B4 - 00

SPECIAL REPORT FOR SC B4.
(HVDC and Power Electronics)

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Special Reporters

The scope of Study Committee B4 covers High Voltage Direct Current (HVDC) systems and Power Electronics for AC networks and Power Quality improvement, the latter generally being known as Flexible AC Transmission Systems (FACTS). The rapid growth of HVDC systems for long distance power flows, for regional interconnectors and for connections to renewable energy sources, coupled with the increasing use of FACTS devices for AC system support, means that the work of SC B4 is highly relevant to the key issues facing the world's power transmission systems.

For the 2014 session a total of 28 papers have been selected, based on the preferential subjects listed below. These papers represent the latest information on HVDC and FACTS schemes in planning, in construction and in operation. Some of the most recent and exciting developments in the field of power electronics are being reported at the session, indicating that there is no reduction in the pace of R&D in the fields of HVDC and FACTS.

The Preferential Subjects chosen by the Study Committee for the 2014 session are as follows.

PS 1 HVDC systems, equipment and applications
- Technology development including HVDC grids
- Connection of renewable resources
- Project planning, environmental and regulatory issues
- Project implementation and service experience

PS 2 FACTS equipment and applications
- Renewable resources integration
- Increased network performance
- Project planning, environmental and regulatory issues
- Project implementation and service experience

PS 3 Power electronic equipment developments
- Converters for renewable generation and energy storage
- DC circuit breakers, DC load flow controllers and fault current limiting devices
- New semi-conductor devices and converter topologies

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1 Preferential Subject 1 : HVDC systems, equipment and applications

Preferential subject 1 considers HVDC systems, including their equipment and applications. A total of 17 papers were received covering technology developments, connection of renewable resources, and project implementation and service experience.

1.1 Technology developments including HVDC grids

B4-107 "Twenties : Conclusions of a major R&D demonstration project on off-shore DC grids" reports on the results achieved in a collaborative European project on a wide range of challenging issues related to DC grids. The work covers the connection of off-shore intermittent power sources, DC grid economics, and control and protection issues. Two hardware demonstrators were developed as part of the project. One was a low power simulator which was used to test the control techniques developed and also to prove the protection algorithms for DC grids. The second was the development of a DC circuit breaker using innovative power electronic and mechanical technologies, which is discussed in more detail in paper B4-301.

B4-112 "Designing fault tolerant DC networks with limited need for HVDC circuit breaker operation" reviews alternative fault clearing methods on DC grids. Simulation studies show the impact of fault clearing using DC circuit breakers, which can rapidly isolate the faulted section of a DC grid and even find application in a point to point cable scheme to allow the converter to remain in service to support the AC system. The paper also studies fault blocking converter solutions, such as the alternate arm converter.

B4-105 "Research work of ±1100kV UHVDC technology" provides an up-date on the on-going project to develop UHVDC technology to deliver 11,000MW of power at a DC voltage of ±1100kV and 5000A DC current. Network planning studies considering the disparity between generation and load centres in China indicate that 6 such schemes will be required, some with distances in excess of 3000km. The research work has focussed on the key converter station equipment, such as the converter transformer, wall bushings, converter valves and DC yard. The paper provides the key rating data for the equipment. Due to their size, site assembly of the transformers will be required, which is described in the paper. Preliminary designs of the valve halls and the complete converter station are presented in the paper.

B4-108 "Special requirements regarding VSC converters for operation of hybrid AC/DC overhead lines" presents the concepts of a pilot project in Germany to convert one circuit of a multi-circuit AC line to DC to achieve higher capacity in an existing corridor. The paper considers the challenges of this concept, including managing inter-system faults in a controlled and effective manner, the ability to achieve multi-terminal operation , and the coupling effects between the AC and DC systems. The scheme will retain the existing transmission line components; hence the DC voltage and current are adjusted to match the electrical and mechanical characteristics of the lines.

B4-116 "New synthetic test circuit for the operational test of new thyristor valve" describes the development of a new test facility in Korea using the well-known concept of a synthetic test circuit applying alternate voltage and current pulses to the test object. In this circuit an additional thyristor switch is added to the conventional circuit, which allows the snubber capacitors on the test object to be pre-charged before turning on the test thyristor valve. An independent high frequency power supply is used to provide power to the gate electronics on all thyristor valves in the test circuit, with the exception of the valve under test. Examples of the simulated current and voltage waveforms are presented in the paper.

Question 1.1:

The research and development of HVDC grids are on-going. Paper **B4-107** presents the results of the European TWENTIES project and Paper **B4-112** presents alternative fault clearing methodologies on DC grids. Is there any technical or economic preference for the use of blocking converters or DC circuit breakers in the development of DC grids? Have other planning studies or equipment developments demonstrated that HVDC Grids will be economically attractive?

Question 1.2:

Paper **B4-105** reports on the development of 1100kV UHVDC technology in China and has identified challenges associated with the implementation of UHVDC. Is the use of UHVDC being considered in other parts of the world and if so what additional challenges are foreseen with the development and implementation of UHVDC?

Question 1.3:

Paper **B4-108** presents the concepts of a project to convert an AC line to DC to accommodate an HVDC system utilising VSC technology. Are there any other projects in operation or in planning with AC and DC systems in close proximity and what are the impacts on the design and performance of the systems?

1.2 Connection of renewable resources

B4-111 "Reliability analysis of design options for off-shore HVDC networks" outlines a methodology for evaluating the reliability of DC grids. This considers the different technology, topology and protection options available to scheme developers. Mean time to fail and mean time to repair data are used for key components of the DC grid, plus the incorporation of probabilistic (Monte Carlo) techniques to assess the impact of wind and wave effects on maintenance access to off-shore wind-farms. The analysis considers different system scenarios including varying levels of system interconnection and system redundancy and operation with and without DC circuit breakers and evaluates the expected level of energy curtailment for each case. Energy curtailment is proposed as the metric for quantifying the reliability of the DC grid.

B4-115 "Technology qualification of off-shore HVDC transmission systems" addresses the issues which will arise for schemes with one or more HVDC off-shore stations, where at present there are few reference projects and limited operational experience. The paper addresses the lack of relevant standards, guidelines or recommendations available to project stakeholders, which may introduce significant risk during the development of such projects. The paper proposes a Technology Qualification process, derived from oil and gas industry experience, which could facilitate faster more efficient and more reliable deployment of off-shore HVDC transmission systems.

Question 1.4:

Paper **B4-111** presents different topologies for off-shore HVDC grids and outlines a methodology for evaluating the reliability of DC grids. Paper **B4-115** proposes a technology qualification process for components of off-shore HVDC transmission systems. How are developers of off-shore systems practically considering the qualification of their equipment, in terms of threat assessment and the ultimate reliability expected from the asset?

Question 1.5:

Paper **B4-115** outlines a methodology to assess the risks for off-shore HVDC stations. In any installation a transformer explosion/fire is a hazard with potentially severe consequences. What preventive and other measures should be taken for off-shore transformer explosions/fire and possible oil spillage to minimise the impact?

1.3 Project planning, environmental and regulatory issues

B4-101 "Optimising the electrical design of the Colombia – Panamá interconnection" describes the planning studies in progress to finalise the design of this scheme. Initial designs for a 600MW at ±450kV have been revised to consider 300MW at ±250kV or 400MW at ±300kV as the optimum technical and economic solution. The original route length of 600km was re-considered to a shorter (480km) route, but issues related to the strength of the Colombian transmission system dictated that the original route be retained. The scheme is being designed to operate as a bi-pole, with a dedicated metallic return conductor.

B4-103 "Final project planning conception for the first 800kV HVDC link of Belo Monte" describes the analysis performed for the two 4000MW, ±800kV bi-poles to be implemented as part of the Brazilian North – South transmission corridor. The 2092km HVDC scheme will be embedded within the Brazilian AC network and the paper presents initial results of electromagnetic transient and dynamic performance studies of the scheme. The converter topology, whether one or two 12 – pulse groups per converter is not being mandated, instead will be left to individual optimisation from manufacturers. Ground electrodes are anticipated at both stations.

B4-113 "The first HVDC project in Indonesia : system study and basic design of Java – Sumatra HVDC link" gives details of the extensive design studies performed for the transmission link from a "mine-mouth" coal fired thermal power station on Sumatra to the major load centre on Java. The scheme is rated at 3000MW operating at ±500kV, using a bi-pole configuration, with ground electrodes at each station. There will be 369km of OHL on the Sumatra side, a 38km submarine cable crossing of the Sunda Strait and 110km of OHL on the Java side. To maximise the system reliability and availability two 12 – pulse converter groups per pole are being proposed and a spare submarine cable is being considered.

B4-114 "Celilo Pacific DC Intertie presentation" reports on the studies performed to determine the optimum solution for the life extension of the northern converter station on the Pacific Intertie. The work considers the merits of retaining the existing four converter architecture or converting the station to the more conventional two converter bi-pole architecture. The latter solution will be adopted, but the decision was made to retain the existing Converter 1 and 2 valve halls. The rationale for the approach adopted, with respect to key station equipment is presented in the paper. On completion the up-graded scheme will be able to operate at 3800MW at ±560kV.

Question 1.6:

Paper **B4-101** describes the planning considerations and design parameters of the Colombia – Panama interconnection. It appears that LCC HVDC was chosen for this interconnection. Is there any other experience from developers of interconnectors on the choice between LCC, possibly with AC system reinforcement, and VSC technology, or should the choice be left to the tenderers?

Question 1.7:

Paper **B4-103** describes the planning studies and technical requirements for the Belo Monte 800kV HVDC project in Brazil and allows manufacturers to optimise their projects. It would be expected that reliability requirements for e.g. operation of the DC system with loss of a converter or for operation with reduced voltage to operate with impaired insulation would also be specified or should the manufacturers be allowed to make proposals on these issues?

Question 1.8:

Paper **B4-113** presents the design studies for the Java – Sumatra HVDC link, with LCC HVDC being the preferred technology. It appears that under certain network conditions the ac system fault level will be low, i.e. a short circuit ratio of less than 1. What experience can be reported to ensure reliable operation at low short circuit levels with LCC HVDC?

Question 1.9:

For the Java – Sumatra link, two series valve groups per pole is proposed, whereas for the Belo Monte scheme this is being left open to bidders. Is there any operational experience which can be reported on the use of one or two 12-pulse converters per pole?

Paper **B4-114** describes options considered to extend the lifetime of the Celilo converter station. Are other owners of HVDC schemes considering life extension and if so what factors are being considered in the analysis? Should topology changes, e.g. to add series or parallel connected converters, or up-grade from monopole to bi-pole, be considered in terms of improved reliability or to increase capacity?

1.4 Project implementation and service experience

B4-102 "New Zealand HVDC Pole 3 project challenges and solutions" highlights some of the engineering issues which were encountered and the novel solutions which were implemented on the scheme. The new Pole equipment was installed in a "brownfield" site alongside live equipment, which brought significant challenges to the project implementation. The paper details the special measures which were introduced to ensure the equipment could withstand the high seismic duty in this region. Coordination of the new and existing equipment, plus the special measure required to operate in a weak AC systems are described in the paper. Integration of the control of the new pole with the existing station control and protection scheme, using equipment from different manufacturers, is described in the paper.

B4-104 "Operational experience of the Madeira River project in the Brazilian interconnected power system under initial configuration" reports on the first energisation of the San Antonio hydro generators with the first block of the 400MW back – to – back (BtB) HVDC converter and the first pole of the 3150MW, ±600kV bi-pole. Delays in the generating plant schedule and Bi-pole converter station and line meant that there was not enough short circuit power available to test the BtB station. This was resolved by installing 500/230kV by-pass transformer to provide a temporary synchronous tie between AC systems, which allowed system testing to proceed. Initial test results for the operation of the BtB station and Pole 1 of the bi-pole, up to 700MW are presented. The paper also discusses a number of equipment failures which were encountered during the commissioning tests.

B4-109 "Design challenges for ±800kV, 3000MW HVDC Champa – Kurukshetra transmission link with Dedicated Metallic Return (DMR) – User's perspective" elaborates the various challenges in the conception and design of this 1035km long scheme in India. The main scheme design parameters are presented in the paper. This will be the first UHVDC project to use a dedicated metallic return conductor instead of the more conventional ground return. The paper presents the project implementation issues which arise from the use of a DMR, which will be strung on the main bi-pole transmission towers. The paper describes different conductor arrangements under consideration. The scheme is being designed for the future addition of a second 3000MW bi-pole, to bring the power transfer capacity up to 6000MW.

B4-110 "Drivers for technology selection in an embedded HVDC link. Case study : France – Spain eastern interconnection" focuses on the performance which can be achieved by Line Commutated Converter (LCC) and Voltage source Converter (VSC) technologies for an HVDC link embedded within an AC network. The paper reviews the merits and de-merits of the two technologies in terms of the steady state and dynamic performance which can be achieved. Analysing the specific case of the France – Spain interconnection, the paper concludes that for most of the criteria considered the VSC technology is the preferred solution.

Question 1.10

Paper **B4-104** describes the initial operational experience of the Madeira River HVDC project in Brazil. The experience shows that for a large complex project the impact of delays of various components on the final commissioning and operation need to be evaluated, and that intermediate operational stages may need to be considered in the planning of such projects.
How are the interactions between separate components of other complex projects, e.g. hydro projects, off-shore wind projects, and those requiring significant AC system up-grade, being taken into account during commissioning of these projects?

Papers **B4-102, 104** and **109** describe projects with the requirement for multi-vendor control systems working in close proximity. What joint studies or testing has been undertaken, or is proposed, to ensure successful interoperability between these systems?

Question 1.11:

Paper **B4-110** provides a comparison of the performance of LCC versus VSC HVDC technologies. Are there other schemes in the planning stages that are considering both technologies and what factors are considered most important? What, if any, consideration is being given to future integration of the scheme into a DC grid, e.g. by the choice of DC voltage, the provision of spare bays in the DC switchyard, etc.?

B4-106 "The operation statistics and analysis of HVDC transmission systems in State Grid Corporation of China 2006 - 2012" considers 14 HVDC, UHVDC and BtB schemes and presents information on their operational statistics. Data on the forced outage rates for each scheme are presented in addition to information on the energy availability achieved by each scheme over this period. Information on the reasons behind the forced outages and the duration of the outages is presented. Focussing on one year (2012) the paper provides information on the number of commutation failures experienced and the reasons behind these failures. As these HVDC schemes now represent a critical part of China's transmission system, the reliability of such schemes becomes increasingly important and the paper lists a number of key aspects on which system owners should focus.

B4-117 "A survey of reliability of HVDC systems throughout the world during 2011 – 2012" presents the biannual review of the reliability and availability as reported from multiple HVDC schemes. Following the reporting protocol developed by B4 AG-04, the report gives data on the energy availability, energy utilisation, forced outage rates and scheduled outage rates. The reasons for the forced outages are classified into six categories of equipment and the results are compared with the cumulative statistics over the period 1983 – 2010. It is noted that the contribution to forced energy unavailability due to transformer failures is significantly reduced compared to past results. The report also provides specific details on thyristor valve failures and commutation failures.

Question 1.12:

Paper **B4-106** provides performance statistics for HVDC schemes in the State Grid Corporation of China. The paper introduces an index of forced energy unavailability which adjusts for the forced energy unavailability due to operation at low voltage. Should this measure be considered for the CIGRE reporting protocol? The impact of severe weather conditions is clearly seen in the data. Have other scheme owners experienced similar outages due to exceptional weather conditions?

China now has a large number of HVDC schemes in operation. The data provided in paper B4-106 would be a very valuable contribution to the data collected by AG B4.04, and the authors and owners of the HVDC systems are encouraged to submit it to AG B4.04 using the normal reporting protocol. Similarly, data for the HVDC schemes in South China would be very welcome and valuable.

Question 1.13:

Paper **B4-117** reports on the reliability of HVDC schemes for 2011 and 2012. Up to now no VSC schemes have reported information on the performance and reliability of VSC HVDC schemes, which would be very useful for planners. Are owners/operations of VSC HVDC schemes collecting performance data and do they intend to contribute to the CIGRE reliability survey in future?

It is noteworthy that contributions to FEU by converter transformer failures has reduced significantly over the reporting period as compared with past results, although paper B4-106 reports on quality problems on some schemes. To what can this reduction in transformer failures be attributed?

2 Preferential Subject 2 : FACTS equipment and applications

Preferential Subject 2 considers FACTS systems, including their equipment and applications. A total of 6 papers were received, covering the integration of renewable energy sources, increased network performance, project planning, and project implementation and service experience. Paper B4-205 was withdrawn by the authors. One paper submitted under PS3 (B4-305) is considered with this group of papers.

2.1 Renewable resources integration

B4-206 "Comparison of field measurements and EMT simulation results on a multi-level STATCOM for grid integration of London Array wind power plant" describes the development and validation of a generic electromagnetic transient model of a multi-level STATCOM based on field measurements. This STATCOM is connected to the world's largest off-shore wind farm, but the detailed model of the controller was not available to the authors. The simulated results from the generic control model developed are compared with the field measurements and show good correlation. The paper proposes that such a generic STATCOM model can be used for system studies for wind farm connections prior to the engagement with a specific equipment vendor.

Question 2.1:

Paper **B4-206** addresses the problem of availability of digital models of FACTS controllers for grid integration studies. Have other workers in this area experienced similar difficulty in obtaining suitable models for use in system studies? Is there any experience which can be reported on the use of generic models?

2.2 Increased network performance

B4-201 "Generic VSC models for project planning studies" describes the development of a generic VSC system model for use in transient stability studies. The model, developed using PSS/E has both steady state and dynamic representations implemented. Fast time stepping is used for the evaluation of the internal dynamics of the controller, with slower time steps for the external stability model. The model was validated against EMT studies for a number of AC side and DC side fault conditions, with good correlation of the results. Such a generic model may find application in planning and pre-specification studies of new projects.

B4-207 "A novel control method in grid interconnection of DG based on adaptive pulse Voltage Source Inverter (VSI) and compare with two other control methods for harmonic compensation and power quality improvement" considers the coupling of Distributed Generation (DG) to the network via VSI interfaces. Many different controllers are available for VSI and in this paper the authors propose a pulse adaption technique for the PWM controller. Simulation studies indicate the improvement achieved in the harmonic content of the current output from the DG and hence injecting less harmonic distortion into the AC network.

B4-305 “Effects of STATCOM in power system in Jeju island” considers the loss of one of the two HVDC links feeding the island and the capability of STATCOMs to support the AC grid. Simulations are presented for three scenarios; with two, one and no STATCOMs in service. Results indicate that without the reactive power support from STATCOMs there would be unacceptable impacts on the Jeju island grid during the trip of one HVDC links.

B4-202 “Smart Power Line (SPL) experimental research project” introduces the concept of an embedded mini-substation introduced into the Overhead transmission lines. Installed at dead-end towers, Switching Modules, Protection Modules and Line Monitoring Systems can be used to make the transmission lines “smarter”. The Switching Module is intended to re-direct the current between one or more sub-conductors, providing a de-icing facility. The technology can also be used to manage power flows and provide additional measurements distributed on the lines. Conceptual designs for the equipment are presented in the paper together with proposals for experimental testing on a 765kV power line.

Question 2.2:

Paper **B4-201** describes the development of a generic VSC system model for use in transient stability studies. Paper **B4-204** describes detailed studies done for a STATCOM including stability studies, sub-synchronous torsional interaction and harmonic resonance. Paper **B4-305** describes a STATCOM study for an island grid. Have owners of VSC HVDC and STATCOM’s experienced problems in the areas of stability, harmonic and other interactions after installation? Are the available generic models adequate for these studies or is there a need for more detailed models to do these investigations?

Question 2.3:

Paper **B4-207** considers alternative control strategies for inverters from distributed generation equipment. Are such techniques viable for other applications, e.g. for FACTS devices, to improve harmonic power quality?

Question 2.4:

Paper **B4-202** proposes novel technologies to make the transmission lines “Smarter”. Are there any other examples where “smart” technology is being applied outside of the sub-station, i.e. on lines and cables, which could enhance the AC or DC power transmission?

2.3 Project planning, environmental and regulatory issues

B4-203 “Dynamic compensation in Indian power system – siting and sizing” describes the large inter-regional power flows in the Indian transmission network and the susceptibility of the network to tripping and large disturbances following faults during depleted operating conditions. The paper reports on a major study to determine the need for dynamic reactive power support on the network, which can provide first swing stability by maintaining system voltage during major disturbances. The study focuses on the Western Region of India and proposes the optimum location and dynamic range of reactive power controllers. The work was based on the use of STATCOM devices, augmented as required by mechanically switched capacitors and reactors.

Question 2.5:

Paper **B4-203** proposes dynamic and mechanically switched compensation at key sub-stations to support the 400kV AC transmission system. What operational experience can be reported on the use of large switched shunt capacitor banks on EHV/UHV systems, in terms of possible amplification of background harmonic distortion levels and what mitigation techniques have been used?

2.4 Project implementation and service experience

B4-204 "Factory test and commissioning test of 450MVA STATCOM project" presents simulation and field test results for a STATCOM installation, comprising two units, on a transmission system connecting a newly installed thermal power plant. Extensive studies of power system stability and over-voltage suppression were performed to assess the operation of the STATCOM. These studies were executed on a real time hybrid simulator, where a low power analogue model of the STATCOM was used in conjunction with the actual contract control system and a real time digital simulation of the AC network. The paper also reports on a study for Sub-synchronous Torsional interaction (SSTI) and on harmonic resonances in the transmission system. Field tests, which optimised the control settings of the two STATCOMS, ensured correct sharing of the duty between the two units.

Question 2.6:

Paper **B4-204** reports on a hybrid test set-up using the well-known "hardware in the loop" system for the controller and real-time simulation of the AC network, but with a low power model of the STATCOM. What advantages does the use of an analogue model bring, which cannot be achieved with a fully digital model? Are there any other examples of the use of this technique or any reported disadvantages of "hardware in the loop" testing?

Question 2.7:

Several papers have reported on the planning, performance and use of STATCOM devices. Is the use of SVC's still being considered when new reactive power compensation is planned for networks? What are the reasons for choosing STATCOM's over SVC's?

3 Preferential Subject 3 : Power electronic equipment developments

Preferential subject 3 considers other power electronic equipment developments. A total of 5 papers were received for this PS, but one of these (B4-305) is discussed under PS2. The other 4 papers relate to DC circuit breakers and semi-conductor devices. No papers were received related to converters for renewable generation and energy storage.

3.1 DC circuit breakers, DC load flow controllers and fault current limiting devices

B4-301 "Development and test of a 120kV direct current circuit breaker" evaluates the short circuit currents which can occur in a multi-terminal DC system. From these studies the duty for a DC circuit breaker is evolved, leading to the requirements for a hybrid mechanical and power electronic (mechatronic) circuit breaker. The paper describes the key components of the breaker including power electronic components, an ultra-fast mechanical circuit breaker, series capacitors and surge arresters. A progressive commutation process is described from the closed state to the open state, which allows current interruption within 5.3ms. The test circuit and test procedure is described for the prototype tests, which cover normal closed state load current duty, open state high voltage withstand capability, and fault current interruption.

B4-304 "Hybrid HVDC breaker – a solution for future HVDC system" contains a detailed description of the hybrid DC breaker, including its controls and design principles. Descriptions of the key components of the hybrid breaker are presented in the paper, including the ultra-fast disconnector. Verification of current breaking capability was performed on the prototype equipment, plus testing of individual components. The paper reviews typical applications for a DC circuit breaker and presents simulations of the system performance which can be expected for a number of scenarios.

B4-303 "A low loss mechanical DC breaker for HVDC grid applications" considers an alternative to the hybrid DC breaker concepts, i.e. a mechanically based device. The functional requirements are similar, i.e. interruption of up to 10kA within 5ms. A standard AC interrupter fitted with an electromagnetic actuator, using a low moving mass and of limited stroke can achieve the required fast opening times. A parallel resonant capacitor/inductor circuit, employing a capacitor pre-charge circuit, can create the necessary high frequency oscillation and rapid current zero crossing for interruption to take place. An 80kV rated demonstrator facility was built and the functionality of the concept was tested up to the target interruption current.

Question 3.1:

Papers **B4-301, B4-304** and **B4-303** present different developments of and prototype tests done on HVDC breakers. A mechanical breaker will inherently be bi-directional. Power electronic breakers may need to be specifically designed to be bi-directional. What are considered to be the advantages and disadvantages of each different solution? What other performance aspects need to be taken into account for application in real networks e.g. operating times of protection systems, discrimination between protection zones, main and back-up protection facilities, breaker-fail performance, etc.?

Question 3.2:

Concerns have been raised about the space requirement, particularly for off-shore applications, and the anticipated costs for these first generation devices. What indications can be given of the future direction of R&D to address these issues?

3.2 New semi-conductor devices and converter topologies

B4-302 "The Bi-mode Insulated Gate Transistor (BIGT), an ideal power semiconductor for power electronics based DC breaker applications" describes the development of a high voltage and high current IGBT and diode structure on a single chip. Device voltage ratings from 3.3kV up to 6.5kV are possible, although a 4.5kV device was used for the evaluations presented in the paper. Performance characteristics for the BIGT are presented in the paper. The main application for the BIGT is in the hybrid DC circuit breaker (B4-304), where the improved characteristics of the BIGT allows a breaking current of 16kA within 5ms of fault initiation, approximately twice the current level of a conventional IGBT based solution. Testing on the main breaker portion has shown interruption at up to 19kA.

Question 3.3:

Paper **B4-302** describes the development of the BIGT, with higher current ratings than present generation IGBTs, and its application for a hybrid DC circuit breaker. Can this device find general application in VSC converters, to achieve higher power levels, without increasing DC voltages? If it is only available from one manufacturer does this provide any overall benefit to the industry, or does it become a niche product used in one application only?