21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

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SPECIAL REPORT FOR SC B4
(HVDC and Power Electronics)

C D BARKER **N PAHALAWATHTHA**
Special Reporters

The scope of Study Committee B4 covers High Voltage Direct Current (HVDC) systems and, Power Electronics for AC networks and Power Quality improvements, 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 2016 session a total of 45 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. The proliferation of the AC to DC conversion systems beyond high voltage transmission to renewable power generation and power distribution has also been evident from the papers received. 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 research, developments and applications in the field of HVDC and FACTS.

The Preferential Subjects chosen by the Study Committee for the 2016 session are as follows.

PS1 HVDC systems and their applications

- Planning and implementation of new HVDC projects (including need justification, environmental and economic assessment)
- Application of new technologies in HVDC, HVDC Grids / Multi-Terminal HVDC
- Refurbishment and upgrade of existing HVDC systems
- Service and operating experience
- New concepts, designs and control algorithms

PS2 FACTS and other Power Electronic (PE) systems for transmission systems

- Planning and implementation of new projects (including need justification, environmental and economic assessment)
- Application of new technologies in FACTS and other PE equipment
- Refurbishment and upgrade of existing FACTS and other PE systems
- Service and operating experience
- New concepts, designs and control algorithms

PS3 DC, FACTS and other Power Electronic (PE) systems for distribution systems

- Applications for harvesting and integration of renewables, power quality improvements and increasing asset utilisation
- Service and operating experience
- Planning and implementation of new projects (including need justification, environmental and economic assessment)
- New concepts, designs and control algorithms

carl.barker1@ge.com nalin.Pahalawaththa@transgrid.com.au

PS1 - HVDC systems and their applications

- *(PS1-1) Planning and implementation of HVDC projects including, need, justification, design, integration of wind generation, environmental and economic assessment.*

Paper B4-101 “A second and longer ±800 kV bipole completes Belo Monte’s integration” describes the completion of the planning for building two bipole HVDC transmission links, connecting the Belo Monte hydroelectric project in the Northern Brazil to the load centres in the South East. Extensive simulations, both desktop and real time, have been carried out confirming the level of their interactions with the nearby HVDC terminals (Madeira and Itaipu) as well as the ac network.

Paper B4-110 “AC-DC interaction study for upcoming ±800 kV, 3000 MW Champa Kurukshetra HVDC link” describes the planning studies for the link, and highlights the multi-infeed interactions, potential for sub-synchronous resonances and generator self-excitation.

Paper B4-124 “Feedback on INELFE France Spain HVDC project” discusses a planning approach taken for the INELFE VSC HVDC project and how the application of new technology, for which there are no existing standards or technical recommendations, has been considered.

Paper B4-130 ”Saudi Arabia Central-West HVDC project: 3500 MW ±600 kV LCC 770km high performance embedded link crossing a desert area” discusses the needs capture for a very harsh environment and addresses how existing AC system data, such as background harmonics, have been captured considering both load and seasonal variations.

Question 1.1:
In planning HVDC links:

- What criteria is used to select the extent of the ac network for detailed modelling and simulation? What simplifications are justified in representing the rest of the network?
- What recommendations can be made for considering new technologies?
- What studies are required, using assumed plant data, prior to awarding the contract? What studies can be postponed until the contract is awarded?

Question 1.2:
For the HVDC multi-terminal networks being planned today:

- What level of interactions with the neighbouring terminals has been observed in the simulation studies?
- To what extent has the previous CIGRE work on screening the level of multi-terminal interactions been used for the planning work?
- What experience now exists of multi-infeed LCC HVDC and how have others considered this experience during the planning phase?
- What approach should be taken to coordinate the commissioning tests to confirm any interaction with the other existing terminals, in particular if they are owned by different owners?

Paper 103 “Smooth coordination and management of impact of Estlink 2 transmission testing on electricity markets, power system operations and system technical performance” describes the careful planning and coordination of the commissioning tests for the EstLink2, within the Nordic electricity market. Planning of the commissioning tests required an active participation of the electricity market, in the form of energy purchasing and selling.

Paper 109 “Commissioning experience and challenges of world’s first 800 kV, 6000 MW NER-Agra multi terminal HVDC system” describes the commissioning experiences and challenges associated with this multi-terminal HVDC system.

Question 1.3:
In commissioning HVDC links in a market based energy trading environment:

- What alternative approaches are available to minimise the impact of the commissioning tests on the market (e.g. circular power flow where appropriate through the same link or via an alternative link)?
- Is there a risk – cost trade off available in scaling down the required commissioning tests, when there is a high cost to the market due to any imposed transmission constraints?
- What are the experiences of and the approaches used by other HVDC links for their commissioning in a market environment?

Paper 111 "Converter transformer inrush control using hybrid pre-insertion resistors and point-on-wave switching in the New Zealand HVDC system" describes the use of pre-insertion resisters together with point on wave switching for limiting the transformer inrush currents in energisation of the converter transformers due to stringent local regulatory requirements.

Question 1.4:
Should utilities highlight the risks – cost trade-offs and challenge the unreasonably tight power quality standards set by some jurisdictions?

Paper 113 "HVDC overhead line design considering LCC vs. VSC technology" highlights the need for consideration and coordination of HVDC converter designs with the HVDC line designs. The switching over-voltages to be expected during dc faults in VSC HVDC schemes could be higher than those expected for LCC HVDC schemes, depending on the equipment available at the converter terminals and the operating conditions.

Paper 128 "Interaction between parallel HVDC and a.c. overhead lines" looks at the coupling between AC and DC transmission lines and in particular the impact of induced AC onto the DC line and how this may affect HVDC cables connected in series with overhead transmission lines.

Question 1.5:
Considering the changing needs of the industry and new technological developments:

- How does the difference in performance required from VSC and LCC overhead transmission lines impact on the economic cost/benefits of their applications?
- With continuing need to reduce the environmental footprint of overhead line transmission, how can the size of DC overhead transmission lines be reduced?
- What level of switching over-voltages are to be expected if VSC HVDC schemes are to use ac lines converted to dc operation?
- What other issues and factors should be considered when an HVDC cable is connected in series with an HVDC transmission line?

Paper 125 "Commutation failures mitigation in multi-infeed network with high renewable penetration: TERNA's experience" discusses improvement of the commutation margin of an LCC scheme by increasing the extinction angle of existing converters.

Paper 127 "Study of backbone structure change from synchronous to asyncronous in China Southern Power Grid" discusses breaking up the AC system and then using HVDC to provide the tie lines between adjacent, islanded, AC networks.

Paper 129 "Experience from a bipole HVDC system with a Voltage Source Converter and a Line Commutating Converter" provides operating experience of a LCC plus VSC hybrid bipole HVDC interconnection and, in particular, discusses the improved commutation failure margin.

Question 1.6:
Considering the continuing and increasing need to make the existing transmission assets "work harder":

- How should the electrical stress and impact of harmonics be taken into account when operating equipment beyond their design envelopes as described in paper 125?
- What are the experiences of other HVDC schemes in the world in operating with an extended extinction angle, under normal or contingency conditions?
- What other technologies or approaches are being used to improve the commutation failure margin for new (or existing) LCC schemes?

Question 1.7:
In papers 127 and 129 the combination of LCC and VSC operating on the same electrical bus is discussed. Are there other planned schemes where VSC and LCC are to be used together? What are the justifications for the combination of technologies?

Paper 126 "Communication-free control solution for the provision of frequency regulation services in HVDC grids: Numerical simulation and experimental validation in a reduced scale platform" describes the potential use of offshore wind generation to provide frequency support to AC systems.

Question 1.8:
Are future offshore wind developments being considered where some part of the transmission capacity is kept in reserve for dynamic frequency support and how is the margin decided? What kind of pricing and procurement methods are proposed to ensure the power is available from the windfarm when needed?

Paper 131 "A survey of the reliability of HVDC systems throughout the world during 2013-2014" presents the biannual review of the reliability and availability as reported from multiple HVDC schemes. Following the reporting protocol 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 1983-2012.

- ***(PS1-2)** Application of new technologies in HVDC, HVDC Grids / Multi-Terminal HVDC.*

Paper 102 "Semi-fullbridge Modular Multilevel Converter: An inherent DC fault current limiting topology" describes a sparse full bridge MMC converter topology that can provide DC fault blocking capability.

Paper 108 "Zambezi (previously Caprivi) Link HVDC interconnector: Review of operational performance in the first five years" presents practical experience of DC overhead line fault clearing on a monopole VSC HVDC link. The paper also provides information on test ground electrodes that have been constructed in advance of building fully rated ground electrodes.

Paper 115 "Enabling DC fault blocking capability of hybrid Modular Multilevel Converter HVDC using asymmetrical full-bridge submodules" presents an adaptation of the full bridge submodule that can provide additional fault blocking back emf. This can be used in series with conventional half bridge submodules within a MMC in order to give fault blocking capability.

Paper 118 "A closer look at protection concepts for DC systems" gives a comparison, through simulation, of DC side fault clearing using full-bridge submodules in an MMC and DC fault clearing using a HVDC circuit breaker.

Paper 119 "Improving the DC fault response of H-bridge MMC-based HVDC networks" presents a means by which a full bridge MMC can be manipulated in order to reduce the restoration time of a HVDC network following a DC fault.

Paper 122 "EMTP simulation verification of full bridge MMC HVDC operational advantages" describes, through simulation examples, how DC side faults can be cleared using a full bridge HVDC MMC topology. The paper also describes the possibility of a hybrid MMC constructed from a combination of full bridge and half bridge submodules.

Question 1.9:
What practical applications for DC side fault clearing exist and what is the measurable benefit vs associated cost? What other topologies and options are available for limiting dc fault currents in VSC HVDC links?

Paper 106 "HVDC power from shore" describes the use of VSC HVDC transmission for providing the power needs of offshore oil/gas platforms. The environmental concerns and the increasing cost of carbon emissions are highlighted as a major driver for using HVDC transmission from shore, in place of generation facilities on the platforms.

Paper 112 "Using classical LCC HVDC to transmit renewable energy from weak AC systems" shows how the converter operating point can track the power generated by the windfarm such that the weak AC tie can provide a commutating emf without having the remote voltage bus significantly impacted by windfarm generation changes.

Paper 121 "Diode-rectifier HVDC link to onshore power systems: Dynamic performance of wind turbine generators and reliability of liquid immersed HVDC diode rectifier units" proposes an alternative method of collecting offshore AC wind power and transmitting it via HVDC, coordinating the control of the offshore wind turbines in order to regulate the power transmission and reactive power flows of the offshore AC network.

Paper 132 "Design consideration associated with DolWin3 and evolution of GE's Grid Solutions Business VSC solution" describes how MMC VSC can be used for offshore windfarm connection to the onshore grid. The paper explains the requirements and constraints of applying such technology offshore and considers the testing requirements.

Question 1.10:
Considering the increasing role HVDC transmission is expected to play in connecting renewable energy into transmission grids:

- At what length of HVDC transmission and/or cost of carbon emissions would HVDC transmission become a more favourable option compared to developing generation on the platforms? Is this seen as a growing market for the supply of electrical power offshore for the oil and gas industry in general or is this unique to specific markets, driven by legislation?
- What reductions of the footprint of the HVDC converters on the platforms are achievable with new technologies and what are the expected cost benefits?
- If LCC is used to connect renewable energy to the network, as proposed in paper 112, what other mechanisms or technologies may be utilised (for example to minimise the impact of filter switching)?

Paper 116 "Test circuit for Voltage Sourced Converter valve in MMC-based HVDC" presents a method of testing the MMC valve which can give stresses representative of those experienced in service.

The issues and developments associated with testing of VSC values are further discussed in the papers 207 and 210. Please refer to Question 2.5.

Paper 117 "Operational experience of new Spain-France HVDC interconnection" presents a control mode that has been implemented on a VSC point-to-point scheme embedded within an AC system, making the VSC HVDC link emulate, in part, an AC transmission line in order to improve the electrical energy sharing between the HVDC link and parallel AC transmission lines.

Paper 120 "Automated operation of parallel VSC HVDC links embedded in an AC power system" shows a theoretical study of multiple HVDC links embedded within a complex AC system using a similar set of control principles as those presented in paper 117.

Question 1.11:
What evidence is available to show the power flow emulation schemes such as that implemented in Spain – French interconnection, or similar strategies implemented in any other schemes, either VSC or LCC, improve the operational stability of the embedding ac power systems?

· ***(PS1-3)*** *Refurbishment and upgrading.*

Paper 104 "Celilo HVDC terminal upgrade project – Pacific NW-SW HVDC intertie system" summarises the upgrade and subsequent field testing of this project.

Paper 123 "Experience from IFA 2000 France-England HVDC interconnector refurbishment project" describes the refurbishment of the existing LCC converter station. The paper sets out the challenges in replacing some, but not all, of the existing equipment.

Question 1.12:
In replacing and upgrading the HVDC links /converter systems, what new features have been included (or planned):

(a) To improve their performance by better accommodating the technological and structural changes:
- taken place in the industry over the last 20 -30 years (e.g. industry deregulation, increased environmental compliance limits, and introduction of electricity trading markets)
- anticipated in the future (e.g. decommissioning of fossil fired generation and shift to renewable generation sources) ?

(b) To ensure that these schemes, when they approach their end of life, can be refurbished with the minimum amount of down-time or risk to the retained infrastructure?

· ***(PS1-4)*** *Service and operating experience.*

Paper 105 "Protective firing in LCC HVDC: Purposes and present principles. Settings and behaviour" describes an approach used for protecting values and thyristors (in LCC) from subjecting to excessive forward voltages.

Paper 107 "50 years of operating experience of Sakuma frequency converter station – Changing roles in the Japanese power system's transition" discusses an HVDC scheme that has now been in service for many years, providing a great deal of operational experiences. Equipment degradation due to the environment and through practical usage has also been identified.

Paper 114 "Nelson River pole 1 thyristor leakage assessment & online monitoring" describes the investigation of thyristor leakage currents in Nelson River HVDC Pole 1. In addition, an online thyristor leakage current monitoring scheme is proposed.

Question 1.13:
- The selection of the protective firing level is shown to impact on scheme costs whilst it is suggesting that not having a positive margin between the switching impulse protective level (SIPL) and the valve Protective Firing (PF) level is not detrimental to the schemes operation.

Is there operational experience that would support this? Are there other margins within LCC or VSC valve application that could be challenged to improve economic viability without detrimental impact on performance?

- Are there other experiences with failure modes of common technical solutions in specific environments such as those described in paper 107 and 114?

PS3 - DC, FACTS and other Power Electronic (PE) systems for distribution systems

- ***(PS3-1)*** *- Applications for harvesting and integration of renewables, power quality improvements and increasing asset utilisation.*

Paper 301 "Studies for characterisation of electrical properties of DC collection system in offshore wind farms" describes the use of DC networks within offshore windfarms as well as for their connection to the onshore ac networks.

Question 3.1:
Conventional acceptance is that far-offshore large power generation requires HVDC transmission whilst near shore is more economical with known, low "risk" AC technology, requiring no development. Is DC able to compete for near shore connections? What is the break-point between AC and DC? Has there been any assessment done in the economic trade-offs associated with using dc networks within offshore windfarms?

- ***(PS3-3)*** *Planning and implementation of new projects (including need justification, environmental and economic assessment)*

Paper 302 "Evaluation of the potential market for MVDC technology and its future development" indicates that there are potential benefits in the introduction of power electronics devices more widely into the distribution systems, but the take up of such systems has been slow owing to a number of technical and non-technical barriers and uncertainties.

Question 3.2:
Has there been any work done in identifying these barriers, uncertainties and strategies developed for overcoming them? Has there been any work done to increase the stakeholder understanding of the benefits of these technologies and to increase the motivation on the part of the distribution companies?

- ***(PS3-4)*** *New concepts, designs and control algorithms*

Paper 303 "Integrating smart solid state transformers into distribution substations" describes the development of a solid state transformer (SST) for replacing the existing aged distribution transformers. It also alludes to the asset management challenges that may be brought up by the introduction of similar power electronics devises into the distribution systems.

Question 3.3:
Papers 301, 302 and 303 propose the use of medium voltage converters. It is perceived today that the appropriate topologies for such converters will be based on those presently being employed at the transmission level or is there an expectation that new topologies and/or devices optimised for medium voltage and power will be developed in the near future?

Question 3.4:
Paper 121 has presented potential use of DC rectifiers on the offshore platforms in transmitting power to shore from offshore wind farms, through HVDC links. Have similar strategies and/or alternative converter topologies, been considered for use for medium voltage distribution applications or for medium voltage connection of offshore wind power plants?

carl.barker1@ge.com nalin.Pahalawaththa@transgrid.com.au

PS2 - FACTS and other Power Electronic (PE) systems for transmission systems

- ***(PS2-1)** Planning and implementation of new projects (including need justification, environmental and economic assessment)*

Paper 201 "Brazilian experience regarding interactions between Series Capacitors and SVCs – Main challenges of Tucurui-Macapá-Manaus interconnection project" discusses the use of fixed series compensation within the AC network, potential for resonances, and the mitigating solutions employed.

Question 2.1:
- What experience exists of such resonances and their consequences within the wider industry? Are similar issues encountered when the series capacitor has an element of dynamic control, such as a TCSC?
- With power system equipment procured over a long time span, likely to be from multiple vendors, how can the various power electronic controllers be successfully co-ordinated?

Paper 204 "Acoustic aspects of dry-type air-core reactors - specification, design, testing, field measurements" highlights the importance of both the correct calculation of harmonic currents generated by a power electronic device as well as establishing the background harmonics to which the equipment will also be exposed. It has also highlighted some innovative solutions for reducing the impact of noise created by the equipment, and the importance of measurement of the noise levels post implementation.

Question 2.2:
What are the experiences on the suggested approaches and any other approaches employed by other utilities for reducing the noise created by ac equipment used in connecting HVDC / FACTS systems?

Paper 208 "Harmonic performance requirements and mitigation for back-to-back HVDC in Turkish transmission system" reports on the harmonic assessment method utilised to establish the limits for the proposed new transmission asset.

- ***(PS2-2)** Application of new technologies in FACTS and other PE equipment*
- ***(PS2-4)*** New concepts, designs and control algorithms

Paper 209 "Magnetically controlled shunt reactor use in 110-500 kV power grids" describes the use of magnetically controlled shunt reactors (MCSR) in some countries, in particular in Russia.

Paper 202 "Blocking reactor as part of SVC system – a novel concept for harmonics reduction and a lowered operational losses" describes the use of an additional reactor within a SVC, providing advantages such as improved harmonic performance, reduced losses and insulation requirements.

Question 2.3:
The papers under PS2 have covered the use of MCSR, SVCs and STATCOMs for enhancing the performance of the power systems. However, the adoption of MCSRs and STATCOMs rather than the SVCs appears to have been slow, as an industry, considering their availability since the early 1990's.
- What are considered the reasons for this slow uptake of STATCOM technology?
- Are the needs of the AC systems changing the selection of SVC over STATCOM?
- What applications are considered as "exemplary" use cases, for SVCs, STATCOMs and MCSRs?

Paper 203 "Comparison of switching schemes for STATCOMs using Modular Multi-Level Converters" introduces the options associated with switching strategies that can be implemented on a power electronic converter in order to improve the power quality.

Question 2.4:
Is this the general trend for such devices or are there alternative methods of power quality control being implemented or considered?

Paper 207 "IGBT explosion test for STATCOM sub-module" describes the test setup, process, measurements etc. associated with the destructive testing of a STATCOM submodule.

Paper 210 "Electrical test of STATCOM valves" presents the ongoing work by the IEC working group developing a standard suitable for testing STATCOM valves.

On the subject of testing of VSC values, a method of testing the MMC valves which can give stresses representative of those experienced in service is also presented in the paper 116 "Test circuit for Voltage Sourced Converter valve in MMC-based HVDC".

Question 2.5:
Considering papers 207 and 210, along with the paper 116:

- What other VSC valve testing methods are employed and how do they represent in-service conditions?
- How do these test methods compare with those associated with the HVDC application where similar power converter building blocks exist?
- How will future converter topologies be tested?

- ***(PS2-3)*** *Refurbishment and upgrade of existing FACTS and other PE systems*

Paper 205 "Essex STATCOM life assessment and extension" provides a detailed description of the process adopted to evaluate the life expectancy of an existing STATCOM and the subsequent decision process used to identify what equipment should be upgraded.

Paper 206 "Planning and commissioning of 130 MVA GCT STATCOM for transient stability improvement" provides the reasons for replacing an existing STATCOM and how this has improved the transient stability of the AC system.

Question 2.6:
Taking into account the experiences from the reported projects and similar refurbishments done in other utilities, what strategies can be recommended to keep FACTS devices in operation where their primary and secondary sub systems are reaching end of life at different rates?