B4 - 00

SPECIAL REPORT FOR SC B4

T. An L. Brand

Special Reporters

Cigre Study Committee (SC) B4 is responsible for DC systems and Power electronics for AC systems. The recent increase in generating power from renewable resources and changes in the power transmission patterns has increased the demand for DC and FACTS devices. A growing interest is also evident in utilizing DC at lower voltages for power distribution purposes. At the same time the recent advances in semiconductor devices and in circuit topologies opens up new possibilities for planning and operation of AC systems. SC B4 plays an important role in this process by providing a platform for the experts to exchange their thoughts and experiences.

For the 2021 session a total of 53 papers were selected based on the preferential subjects listed below. These papers represent the latest information on DC systems and FACTS schemes at various stages of planning, construction and operation. The papers selected and submitted covered many aspects of DC and FACTS, including:

- Line commutated converter (LCC) applications
- Voltage source converter (VSC) applications
- Comparison between the LCC and VSC for their applications in different systems
- DC projects, planning and implementing DC systems and FACTS
- Energy Storage in conjunction with DC systems
- Multi-terminal systems
- DC control and protection systems
- Simulation tools and their application in DC and FACTS
- Reliability and availability assessment of DC and FACTS
- Refurbishment and life assessment of DC and FACTS devices
- DC and FACTS in distribution systems

It is clear that the interest in DC and FACTS is strong and continues to challenge our industry for new ideas and concepts.

The Preferential Subjects chosen by the Study Committee for the 2021 session are as follows.

PS 1 HVDC Systems and their Applications

- Planning and implementation of new HVDC projects including need, justification, design, integration of renewables, environmental assessment, and economic assessment
- Application of new technologies including cyber security and advanced controls to address emerging network issues, DC grid, multi-terminal HVDC, hybrid HVDC systems and HVDC circuit breakers

Ting An: anting66@qq.com
Les Brand: les.brand@amplitudepower.com

- Refurbishment and upgrade of existing HVDC systems, service and operating experience of converter stations including offshore converters, and implications for converter equipment resulting from the conversion of AC circuits to DC circuits

PS 2 DC and Power Electronics for Distribution Systems

- DC applications in distribution systems
- Power Electronics applied in distribution projects, including economics and reliability
- New concepts and designs of equipment

PS 3 FACTS

- Planning and implementation of new FACTS projects including need, justification, for integration of renewables, environmental assessment, and economic assessment
- Application of new technologies in FACTS and other Power Electronic equipment, including interfacing generation and storage to the network
- Refurbishment and upgrade of existing FACTS and other Power Electronic systems; service and operating experience

PARIS GROUP DISCUSSION MEETING (GDM)

1. Contributors should upload your contribution on the *Registrations platform* – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials before **July 20th, 2021** for a prior screening and a good organization of the Group Discussion Meeting.

Important points:

- *Access to contribution uploading is given only to duly registered delegates.*
- *As a consequence, registration to CIGRE Session should be finalized before uploading contribution(s) online.*
- *Register now for the Session Click here*
- *Contributions uploading will be open at the beginning of May.*

2. Special Reporters will review the prepared contributions (power point presentation with max 3 slides + written contributions with max 1000 words per contribution); selection of accepted contributions. A guide for contributors as well as templates and sample pages will be available on the CIGRE Centennial website - see Group Discussion Meetings in the top menu bar

3. Any recommendations or changes to the contributions will be provided to the contributors by the special reporters directly on Registration platform by **August 4th, 2021**. Contributors are encouraged to visit their account on the Registration Platform to see the result of this review. Final decision of acceptance will be made by **August 10th, 2021**.

4. After the acceptance, CIGRE Central Office will ask all accepted contributors to access the LENI system to record voice-over file as a backup just in case the lively participation shows any issue. CO provides the guidelines and suitable information related to this LENI system shortly.

5. SC B4 will have two GDM sessions on **August 18th and 19th, 2021**. The contributors will be notified the exact time slot of the presentation prior to the GDM session.

PS1 - HVDC systems and their applications

(PS1-1) Planning and implementation of new HVDC projects including need, justification, design, integration of renewables, environmental assessment, and economic assessment

Paper B4-101 "Brazilian Experience in Switching 800 kV LCC Converter Transformers"
This paper describes the outcomes of investigations into the employment of point-on-wave devices and pre-insertion resistors for mitigation of inrush currents during the energization of the converter transformers for the 800kV Xingu-Estreito and the 800kV Xingu-Terminal Rio bipole HVDC systems.

The outcomes of the converter energization studies are presented, and the paper concludes that the pre-insertion resistors proved to be effective (where employed on the Xingu-Terminal Rio system) and if employed, would have removed operational constraints imposed on the Xingu-Estreito system.

Question 1.1:

- As HVDC systems become larger, what challenges and what impacts on the AC network have been experienced or considered for the energization of these large HVDC converter transformers?
- What mitigating methods, such as pre-insertion resistors, point-on-wave switching, or others, have been employed to address these challenges or impacts?

Paper B4-103 "The Measurement of HVDC Ground Electrodes Resistance"

This paper presents an alternative approach to the fall-of-potential method for the measurement of ground electrode resistance, based on the measurement of potential between the DC neutral bus and the local grounding grid at the converter station. The paper describes both methods and states that the alternative approach is suitable to high-resistivity environments, where the fall-of-potential method would require the measurement of a very long surface potential profile which both takes time and presents logistical difficulties. Examples of electrode resistance measurement are provided using both methods.

Paper B4-106 "Compacting HVDC VSC and LCC Converter Stations for Land Use Minimization"

This paper discusses the aspects that should be considered in connecting an MMC/LCC DC converter station to an AC substation and compares the dimensions of two different types of VSC valve halls (MMC and cascaded two level) of two VSC schemes with different configurations (symmetrical monopole and bipole converters) and LCC valve halls of three projects with different power ratings. The volume metrics of three compacted onshore converter stations of 1000 MW, 1400 MW and 1800 MW were estimated and the compacted valve halls of the offshore project of DolWin3 and the onshore project of INELFE are compared in the paper. The considerations for an onshore compact converter station are outlined and, finally the paper is ended with the key findings.

Question 1.2:

Several offshore projects have been successfully constructed and commissioned in operation and are under construction and planned to be implemented around the world, especially in Europe, and the dimensions of the platforms are continually designed to be compacted.

- What are the main challenges to be faced and key factors to be considered for further reduction of the total dimensions of offshore platforms?
- What are the major impacts on the losses, reliability and capital costs of the compacted MMC-VSC and LCC converter stations, any examples?

Paper B4-108 "Black start and system restoration utilizing the NEMO Modular Multilevel Converter – a practical test in the Belgium transmission system"

This paper describes the testing of the black start capability of the NEMO Link Interconnector on the physical system. The NEMO Link Interconnector is a 1GW HVDC link between Belgium and the UK and is equipped with black-start capability. The converters are connected via 140km of subsea and underground cables. The paper describes the concepts and options of black-start functionality as it pertains to a HVDC interconnector. To test this functionality, a microgrid within the Belgium transmission network was determined and the procedures applied to test both sequential and collective black start functionality developed and described in this paper. The paper also describes how the issues created by low short circuit levels and low ratio of zero-sequence and positive sequence impedance in the microgrid were addressed. The paper concludes that the collective ("soft start") energization method avoids issues due to zero-sequence current and voltage oscillations in the microgrid, leading to the abandonment of the sequential black start functionality and the adoption of the collective black start procedure.

Paper B4-127 "Functions and Commissioning test of New Hokkaido-Honshu HVDC Link"

This paper provides an overview of the features of the new Hokkaido-Honshu HVDC link in Japan and presents the outcomes of the tests performed during the commissioning of the system in late 2018

and early 2019. The new Hokkaido-Honshu link has a rating of 300MW and utilizes MMC-VSC technology in a monopole metallic return configuration. The features and functions of the new system include automatic frequency control, reactive power control, high speed restart (due to DC overhead line fault), black start and stabilization when the connected network at Hokkaido is isolated from the rest of the AC system. The paper describes the testing of the black start functionality, including configuration of the nearby transmission system and thermal power generators to create a test system, which was successful. The paper concludes that the commissioning tests were completed successfully and that the system went into commercial operation in March 2019.

Question 1.3:

Papers B4-108 and B4-127 describes a methodology for testing the black start functionality of a VSC HVDC system on the energised network.

- What approaches have been applied to the testing of black start functionality on other VSC HVDC systems with this capability and what were the outcomes?

Paper B4-109 "Commissioning of VSC HVDC Converters for STATCOM Operation"

This paper presents the sequence applied to and the outcomes of the commissioning of the Norwegian converter station of the Nordlink HVDC interconnector between Germany and Norway. Nordlink is a 1,400MW rated HVDC system utilizing multi-level voltage source converter technology. Nordlink is designed as a bipole with a number of different operating modes which were able to be tested in STATCOM operation at the Norwegian end. Subsystems testing started in autumn 2018 while the high voltage energization and terminal tests were performed in July 2019. The outcomes of the initial high voltage energization, first deblock, maximum reactive power and AC voltage control tests are presented. The paper concludes that the commissioning of the converter in STATCOM operation mode was successful and that the ability to undertake such commissioning allows operation modes to be tested and verified without needing to coordinate with the other converter station and electricity market, providing a degree of flexibility in the test program.

Paper B4-112 "Challenges of HVDC standardization in external insulation design of converter stations"

This paper presents some of the challenges that are foreseen with the standardization of HVDC systems in external insulation design of converter stations. The aspects on overvoltage stresses, site conditions and indoor halls of external insulation design and the impact of standardization on HVDC converter station design are discussed in detail in the paper. How the external insulation can help to reduce environmental impact of HVDC converter stations and the importance of allowing freedom and innovation in certain areas of insulation coordination and external insulation design of HVDC stations are also addressed in the paper.

Paper B4-115 "System studies for the Baihetan-Jiangsu ±800 kV Hybrid UHVDC project"

This paper presents the system studies undertaken for the upcoming Baihetan-Jiangsu ±800 kV hybrid UHVDC project, which is proposed to transmit 8 GW hydro power from the Baihetan dam to a load centre in Jiangsu Province on the east coast of China. A novel hybrid UHVDC topology is proposed for this project and used in the paper for the studies performed mainly on control objectives and allocation in the different converters, system dynamical performance when starting up VSC converters one by one with LCC in operation, tripping a VSC converter due to a converter bus fault, AC fault ride through and DC fault ride through.

Question 1.4:

The topology of the hybrid UHVDC system used in the paper is LCC converters at the rectifier end, and one LCC converter in series with three paralleled VSC converters at the inverter end.

- Are there any other topologies for the hybrid HVDC systems proposed?
- What are the major concerns/challenges with operating a system similar to that described in the paper?
- Are there any other hybrid HVDC projects under consideration/development/planning?

Paper B4-116 "Planning and implementation of an HVDC link embedded in a low fault level AC system with high penetration of wind generation"

This paper describes transmission investment planning for the Caithness-Moray Transmission project in the UK by carrying out a cost benefit analysis, and the planning and performance studies for the very weak AC system in the Caithness area. The design and engineering for a five terminal HVDC system are detailed in the paper. The conclusion drawn in the paper is that the benefits of early delivery for connection of renewables to limit carbon emissions supported by favourable cost benefit analysis made it the preferred solution compared to onshore AC transmission rebuild options.

Paper B4-118 "Dynamic stability issues of VSC-HVDC systems in AC Transmission Emulation Control: the Piossasco - Grande Ile case"
This paper presents the methodology for investigating the behaviour and selecting optimal parameters of Hybrid Control Mode (HCM) from the dynamic stability point of view for the Piossasco - Grande Ile Italy-France HVDC interconnection project. The numerical application described in the paper validates the model built both in the Digsilent Power Factory and Matlab environments. The methodology proposed can be applied to any HVDC equipped with HCM function to address the parameters tuning.

Paper B4-119 "Design and functional aspects of a new HVDC link of Crete Island with the mainland Transmission System of Greece"
This paper describes the second phase of interconnection between Attica, Greece and Crete via a 2 x 500MW bipole HVDC link. The first phase will be a double AC link with a capacity of 2 x 200 MVA. The new HVDC system will be a bipolar link with a current return path through the sea via two shoreline electrodes. The HVDC converter stations will utilize MMC VSC technology using half-bridge submodules and will have the capability to black start the Crete system. The converter stations will be connected using mass-impregnated non-draining (MIND) cables with a route length of 380km. The paper presents the challenges faced to ensure the system can operate without the HVAC cable system and local generating units in service, i.e. asynchronous operation into a weak grid and to ensure a smooth transition between the various modes. The paper also describes considerations made in the design for a future extension of the HVDC system to a multi-terminal HVDC link in the area of the south-east Mediterranean Sea, including the addition of DC circuit breakers.

Question 1.5:

The system described in paper B4-119 will operate in parallel with a HVAC transmission circuit into a system that could be islanded and without synchronous generation. Issues associated with operation of the HVDC system into a weak-grid, and the smooth transition into this mode are addressed.

- What other systems are installed, planned or under construction that face these, or similar, issues?
- What strategies and methods have been applied to overcome these challenges?

Paper B4-121 "A new approach to operational type testing of HVDC valves"
This paper presents a new approach for the electrical type testing of VSC valves, particularly the "operational" type tests. These tests require the alternate application of high voltage and high current to the test valve for a prolonged period of time. The paper describes a new test facility built in Stafford in the UK, which uses four series strings of full-bridge sub-modules connected in parallel which, in effect, form a "programmable waveform generator". This paper describes the operation of the test circuit in both LCC and VSC mode and concludes that the new facility is versatile and capable of testing both LCC and VSC valves.

Paper B4-126 "The Celtic Interconnector – linking the electricity grids of Ireland and France"
This paper describes the objectives, benefits and project development approach of the Celtic Interconnector, a proposed new 700MW HVDC system connecting the Irish and French transmission systems. The systems will be connected through 600km of HVDC submarine cable and 75km of HVDC land cable. The system will utilize VSC technology in a symmetric monopole configuration. The paper describes the overall rationale for the project, which includes improved market integration, enhanced security of supply and the increased use and development of renewable energy sources in Ireland by allowing the export of renewable energy to France and Europe. The paper then describes the process for the selection of the connection points in both Ireland and France and the outcomes of

the marine route desktop study and marine surveys. The paper concludes that significant benefits of linking the transmission systems of Ireland and France have been demonstrated and that the project is on course for completion in 2026.

Question 1.6:

Paper B4-126 lists as one of the benefits to interconnection, the potential to develop renewable energy resources through increased interconnection allowing the power from these sources to be exported.

- What other projects are under development with a similar goal?
- To what extent have the benefits been proven to justify the cost of the HVDC interconnection?

Paper B4-132 "Calculation method for peak short-circuit currents for the security of HVDC grids"

This paper proposes a simple calculation method for estimating the prospective peak short-circuit current in meshed HVDC grids during the planning phase when limited data of the grids is available. The calculation method is based on an equivalent circuit and the equations to calculate the elements of the equivalent circuit directly from basic converter and line data are derived. The suitability of the proposed calculation method is validated by the results from PSCAD/EMTDC for a meshed HVDC test grid.

Paper B4-133 "System Design and Development of HYOSUNG 200MW BTB VSC-HVDC in a KEPCO System"

This paper presents the design of the 200MW/±120kV BTB (Back-To-Back) VSC HVDC interconnection to be put in operation in 2023, for reducing the fault current of the KEPCO (Korean Electric Power Corporation) grid in Korea. The Hardware-In-the-Loop-System tests with the actual controller conducted to verify the system parameters and the control algorithms designed, the operational tests and witness tests of the converter valves for the project are detailed in the paper.

Paper B4-135 "Seismic Design and Validation of the HVDC Valve Structure"

This paper presents the valve structure of a 200MW HVDC system designed to meet the seismic requirements of Korean transmission and distribution equipment and verified through testing and finite element analysis and proposes two methods to improve seismic performance in terms of design. One method is to diagonal braces to distribute the seismic load of the post insulator supporting the valve structure and the other is to increase the stiffness in the horizontal direction by adding an insulation beam to reduce the seismic load of sub module mounting.

Question 1.7:

- What are the most vulnerable elements of a VSC-HVDC valve with respect to resonances caused by earthquakes?
- Two methods have been proposed by the paper, are there any other methods for improving the capability of valve structure to withstand earthquakes?
- Are there any experiences for fastening HVDC-valves on a platform to withstand the sea waves during transportation at sea?

(PS1-2) Application of new technologies including cyber security and advanced controls to address emerging network issues, DC grid, multi-terminal HVDC, hybrid HVDC systems and HVDC circuit breakers

Paper B4-102 "Principles for paralleling HVDC-LCC converters: point-to-point transmission, multi- terminal and HVDC grids"

This paper presents the main principles including the necessary controls and dynamics, the principles of current sharing and margin allocation in the presence of a small inverter. It describes normal paralleling and de-paralleling of converters and protective de-paralleling. Examples of the application of these paralleling and de-paralleling principles in HVDC -LCC systems are given in the paper.

- The North East Agra HVDC Multi-Terminal Transmission scheme (NEA800) which is rated 6000 MW, 800kV to transmit hydropower from the north-eastern part of India to the region of Agra, over 1700 km.

- The Itaipu HVDC Transmission which consists of two bipoles each rated at 3150 MW at ± 600 kV.
- The Rio Madeira HVDC Transmission system which consists of two bipoles each at rated 3150MW at ±600 kV.

Question 1.8:

- What are the major challenges to the design of paralleling HVDC-LCC converters for different types of applications, such as point-to-point transmission, multi-terminal and HVDC grids respectively?
- What are the effects of commutation failure to the performance of the paralleling system?
- What key technical aspects should be considered and assessed if an existing HVDC-LCC transmission scheme is to be paralleled with a newly proposed HVDC-LCC/VSC supplied by different manufacturers?

Paper B4-104 "Large-capacity multi-infeed HVDC configuration managing simultaneously scheduled line outages to ensure power system security"
This paper firstly summarizes the conceptual basic system performance indices for AC/DC systems including SCR (Short Circuit Ratio), ESCR (Effective Short Circuit Ratio), MIIF (Multi-infeed Interaction Factor), Multi-Infeed Potential Interaction (MIIF x Pdcj/Pdci) and MISCR (Multi-infeed Interaction SCR). Then the systematic procedure for determining the weekly schedule for equipment maintenance to safely manage the numerous TL disconnection requests from the transmission agents is discussed. The numerical values for the AC/DC single and Multi-infeed interaction indices are presented next for two Brazilian interconnected power systems. After that, comparison of the AC/DC interaction indices at the four Inverter Buses under (N-1) operating conditions is conducted. The paper finally presents the sensitivity of the AC/DC interaction índices to the increase of the SE region inertia.

Paper B4-105 "Simulation and Development of HVDC Control Room with Advanced HMI, Interface Systems, Analytical Tools and Cyber security Infrastructure and Monitoring"
This paper dives into critical portions of HVDC systems and their applications based on use cases at a unique HVDC link in the northeast USA for the multi-terminal HVDC link. This paper provides a discussion for HVDC control room system applications for hardware and software, from a customer point of view. This paper discusses successful technologies interfacing HVDC control systems to transfer data events and indications with other multi-terminal links, by looking at serial telecom links and using serial to IP connections to transfer data with polling interval adjustments. The impact of NERC CIP compliance and policies and how it impacts on the HVDC utilities are also presented in the paper.

Paper B4-110 "Open-Source HVDC Control – a High-Level Perspective"
This paper discusses a possible implementation of an open-source HVDC control approach and the associated technical and non-technical aspects of such approach. The technical aspects include implementation, benefits, technical improvements, and some open research questions, whereas the non-technical aspects contain industry perspective, customer perspective, academia perspective, licensing, patents organization, warranty, cyber security, critical infrastructure, and standards and regulatory and financial framework. The paper states that the open-source approach can be useful to solve current as well as future control-related problems, both in point-to-point links as well as in multi-terminal, and multi-vendor HVDC grids.

Paper B4-114 "Improved VSC HVDC for overhead line HVDC transmission"
This paper presents an improved voltage source converter (VSC) based HVDC system, in which the converter is composed of mixed half-bridge (HB) and full-bridge (FB) cells, and compares the LCC based HVDC and the improved VSC HVDC in detail regarding the DC Fault Ride-Though (DCFRT) and demonstrates the performance. The challenges for the improved VSC HVDC are addressed and a robust solution is proposed. It is concluded that the improved VSC HVDC will be a technology that is a reliable and cost-effective solution for overhead line HVDC transmission.

Paper B4-120 "Multi Terminal Extension of Embedded Point to Point VSC HVDC Schemes"
This paper identifies the technical feasibility of multi-terminal extension of existing VSC-HVDC schemes, assesses the performance of a co-simulation study with VSC models from different suppliers,

highlights the testing and demonstration requirements for multi-vendor HVDC system and outlines the risks that would need to be managed by multi-vendor HVDC projects. It details the design, testing and demonstration requirements associated with the development of multi-vendor, multi-terminal VSC-HVDC systems.

Paper B4-138 "Technical solutions to predict and mitigate inadvertent interaction of two parallel connected VSC-HVDC schemes feeding an islanded offshore Oil and Gas grid"
This paper describes the technical challenges raised by the Johan Sverdrup Phase 2 project, which is a multi-vendor HVDC system feeding an islanded offshore oil and gas grid, and especially the analysis of interactions between the two HVDC links (Phases 1 and 2). The paper describes the main functions specified for the final global controller, presents simulation results in order to illustrate how the HVDC systems setpoints can be coordinated for a safe and secure operation, and describes the transitions from standalone operation to parallel operation.

Question 1.9 (combined question for Papers B4-110, B4-120 and B4-138):

More and more HVDC schemes have been commissioned, and are under construction and planning and also multi terminal HVDC systems and grids normally are developed gradually from the point to point HVDC schemes and may involve multi-vendors.

- What are the common interaction and interoperability issues which should be dealt with by all parallel operated schemes?
- What are the major challenges to design a multi-terminal multi-vendor extension from point to point HVDC schemes?
- What are major concerns to operate the multi-vendor HVDC systems and grids?
- Are there any extensions under planning, study or development?

Paper B4-122 "Combined Bridge MMC as efficient solution for HVDC systems with DC fault ride through requirements"
This work provides a comprehensive review of a combined (half and full) bridge MMC for HVDC applications with overhead lines for DC fault ride through, summarizes the key features of HVDC to enable reliable grids, discusses three major design criteria for steady state operation, AC fault ride through and DC fault ride through and presents the respective performance of the combined bridge MMC and specific topics concerning design and control. The major design aspects and cost comparison for the combined bridge MMC are also summarized in the paper.

Paper B4-107 "Towards a deployment plan for a future European offshore grid: development of topologies"
This paper presents the methodology, results and main findings of the study of the development of the future offshore grid topologies for the North Sea for the PROMOTioN project for the period 2020-2050 to provide inputs to a deployment plan of the project. The methodology used in this study includes a screening of the North Sea to identify the best areas for offshore wind production, the use of a dedicated optimization algorithm and market simulations of the North Sea countries. The technical viability of the proposed topologies and the impact on the AC-grid has also been demonstrated and analysed by simulating different protection strategies of the offshore grid.

Paper B4-123 "Towards a deployment plan for a future European offshore grid: cost-benefit analysis of topologies"
This paper provides an evaluation of investments, costs and potential (societal) benefits for each different development configurations developed in a reference paper to give recommendations for a deployment plan of a future European HVDC meshed offshore grid in the North Sea. The reviewed and adapted ENTSO-E techniques to construct a Cost-Benefit Analysis (CBA) model via a modular approach was developed, simulation of three major grid configuration options were performed and the corresponding results of the quantified costs and benefits with respect to Business as Usual (BAU), National Distributed (NAT), European Distributed (EUR), European Centralized (HUB) concepts are presented in the paper.

Question 1.10:

- Can the Cost-Benefit Analysis (CBA) model developed in B4-123, methodology and findings presented in B4-107 of the topology development of the future offshore grid in the North

Seas be adopted for the offshore grids in other situations or are these unique to this project because of the nature of the North Sea countries?

- What are the specific aspects and requirements which shall be considered in the design of DC grids?
- Are there any other future offshore HVDC grids or multi-terminal systems proposed to be developed that can benefit from the approaches presented in B4-107 and B4-123?
- Are there other possible configurations proposed for offshore HVDC grids?

Paper B4-124 "Demonstration of Multi-terminal DC Grid Integration with an MMC Test Bench"
This paper investigates the Power-Hardware-in-the-Loop implementation of a MTDC network including OWFs in a laboratory setup at the RWTH Aachen University as part of the Horizon 2020 project. A test case of a 4-terminal DC network comprising two OWFs is simulated both as a full-scale model and a lab-scale test bench to compare the results obtained by two different models and assess their respective system's performance and control behaviour.

Paper B4-125 "Improving synthetic inertia provision by power electronic interfaced power sources to support future system stability"
This paper investigates the impact of high penetration of power electronic interfaced power sources (PEIPS) on the frequency stability of the power system when synthetic inertia is provided by PEIPS, analyses the aspects of provision of synthetic inertia (SI) by PEIPS by varying their power output proportionally to the RoCoF of the power system, conducts the sensitivity analysis of the synthetic inertia impact on the frequency and power curves and presents several options for a zone-selective control scheme.

Question 1.11:

- What are the limitations and restrictions of the synthetic inertia provided by power electronic interfaced power sources to support power system stability?
- Does the provision of synthetic inertia increase the rating of power electronic interfaced power sources?

Paper B4-129 "Method for detecting of faulted section in cable-overhead HVDC line"
This paper describes an algorithm for DC lines with both cables and overhead transmission lines, which determines whether a DC line fault is present in either the cable section or overhead line section of the DC line. The outcomes of simulation studies to demonstrate the performance of the algorithm are provided in the paper.

Question 1.12:

The algorithm described in paper B4-129 is purported to be able to differentiate between a fault occurring in the converter station, the cable section and the overhead line section with sufficient accuracy to confidently determine whether the DC scheme should reclose (restart) or trip and lock out.

- What other methods are being investigated, implemented and/or demonstrated to provide this degree of selectivity of cable fault location for HVDC systems with both cables and overhead lines?

Paper B4-130 "Improvement of the oscillatory behaviour of the HVDC link between Spain and France"
This paper describes the process and outcomes of the investigation of the response of the INELFE HVDC link between France and Spain to inter-area oscillations that occurred in the Continental Europe system in late 2016. It explains the studies performed to determine required control changes to improve performance and to verify no adverse impact on system security, and how these control changes were implemented and validated on-site.

Question 1.13:

Paper B4-130 describes the implementation of angle difference control for active power control across an HVDC link operating in parallel with one or more AC transmission lines.

- What other control strategies have been implemented, or investigated for implementation on HVDC schemes operating in parallel with AC transmission lines?

Paper B4-131 "Optimization and Simulation for Network Performance of Back to Back VSC-HVDC Systems"

This paper analyses the operation risks of VSC-HVDC connected power grids, studies an optimized scheme of the ±420kV "Yu-E" back to back VSC-HVDC project for network performance, proposes two resonance suppression/optimization methods to resolve resonance identified and to achieve island steady operation, and builds a closed-loop simulation platform based on RTDS for engineering tests.

Question 1.14:

The scheme studied and methods proposed in this paper have been used for the "Yu-E" back to back VSC-HVDC project which has been in operation since 2019.

- Are there any other similar projects commissioned in operation recently, under planning or construction?
- Apart from the resonances observed for the "Yu-E" back to back VSC-HVDC project, what were the other challenges/issues faced/solved for the project or other similar projects?

Paper B4-136 "Fundamental Frequency Blocking Filters for Champa- Kurukshetra HVDC ±800kV, 6000MW HVDC Parallel Bipole Transmission System – Design Consideration"

This paper discusses the impact of the operation of parallel 765kV and 400kV AC overhead transmission lines on the Champa-Kurukshetra HVDC scheme in India. The parallel AC lines are modelled along with the ±800kV HVDC overhead transmission line and the HVDC converters to quantify the impact and to determine the design of the fundamental frequency blocking filters to be installed on the DC side. The modelling is then used to demonstrate the effect of the blocking filter to reduce DC currents in the converter transformers.

Question 1.15:

The shortage of available easements to install both AC and DC overhead transmission lines is likely to lead to more instances of the AC and DC overhead line circuits sharing the same easement and being in close proximity to, or on the same towers as, each other. This paper has addressed the issue through the design of fundamental frequency DC blocking filter.

- For other HVDC systems with similar challenges, how has the issue of AC-DC interaction been addressed or proposed to be addressed?

Paper B4-137 "Assessment of protection strategy options for future DC grids"

This paper proposes a set of three measurable Key Performance Indicators (KPI), i.e. effectiveness, failure and Economic, that demonstrates how four protection strategies are effectively achieving key objectives and presents a methodology for HVDC grid protection strategy comparison and evaluation based on a multi-criteria approach using the KPI. The efficiency KPI quantifies the impact of a protection strategy on the fault clearing times and power restoration process, the failure KPI assesses features related to the malfunctioning of a protection strategy and the economic KPI quantifies the capital and operational costs of a strategy. A Multi-Terminal high voltage Direct Current (MTDC) grid test benchmark is considered to illustrate the methodology for protection strategy evaluation and comparison for the protection strategies proposed within the EU project PROMOTioN (PROgress on Meshed HVDC Offshore Transmission Networks).

Question 1.16:

HVDC grids are expected to be developed gradually with the extension of point-to-point and/or multi-terminal schemes. The paper assesses the protection strategies based on a four terminal HVDC grid with one mesh.

- What are the impacts of the grid extensibility on the performance of HVDC grid protection strategies?
- What are major aspects which need to be considered for the interoperability of different protection strategies within the same grid?

(PS1-3) Refurbishment and upgrade of existing HVDC systems, service and operating experience of converter stations including offshore converters, and implications for converter equipment resulting from the conversion of AC circuits to DC circuits

Paper B4-111 "European Experiences in HVDC System Reliability and Availability"
This paper describes the findings and results of the European Network of Transmission System Operator for Electricity (ENTSO-E) task force established to find ways to improve HVDC system reliability and availability. The paper focuses on HVDC converter stations and starts out by summarizing key aspects of HVDC reliability and availability and providing some statistics based on CIGRE and other sources. A summary of experiences and challenges met by ENTSO-E members during pre-planning, specification, tendering and technical design, with some examples to improve reliability and availability is provided. Key technical areas addressed include provision of a bypass path for DC smoothing reactors, DC filter switching arrangements, real time monitoring of the valve hall, addressing pollution within the DC smoothing reactor, strategies for shortening replacement times for spare transformers, design considerations for valve cooling systems and other auxiliary systems. System issues and operation and maintenance issues are discussed. The paper concludes that reliability should be a high focus during the first stages of a HVDC project.

Paper B4-113 "HVDC Lifecycle management – a Reliability & Availability perspective"
This paper examines lifecycle management of a HVDC system from an industrial service perspective. It starts out by providing a summary of lifecycle management and an explanation of the "service ecosystem" which includes manufacturers, operators and contractors and then proceeds to provide user examples of challenges experienced by HVDC users. The issues of improving long term reliability, availability and resilience are addressed through examples such as management of climate conditions, minimization of outage windows and improving physical and cyber security. Other areas addressed include proactive maintenance methods, use of systems to support data collection (datalogging, asset management systems and implementation of a digital twin), improved root cause analysis, improved collaboration, consideration of the cost of unavailability and potential service contract models.

Paper B4-117 "Levelized Energy Cost Improvement through Concept Selection and Availability Optimization for the Norfolk Windfarms' Export Links"
This paper presents a number of assumptions that can be made to estimate the mean time between failures of XLPE HVDC cables from publicly available information, illustrated by using the UK Norfolk windfarm as a study case. It proposes to use energy not transmitted as a metric to choose between different HVDC export link grid concepts to calculate the outage times, energy availability and expected energy not transmitted for each grid concept. A method to evaluate availability of HVDC connected WPP's based on publicly available data and real-life project considerations is discussed.

Question 1.17:

Tens of VSC-HVDC cable projects have been constructed in operation in the last two decades around the world.

- Are the results obtained from the real projects comparable to those presented in the papers?
- If large differences are observed what are major factors affected the results?

Paper B4-128 "Experience in the HVDC equipment development for Vyborg converter station upgrade at SS 330/400 Vyborg PJSC FGC UES"
This paper describes the configuration and operation of the Vyborg converter station, a back-to-back HVDC system that connects the power grids of Russia and Finland. The system was put into operation in 1981 and the converter valves have reached end of life and require replacement. The paper presents the process and outcomes for the development and manufacture of the new converter valves, including how these were tested, installed and commissioned.

Paper B4-134 "The Method of Components Critical Priority Assessment for HVDC Station Asset Management System"
This paper conducts FMEA (Failure-Mode Effect Analysis) and FTA (Fault-Tree Analysis) for a VSC HVDC system to identify key equipment and find root causes of failures, and assesses the importance of the components in a VSC-HVDC substation, discusses sensor development and prioritization of

facility maintenance and undertakes sensitivity analysis of FTA of certain scenarios. The purpose of this study is to prioritize sub-systems using preventive diagnostic technology that could be applied according to the importance of the sub-system in the HVDC station.

Paper B4-139 "A survey of the reliability of HVDC systems throughout the world during 2017 – 2018"

CIGRE Advisory Group B4.04 collects data annually on the reliability performance of HVDC systems in operation throughout the world. This report is a summary of the reliability performance of HVDC systems in operation worldwide during 2017 and 2018. This report is based on reporting from 49 LCC systems and three VSC systems for 2017 and 50 LCC systems and four VSC systems for 2018.

Question 1.18:

With only 3-4 VSC systems reporting, but with an increasing demand and interest in the development of VSC projects worldwide, a greater sample size of data is needed to assist those considering VSC to undertake reliability planning and assessment.

- What is the experience of other VSC owners and operators in regards to the reliability of the VSC converter stations?
- What have been the main causes of forced unavailability for VSC converters?

PS 2 - DC and Power Electronics for Distribution Systems

(PS2-1) DC applications in distribution systems

Paper B4-201 "Engineering Design and Control Method for Hangzhou's Flexible DC Distribution Network"

This paper describes the DC distribution network project which has been developed and installed in Hangzhou, China. With a view to minimize space requirements for the equipment and reduction in cost at the DC level, the project uses a transformer-less DC connection. The paper describes key aspects of the design to manage issues created by faults on the AC network, and to minimize impacts on the AC network during start-up of the DC transformer. The DC circuit breaker used in the scheme is also described, which uses a bridge rectifier structure with diodes and measures implemented to limit the rate of short-circuit current during operation.

Question 2.1:

Paper B4-201 describes key design considerations for DC distribution converters to minimize space and cost, both of which are key drivers to the adoption of DC distribution.

- What other design philosophies or techniques have been applied for DC distribution systems to minimize equipment space and cost?

Paper B4-203 "Development of Multi-Terminal DC link in Distribution Network"

This paper describes a decentralize-based operation of the MT MVDC system to make connections of the adjacent feeders more flexible to balance feeder load and minimize loss through optimal output power control over time without requiring data measurement of power generation and load demand, and proposes a method to determine the optimal operating point of the VSCs for loss minimization purposes using only the information from the PCC. The comparison of total line losses of the decentralized-based with the existing centralized control-based control methods is performed to evaluate the proposed method using the modified IEEE-33 test networks.

Question 2.2:

This paper concludes that the proposed decentralized control-based method via a MT MVDC system has greater impact on the total line loss reduction which is of very similar effect on the loss reduction to the centralized control-based method that requires all generation and load data from the connected distribution networks in real-time.

- Are there any other applications/projects of MT DC systems proposed for load balancing and loss reduction in distribution networks?

Paper B4-204 "The Flexible Power Link of Western Power Distribution: A Case Study"

This paper provides a case study for a Flexible Power Link (FPL) connecting parts of the Western Power Distribution Plc 33kV network in the southwestern part of the UK. The FPL is described as

back-to-back three-phase, three-level converters, with associated transformers and harmonic filters. The transformers are installed in the same tank for space saving and to minimize the scope of noise mitigation. The paper describes the features and functionality of the FPL and the outcomes of the commissioning and site acceptance testing to demonstrate required performance.

Question 2.3:

Paper B4-204 presents an application for medium voltage DC to address issues and limitations on the AC distribution network.

- What other applications are being developed or considered and what network issues are they intended to address?

(PS2-2) Power Electronics applied in distribution projects, including economics and reliability

No papers were submitted for this topic.

(PS2-3) New concepts and designs of equipment

Paper B4-202 "A New Method for Distinguishing DC Line Faults in Flexible DC Distribution System"

This paper proposes a new grounding method for a ±10kV DC distribution system where the neutral point of the coupling transformer on the valve side earths through a medium resistance and presents a new strategy of fault location and protection including adaptive amplification coefficient for the MV DC power distribution system.

Question 2.4:

- How can the contribution of the DC loads/generators (i.e. electric vehicle/ photovoltaics/energy storage) to DC fault currents be considered as the DC loads can be connected at the DC side of DC distribution system?
- What are the major impacts of DC loads/generators on DC fault current?

PS 3 - FACTS

(PS3-1) Planning and implementation of new FACTS projects including need, justification, for integration of renewables, environmental assessment, and economic assessment

Paper B4-302 "Recent FACTS Applications in Chesf Power Grid: Aspects of Technological Development"

This paper describes the design, analysis and commissioning of the Tauá SVC, a -45MVAr to 90MVAr SVC installed in the Chesf transmission system in Brazil. The paper explains the rationale for selecting an SVC design over a VSC STATCOM solution and the key components and features of the implemented SVC design, including the implementation of automatic gain calculation and gain supervisor schemes, a series blocking reactor for improved performance and a control scheme to coordinate operation with a nearby SVC. The SVC performance during AC faults is demonstrated through Alternative Transients Program (ATP) and RTDS simulations. The paper concludes by proposing a hybrid SVC design with a multilevel VSC based STATCOM installed in parallel with a TSR and/or TSC.

Paper B4-309 "NSSS STATCOM – The Optimal Dynamic Reactive Support Solution for a Weak Network"

This paper describes the implementation of STATCOM technology to address issues created by the weakening of the North Shore Loop, located in the northeastern Minnesota transmission system. The primary concern was the loss of dynamic reactive power support due to the retiring or conversion to non-baseload operation of the existing coal-fired generators. Both SVC or STATCOM technologies were considered, and STATCOM selected due to this being the only technology offered by the bidders. The paper describes a number of weak system challenges discovered during the design and engineering phase and how these were addressed by the STATCOM design, including transient overvoltages, harmonic resonance, transformer inrush and the starting of large motors.

Paper B4-310 "Study and Operational Experiences of STATCOM for Emerging Grid with Renewable Power Network"

This paper describes the implementation of STATCOMs on the Indian transmission network. The reasons for choosing STATCOMs over other FACTS devices such as SVCs are provided, which included the comparative better reactive power performance at low voltages, quicker response times, smaller installation space and the modular design of the STATCOMs, The paper describes the challenges created by the increase in renewable energy installations and how the STATCOMs can help address these challenges. The paper finishes with some cases studies of STATCOMs performance in the Indian transmission network and lessons learned from operational experiences.

Question 3.1:

Papers B4-302, B4-309 and B4-310 present the outcomes of technology selection to address dynamic reactive power requirements in their respective systems. In paper B4-302, a VSC based STATCOMs was not a preferred solution, with the main reason stated as being due to the natural symmetry in these devices and the need in the Brazil system for asymmetrical ranges. In paper B4-310, a STATCOM is preferred over SVC because of the VQ characteristic, quicker response times, smaller footprint and modular design. In paper B4-309, either STATCOM or SVC was considered acceptable, although a STATCOM was selected based on the response of the bidders.

- What are the outcomes of other analyses and technology evaluations for addressing similar problems to those described in these three papers?
- Are there other instances where an SVC solution was preferred over a VSC based STATCOM and what were the primary drivers for this selection?

Paper B4-311 "Ascutney SVC - Engineering, Testing and Commissioning"

This paper describes the engineering, testing and site commissioning activities undertaken for the completion of the -25 / +50MVAr SVC, which was installed at Ascutney Substation in Vermont, USA in late 2018. The primary purpose of the SVC is to provide voltage support during certain contingencies, although the SVC also provides regulation of the 115kV AC bus voltage and can limit overvoltages during light load conditions. Key elements of the design are described, including the use of circuit breakers on the AC filter banks, addition of the grounding transformer bank and additional operation modes. The design includes provision for future build-out and expansion of the site. The outcomes of performance evaluation during site commissioning tests are provided, including performance during transformer energization, step responses, verification of the VQ/VI characteristic, heat run testing, harmonic performance, losses and audible noise. In particular, mitigations were required for the audible noise to achieve the specification requirements.

Paper B4-312 "First Swing Stability and SSR Mitigation in KEPCO Grid by Using TCSC"

This paper is focused on first swing control and SSR mitigation which are the application of interest in the South Korean power system, highlights the challenges in the design on the TCSC components and control, and presents the results of power system studies and HIL tests which were performed to analyze the operation of the TCSC and confirm the benefits of having the TCSC in the grid. It is concluded that the TCSC solution can enhance the power system stability and mitigating SSR.

(PS3-2) Application of new technologies in FACTS and other Power Electronic equipment, including interfacing generation and storage to the network

Paper B4-301 "Advantages of M-SSSC Devices over Traditional Series Compensation

This paper summarises the operational and economic benefits and advantages of Modular Static Synchronous Series Compensators (M-SSSC) over fixed series capacitors (FSC) for increasing power transfer of transmission facilities via PSCAD simulations based on the IEEE Second Benchmark Model (SBM) to demonstrate the effectiveness of the M-SSSC on SSR mitigation. It is recommended in the paper that utilities should prioritize evaluation of utilizing M-SSSC solutions for series compensation to improve transfer on transmission facilities.

Paper B4-303 "Phoenix: The World's First Hybrid Synchronous Condenser System"

The paper describes the Phoenix Project, a Hybrid Synchronous Condenser scheme that combines a synchronous condenser with a STATCOMs, to be installed at a demonstration site at Neilston in Scotland. The scheme parallels the STATCOMs with the synchronous condenser via a three winding

transformer connected to the AC network. The synchronous condenser provides inertia support, overload support and short-circuit current contribution whereas the STATCOMs provides better dynamic voltage support, over-voltage mitigation, power oscillation damping and power quality management. The paper describes key elements of the design, key features and control modes and presents the outcomes of the factory system tests and dynamic performance tests completed in late 2019. The project is expected to be in operation by second quarter 2020.

Paper B4-304 "Capability and Flexibility of Energy Storage Enhanced STATCOMs in Low Inertia Power Grids"

The paper presents the outcomes of a study of energy storage enhanced static synchronous compensators (E-STATCOMs) to address low inertia challenges by limiting the rate of change of frequency and reduce frequency variations during network events. The E-STATCOMs system studies is comprised of a VSC converter with an energy storage device, operated using a grid-forming control philosophy. The paper presents the outcomes of modelling of the E-STATCOMs concept and compares its performance against the performance of similarly sized synchronous generators. It concludes that the E-STATCOMs provided enhanced flexibility in responding to network frequency events and serves as a greater source of inertia and fast frequency response than its synchronous generation counterpart.

Question 3.2:

The solutions presented in papers B4-303 and B4-304 have been developed to address the challenges related to low inertia, short-circuit levels and/or voltage control, driven largely by the increasing penetration of non-synchronous generation.

- What other innovative FACTS approaches to addressing these issues have been, or are in the process of being, implemented on AC networks?

Paper B4-306 "Evaluating Modular Voltage Source Converter Based Technology in the GB Transmission System with EMT Studies"

This paper develops a solution to provide control over power flow using series connected modular multi-level voltage source converter power flow control (VSC PFC) technology, i.e. M-SSSC, which has the potential to offer more flexible and dynamic functionality than traditional power flow technology, evaluates system performance on dynamic response and the harmonic immunity of the M-SSSC and discusses the overall set of issues.

Paper B4-307 "Development of active filter function for STATCOM"

This paper describes the design of power system active filtering function by implementation of the active filtering function in an actual STATCOM that was delivered and installed in the United States in 2019. The system performance of the active filtering function of the STATCOM was verified by the simulator tests at the factory and the commissioning tests at site.

Question 3.3:

It is an effective and economic method to reduce harmonic distortions at specific orders, e.g. 5^{th} and 7^{th} by implementing active filtering functions via control system of electronic power devices.

- Have similar active filtering functions been implemented/designed in the control systems of HVDC systems?
- Are there any examples of other available technologies now being used for harmonic improvements, e.g. hybrid filters?

(PS3-3) Refurbishment and upgrade of existing FACTS and other Power Electronic systems; service and operating experience

No papers were submitted for this topic.