B4 - 00

SPECIAL REPORT FOR SC B4
(HVDC and Power Electronics)

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Special Reporters

INTRODUCTION

The work of CIGRE Study Committee B4 covers all aspects of HVDC and Power Electronics. The work includes monitoring the performance of existing transmission systems, planning, design, testing and operational issues of the new projects. The scope of B4 addresses all the relevant target groups in the power industry interested in power electronics. Economic and environmental subjects of this technology are also covered.

A total of 26 papers have been selected in accordance with the three preferential subjects for the 2010 session. These papers introduce state-of-the-art practices of great interest regarding HVDC and FACTS system technology. There is every reason to expect that recent progress on VSC topologies and HVDC grid concept open up a new era of HVDC and FACTS application. The information provided in the selected papers makes a valuable contribution for the continuing improvement and development of the HVDC and power electronics industry.

The contents of some of the papers are not confined to one preferential subject only. Where relevant, some aspects of such papers are discussed under other preferential subjects as appropriate.

The preferential subjects decided by the Study Committee for the B4 2010 Sessions are:

1. Developments in HVDC and FACTS technology

- 1.1 HVDC transmission at 800kVdc and above
- 1.2 New topologies and developments in VSC Transmission
- 1.3 Multi-terminal and meshed HVDC configurations
- 1.4 HVDC and FACTS as a means to improve system capacity, performance and efficiency

2. HVDC and FACTS – operating experience and new projects

- 2.1 Interconnection using land and/or submarine cables and/or overhead lines
- 2.2 Embedding of HVDC and FACTS in AC networks
- 2.3 Renewable energy applications

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3. HVDC and FACTS project development issues

- 3.1 Environmental issues for HVDC and FACTS schemes, including visual impact, earth return, audible noise, EMF & Ions
- 3.2 System performance with embedded HVDC links, including multi-infeed and ancillary services
- 3.3 Options considered, regulatory, licensing, project funding and technical risks issues

1. Preferential Subject 1: Developments in HVDC and FACTS technology

Preferential subject 1 deals with innovative HVDC and FACTS technology developments such as UHVDC, new VSC topologies and meshed HVDC configuration. New approaches for HVDC and FACTS application to improve overall grid performance are also included. A total of 11 papers were accepted in response to this subject.

1.1 HVDC transmission at 800kVdc and above

B4-102 "The Xiangjiaba-Shanghai 800kV UHVDC project – Status and special aspects" presents the current status of the 800kVdc UHVDC technology and how the experience gained at a long term test station is being utilized in executing the Xiangjiaba-Shanghai UHVDC project (±800kVdc, 6400MW) in China. In the equipment development, the importance of voltage grading design for the equipment connected to pole voltage is emphasized. Special attention was paid to converter transformers, bushings and external insulation. Long term testing has provided confidence in the design of 800kV HVDC equipments. The design features and equipment specifications, of the Xiangjiaba-Shanghai UHVDC project is then summarized. Finally, the latest progress is described to report that the converter stations passed Open Line test at 800kVdc in December 2009.

B4-103 "Concept to design – Multi-terminal at 800kV HVDC: NER/ER – NR/WR Interconnector – I project in India" presents preliminary design of the ±800kVdc, 6000MW HVDC Multi Terminal Interconnector. The project is planned to collect hydro power in the North-Eastern region and to transport it to a major load centre. Two rectifiers, one in the state of Assam and another one in the state of West Bengal will connect to one 1728km long DC line and bring power to an inverter station at Agra located close to New Delhi, which will have .two bipole converters in parallel, thus forming a three-terminal HVDC system. The descriptions in the paper include operation and control strategy such as fundamental control modes, paralleling, de-paralleling and coordination between the stations, and fault handling strategy. Some special features such as a line fault locator, DC switches and indoor DC yard are also introduced.

B4-105 "Technical feasibility and research and development needs for ±1000kV and above HVDC system" describes the result of a feasibility study and R&D needs identified for HVDC transmission at 1000kVdc or above. The following conclusions and recommendations are presented in this paper.

- UHVDC at 1000kVdc is economical for transmission of large amounts of power, more than 7000MW for a distance of more than 1500km.
- The operating record of the two first 800kVdc transmissions in China shall be evaluated as an input for development of 1000kVdc equipment and to decide upon a new project with 1000kVdc rating.
- The major challenges at development of 1000kVdc converter station equipment are air insulation of thyristor valve, transformer oil/paper insulation, and designs of bushing, switchgear equipment and support insulators taking electrical, mechanical and thermal stresses into consideration.
- When designing the overhead line towers and conductors to minimise the cost of the total HVDC systems, the operating experience of the 800kVdc lines in respect of electric fields, ion density, audible noise, radio interference and flashover performance shall be taken into account.

Question 1.1:

What are the latest developments and knowledge break-throughs in the design of HVDC systems at 800kVdc and above particularly in terms of equipment insulation and insulation coordination? What were the main lessons learned from the development of 500kVdc and 600kVdc schemes? Contributions on the equipment design considering mechanical and thermal stresses, as well as environmental impact, are also welcomed. What role did numerical analysis tools play in supporting the design of 800kVdc?

Question 1.2:

Is there sufficient information available to specify the 800kVdc and above HVDC systems and components? What is the basis for specifying insulation levels for testing the equipment and for design of the dc station yard? Are the existing standards sufficient for procurement and testing purposes?

Question 1.3:

What is the main driving force leading to the expansion of applications of HVDC systems at 800kVdc and above? What are the factors or the conditions that make UHVDC systems including multi-terminal configurations the most cost competitive solution? How do special operation, control and protection strategies improve HVDC system and overall system performance of the combined ac and HVDC system?

1.2 New topologies and developments in VSC Transmission

B4-101 "Trans bay cable – world's first HVDC system using multilevel voltage-sourced converter technology" describes the specification and the present status of the Trans Bay Cable Project (TBC). TBC is the world's first HVDC project employing voltage source converters in modular multilevel converter (MMC) topology. The active power transmission capability of 400MW and the voltage of ±200kVdc will be both records for the rating of VSC HVDC Transmission. The TBC system is designed to supply electric power into Downtown San Francisco from the East Bay. Thanks to the capability of VSC HVDC to provide voltage support, it is expected to improve network security and reliability. This paper first discusses HVDC system configuration including grounding scheme and converter arrangement with MMC. This is followed by a discussion of the performance of the MMC arrangement, during imbalanced ac system operation and during ac system faults.

B4-104 "Characteristics and benefits of modular multilevel converters for FACTS" discusses the characteristics and the benefits of the MMC topology when applied to FACTS. The FACTS device developed is ±25Mvar STATCOM assembled in a container. The authors point out several advantages of MMC. It reduces insulation stresses and the high frequency interferences initiated by the steep voltage pulses, as the highest voltage step is limited to the maximum voltage of a single module. High equivalent switching frequency is achieved while keeping losses low with modest switching frequency of the individual converter modules, minimising the harmonic filtering requirement. MMC application leads to a compact, modular, scalable and reliable solution. As a result, FACTS devices using MMC technology have a possibility to be cost competitive compared with other solutions.

B4-110 "HVDC VSC transmission with cascaded two-level converters" presents a variation of the MMC topology for VSC HVDC, which is referred to as a cascaded two-level (CTL) converter. The CTL converter has the same topology as that of the MMC introduced in Paper 101, but the arm within a single module or a cell of half bridge type consists of series-connected press-pack IGBTs and each cell is operated by the PWM control with typical switching frequency of 150Hz. The authors states that losses are reduced to roughly 1% per converter through a combination of methods. This paper summarizes the feature of the CTL converter regarding circuit configuration and control scheme. The paper describes the fundamental design of cell capacitors, reactors and a transformer as well as the valve itself. The control system structure is also explained.

B4-111 "A new hybrid voltage-sourced converter topology for HVDC" proposes a new hybrid VSC, which is a combination of series connected semiconductor switches called "Director" valves and multilevel converter cells, for HVDC transmission. The basic concept of the hybrid VSC is to take full advantage of the two distinct topologies of two-level converter and MMC. The MMC part provides a wave-shaping function while the Director valves serve the main part of power transmission. The authors state that the primary benefit of the hybrid VSC lies in the fact that fewer MMC cells are required, and that the dc converter cell capacitors, which dominate the size and weight of each power electronic module, can be reduced. This paper first summarizes the hybrid VSC concept and then describes some variations to construct a VSC HVDC converter. This is followed by the discussions of converter rating, loss performance and network fault responses in the form of a comparison with usual MMC VSC.

Question 1.4:

Can the principal benefits of the new VSC topologies for HVDC be presented quantitatively, for instance, in terms of efficiency, ac filter requirement, space requirement, EMI, fault response, reliability and cost, using the 2-level OPWM controlled VSC as unity? How do the benefits vary with the capacity of the HVDC system? Will the new VSC topologies displace the existing two or three level converter topologies in all HVDC application? Are there other topologies that could become viable and attractive if suitable semi-conductors are developed?

Question 1.5:

What are the most important/critical aspects of the design of VSC HVDC systems with the new topologies to achieve good performance? Some aspects of the new topologies are common with the 2- or 3-level topologies. Which aspects of the main circuit design have already been tested or verified, such as grounding (at the middle, at one end of the converter), valve stresses, control principles, etc…)

Question 1.6:

What are the current development and expectations for FACTS devices with the new VSC topologies? What are the main factors that differentiate the MMC concept from the two or three level converters, when considering medium voltage FACTS applications where the two or three level converters have found acceptance?

1.3 Multi-terminal and meshed HVDC configurations

B4-108 "Reliability study methodology for HVDC grids" discusses the expected reliability performance of HVDC grids in comparison with EHVAC grids. A reliability study methodology, along with failure statistics from open sources, is used to illustrate components and fault combinations that might have a dominating impact on the overall reliability of the power transmission systems. For a basic understanding of fundamental differences with respect to reliability characteristics, calculations are performed for a number of simple EHVAC and HVDC point-to-point connections with a line length of 1000km. The report only considers HVDC grids based on VSC technology with a voltage level in the range 600-650kV and power transfer capacity around 2500MW in a bipolar configuration. The reliability study is focused on the availability of power transfer capacity. The calculations show that the availability is very similar for EHVAC and HVDC connections if similar redundancy exists in the form of redundant transformers and converters.

B4-109 "Continental overlay HVDC-grid" discusses the methodology and case study results for a power flow analysis of VSC HVDC grids. Requirements on power flow control in VSC HVDC grids are also discussed together with presenting a possible control scheme to fulfil the requirements. The control scheme is the droop-control having a similar control concept as the frequency control in an ac system. This paper first explains the fundamentals of active power balance control and steady-state power flow calculation. It includes an important point that the power balance indicator in a dc system is the dc voltage. Through case studies, it reaches a conclusion that using one dc-station for controlling the dc voltage in a large HVDC grid has a major impact on the ac-system connected to that station and makes it impossible to fully utilize that converter station. The authors then deliver a comment that a new power flow control strategy for large HVDC systems such as in an overlay HVDC grid is needed.

Relevant information on operation and control strategy for multi-terminal HVDC grid is also provided in Paper **B4-305**, but the discussion is limited to the application for integrating large offshore wind farms.

Question 1.7:

What essential technical developments and standards are required to realize a large HVDC grid? What are the economic, environmental and regulatory barriers? If possible, a discussion based on a concrete project is preferable. What are the latest developments regarding HVDC grids in areas such as system configuration, system analysis and control strategy?

Question 1.8:

HVAC and HVDC networks will perform very differently, because of the controllability of HVDC and the natural response of HVAC networks. To what extent can the reliability and the availability of the systems be determined in a comparable way? What kind of data should be collected to make an accurate evaluation? What kind of reliability models are needed to support planners with information about the reliability of HVDC grids?

1.4 HVDC and FACTS as a means to improve system capacity, performance and efficiency

B4-106 "Viklandet and Tunnsjødal SVCs – Design, project execution and impact on grid utilization" presents Norwegian experiences on SVC installation project to increase the import capacity to the central Norway region showing rapid demand growth. Two new ±250Mvar SVC, together with nine 100Mvar shunt capacitor banks, have been installed around the region in 2008. The paper discusses the design and project execution of the SVC stations, as well as operating experiences during the first year of operation. The discussion starts with main design and specifications of the two SVC stations. The thyristor valves, control and protection systems are described. Special features including power oscillation damping and some environmental contaminant systems are discussed. The discussion is followed by information about the project execution and information which shows satisfactory operating experiences in terms of reliability and availability performance.

B4-107 "The use of a static synchronous series compensator (SSSC) for power flow control in the 220 kV Spanish transmission network" describes the development of a Static Synchronous Series Compensator (SSSC) for power flow control in the 220kV Spanish transmission network. The paper starts with a discussion on the need for power flow control equipment, specifically to minimize the risk of overload situation in a 220kV line, in the Spanish grid. Taking system parameters into account, the specification and the corresponding design of a SSSC including control strategy have been discussed. The estimated nominal capacity of the SSSC is 47MVA, and this achieves the desired controllability on the line which has a nominal power of 340MVA. The design is verified through simulation analyses on the power flow and the short circuit current. In addition, as a necessary procedure for FACTS projects, a discussion about the location selection for the prototype installation is performed.

Question 1.9:

The papers have described the technical aspects of the need for the FACTS devices and the technical benefits that they bring. What economic benefits do these and other recent FACTS and HVDC projects in commercial operation, under construction or being planned bring in respect of increased system capacity, performance and system efficiency? What other measures were considered and how did these compare in respect of cost, efficiency and performance?

Question 1.10:

What are the state-of-the-art technologies in system design, construction and installation, which directly contribute to cost reduction of FACTS and HVDC projects? In the same context, comments about the experiences in regards to new ways and means in the project implementation are also welcomed.

2. Preferential Subject 2: HVDC and FACTS – Operating Experience and New Projects.

Preferential subject 2 opens the forum for presentation of new projects as well as experiences from existing projects either using HVDC or using FACTS. A total of 9 papers was accepted for this subject. An interesting angle to this is the subject of renewable energy applications.

2.1. Interconnections using land and/or submarine cables and/or overhead lines.

B4-202 Aysén-SIC HVDC transmission system. Planning studies.
The paper describes the transmission planning studies for a large hydroelectric generating complex in the sparsely populated Southern part of Chile. The background for the project is also presented: the needs in the high demand areas, and the hydroelectric potential in the South. A comprehensive analysis is presented of different options and of their impact on the total costs.

B4-203 HVDC VSC (HVDC Light) transmission – operating experiences
The paper reports the experiences with two of the first VSC HVDC transmissions in the world, both commissioned in 2002: Both using three-level converters, and both using cables; one undersea cables, the other using underground cables.

B4-204 The Rómulo project, Spanish peninsula – Mallorca (243 km, 250 kV, 2x200 MW): first Spanish HVDC link
The paper reports on the characteristics of the submarine transmission with HVDC classic converters, expected to enter commercial operation in 2011. On the Mallorca terminal, GIS was chosen for the switchgear, while for both stations, the filters are installed indoors. For the submarine cables, an extreme depth had to be considered (1485m). Besides, a metallic return cable is provided.

B4-208 Design studies for the 3150 MW, ±600 kV UHVDC Bipole 2 of the Rio Madeira long distance transmission
The Rio Madeira hydroelectric development requires significant transmission capacity to the load centres in the vicinity of Sao Paulo. Two bipoles are under design, and the paper describes the studies for different electrical aspects for one of them. Many studies have been done but some remain to be done jointly with the supplier of the first bipole and the Back-to-Back converters

B4-209 A survey of the reliability of HVDC systems throughout the world during 2007 - 2008
This is the report of SC B4’s Advisory Group AG-04 on the data collected annually regarding the reliability and availability of HVDC systems in operation throughout the world. The report contains

statistics on frequency and duration of outages. Rather than dealing with analysis, the report deals with synthesis, and it even combines the new data with the previous.

Question 2.1:

For the Rio Madeira transmission, the two bipoles will be supplied by different manufacturers. In this double bipole transmission the term optimisation can lead to different solutions, depending on the target function chosen for each bipole. Have conflicting targets been identified in some areas (ac filtering? stabilising functions? other?)

Question 2.2:

Environmental issues were strong driving factors for the adopted solutions in some of these projects. In at least one of them, there was still resistance even after it was built, even though the solution was deemed the most environmentally friendly. Are there other examples of recent projects where the environmental issues are the drivers and/or the main obstacles? Is there a trend towards increasing use of indoor designs, and what are the benefits and disadvantages? What was behind the use of a return cable in the undersea project?

Question 2.3:

With de-regulation, there have been disincentives to outage reporting from HVDC system operators. Have the authors seen this trend increasing or decreasing? Is there an estimation of the percentage of non-reporting systems? With the growing number of VSC HVDC schemes, is it possible for CIGRE to start collecting reliability and availability data for the benefit of existing owners, as well as for future owners?

2.2. Embedding of HVDC and FACTS in AC Networks.

B4-201 Comparison of active filters topologies in medium voltage distribution power systems.
The paper deals with an interesting application of corrective devices. Filtering needs arise sometimes because of the harmonic generation in the HVDC or FACTS devices, but they can also arise because of the resonances that can be created by the existence of capacitors. Good descriptions are given of possible configurations, with behaviour and consequences explained.

B4-206 Static Var Compensator designed to enhance the operational reliability of Finnish transmission network
The paper gives a comprehensive presentation of the Static Var Compensator, including the effects it has on the Finnish grid. The discussions include the different higher hierarchy possible control principles.

B4-207 450 MVA Statcom installation plan for stability improvement
The paper presents an installation with a very large STATCOM for improving stability in the Nagano area of Japan. The STATCOM uses Gate Commutated Turn-off thyristors arranged in several secondary windings in a multi-stage configuration.

Question 2.4:

With active filters an old question becomes more apparent: “Zero voltage distortion” may mean absorbing harmonic currents from the surrounding busses, while “Zero current distortion” may leave a significant voltage distortion on the bus. What are the preferred definitions? What are the trends?

Question 2.5:

HVDC links, as well as SVC's and STATCOM's increase the ac system reliability or stability, and this is normally used to increase the loading limits on the transmission system keeping the reliability or stability limits constant. Is the added capacity assessed and given value in some systems when dispatching? Considering that an AC system grows stronger with time, are the stabilising or other ancillary functions equally valuable after some years? The choice between an SVC and a STATCOM is usually made based on economics. How is the economic benefit of the STATCOM's faster response, greater output at lower voltage and other benefits evaluated? Comments on the choice for these and other similar cases are invited.

2.3. Renewable Energy Applications.

Paper **B4-202** has been discussed under Subject 2.1, but it also relates to Subject 2.3

B4-205 FACTS for enabling wind power generation
The paper describes the past and present environment for developing wind generation in Australia and New Zealand, and how FACTS helps overcome some of the difficulties there. A glimpse is provided of the expected regulations that will govern at least the electrical system aspects of this source. Many of the aspects dealt with are also present in other countries.

Paper **B4-208** has been discussed under Subject 2.1, but it also relates to Subject 2.3

Question 2.6:

In some forums, hydropower is not included in the Renewables arsenal. How is it regarded in the business environment in which the utilities operate? How is it regarded by others? As HVDC and FACTS make more hydroelectric projects feasible, are these means seen as positive or negative by utilities and the public?

Question 2.7:

The grid code requirements seem to be quite diverse. As non-dispatchable renewables take a larger portion of the total installed generation will the ancillaries services of conventional generation (voltage support down to zero, inertia emulation, etc) have to be provided by power electronics? Are there any examples of this being done today or at least being planned?

3. Preferential Subject 3: HVDC and FACTS Project Development Issues.

Preferential subject 3 opens the forum for presentation and discussion of environmental interactions, HVDC and FACTS performance when embedded in ac systems, including ancillary services, and diverse aspects of licencing, funding, and project development. A total of 6 papers were accepted for this subject.

3.1. Environmental issues for HVDC and FACTS schemes, including visual impact, earth return, audible noise, EMF & Ions.

B4-302 Caprivi Link HVDC Interconnector: Site selection, geophysical investigations, interference impacts and design of the earth electrodes

The paper gives insight into aspects not very often discussed in B4, yet fully relevant, such as the selection of sites for the electrodes, with due consideration to electrical and thermal characteristics of soil and deep soil, and the different investigations made to assess them, as well as the influence of the electrodes on the environment. An overview of the project characteristics and application are also given.

Question 3.1:

The economic and efficiency benefits of earth electrodes are well known in the B4 community. Many older HVDC schemes decided the electrode location based on the earth's upper crust resistivity alone. The newest ones also consider the deep earth conditions. What were the main motives behind taking a deep survey? Are there other projects under consideration for which full geological studies have been done or are contemplated for the electrode sites? Are there other projects where earth or sea electrodes are being considered?

3.2. System performance with embedded HVDC links, including multi-infeed and ancillary services.

B4-303 Power quality assessment when integrating an HVDC link to existing power grids
The paper deals with the ac system power quality from the point of view of harmonics. As harmonics are generated in the conversion process, they can affect the ac system. AC filters at the converter station can compound the issue. Significant efforts have been devoted to optimise the study methods in frequency and time domains.

B4-304 HVDC-interaction-strength index for systems with multiple HVDC infeeds
The paper deals with multi-infeed interactions in the China Southern Power Grid. The region has at present 4 fully operational HVDC links with a fifth one already under test operation, and all of them feed the same area. The different interaction indices in present use are assessed, and a new index is proposed.

B4-305 Multi-terminal HVDC grid for network interconnection and renewable energy integration.
The paper deals with the first step on the question of HVDC grids, and it devotes itself to grids using VSC converters, as this is the technology expected for such grids. The paper advocates the use of dc voltage droop, which is the logical extension of the well proven technology used for power sharing among generators in an ac system. As in them, the paper also advocated some refinements to cope with different disturbances and function borders.

Question 3.2:

Multi-infeed issues are on the rise, as is natural due to the proliferation of HVDC links. Different indices have different advantages and disadvantages as they have to balance the ease of use against the accuracy. Comments on this issue are invited. Comments on the possibility to perform quasi real-time assessment by system operators are also invited.

Question 3.3:

For multi-terminal dc grids with VSC converters voltage droop on the DC side appears to be the method proposed by several experts. Are there other methods proposed for power sharing? In an intelligent network, fast communication could be used for the front control, and droop only used as a back-up. Has this been considered, or would the requirements on communication become too high?

3.3. Options Considered, Regulatory, Licensing, Project funding, and Technical Risks issues.

B4-301 New operation and control scheme of HVDC link under power market environment.
The paper presents a method to increase the flexibility of a conventional HVDC link so as to be able to operate at a net power below the traditional 0.1pu level. Insulation stresses are also reduced on the cables, as multiple polarity reversals are avoided near zero power.

B4-306 HVDC Madeira transmission system **-** planning development and final design
This paper presents the same project as paper B4-208, but at is initial stage: planning development. It presents the different alternatives that were studied for the transmission. In addition to the usual criteria of stability and recovery for different contingencies, the accelerating torque on the generating units was also an issue, but found not to be unusual for the power industry. Due to the long lines and low inertia of the hydro machines, controlling overvoltages was also an issue.

Question 3.4:

The manner in which the Madeira project was decided by Tenderers bidding for a large number of lots has an impact on financial, technical and other matters. Is it possible to summarise the main advantages and disadvantages resulting from the chosen process, both from the Owner's perspective and from the Contractor's perspective? Will we see many similar arrangements in the future?

Question 3.5:

The need to operate HVDC links at or near zero power has been raised before. The increase of wind power generation in islanded systems originally fed by the dc link creates a strict need. A similar but economical need exists when optimising the dispatch in a complex system. There are some schemes in the world that approach the need either by allowing low minimum direct current, or that go to reversing power in only one pole. Comments are invited regarding the limits and equipment consequences with the first method. So are comments on the hysteresis used and the losses incurred with the second method. Excluding VSC converters, are there other methods?