SPECIAL REPORT FOR SC B4

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Special Reporters

J. HU – Chair
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CIGRE Study Committee (SC) B4 is responsible for advancing and applying the technologies of DC and Power electronics in both transmission and distribution systems as well as DC Converters for the integration of distributed renewable (PVs) and energy storage, to provide the reliable power integration, transfer, operation and quality.

A total of hundred and twenty-three (123) papers including three (3) NGN papers were selected based on the preferential subjects chosen by the SC B4 for the 2026 session as listed below. In some cases, the preferential subjects have been further broken down into subcategories to identify common themes. These papers represent the latest information on many aspects of DC and FACTS technologies, applications, and operations.

PS 1 DC Equipment and Systems

- PS1.1: Planning, design, performance, testing and commissioning of DC equipment and systems including point to point, multiterminal and DC grids, especially offshore DC systems.
    - *PS1.1-1: LCC & Hybrid HVDC*
    - *PS1.1-2: VSC HVDC*
    - *PS1.1-3: Offshore HVDC*
    - *PS1.1-4: Multi-Terminal & DC Grids*
- PS1.2: Refurbishment and upgrade of existing DC systems.
- PS1.3: Service and operating experience of DC converter stations and systems, especially VSC based DC systems and offshore DC systems.
    - *PS1.3-1: Reliability Assessment*
    - *PS1.3-2: Insulation Performance*
    - *PS1.3-3: Operational Experience*
    - *PS1.3-4: Maintenance Experience*
    - *PS1.3-5: Digitalization, Monitoring, and Digital Twin Applications*

PS 2 FACTS and Power Electronics

- PS2.1: Planning, design, performance, testing and commissioning of FACTS and other PE devices including inverter-based generation.
    - *PS2.1-1: STATCOM & SVC*
    - *PS2.1-2: Other Power Electronic Devices*
- PS2.2: Refurbishment and upgrade of existing FACTS and other PE devices.
- PS2.3: Service and operating experience of FACTS and other PE devices.

PS 3 New Technologies and Concepts of DC and FACTS Enabling Energy Transition

- PS3.1: New technologies/concepts to address network issues associated with green energy transition such as application of grid-forming converters, multi-vendor interoperability.
    - *PS3.1-1:Grid-Forming Control and Dynamic Performance*

    - *PS3.1-2: Multi-Terminal HVDC Design, Protection, and Operation*
    - *PS3.1-3: Simulation and Testing*
- PS3.2: New Concepts, Technologies and design of DC converters and PE devices for both transmission and distribution systems including interfacing generation and storage to the network, energy hubs/islands, etc.
    - *PS3.2-1: UHVDC Transmission System*
    - *PS3.2-2: Medium Voltage DC*
    - *PS3.2-3: DC Protection and DC Circuit Breakers*
    - *PS3.2-4: – Grid Support, FACTS, and Digital Substations*

PARTICIPATING IN THE 2026 PARIS SESSION

You are invited to participate in discussing this Special Report at the SC B4 session held on **Friday August 28th, 2026** ***from 9:00 AM to 6:00 PM, in the Grand Amphithéâtre*** **(Level 1)** at the Palais de Congress de Paris.
The reporters have compiled up to 21 questions; these are not specifically aimed at the papers' authors but are synthesised from common issues and trends identified in across the papers. This provides the opportunity for a broader response and participation in the discussion session.
We encourage you to share your views or experiences in response to the specific questions in this report. During the Group Discussion Meeting, each prepared contribution will be allocated a time slot of three to four minutes for a presentation.

Procedure for contributions.

1. Contributors should upload contributions on the registrations portal – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials before **Saturday 1st August 2026** at latest, for a prior screening and a good organization of the Group Discussion Meeting. Important points:
2. Access to contribution uploading is given only to duly registered delegates.
3. Therefore, registration to CIGRE Session should be finalized before uploading contribution(s) online.
4. Register now for the Session registrations
5. Contributions uploading will be open at start of June.
6. Special Reporters will review the prepared contributions (Power point presentation with max 3 slides and a written word file with max 1000 words per contribution). A guide for contributors as well as templates and sample pages will be available on the Paris Session webpage. **Important notice:** No commercial names are to be included in presentation or the written summary (even TSO/DSO names).
7. Any recommendations or changes to the contributions will be provided to the contributors by the Special reporters directly on the Registration platform between ***August 7th to August 14th, 2026***. Contributors are encouraged to visit their account on the registrations portal to see the result of this review.
8. All contributors with accepted/finalised contributions will be contacted by the Special reporters between ***August 7th to August 14th, 2026***, to finalize the presentation and receive the instructions regarding the session. Final versions of the contributions must be submitted by ***Sunday 16th August 2026.*** Contributions received after the deadline will not be considered for presentation at the GDM.
9. Important note:
    - All contributions must be uploaded prior to the Conference in Paris.
    - Last minute changes to the contributions will not be granted.
10. During the GDM, the Study Committee Chair may call for spontaneous contributions which will only be verbal with no slides. All attendees are eligible to make such a contribution. Attendees who provide a spontaneous contribution are allowed to deliver a written contribution which will be included in the Session Proceedings. This text is required to be forwarded within a maximum delay of two weeks after the Study Committee GDM Session (i.e. by ***Friday September 11th, 2026***) to the SC Chair (j.hu@rbjengineering.com).
11. It is expected that the questions relevant to the Preferential Subjects will attract many prepared contributions. The number of contributions for each Preferential Subject (PS1, PS2 and PS3) may need to be limited. The selection will be based on relevance, quality, and time of submission of the contribution.
12. Please note that accepted contributors will be required to attend one of the two short pre-session meetings with the Special Reporters on Thursday, August 27, 2024, from 10AM-Noon and 2PM-4PM, in Room 233 at the Palais de Congress de Paris to finalize presentation arrangements including the final details of their contribution and the latest instructions (such as schedule).

POSTER SESSION

Authors of SC B4 Session papers are required to present their papers during the **SC B4 Poster Session scheduled on *Thursday August 27 from 14:00pm to 18:00pm*** in Halle Ternes on level 1. Template and instructions on poster preparation are available on the CIGRE 2026 Session website. Posters will be displayed on digital screens. **Poster presentations must be uploaded on the ConfTool platform *by 29th* June at the latest** for review by the poster session convener. Poster conveners may ask for a final version incorporating any requested changes, which must be uploaded by ***August 14th 2026***. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session, he/she or the relevant National Committee is requested to send a substitute presenter.

PS 1 – DC Equipment and Systems

PS1.1 – Planning, design, performance, testing and commissioning of DC equipment and systems including point to point, multiterminal and DC grids, especially offshore DC systems.

PS1.1-1 – LCC & Hybrid HVDC

Paper B4-10567 "Transient Over-voltage Studies of ±800kV, 6000 MW LCC HVDC connected with RE source of Solar and Wind"

The paper presents an EMT-based transient overvoltage study, using simulation software, for a double-bipole LCC HVDC scheme rated at ±800 kV, 2 × 3000 MW, connected to renewable-dominated weak grids. It provides a description of the study steps and presents AC- and DC-side transient overvoltage findings.

Paper B4-11013 "Operational and Commissioning Challenges and mitigation measures while integrating new HVDC Bipole with existing +/- 800kV HVDC Bipole with DMR system"

The paper presents design, commissioning, and operational considerations for integrating a new ±800 kV, 3000 MW HVDC bipole with the existing ±800 kV Champa–Kurukshetra bipole using a common DMR to form a 6000 MW parallel bipole scheme. Topics include controlled charging, neutral surge arrester design, NBGS protection, common earthing, and commutation failure protection coordination.

Paper B4-11421 "Addressing specific challenges for harsh environmental conditions and integration with large solar park for Khavda – Nagpur HVDC transmission"

The paper presents an overview of the ±800 kV, 6000 MW Khavda–Nagpur HVDC project in India, including ratings, overload requirements, and operating modes. It describes project-specific challenges including high seismic requirements, severe pollution, an indoor DC hall, enhanced creepage, and dynamic performance considerations for integration with large solar parks and nearby HVDC systems.

Paper B4-12051 "Commutation Failure Prediction in LCC-HVDC under Severe Voltage Distortion"

The paper proposes an analytical commutation failure prediction framework for LCC-HVDC under distorted AC grid conditions in multi-infeed environments. The commutating voltage waveform is reconstructed analytically using harmonic, inter-harmonic, and Prony-based modeling. Validation on a CIGRE multi-infeed benchmark compares prediction accuracy with conventional CFPREV and critical commutation voltage methods.

Paper B4-12078 "Relevant Challenges and Lessons Learned from the Kimal-Lo Aguirre HVDC Project in Chile"

The paper reviews design-stage challenges and lessons learned from the ±600 kV, 3000 MW Kimal–Lo Aguirre LCC-HVDC project in Chile. EMT studies identify risks including AC breaker transient recovery voltage stresses, AC/DC interactions under weak-grid conditions, fault behavior involving the metallic return, and grounding in high-resistivity soils, with associated mitigation measures.

Paper B4-12510 "Optimization of Dynamic Phasor Modeling for LCC-HVDC Systems Based on Fourier Transform"

The paper proposes a systematic dynamic phasor modeling method for LCC-HVDC systems based on Fourier transform properties and switching functions, addressing the absence of a modular method to represent the switching function. Dynamic phasor expressions for a twelve-pulse LCC HVDC scheme are derived and applied to the CIGRE benchmark system, compared against an EMT model.

Q1.01:

There are certain known limitations in LCC based HVDC converters for integrating large scale IBRs (Inverter Based Resources) connected either in islanded systems or weak systems. What improvements have been made in LCC or Hybrid HVDC schemes to overcome these limitations to garner the benefits of LCC schemes?

PS1.1-2 – VSC HVDC – Design, Equipment & DC-Side Fault Performance

A. Planning, Design, and Project Implementation

Paper B4-10560 "Planning and Design of a ± 320 kV/1000 MW Hybrid City-Infeed VSC-HVDC Link"

The paper presents the planning, design, and operational features of the ±320 kV, 1,000 MW Kudus–Aarey VSC-HVDC Hybrid City-Infeed Link strengthening power supply to Mumbai, India. The scheme combines an overhead line and underground cable feeding a dense metropolitan receiving end through a compact converter station, developed under right-of-way, land, short-circuit, and environmental constraints.

Paper B4-10940 "The construction and system study of the Higashi-Shimizu frequency converter station (VSC BTB link)"

The paper describes the expansion of Japan's east–west power interconnection through installation of two 300 MW VSC back-to-back frequency converters at the Higashi-Shimizu substation, with commercial operation planned for 2028. Site constraints required compact indoor designs and secondary-side energization, with transformer inrush and commutation failure risks mitigated through phase-controlled switching.

Paper B4-12050 "Key facilitators of HVDC systems for advanced electrical infrastructures"

The paper presents a manufacturer perspective on the organization of HVDC projects from planning to commercial operation, proposing standardization of converter transformer designs and use of the round-power capability of HVDC links to support design, construction, and commissioning. Project execution timelines are discussed, with attention to standardization and parallelization of hardware and software engineering.

Paper B4-12446 "Optimizing of VSC HVDC-Systems with the use of an On-Load Tap Changer Transformer"

The paper investigates the role of on-load tap changers in VSC-HVDC systems, focusing on how OLTC operation can affect converter efficiency, operational flexibility, and fault-tolerant capability. The work reports that OLTC-supported operation can reduce converter losses by approximately 2.8% to 8.7%, may reduce required submodule redundancy, and could affect operational security.

B. Grid-Forming Control, Inertia, and System Performance

Paper B4-10774 "Dynamic Equivalent Network Methods for Grid Forming Performance Test"

The paper investigates two dynamic network equivalent methods for assessing grid-forming HVDC and inverter-based resource performance, addressing limitations of Thevenin-equivalent representations. Method 1 is a low-order analytical model estimating system inertia and frequency dynamics; Method 2 is a data-driven approach deriving the inverse Jacobian Transfer Matrix at the PCC. Simulation comparisons identify applicable conditions.

Paper B4-11079 "The Impact of Synchronous Grid Forming on the Rating of HVDC Transmission Links"

The paper examines why Synchronous Grid Forming operation at one end of a point-to-point MMC-HVDC link can require reducing DC voltage, increasing stress on major components unless the SGFM operating range is constrained. A phasor model studies interactions between link ends, including DC circuit capacitance, permitted DC voltage reduction, and controller response speed.

Paper B4-11305 "True Inertia Constant of Synchronous Grid-Forming Control Strategies"

The paper presents an analytical comparison between PLL-based and PLL-free Virtual Synchronous Machine implementations within synchronous grid-forming control frameworks. Static RoCoF expressions are derived, showing that in the PLL-free implementation the effective system inertia depends on the inertia constant, damping coefficient, and low-pass filter time constant. A tuning guideline is proposed and validated.

Paper B4-11342 "Grid-Forming Control for Reactive Power Sharing in Bipolar MMC–HVDC Systems Under Asymmetric Grid Conditions"

The paper studies a bipolar MMC-HVDC system in grid-forming mode when the two converter poles see different AC-side impedances between PCCs and the point of interconnection. An impedance-compensated grid-forming control is proposed that adjusts each converter's voltage reference using its local PCC–POI impedance and current, examined through simulations of reactive power sharing.

C. Grounding, Protection, and DC Fault Handling

Paper B4-10561 "Impact Assessment of Converter Neutral Grounding on Transient Performance in Rigid Bipole VSC-HVDC Systems"

The paper analyzes how converter neutral grounding methods and transformer saturation affect transient over-voltages, transient recovery voltages, and surge arrester duties in rigid bipole VSC-HVDC systems. Through EMT simulations under various fault conditions, the study concludes that grounding at both ends and managing transformer saturation are key to limiting voltage stresses.

Paper B4-11599 "DC Overhead Line Fault Ride-through Schemes Comparison in End-to-end VSC-HVDC System"

The paper compares DC fault ride-through performance of a half-bridge MMC bipole and a hybrid bipole combining half-bridge and full-bridge submodules for DC overhead line fault ride-through in end-to-end bipolar MMC-HVDC. It presents fault current paths, sequencing, and timing comparisons, including AC circuit breaker-based and hybrid MMC-based solutions.

Paper B4-11600 "8 GW VSC UHVDC transmission -- Fault handling in the Gansu-Zhejiang ±800 kV project"

The paper presents functionalities developed for a hybrid VSC converter (HB+FB) rated at 8 GW, ±800 kV in China, focusing on design and control measures for fault performance and equipment protection. Functions discussed include limiting fault current during external DC line faults, overcurrent limiting, surge arresters in upper-bridge valves, and high-speed switches limiting arrester energy.

Paper B4-11823 "Control and Recovery of DC Faults in Overhead Line UHVDC Systems: A Comparison of Full-Bridge and Half-Bridge MMCs"

The paper develops and compares recovery frameworks for ±800 kV, 8 GW overhead line UHVDC systems based on Half-Bridge and Full-Bridge MMC topologies. Real-time simulations of a bipole configuration with Dedicated Metallic Return apply a 100 ms pole-to-ground transient DC fault, and the work reports that FB-MMC achieves faster overall recovery than HB-MMC.

Paper B4-12345 "Design Implications of DC Grounding in Bipolar VSC-HVDC Systems"

The paper examines the impact of DC grounding configuration and surge arrester selection on the design of bipolar VSC-HVDC systems with dedicated metallic return. Simulation results show the influence of neutral grounding resistor and neutral bus arrester protective levels on AC breaker current zero-crossing behavior, valve terminal-to-terminal voltage, and DC pole overvoltage profiles.

D. Testing, Stability, and Simulation Methods

Paper B4-10783 "Optimized Real-time simulation for VSC-HVDC bipolar scheme with physical control replica in the loop"

The paper investigates methods to improve real-time EMT simulation performance for a VSC-HVDC bipolar scheme with Hardware-in-the-Loop physical control replica integration in the InterOPERA project context. Two approaches are evaluated: path-based partial refactorization and the Compensation Method, with validation showing up to approximately 24% reduction in simulation time-step, partial refactorization preferred.

Paper B4-11532 "Micro-sector Analysis of Harmonic Instability for HVDC Systems Interconnected to Weak Grids"

The paper proposes a micro-sector-based impedance method for harmonic stability assessment of VSC-HVDC systems connected to weak AC grids. Conservative harmonic impedance sectors are identified and loci analysis is performed accordingly, assessing risky configurations in detail while reducing effort on safe configurations. One selected case is verified in the time domain.

Paper B4-11621 "A Review of Practical Approaches to Dielectric Valve Terminal AC-DC Tests for Modular Multi-level Voltage Sourced Converters"

The paper evaluates the AC-DC dielectric test methods M1 and M2 defined in IEC 62501 for MMC VSC valves equipped with Rapid Discharge Resistor circuits. These circuits introduce challenges for dielectric testing due to their active operation. A hybrid M1–M2 approach is proposed, combining M1 for operational type tests with M2 for dielectric type tests.

Q1.02:

GFM control is receiving growing attention in power systems, particularly because of its potential to provide network strength and improve system stability.
a) What are the principal technical and system-integration challenges associated with the deployment of GFM HVDC systems, particularly regarding design choices, functional specifications, equipment ratings and control tuning?
b) As GFM-HVDC moves from demonstration projects toward large-scale deployment, what lessons learned and validation approaches should guide future projects, particularly regarding expected performance, dynamic modelling approaches, and the minimum testing requirements for weak-grid operation, islanding, converter interaction, and fault ride-through capability?

Q1.03:

Over the past decade, LCC HVDC technology has been the preferred solution for UHVDC transmission, particularly for very high-power long-distance applications. With recent advances in semiconductor devices, VSC HVDC is now emerging as a credible alternative for UHVDC transmission.

a) What experience has been gained so far in the development and implementation of UHVDC projects based on VSC technology?
b) What are the key technical, operational, and economic factors to consider when selecting between LCC and VSC for very high-power transmission applications?
c) What are the main differences between these two technologies in the context of UHVDC, and how do these differences influence project design, system integration, and operational performance?

Q1.04:

Due to the high demand for HVDC equipment in the market, the cost of HVDC projects have increased significantly during the last decade. Projects of higher ratings get attention of the main OEMs due to many reasons. This market situation makes it difficult for the relatively smaller projects to get the required attention and cost optimized solutions that lead to such projects being scrapped. What cost competitive solutions are available for relatively small HVDC projects?

PS1.1-3 – Offshore HVDC

A. Design, Equipment, and Offshore Transmission Architecture

Paper B4-10310 "±525kV 2GW Bipole VSC-HVDC Offshore Transmission Projects – Critical Review and Status Updates"

The paper reviews the current status of ±525 kV, 2 GW bipole VSC-HVDC offshore transmission projects in the Netherlands and Germany connecting offshore wind farms to onshore grids. It describes the evolution from conceptual design to early execution, and addresses point-on-wave switching, AC GIS optimization, harmonic damping, cable interface impacts, multi-terminal readiness, and platform design.

Paper B4-10780 "Converter transformer in HVDC offshore projects: an approach for risk assessment"

The paper presents a Monte-Carlo-based risk assessment framework for evaluating converter transformer strategies in offshore HVDC projects, with explicit valuation of short-circuit withstand testing as a risk mitigator. Total cost including CAPEX and socio-economic cost of spilled energy is quantified, illustrated by a case study of three 2 GW HVDC bipole projects.

Paper B4-10942 "Study on mechanical design requirements for HVDC valve tower in floating offshore converter stations"

The paper investigates mechanical design challenges of HVDC valve towers for floating offshore converter stations. It identifies offshore-specific mechanical requirements, particularly wave- and wind-induced oscillations and cyclic fatigue, and develops a methodology to define environmental loading. Accelerated fatigue testing on Station Post Insulators identifies stiffness degradation at the flange–tube joint.

Paper B4-11595 "Topology and Control of High Transformation Ratio and Large Capacity DC Transformer Based on Multi level Current Source"

The paper proposes a high-voltage, large-capacity DC transformer for GW-scale renewable energy applications based on a face-to-face topology combining a 7-level multilevel current-source converter on the low-voltage side with an MMC on the high-voltage side. Analytical expressions for CSC characteristics are derived, and a two-degree-of-freedom fundamental-frequency modulation method is proposed.

B. Control, Testing, and System Validation

Paper B4-10786 "PQU diagram capabilities and operational needs for offshore HVDC converter stations"

The paper analyses P–Q–U capability requirements for offshore HVDC converter stations connecting offshore wind farms, examining the implications of applying onshore grid PQU requirements to offshore HVDC. Using load-flow studies and a 2 GW ±525 kV bipole HVDC case, three alternative PQU envelopes are defined and assessed for converter design, losses, cooling, and economics.

Paper B4-10788 "Risk analysis of offshore commissioning during power transmission tests"

The paper presents a risk-based analysis of HVDC commissioning for offshore wind farm connections, focusing on transmission tests under limited or unavailable active power. Full-power, partial-power, and no-active-power test cases are compared, and mitigation strategies are evaluated, including factory and replica testing, early-stage verifications, thermal extrapolation, bipole topologies, and round power tests.

Paper B4-11345 "Integrated EMT Modeling and Network-HILS Verification for HVDC Interconnection of the Southwest Offshore Wind Farm in South Korea"

The paper presents an integrated EMT modeling and Network hardware-in-the-loop verification framework for HVDC interconnection of large-scale offshore wind farms in South Korea. Offline EMT simulations verify dynamic characteristics and operating scenarios, and a Network-HILS platform with physical DC network hardware is used for hardware-inclusive validation.

Paper B4-11771 "Design of generation runback scheme for a HVDC-connected wind farm"

The paper presents the design, implementation, and planned validation of a generation runback scheme (RBS) for the Sunrise Wind 924 MW offshore wind project connected to shore via a ±320 kV MMC-based VSC HVDC link. A three-stage redundant RBS is described, with EMT simulations, real-time testing, and subsystem tests preceding planned field testing.

Q1.05:

In recent years, numerous projects have been awarded for the design and construction of 2 GW, ±525 kV HVDC links to connect offshore wind farms that may also pave the way for future interconnector applications.

a) What are the key challenges identified so far in the development of this technology? What lessons learned can already be shared regarding design choices, and how can these insights help improve the functional specifications provided to HVDC OEMs?

b) These HVDC solutions are based on Dedicated Metallic Return (DMR) configurations, where the DMR cable is usually procured separately from the HVDC converter contract. Considering that neutral-point grounding design is performed by the HVDC OEM, what specific technical requirements related to DMR operation - mainly transient overvoltages, grounding interactions and insulation coordination - should be identified early and transferred to the cable supplier for proper DMR cable design?

Q1.06:

As offshore HVDC projects move from standardized point-to-point links toward MTDC-ready architectures that may be integrated in stages, what minimum control, protection, and interoperability functions should be implemented and tested during the first project phase, even before multi-terminal operation is activated? What design verification framework is needed for next-generation offshore HVDC equipment exposed to non-traditional stresses?

PS1.1-4 – Multi-Terminal & DC Grids

A. Planning / architecture / interoperability

Paper B4-10775 "Integrating protection and control in the reliability and resilience-informed planning of future MTDC grids"

The paper focuses on coordinated planning and control of MTDC grids. It proposes basic control schemes for MTDC grids, establishes the system model, and presents preliminary verification through contingency RMS case studies of a North Sea MTDC grid with and without coordinated control.

Paper B4-11547 "Planning and Specification Challenges for Bipole Multiterminal HVDC Systems"

The paper presents planning, specification, and operational characteristics of a U-shaped bipole multi-terminal HVDC system for integrating renewable energy into weak and partially isolated AC networks. Bipole radial MT-HVDC configurations are examined relative to symmetrical monopoles in terms of availability, security of supply, and fault resilience, including DC fault clearance using conventional AC breakers.

Paper B4-11594 "Multi-terminal HVDC Transmission Technology for Offshore Wind Power Adopting Hybrid Cable-OHL and Its Applications"

The paper proposes an offshore–onshore integrated HVDC transmission scheme based on an onshore DC hub for transmission of ultra-large offshore wind power (approximately 10 GW class) from deep-sea wind bases to inland load centers. Economic analysis and simulations examine fault isolation, ride-through performance, DC fault clearing approaches, and cost considerations.

Paper B4-12384 "Towards Resilient HVDC Networks: DC Switching Stations and Multi-Vendor Interoperability"

The paper defines the structure, function, and functional requirements of a DC switching station and its constituent units and elements. It proposes a function-oriented, modular requirement framework for DCSS designed to accommodate different vendor solutions while supporting scalable HVDC network development and interoperability, addressing DC Switching units, DC Bonding units, and DC Bus units.

B. Control / operational coordination / resilience

Paper B4-11418 "Effect of Temporary VSC-HVDC converter blocking on Multiterminal HVDC and offshore windfarm performance"

The paper examines the effect of temporary converter blocking on offshore wind farm performance in a multi-terminal DC system, focusing on a bipolar three-terminal offshore grid connected to two wind farms. Different DC fault scenarios assess how VSC-HVDC converters block and the resulting impact on offshore grid stability, using vendor-provided models.

Paper B4-11420 "Hierarchical Primary–Secondary Control of HVDC Grids: Challenges of Droop Control Schemes in Ensuring Safe Operation under Large-Scale Renewable Integration"

The paper investigates limitations of single-segment and multi-segment active power–DC voltage droop control schemes in MTDC systems with multiple renewable terminals under contingencies such as converter trips and DC faults. Time-domain simulations on a six-terminal bipolar MTDC test system show that faster secondary control reduces sustained DC overvoltage stress.

Paper B4-11633 "A Strategy for Enhanced Resilience of the NEOM Grid U-shape HVDC"

The paper discusses security-of-supply strategies for the NEOM Grid of the Future based on a multi-terminal HVDC backbone using U-shaped bipolar modules with dedicated metallic return. The study focuses on a terminal supplying a 2 GW isolated load island and examines how energy storage or generation affects transient stability under contingencies including DC faults.

Paper B4-11817 "Coordinated Frequency Support in Multi-Terminal HVDC Network Via Grid-Forming Converter with Dynamic Power Allocation"

The paper proposes MHFSC, a decentralized, event-triggered coordination strategy for frequency support in MT-HVDC systems using grid-forming terminals and offshore wind plant reserves. Each terminal detects local frequency events, exchanges minimal signals, and uses a severity-aware allocation, evaluated through EMT case studies on a three-terminal meshed MT-HVDC.

C. Protection philosophy / methods / standards

Paper B4-10121 "Trade-offs in HVDC Protection System Design – Investigation into Protection Margin and Threshold Setting for Future DC Grids"

The paper addresses tuning of HVDC protection functions for conditions such as long cables with noisy measurements and introduces a methodology for evaluating protection functions based on detection time and relative protection margin. A logical combination approach combines single-ended fault detection algorithms to achieve higher margins, tested through a simulated Princess Elisabeth Island case study.

Paper B4-10122 "Protection system design for HVDC switching stations and electrical energy hubs"

The paper describes a three-phase sequential design methodology for HVDC grid protection applied to centralized DC switching stations and energy hubs, comprising system-level conceptual design, component-level detailed design including reactor sizing, and system-level performance evaluation. It includes a DCCB placement algorithm and a reactor sizing approach, with an energy hub case study concentrating inductance into the DCCB.

Paper B4-12031 "Discussion of simplified methods for short-circuit current calculation in HVDC networks"

The paper presents a foundation for international standards on short-circuit current calculation in HVDC networks, addressing a gap as HVDC systems evolve toward multi-vendor, multi-terminal grids. A methodology for determining DC short-circuit currents is proposed, providing a structured basis for standardization activities.

D. Switching stations / DC breakers / Fault Current limiting equipment

Paper B4-10555 "Analysis of DC Switchyard Schemes for Multi-Terminal HVDC Systems with DC Circuit Breakers"

The paper investigates DC switchyard schemes for multi-terminal VSC-HVDC systems using hybrid HVDC breakers, considering a half-bridge MMC bipole topology. Multiple architectures (single bus, feeder breakers, double bus double breaker, 1½ breaker, ring bus) are evaluated on a four-terminal bipole MTDC against contingency impact, availability, CAPEX, and expandability using a weighted-index approach.

Paper B4-12289 "A hybrid HVDC Breaker for 525 kV DC Switching Station Applications"

The paper presents a 550 kV Hybrid HVDC Breaker platform for use in 525 kV DC Switching Stations within multi-terminal HVDC grids. It describes the HHB architecture comprising main, commutation, and energy-dissipation branches, with features including proactive current limitation, multi-shot auto-reclosing, soft-start energization, and controlled charging.

Paper B4-12511 "Low-loss Bidirectional DC Circuit Breaker with Capacitance Self-charging Ability"

The paper presents a bidirectional DC circuit breaker based on a vacuum switch and coupled inductor topology with a self-charging capacitor mechanism. The design targets two limitations of existing DCCBs: conduction losses in solid-state circuit breakers and external capacitor pre-charging in mechanical DCCBs. The operating mechanism, validation, and bidirectional capability are presented.

Paper B4-12512 "A novel low-impedance bidirectional voltage-clamped fault current limiter based on a coupled inductor"

The paper proposes a bidirectional voltage-clamped fault current limiter for VSC-HVDC systems based on three-winding coupled inductors, bidirectional IGBT switches, and metal-oxide varistors. The device achieves near-zero equivalent inductance during normal operation and reconfigures to a high-inductance, voltage-clamped mode under fault conditions, with coordination with DC circuit breakers and cost comparison reported.

E. Transient impacts / equipment stress / commissioning findings

Paper B4-11130 "Investigation of Fast-Front Transients in HVDC Switchgear for CMS Multiterminal HVDC System"

The paper investigates fast-front transients observed during commissioning of the Noss Head DC Switching Station within the Caithness–Moray–Shetland multi-terminal HVDC system. Through EMT simulations, site measurements, and high-frequency campaigns, the root cause of apparent voltage collapse signals and unintended protection trips is identified as fast-front electromagnetic transients during high-speed switch operations.

Paper B4-12359 "Impact of DC Circuit Breakers on Transient Stresses within Modular Multilevel Converters in Bipolar HVDC Systems"

The paper investigates how integration of Fast DC Circuit Breakers in multi-terminal HVDC systems affects transient voltage and current stresses within modular multilevel converters in bipolar HVDC. EMT simulations indicate that DCCB integration increases terminal-to-ground voltage stresses while current and submodule voltage stresses remain largely unchanged, and faster DCCBs reduce voltage stress.

Paper B4-12410 "On Transient Electrical Cable Stresses in Next Generation Multiterminal HVDC Systems"

The paper investigates transient voltage stresses on HVDC land cable systems in future multi-terminal HVDC grids with integrated DC circuit breakers, using EMT simulations on a planned six-terminal system in Germany with ±525 kV cables. The parametric study identifies maximum overvoltage levels and voltage waveshapes induced by breaker operations during rare fault events.

Q1.07:

What are the key design aspects of control, coordination strategies, and interoperability requirements in multi-terminal HVDC systems to achieve scalability, maintain secure operation, frequency support, and continuity of supply under contingencies such as DC faults, converter blocking, and large renewable disturbances?

Q1.08:

How do breaker operations and high-speed switching phenomena in present-day and near-future multi-terminal HVDC networks influence transient stresses on converters, cables, and switchgear, and what

are the resulting implications for equipment specification, insulation coordination, and commissioning practice?

Q1.09:

One of the main concerns related to evolving HVDC grids is the ability to share detailed EMT models for simulations and under certain scenarios to integrate control cubicles from different OEMs in a real time testing environment. What options do we have now to overcome the intellectual property concerns and what aspects should we build in the future to support such tests?

See additional questions under section PS3.2.

PS1.2 – Refurbishment and upgrade of existing DC systems

Paper B4-10572 "Life assessment and refurbishment of ±500kV, 2500 MW Talcher-Kolar HVDC Converter Stations"

The paper addresses life extension and performance improvement of the approximately 25-year-old ±500 kV, 2500 MW Talcher–Kolar HVDC link in India, describing a component-focused refurbishment philosophy. Upgrade options are examined, including integration of VSC technology with the existing thyristor-based bipole to form a Hybrid HVDC arrangement, and feasibility of upgrading continuous capability to 2500 MW.

Paper B4-10939 "Confirmation test in refurbishment of the control and protection system devices and thyristor valve modules in the 300 MW Shin-Shinano No.2 frequency converter"

The paper describes the refurbishment of the 30-year-old, 300 MW Shin-Shinano No.2 LCC back-to-back frequency converter station in Japan, where OEM support was no longer available. It documents multi-vendor control and protection replacement with hardware-in-the-loop testing, valve module hardware refurbishment, unexpected phenomena and their resolution, and on-site test results.

Paper B4-11724 "Upgrade of Monopole to Bipole in ±500kV, 3000MW Bukdangjin-Godeok LCC HVDC Link - Strategy and Commissioning Experience"

The paper describes the planning, execution, and commissioning of adding a second pole to an existing operating monopole HVDC project in Korea, upgrading a +500 kV, 1500 MW monopole to a ±500 kV, 3000 MW bipole within a 40-day outage window. It documents the pre-outage technical review, commissioning experience, and the upgrade strategy.

See questions under section PS1.3.

PS1.3 – Service and operating experience of DC converter stations and systems

PS1.3-1 – Reliability Assessment

Paper B4-11765 "Survey of the Reliability of HVDC Systems Throughout World during 2023-2024"

The paper presents the biennial CIGRE Advisory Group AG-04 survey on the reliability performance of HVDC systems worldwide for 2023 and 2024, compiling data from over 115 HVDC systems. It updates a historical record spanning 53 years, reports trends in Forced Energy Unavailability, and documents extended outages caused by cable issues and equipment failures.

Paper B4-11874 "RAM Analysis of an HVDC Multi-purpose Interconnector for Offshore Wind Integration"

The paper presents a Reliability, Availability, and Maintainability study of a 3-terminal hybrid HVDC interconnector intended to integrate offshore wind in the North Sea. It compares symmetrical monopole, rigid bipole, and bipole configurations, identifies critical components contributing to equivalent unavailability, and discusses offshore transformer overloading, cable length, and AC GIS configuration.

Paper B4-11875 "Analysis of reliability of Nordic HVDC interconnectors based on DISTAC data from 2016-2022"

The paper analyzes operational outage data from Nordic and Baltic HVDC interconnectors reported to the ENTSO-E DISTAC database over 2016–2022, comparing availability and reliability between LCC and VSC technologies. The dataset includes 20 HVDC interconnectors, and overall availability, outage frequency, outage duration, and fault origins are evaluated at the converter station level.

PS1.3-2 – Insulation Performance

Paper B4-10556 "Operational Experience of HVDC Insulators under Climatic Variations & pollution deposit conditions in ±800 KV indoor DC Yard at Agra Terminal of NEA800 HVDC link and mitigations thereof"

The paper presents operational experience from the ±800 kV NEA UHVDC link in India, focusing on insulation performance in an indoor DC yard in a highly polluted and humid environment. It describes environmental conditions causing surface tracking on porcelain insulators and pole tripping, and presents mitigation measures including improved insulator shed profile and creepage distance.

Paper B4-11104 "Insights from salt-fog testing on high-voltage insulators used in HVDC converter stations"

The paper presents Terna's experience with salt-fog testing of high-voltage insulators used in HVDC converter stations under coastal, industrial, and dust pollution conditions. Results covering porcelain, polymeric, and RTV-coated insulators are consolidated, and Terna's testing procedure is compared with established international methodologies for AC and DC applications.

Paper B4-12012 "Operational Experience with Composite Insulators for HVDC Air Core Reactors in Outdoor Polluted Environments"

The paper compares porcelain, RTV-coated porcelain, hybrid insulators, and hollow-core composite insulators for HVDC station post applications, focusing on air-core dry-type reactors where support insulators serve as both external insulation and load-bearing elements. Operational experience is outlined together with qualitative comparison, four project application examples, operational surveys, and OEM commentary on IEC pollution tests.

PS1.3-3 – Operational Experience

Paper B4-10558 "Design and system studies consideration for enhancement of reverse power flow capacity of ± 800kV HVDC system."

The paper presents a methodology and high-level framework for analyzing the impact of full reverse power flow operation on the design of an HVDC scheme, and for modifying existing HVDC links to operate in full bi-directional power mode. The motivation for full reverse power capability and the framework structure are described.

Paper B4-10559 "Operational Experience of Steady-State and Dynamic Reactive Power Capabilities of the Pugalur–Thrissur VSC-HVDC System"

The paper reports operational experience from the ±320 kV, 2000 MW Pugalur–Thrissur VSC-HVDC link in India, focusing on converter-based reactive power control for voltage regulation in the Southern Region. It documents voltage and reactive power control features of the symmetrical monopole, and presents observed steady-state, seasonal, diurnal, and transient behavior including a single-phase fault case.

Paper B4-10563 "DC Line Fault Recovery Performance of the India's first ±320kV VSC HVDC Pugalur-Thrissur Link"

The paper presents DC line fault ride-through operational performance of the Pugalur–Thrissur VSC HVDC link, India's first VSC-based HVDC system, documenting the recovery sequence and Transient Fault Recorder evidence from pole-to-ground OHL fault cases. Five years of field data are reported, including selective fault detection between overhead line and cable sections and coordinated dual-HVDC operation.

Paper B4-10573 "Analysis of Higher 5th Order Harmonics & tripping of Type 3 filters (5/27) at HVDC Rihand & Dadri terminals"

The paper presents the impact of high background harmonic distortion on the operation of an LCC HVDC link in India. The discussion begins with the observed problem of filter tripping and addresses related topics including specialized power-quality measurements, source identification, and mitigation alternatives, based on operational experience.

Paper B4-11103 "On the analysis of faults along HVDC land electrode lines"

The paper analyzes fault mechanisms in HVDC land electrode cable systems, focusing on faults that do not fully interrupt the electrode line and may remain undetected. Modelling of representative VSC-HVDC configurations shows that fault location, fault resistance, and electrode geometry influence ground current magnitude, and concludes that improved fault detection and detailed 3D modelling are needed.

Paper B4-11285 "Enhancing Electrical Protection and Automated Control Systems for HVDC Auxiliary Services: A Comprehensive Study Case"

The paper introduces auxiliary power system requirements for HVDC and describes how existing protection IEDs can be used to design and implement an Automatic Transfer Scheme for configurations with more than two sources. Custom logic implemented on the IEDs is described as a means of providing supply transfer capability for HVDC Auxiliary Services.

Paper B4-11727 "Restoration Strategy for Bipolar MVDC Systems Following Fault Events"

The paper presents a strategy for system restoration in MVDC bipole systems following fault events, where constrained protection capability is supplemented by post-trip analysis enabling selective reclosing and continued service of healthy conductors. The work addresses how MV AC feeders can be converted into MVDC systems and how protection systems can be developed.

Paper B4-12587 "Assessment of Station & System Tests of the Attica - Crete HVDC Interconnection"

The paper presents system and operational acceptance tests for the Attica–Crete HVDC interconnection between a VSC HVDC system and a weak AC network. It covers test procedures and field results addressing grid-forming behaviour, contingency response, pole trip tests, AC link outage, and unexpected events including protection miscoordination and subsynchronous oscillations.

PS1.3-4 – Maintenance Experience

Paper B4-11438 "Unlock Capacity through HVDC C&P Replica-as-a-Service Business Model"

The paper introduces and analyzes the Replica-as-a-Service business model for HVDC Control and Protection system testing, training, and validation. It summarizes types of replicas in use, their applications including multi-vendor studies, and the pros and cons of end-user-owned versus vendor-managed replicas, considering services delivered through a vendor-managed replica with access sold as a service.

Paper B4-11851 "Transitional HVDC Systems Operation and Maintenance Strategy"

The paper presents the operation and maintenance strategy developed by Nova Scotia Power Maritime Link Inc. for HVDC system assets, facilities, and equipment. It describes the evolution of the O&M approach from an initial OEM-supported model toward one involving internal resources and local contractors, and discusses staffing, contracting philosophy, competency development, and knowledge transfer.

PS1.3-5 – Digitalization, Monitoring, and Digital Twin Applications

Paper B4-10123 "Development of an analysis tool utilizing robotic image acquisition for early detection of thermal anomalies in HVDC converter equipment"

The paper describes SARTA, an automated robotic inspection system developed by Elia Group for HVDC converter equipment in environments not accessible during service. An autonomous robot

captures thermal and optical images daily, and cloud-based image processing identifies temperature deviations and potential issues, with results compiled into reports to detect problems early and support maintenance.

Paper B4-11853 "HVDC Digital Twin – Maturity Level and Use Cases"

The paper presents a framework for understanding HVDC Digital Twins, describing their evolution from documentation tools toward more comprehensive and potentially autonomous functionality. A maturity-level model is presented, together with use cases at different stages of an HVDC project life cycle, and discussion of standardization, interoperability, and advances in modeling and analytics.

Paper B4-12292 "Digital Wideband DCCT with advanced Signal Processing and IEC 61850 Communication Services"

The paper presents application of the IEC 61850 communication standard to HVDC systems by integrating a digital wideband DC current transformer into a process bus architecture. The work covers protection, control, and revenue signals from the DCCT, examining adaptation of standardized process bus concepts from AC systems and the need for DC-specific data models.

Paper B4-12407 "Piloting Wireless Communication-based Condition Monitoring in an HVDC Station"

The paper reports a pilot deployment of a Bluetooth Low Energy-based wireless sensor network for temporary condition monitoring in an operational VSC-HVDC station in Germany. The system uses battery-powered environmental sensors communicating via BLE to gateways, with cloud integration and a security-by-design architecture, and communication performance is analyzed under the station's electromagnetic conditions.

Q1.10:

a) As a facility Owner, how should organizations balance day-to-day operational OPEX requirements with increasing post-warranty repair and maintenance costs for aging HVDC/LCC assets?
b) What are the typical lifecycle management strategies and focus areas across the major asset stages (e.g., 5-year, 10-year, 15-year, and 20+ year horizons), particularly in relation to reliability, spare parts management, obsolescence planning, refurbishment, life extension, and replacement planning?
c) How can HVDC facility owners and operators optimize HVDC maintenance models, skills development, and test infrastructure to reduce lifecycle cost while preserving system reliability?

Q1.11:

As HVDC systems continue to increase in scale, complexity, and operational importance, the role of advanced monitoring, diagnostics, and condition assessment becomes increasingly critical for maintaining high reliability and minimizing unplanned outages.

a) What unexpected fault events, operational issues, or system behaviours were identified that provide important lessons learned for the broader HVDC industry? Which events are most valuable for knowledge sharing and future system design improvements?
b) How can digital sensing, automated monitoring, and digital twin applications be integrated to strengthen HVDC diagnostics, decision-making, and predictive maintenance, especially for aging HVDC fleets? What special considerations should taken into account for multi-vendor HVDC fleets, where operational data may come in different formats.

Q1.12:

With many existing LCC systems approaching end of life, what are the recommended strategies for technology upgrades? Is it preferable to pursue a brownfield approach focused on asset life extension and spare parts replacement, or to plan for a greenfield replacement using new LCC or VSC technology with staged line cutovers? Additionally, what are the key challenges associated with brownfield upgrade planning, long-term site decommissioning, equipment salvage, and the development of greenfield replacement projects?

PS 2 – FACTS and Power Electronics

PS2.1 – Planning, design, performance, testing and commissioning of FACTS and other PE devices including inverter-based generation.

PS2.1-1 – STATCOM & SVC

Paper B4-10584 "Experience of STATCOM for Improvement of Voltage Stability & Assistance in Avoiding Loss of Generation of Renewable Energy (Inverter Based Solar Power) in Western India"

The paper documents wide-area disturbances in the Rajasthan renewable energy corridor in India during 2022–2023, quantifying loss of 2–7 GW of inverter-based generation triggered by local faults, and articulates an associated voltage instability mechanism. It presents before-and-after evidence comparing pre- and post-STATCOM conditions, and describes hybrid STATCOM and switched shunt devices stabilizing the 765 kV network.

Paper B4-10589 "Enhancing Grid Resilience of RE dominant Power System's through STATCOM's – A Practical Illustration"

The paper presents a STATCOM installation connected at 500 kV for network voltage support, providing a general overview of the system and performance characteristics of the installation.

Paper B4-10592 "Optimisation of MSR & MSC switching instances during Auto mode operation of STATCOM to enhance the life of the equipment"

The paper addresses frequent switching of Mechanically Switched Reactors and Capacitors in STATCOM systems, which causes circuit breaker wear and reduced equipment life. An optimisation logic based on adaptive voltage reference band settings derived from short-circuit level, reactive power, and historical grid data is proposed, with reported reduction of approximately 65% in switching operations.

Paper B4-11365 "Synchronous Grid-forming STATCOM Supercapacitor Energy Storage - Control During Active-Power Involving Events"

The paper presents a control strategy for synchronous grid-forming STATCOMs with energy storage providing frequency and active-power support while enforcing current and DC-link voltage limits. Supercapacitor energy storage enables fast active power injection or absorption, and simulation results examine compliance with requirements, RoCoF mitigation, active-power response, and dynamic performance.

Paper B4-11601 "Active Impedance Reshaping for High-frequency Resonance Suppression of Renewable Energy Power Stations with STATCOM"

The paper addresses field issues where STATCOM current and PV plant bus voltage oscillate at high frequencies, causing blocking, tripping, and potential hardware damage. The work identifies STATCOM negative damping interacting with collector-line impedance variation as the cause, and proposes an impedance-reshaping method based on current-sampling low-pass filtering, validated by HIL simulations.

Paper B4-11979 "Introduction of Containerized STATCOM up to 200Mvar Rating"

The paper describes a modular containerized STATCOM solution with ratings up to 200 MVAr for reactive power supply during N-2 outages, addressing high-MVAr STATCOM requirements through a mobile, rapidly deployable configuration. Design considerations for dynamic reactive power and voltage support from a containerized STATCOM are presented.

Paper B4-12609 "The largest 1 Gvar STATCOM Deployment in the Korean Power System: Architecture, Control, and Operational Approach"

The paper presents the design, deployment, and operational strategy of a 1 GVAr STATCOM installation at the Shin-Okcheon substation in South Korea, addressing voltage stability constraints and

transmission bottlenecks. The installation comprises a modular 2 × 500 MVAr architecture with a hierarchical Master Controller for coordinated control, fault containment, and availability.

Q2.01:

As STATCOMs evolve from reactive-power devices into grid-forming assets with battery or supercapacitor energy storage, how should utilities validate that their controls improve voltage and frequency stability without introducing new instability modes? What are the important considerations for justifying additional cost of energy storage STATCOMs?

Q2.02:

Considering the recent deployment of high-rating STATCOMs at EHV levels, including 500 kV applications, what experience has been gained regarding commissioning, control coordination, and early operational performance, and how may this experience inform future utility practice in renewable-dominant networks?

PS2.1-2 – Other Power Electronic Devices

A. Power Converter Dynamics and EMC

Paper B4-10277 "Advanced simulation framework for AC/MTDC power systems"

The paper introduces HARMONY, a C++-based open-source framework unifying optimal power flow and harmonic stability analysis for AC/MTDC hybrid power systems. It implements an Adjusted Modified Nodal Analysis for impedance reduction, derives a corrected DQ-frame admittance transformation theorem, and integrates SOCP-based OPF to provide operating points informing impedance-based frequency-domain stability assessment.

Paper B4-11461 "Grid-Connected Characteristics Analysis of GFL PCS and GFM PCS under Dynamics Perspective"

The paper presents a unified small-signal rotational dynamics modeling perspective for grid-connected power conversion systems under both grid-following and grid-forming control, describing how internal voltage amplitude and frequency evolve under disturbances. Comparative analysis examines how GFL frequency dynamics depend on PLL bandwidth and how GFM inertial characteristics arise from virtual synchronous generator control.

Paper B4-12454 "Design and Testing of Filters to Reduce EMC Interference in a Power-Flow Controller Based on Power electronics"

The paper presents an EMI mitigation strategy for a transformer-less power-flow controller for low-voltage grid applications, covering EMI filter design for the Active Front End and common-mode noise suppression for the Dual Active Bridge. A methodology comprising noise modeling, parasitic analysis, filter design, simulation, and experimental validation is described and evaluated.

Paper B4-12513 "Tradeoff for Power Loss and Electromagnetic Interference of IGBT Devices in Converter"

The paper addresses the trade-off between switching losses and electromagnetic interference in high-voltage, high-power IGBT devices using equivalent linearized waveforms. Analytical SL models and frequency-domain EMI spectrum envelope models are validated against double-pulse experiments, and NSGA-II multi-objective optimization is applied to explore the SL–EMI trade-off and generate Pareto-optimal solutions.

Paper B4-12627 "Impact of Nearest-Level Modulation harmonics on the Small- Signal Dynamics of the Modular Multilevel Converter"

The paper investigates how harmonics produced by Nearest-Level Modulation influence small-signal dynamics and frequency-domain admittance identification of Modular Multilevel Converters. Two models are compared: the Arm-Averaged Model and a quantized MMC model including NLM. The work analyzes how quantization harmonics affect admittance measurements and stability conclusions, and evaluates mitigation strategies.

B. Stabilizing and Power Flow Control Devices

Paper B4-11105 “"Commissioning and Field Testing of 40 MW Stabilizing Devices in the Italian Transmission Grid"”

The paper describes the commissioning and on-site testing of a 40 MW Stabilising Device, or Regulating Resistor, installed by Terna at the Rizziconi substation in Italy. The device uses a back-to-back converter combining STATCOM-type reactive power control with resistive active-power absorption. The paper details plant layout, control architecture, and a test campaign.

Paper B4-12450 “Rapid tripping of a NH fuse using a power-flow controller with high-frequency current injection”

The paper addresses fuse-based protection effectiveness in inverter-dominated low-voltage grids where reduced short-circuit levels limit conventional tripping. A UPFC/Quality Conditioner injects a high-frequency current component following fault detection; because fuse impedance increases with frequency, this reduces tripping time. The topology, control strategy, and HIL/real-time simulation validation are presented.

Q2.03:

What are the major technical challenges in the design and deployment of MMC-VSC-based power flow controllers for the transmission systems, and how do converter topology, modulation strategy, protection coordination, and grid-forming control affect dynamic power-flow regulation and stability in weak renewable-dominated grids? What are the advantages and disadvantages compared to conventional power flow controller such as phase shifting transformer and conventional UPFC?

PS2.2– Refurbishment and upgrade of existing FACTS and other PE devices

No papers under this topic.

PS2.3– Service and operating experience

Paper B4-10586 “Operational Experience of STATCOM in POWERGRID- challenges and mitigation”

The paper presents four years of operational experience from a ±300 MVAr STATCOM installation in POWERGRID, identifying field failures observed primarily in the MV yard and cooling system, and describing low-cost mitigation measures affecting availability and mean time to repair. The observations are consolidated into a preventive maintenance strategy for utilities.

Paper B4-12305 “Experiences and recommendations for parallel operation of SSSC devices, Candelaria – Ternera 220 kV circuits case”

The paper presents operational experience with single-phase modular Static Synchronous Series Compensators installed on the parallel 220 kV Candelaria–Ternera circuits in northern Colombia. The operating principle of the VSC-based SSSC modules and their fixed-reactance control mode are described, and two operational challenges observed after commissioning are analyzed with mitigation measures validated through simulation.

PS 3 – New Technologies and Concepts of DC and FACTS Enabling Energy Transition

PS3.1 – New technologies/concepts to address network issues associated with green energy transition such as application of grid-forming converters, multi-vendor interoperability.

PS3.1-1 – Grid-Forming Control and Dynamic Performance

Paper B4-10810 "An Owner's Perspective on the Implementation of Grid-Forming Controls for VSC HVDC and STATCOM Projects"

The paper presents an owner's perspective on procurement, specification, and design-phase implementation of grid-forming controls for two Minnesota Power projects: the Riverton ±300 Mvar GFM STATCOM and the UMEX VSC HVDC modernization and expansion. It describes supplier engagement, technical specification development, dynamic performance studies, and aligning specifications with supplier offerings.

Paper B4-11267 "Assessment of Multiterminal HVDC Systems with Grid-Forming Converters in the Brazilian Power System"

The paper presents an EMT-based evaluation of a three-terminal VSC-based MTDC system with one grid-forming converter integrated into the Brazilian power system, connecting the Northeast, Southeast, and South regions. The work investigates the effect of GFM control in addressing commutation failures in the Southeast Electrical System, with one VSC station proposed at Cachoeira Paulista.

Paper B4-11281 "Expanded Grid-Forming Solution and SGFM Control in HVDC System to Harvest Additional Energy from Offshore Wind Farms"

The paper proposes a communication-free control strategy for offshore HVDC systems coupling offshore and onshore AC networks through DC-link voltage variations. A phase-jump functionality uses DC-link energy deviation to trigger phase adjustments at the offshore converter, mobilizing Synchronous Grid-Forming wind turbines to inject active power, with sensitivity analyses on measurement delays and inertia.

Paper B4-11282 "TenneT 2GW Bipole Offshore HVDC Transmission Schemes – Key Advanced Control Features"

The paper presents control strategies for 2 GW, ±525 kV bipole VSC-HVDC offshore transmission systems connecting North Sea wind farms to onshore grids. Elements analyzed include Synchronous Grid-Forming control, Constrained SGFM for DC voltage stability, phase-jump functionality, bipole coordination, and islanded operation with black-start capability, under faults, pole contingencies, and restoration scenarios.

Paper B4-11809 "Grid Forming STATCOM Dynamic Performance: A Technical Study"

The paper presents a power-decoupled grid-forming STATCOM developed to support dynamic stability in systems with increasing inverter-based resources. The proposed GFM-STATCOM removes active-reactive power cross-coupling, enabling independent power responses. Evaluations cover grid code conformity, fault ride-through, harmonic and RMS stability, and various interactions.

Paper B4-11854 "A Novel Grid-Forming Controller Based Upon DC-Side Dynamics"

The paper proposes a grid-forming controller that regulates active power using only DC-side dynamics, in contrast to GFM controllers depending on AC-side measurements through a PLL. A Vdc–ω control structure is developed with virtual-impedance current limiting, and EMT simulations compare the proposed method with a conventional droop controller for response speed, stability, and fault ride-through.

Paper B4-11951 "DC FRT Analysis and Disturbance Propagation of Grid-Forming HVDC Converters in Future MTDC Systems"

The paper investigates the behavior of a multi-terminal DC system during DC faults, focusing on how Grid-Forming control affects fault ride-through and disturbance propagation. Using a bipolar MTDC

grid model with offshore wind integration, EMT simulations examine the AC/DC dynamic coupling introduced by GFM converters and the role of control coordination and converter-level energy storage.

PS3.1-2 – Multi-Terminal HVDC Design, Protection, and Operation

Paper B4-10104 "New Concepts in Overall Control of Large Renewable Generation Hubs Connected to Load Centers through Grid-Forming Multi-Terminal HVDC Technology"

The paper presents a four-layer hierarchical control architecture (EMS, Main Controller, PPC, Inverter) for coordinating multi-plant Large Renewable Generation Hubs connected to AC grids via multi-terminal VSC-HVDC with AC tie-lines. It introduces a Main Active Power Controller and Main Reactive Power Controller, describes integrating diverse OEM plant controllers into a unified strategy, and includes simulations.

Paper B4-10790 "Insulation Coordination in Bipolar Multi-Terminal HVDC Grids"

The paper presents a methodology for incorporating insulation coordination into early-stage bipolar multi-terminal HVDC grid design using vendor-neutral generic EMT models within the InterOPERA project. It proposes a stepwise methodology covering arrester protective levels, grounding resistor screening, and DC fault transient envelope studies, applied to a 2 GW, ±525 kV three-terminal demonstrator.

Paper B4-10943 "Development of guidelines and HIL simulation on the control and protection scheme for multivendor multi-terminal HVDC systems"

The paper presents guidelines for control and protection schemes in multi-vendor, multi-terminal HVDC systems developed within a Japanese national R&D project. The framework aims to enable MT-HVDC implementation and testing without full disclosure of proprietary control details, covering HIL verification approaches, simulation exchanges, shared waveforms, and case studies on protection tuning and blocking.

Paper B4-11283 "HansaLink: Multiterminal HVDC Rigid Bipole Offshore MPI"

The paper presents design aspects of the HansaLink three-terminal rigid bipole multi-purpose interconnector linking the UK, Germany, and an offshore wind farm using ±525 kV MMC technology. Topics include AC and DC pre-insertion resistors, DC discharge bypass switches, the impact of AC network strength on energization, and reconfiguration to asymmetric monopole operation.

Paper B4-12393 "Modelling Protection Concepts for Multi-terminal HVDC Systems for Congestion Management"

The paper presents a modelling framework integrating fully selective, partially selective, and non-selective multi-terminal HVDC protection schemes into steady-state, optimization-based congestion management simulations for transmission planning. A case study on a German three-terminal system quantifies redispatch costs, outage hours, and remedial-action volumes as protection zone size varies.

PS3.1-3 – Simulation and Testing

Paper B4-10794 "Testing models and physical C&P replicas prior to interaction studies in a MV and MT context"

The paper describes lessons learned from testing single-vendor HVDC models and Control & Protection replicas from several vendors in the same environment in preparation for multi-vendor MT-HVDC testing within the InterOPERA project. It addresses integration, replica requirements, documentation, modelling, EMT tools, and data storage, including issues encountered and how they were resolved.

Paper B4-11431 "Virtual Control and Protection System in Real Time Software in the Loop"

The paper examines alternative real-time testing architectures for HVDC control and protection systems, focusing on I/O-free RT-HIL replicas and Real-Time Software-in-the-Loop configurations. Traditional hardware-based environments are compared with software-integrated approaches amid increasing project complexity, and the work discusses challenges and limitations of each alternative based on demonstrations.

Paper B4-11656 "Digital Twin-Enabled Support for Network Restoration: A Case Study on Grid-Forming Controlled HVDC Interconnectors"

The paper presents a Hardware-in-the-Loop-based digital twin for simulating grid restoration scenarios using HVDC interconnectors. A systematic approach for comparing scenarios and varying protection settings during restoration is proposed. The system integrates the power system, measurement system, EMS/SCADA, and a real-time simulator with protection relays to assess restoration alternatives following a blackout.

Paper B4-12644 "Effect of Power Electronic Converter Parameters on Converter- driven Stability in Transmission Grids with High Converter- interfaced Device Penetration"

The paper addresses the detection and analysis of converter-driven stability issues using frequency-based analysis techniques in electrical power grids with high penetration of converter-interfaced devices. The work examines how power electronic converter parameters influence converter-driven stability in an 11-bus AC system with multiple inverter-interfaced units.

Q3.01:

a) Which technical challenges in multi-vendor MTDC systems still require coordinated development across the industry, and which stakeholders should be involved to address them effectively?
b) What are the remaining gaps in methodologies, testing procedures, or standards for validating multi-vendor MTDC interoperability before project deployment?

Q3.02:

From an owner's perspective, as GFM HVDC, GFM STATCOMs, and multi-vendor MTDC systems move into procurement, how should measurable performance requirements, study methodologies, and supplier deliverables be specified so that different vendor offerings can be fairly compared and reliably validated?

Q3.03:

Multiple papers have addressed various aspects of grid forming (GFM) converters. There are different implementations of GFM controls, the details of which are not necessarily available due to intellectual property concerns. Understanding such differences and any technical limitations are important for the Owners at early stages of a project.

a) What options are available at early stages of a project to identify potential limitations of the implementation of a certain GFM control approach?
b) What sort of studies need to be performed to identify the need for GFM converters and figure out any limitations?
c) What are the main performance requirements to be specified for GFM converters?

Q3.04:

What are the minimum network model fidelity and network representation requirements for HVDC studies to capture renewable-specific dynamic behaviour, especially when assessing performance under weak-grid or renewable-rich operating conditions?

PS3.2 – New Technologies and Concepts

PS3.2-1 – UHVDC Transmission System

Paper B4-11462 "Key Technologies and Research Applications of UHVDC Current Source Converters Based on RB-IGCT"

The paper reviews UHVDC current source converter technologies enabled by Reverse Blocking Integrated Gate Commutated Thyristors. Two approaches are described: the Hybrid Commutated Converter, which adds active turn-off capability to LCCs, and the IGCT-based Current Source Converter for self-commutated operation, with real-time simulation tests presented for both configurations.

Paper B4-12515 "System Design for the World's First ±800 kV 8 GW VSC-UHVDC Transmission Project"

The paper presents the system design of the Gansu–Zhejiang ±800 kV, 8 GW VSC-UHVDC project, described as the world's first ±800 kV/8 GW VSC-UHVDC, with 5 kA DC current and approximately 2400 km transmission distance. The paper addresses system stresses including large submodule energy storage, transient overvoltage, long communication delays, and AC faults.

PS3.2-2 – Medium Voltage DC

Paper B4-10793 "Superconducting Medium Voltage DC Transmission: Architecture, Protection, and Simulation Insights"

The paper presents the SCARLET project concept for medium-voltage DC transmission using superconducting cables, particularly for offshore wind farm export. Two configurations are described: one based on High-Temperature Superconductor tapes at ±50 kVDC cooled with liquid nitrogen, and another based on Magnesium Diboride wires at ±25 kVDC cooled with liquid hydrogen.

Paper B4-11388 "Medium voltage railway dc-dc converter design and performance"

The paper presents the design and control of a face-to-face three-phase modular multilevel DC–DC converter for railway applications. It addresses power transfer capacity, operation under dynamic conditions, and the frequency limit to which a 50 Hz transformer can be used, providing an overview of the state of the art together with operating principles.

PS3.2-3 – DC Protection and DC Circuit Breakers

Paper B4-10944 "Analysis of DC circuit breaker performance in multi-terminal HVDC grids considering fault dynamics and reclosing behaviour"

The paper analyzes DC circuit breaker interruption energy and rapid auto-reclosing for the VSC Assisted Resonant Current DCCB in MTDC grids containing overhead line spans. EMT case studies are combined with an energy-absorption expression, and sensitivities to fault location, settings, design choices, and fault type are evaluated for MOSA energy rating sufficiency.

Paper B4-10945 "Operation of modular VARC DC-CB under load and fault current and the impact on system dynamics"

The paper presents operation of the VSC Assisted Resonant Current DC circuit breaker under load and fault current interruption conditions. Different line current switching events are investigated by varying the number of suppression modules switched, with the work reporting that reducing modules switched for load current conditions reduces voltage stresses in the DC system.

Paper B4-11109 "Development of a Novel Polarity Reversal Inhibitor for Future MT-HVDC"

The paper proposes a Polarity Reversal Inhibitor, a passive modular diode and MOV device intended to clamp negative voltage transients and suppress polarity reversal following DCCB operation in meshed MT-HVDC grids. An EMT study shows the PRI can clamp polarity reversal and reduce breaker MOSA energy duty, with laboratory tests on a 24 kV prototype.

Paper B4-11550 "Performance Study and Specification Framework for DC Circuit Breakers in Multi-Terminal HVDC Networks"

The paper presents a performance study and specification framework for DC Circuit Breakers in a 12-terminal ±525 kV multi-terminal HVDC bipole network representing a future Great Britain DC grid. Using real-time simulation, hybrid DCCB behavior is assessed under multiple scenarios, with metrics including peak breaker current, energy absorption, transient interruption voltage, and interruption time.

Paper B4-11857 "An Interline Multiport DC Circuit Breaker with Power Flow Controller"

The paper proposes an Interline Multiport DC Circuit Breaker with Power Flow Controller for multi-terminal HVDC grids, integrating DCCB functionality with DC power flow controller capability into a multiport device to reduce footprint and cost. The topology provides simultaneous multi-line fault

interruption, redundancy, and duty-cycle-based power flow control, examined through EMT simulations.

Paper B4-12413 "Ultra-fast Power Electronics based HVDC Circuit Breaker: A Paradigm Shift towards System Flexibility and advanced Control Features"

The paper presents a power-electronics-based HVDC circuit breaker designed for multi-terminal HVDC grids, with fault interruption capability on the order of 100 µs using modular IGBT-based current suppression modules combined with a residual mechanical switch, advanced control, and forced cooling for multiple reclosure attempts. Modular configuration aspects are also described.

PS3.2-4 – Grid Support, FACTS, and Digital Substations

Paper B4-10876 "Deployment Considerations of Autonomous Robots in HVDC Converter Stations"

The paper proposes a unified, vendor-neutral functional specification framework for autonomous inspection robots in HVDC converter stations and associated substations. It consolidates environmental and operational challenges across indoor valve halls and outdoor yards into structured capability-based requirements, supporting standardization and procurement discussions in digitization and robotics.

Paper B4-11107 ""Experimental Validation of a Low-Voltage Prototype of a Converter-Transformer for HVDC Applications""

The paper presents the design, realization, and laboratory validation of a low-voltage prototype of a Modular Multilevel Converter-Transformer topology for HVDC applications. The architecture combines transformer and converter functions, eliminates distributed submodule capacitors, and supports AC/DC, DC/AC, and DC/DC conversion. A 1 kVA prototype demonstrates artificial DC current zero crossings induced through modulation control.

Paper B4-11463 "Low-Frequency AC Transmission for Offshore Wind Power: Key Technologies and Grid Integration Challenges"

The paper reviews technologies and challenges for low-frequency AC transmission used to integrate offshore wind power, including point-to-point and multi-terminal architectures. AC/AC converter topologies are compared, including back-to-back MMC and modular multilevel matrix converter. A fault ride-through strategy is introduced using the Yuhuan No.2 LFAC offshore wind project as a case study.

Paper B4-11465 "Feasibility Study on Cancelling the DC Choppers in VSC-HVDCs for Renewable Energy Integration"

The paper proposes a modified MMC topology with distributed energy consumption function for VSC-HVDC systems in large-scale renewable energy transmission, integrating distributed energy consumption into each submodule to manage surplus energy during faults. The operating principle and AC and DC fault ride-through methods are presented, with EMT simulations and prototype-level experimental verification.

Paper B4-11699 "Electrification of offshore platforms using Static Frequency Converters - Concept analysis for the Norwegian grid"

The paper investigates Static Frequency Converter technology for Power-from-Shore electrification of offshore oil and gas platforms in Norway. Three architectures are analyzed: onshore frequency conversion, offshore frequency conversion, and low-frequency HVAC transmission. The study concludes that onshore SFC-based conversion suits the Norwegian context, supported by power flow, short circuit, dynamic, and protection studies.

Paper B4-11855 "FPGA-Based Modelling of Modular Power Converters for Data Centres System Interconnection and Integration Studies"

The paper presents an FPGA-based EMT modeling framework for modular solid-state transformers used at the interface between data centers and high-voltage AC systems. The framework includes a hybrid

CPU–FPGA multi-rate real-time solver and switching-function equivalent models. A case study of a 45 MVA SST with battery interface demonstrates active-power smoothing and voltage support.

Paper B4-12129 "Innovation and Challenges in the Implementation of Series FACTS in 500kV Transmission Lines of the Peruvian System"

The paper describes the integration of a Static Synchronous Series Compensator FACTS device in the 500 kV Peruvian electrical grid. It summarizes the planning, design, and realization of the technology in this large electrical system, and reports lessons learned in defining main component selection of series compensation based on SSSC at the 500 kV level.

Paper B4-12297 "Economic Analysis of Solid-State Transformers for Modern Power Systems"

The paper presents an economic analysis of solid-state transformers relative to conventional low-frequency transformers across three connection scenarios for indoor and outdoor installations. A modular ISOP SST topology is assumed, and component-level cost estimation is benchmarked against an inflation-adjusted LFT cost of 29 USD/kVA, with long-term cost trend projections discussed.

Paper B4-12298 "Advanced Management and Power Quality Performance of Hybrid Transformers in modern Distribution Networks"

The paper describes a 250 kW hybrid transformer prototype developed jointly by ENEL and Hitachi Energy and deployed in a 20 kV MV distribution substation in Brindisi, Italy. The architecture combines a conventional distribution transformer with back-to-back converters, enabling voltage regulation, reactive power compensation, phase load balancing, harmonic filtering, and power flow control.

Paper B4-12430 "E-STATCOM, the first of its kind: Design and performance of a supercapacitor energy storage integrated into a STATCOM"

The paper presents the design, control concept, and operational experience of a 300 MVA E-STATCOM equipped with supercapacitor-based short-term energy storage providing reactive power support and fast active power response for inertia emulation in the German transmission grid. Ageing and availability aspects are addressed alongside initial operating experience.

Q3.05:

As the technology selection moves from LCC-only bulk transmission toward VSC-UHVDC, hybrid LCC/VSC, advanced current-source converters, and DC fault-managed architectures, what should be the evaluation framework for the future "ultimate form" of UHVDC? Which performance thresholds must these emerging technologies meet before they can displace or complement LCC at ultra-high voltage and multi-GW scale?

Q3.05:

CIGRE One Grid advocates for planning, operating, and governing the entire electrical network as a single, integrated ecosystem. Should it be treated mainly as a targeted solution for applications such as hyperscale data centres, renewable energy integration, ports, and industrial parks, or as a broader architectural layer across the grid? What practical evolutionary pathway should the industry prioritize to enable this transition, including phased retrofit of existing AC infrastructure, hybrid AC/DC operation, or clean-sheet MVDC design?

Q3.06:

With all the increased demands and rapid load variation on the grid, especially from AI data centers, how are the new technologies able to address these challenges, and able to address them quickly in terms of being installed and in service? What additional aspects must be considered in converter designs to support such variations?