controlled environment for validation, addressing key challenges of resilience, inertia adequacy, and dynamic stability.

5.4.3 Mapping the requirements for addressing challenges

According to the challenges and requirements defined in Section 4, the Cypriot demo along with the three tools that will be developed and demonstrated in Cyprus are expected to address the following challenges and requirements.

Table 14 Mapping requirements to challenges for the Cypriot Demo

Challenge Category	Req. ID	Requirement Summary	Mapped Tool(s)	Justification
C1: Advanced Control and Stability	**R1.1, R9.1**	Grid forming control to establish voltage and frequency	**Tool#13**	Tool#13 manages power flow, voltage regulation, and transition handling in HVDC converters under both GFM and GFL modes
	R1.2	Inertia estimation using ambient measurements	**Tool#12**	Tool#12 estimates inertia in real time
	R1.3	Adaptive droop control to manage power sharing	**Tool#13**	Tool#13 manages the provision of frequency support based on adaptive signals received by the controllers
	R1.4	Virtual inertia	**Tool#13**	Tool#13 provides virtual inertia to the interconnected systems through the control of the HVDC link
C3: Communication and Interoperability	**R3.1**	Inertia Estimation	**Tool#12**	Tool#12 establishes a reliable communication framework through IEEE C37.118 protocol.
C9: Reliability and Maintenance	**R7.1**	Ensure N-1 redundancy	**Tool#9**	Simulated N-k cascading effects that will ensure that in any high impact low probability events will not violate N-1 conditions.
C10: Power Electronics and Converters	**R12.2**	Power converters allowing bi-directional flow	**Tool#13**	Tool#13 ensures the stability of the interconnected system through HVDC link using bi-directional power converters
C12: Scalability and planning	**R15.1**	Support long-term resilience planning	**Tool#9**	Weather-induced stress testing supports infrastructure planning for climate resilience

6. Conclusion

The development of hybrid AC/DC grids marks a significant advancement in modern power systems, offering enhanced efficiency and flexibility while facilitating greater integration of renewable energy sources. This comprehensive analysis has systematically explored the critical aspects of these emerging grid architectures, including their boundary conditions, technical requirements, operational challenges, and practical demonstrations. The findings present both the substantial potential of hybrid grids and the key obstacles that must be addressed to enable their widespread implementation.

A central conclusion from the in-depth analysis of the current technologies and the grid and regulatory posture is that successful deployment of hybrid AC/DC grids relies on **three fundamental pillars**: **advanced power electronics**, **robust grid management strategies**, and **harmonized regulatory frameworks**. The critical role of converter technologies, particularly voltage source converters, has been clearly demonstrated in enabling seamless power transfer between AC and DC networks. However, significant challenges remain in maintaining system stability, managing faults, and ensuring interoperability between different grid components. These challenges necessitate the development of sophisticated control mechanisms, adaptive protection schemes, and real-time monitoring capabilities to ensure reliable operation under varying conditions.

The regulatory landscape emerges as equally crucial to the future of hybrid grids. Current standards and grid codes, while comprehensive for traditional AC systems, might still require substantial evolution to properly accommodate hybrid architectures. The analysis highlights the pressing need for updated connection requirements and operational guidelines specifically tailored for DC technologies. This regulatory gap presents both a challenge and an opportunity for collaborative efforts between policymakers, industry stakeholders, and research institutions to develop appropriate frameworks that can support safe and efficient grid integration.

This report also identified the practical approach to advance solutions for the identified technical and regulatory challenged as they are foreseen within the upcoming implementations in the four HYNET demonstration sites. Specifically, In France, the focus will be on solving frequency stability issues in weak and isolated grids while developing solutions for contingency management in distribution networks facing mass integration of high-power electric vehicles. The Norwegian demonstration takes a forward-looking approach by aiming to develop methodologies for long-term analysis of interconnected hybrid transmission systems, using as a case study a planned offshore energy hub that will link southern Norway to a neighbouring country. This demo will thus focus on critical assessments of cost-benefit trade-offs, network security, and inertia loss mitigation strategies that will inform future investment decisions in cross-border interconnections. Montenegro's demonstration will address challenges related to high levels of renewable energy integration, particularly in coordination with a new HVDC interconnection to Italy. Through detailed simulation models incorporating hourly generation and demand profiles, this demo aims at conducting comprehensive power flow analyses under various contingency scenarios. Particularly this demo aligns with identified challenges for optimizing network adequacy and security while balancing regional costs and benefits. The Cyprus demonstration represents perhaps one of the most ambitious validation case, tackling the complex challenges of a weak, islanded grid with high renewable penetration. By incorporating the future Great Sea Interconnector into a digital twin of the Cyprus transmission system, researchers will be testing advanced solutions for inertia estimation, frequency support, and resilience against weather-induced cascading failures.

Looking forward, several key actions which were identified as viable options to accelerate the adoption of hybrid AC/DC grids will be further developed in the other WPs and finally validated as part of the listed demo sites. Further, the need for comprehensive standardization efforts that address interoperability, protection coordination, and compliance requirements were also evaluated within the preliminary assessment of the four HYNET demos. It is concluded that hybrid AC/DC grids represent a transformative solution for future energy systems, offering the potential to significantly enhance renewable energy integration while improving overall grid resilience and efficiency. However, realizing this potential requires coordinated efforts across technical, regulatory, and operational domains. The insights provided in this deliverable offer a solid foundation for addressing current challenges and guiding future developments in this critical area of power system innovation.

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