GROUP B4

HVDC and Power Electronics

SC B4 2006 SESSION

Special Report

Summary Report

General Report

B4 - 00 CIGRE 2006

SPECIAL REPORT FOR GROUP B4
(HVDC and Power Electronics)

Mohamed ZAVAHIR **Kent SØBRINK**

Special Reporters

A "POSTER SESSION" IS SCHEDULED DURING THE SESSION ON WEDNESDAY 30th AUGUST TO ALLOW AUTHORS TO ANSWER QUERIES FROM DELEGATES ON THEIR PAPER.

- **8.45 a.m. to 10.45 a.m. for Papers B4.101 to B4.207**
- **11.00 a.m. to 1.00 p.m. for Papers B4.208 to B4.310**

INTRODUCTION

The Mission of SC B4 is "To facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of HVDC and power electronics. To add value to this information and knowledge by synthesising state-of-the-art practices and developing recommendations". 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 27 papers, including one invited paper, have been selected in accordance with the three preferential subjects for the 2006 session. The papers represent important information and are imparting essential knowledge for the continuing improvement and development of the industry. These papers in line with the preferential subjects are aimed at making a valuable contribution to the Mission of SC B4.

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

The preferential subjects decided by the Study Committee for the B4 2006 Sessions are:

1. New HVDC and Power Electronic (PE) Technologies and Projects

1.1 Enhanced Voltage Sourced Converter Applications
1.2 Advances in PE Devices
1.3 Novel PE Applications
1.4 New HVDC Projects.

2. Issues Concerning HVDC and Power Electronic Projects

mohamed.zavahir@transpower.co.nz
kent.sobrink@energinet.dk

2.1 Environmental Requirements for New Applications and Upgrades
2.2 Environmental Monitoring Programs for Existing Schemes
2.3 Fault Diagnosis and Lifetime Prediction at Operation and Maintenance Levels
2.4 Operating Experiences of Projects
2.5 Studies and Experiences on Cost Reduction.

3. Role of HVDC and Facts to assist System Performance

3.1 Dynamic Design Requirements of Projects for Severe Operating Conditions
3.2 HVDC and PE Technologies' Contributions to System Restoration
3.3 Studies and Experiences on How to Incorporate HVDC and PE Modelling into System Planning
3.4 Technical and Economic Benefits Experienced.

Preferential Subject 1 -New HVDC and Power Electronic (PE) Technologies and Projects

Preferential subject 1 deals with advances in PE technologies and new applications to projects.
A total of 7 papers were accepted in response to this subject. Two papers presented for PS 3 are also relevant to this subject.

1.1 Enhanced Voltage Sourced Converter (VSC) Applications

Paper B4-103 describes a Voltage Sourced Converter (VSC) application for unbalance compensation for railway substations in France. The railway traction system introduces a varying electrical load causing a significant amount of unbalance in the connected a.c. system. The main electrical impacts of the loads are voltage unbalance and voltage harmonics due to harmonic current. Traditionally, the resulting unbalance problem has been resolved by using operating modes of the HV or EHV network, by specific switching operations, or by setting a V-type power supply. In extreme cases, the solution requires an increase of the short circuit level at the point of connection to the network. This paper outlines the unbalance problem and describes an experimental solution using VSC based on GTO devices. The authors highlight the reasons for selecting VSC over a conventional static var compensator (SVC) with TCR/FC and TCR/TCSC for this application. The advantages of this compensator above grid reinforcement appear to favour this solution. This is a classic application of FACTS devices for improving power quality in power systems.

Question 1.1-1:

A strong feature of FACTS devices proposed is the ability to improve power quality in the transmission system. However, very few utilities have embraced FACTS technology for widespread application. Are there any enhanced VSC applications similar to that described in B4-103 used for power quality improvements in large scale?
The VSC-based compensation (FACTS devices) was compared to traditional SVCs from the introduction of other FACTS devices. The main emphases were on investment costs and equipment reliability. What developments have taken place during the last decade that could make VSC-based devices more attractive or otherwise?

Paper B4-105 discusses the development work carried out on furthering the capability of VSC transmission technology beyond its present limits of ±150 kV and 350 MW. The recent developments in VSC transmission technology in four major areas – valves, cable system, system design and HVDC control – are reported. With these commendable developments, the authors expect to attain voltage and power ratings of ±300 kV and 1000 MW in the future. The benefits of VSC transmission has been well received by the industry, with its ability to integrate seamlessly into an a.c. system (independent on system strength and not needing reactive support), stability improvement, highest level of controllability, etc.

Several challenges to this rapidly evolving technology have been addressed in this paper. A pre-requisite for the increased application is that this technology competes with traditional transmission both HVAC and classic line commutated HVDC systems. The high losses are being addressed by reducing switching losses and increasing the transmission voltage. The development in cables, both ratings and increased laying depths, promises a better use of this technology for submarine applications.

The ability to use overhead transmission lines, whether constructing new or converting existing a.c. transmission circuits, is still an area that deserves serious attention. Although the use of overhead transmission lines would be impossible in specific cases, where the only choice is a cable option due to environmental reasons or submarine crossings, overhead lines would generally still be a competitive solution. Often, a combination of lines and cables would be desirable and cost effective. The reported developments indicate that VSC technology has a future and commitment from the industry.

Question 1.1-2:

What other developments are required to make VSC transmission a technically and economically viable alternative against traditional HVDC or AC transmission? Are there any examples of life cycle cost-benefit analyses comparing the use of VSC on overhead lines against cable transmission or a.c. transmission lines?

1.2 Advances in PE Devices

New and diverse applications of PE technology hinge on the development and progress made with PE devices. Both papers **B4-105** and **B4-107** describe the recent developments with PE devices in terms of increased power handling capacity and performance improvements, such as reduction in losses. Fast development of new PE devices while beneficial in terms of technology improvement may be an issue for recently proposed projects. The issues may be concerned with technology obsolescence or in case of unexpectedly high failure rates a major replacement of the PE device. Any such designs should have some level of future proofing and manufacturer support to the end of economic design life of the plant.

Question 1.2-3:

What is the typical product development time for new PE devices? What measures can be used to ensure that the new installations are supported in the long run, or replaced without resorting to significant change or total replacement of the installation? What life cycle and reliability assessments are available for new PE devices? What are the potential advantages expected from the developments described in the papers B105 and B4-107?

Paper **B4-102** describes TCSC developments in China where a significant amount of fixed series capacitors (FSC) are already in place. The growing system demand necessitates some percentage of dynamic compensation to be added to these series capacitors, as opposed to network augmentation. Several papers concerned with TCSC developments are presented to PS 2 and PS 3. Papers B4-305, 308 and 310 describe direct TCSC implementations as opposed to a staged implementation with FSC followed by introduction of thyristors at a later stage.

Question 1.2-4:

Do most series compensation projects allow for future dynamic compensation in order to preserve the future option value of not investing immediately? If so, what design considerations are made at the first stage of the project?

1.3 Novel PE Applications

The application of HVDC for de-icing HVAC lines built up with severe ice loading during snow storms is explained in paper **B4-101**. The transmission system in Quebec region is frequently exposed to ice accretion resulting from atmospheric icing or freezing rain. In January 1998, three consecutive ice rains in five days subjected the entire south-western network to extreme conditions. In some places, radial ice accumulation of over 75 mm was observed. The storm damaged an area of over 900 km of transmission line sections over the 3200 km of lines subjected. It caused 150 towers to collapse damaging 10 lines on the 735 kV network. A combination of tower reinforcement and de-icing methods are proposed to improve the security by ensuring that the 735 kV network backbone remains intact.

The first de-icing facility (250 MW, ±17.4 kV, 7200 A) will be installed at 735/315/230 kV Lévis substation in Canada. It will generate enough current to de-ice 735 kV a.c. lines of a length of up to 240 km. This facility is strategically located to enable de-icing five lines in less than one day. Most of the time, the de-icer will be used as a static var compensator to improve local voltage regulation and to ensure its availability for de-icing purpose when needed within one hour. This solution uses standard technologies based on established HVDC/SVC equipment. Given the infrequent use of the de-icer, the designers must be commended for maximising the use of the installation as a static var compensator on a regular basis.

This paper describes the use of HVDC for non-conventional purpose and has the opposing requirements to that of HVDC transmission, i.e. lower voltage and higher current. In this case, the power rating is minimised, and the conductor current is increased for de-icing an a.c. line.

Question 1.3-5:

Power Electronics and FACTS technology has been available for more than a decade. What are the obstacles that limit the application of non-conventional ideas in the power system as in B4-101? Are there any other new and interesting applications where PE devices can be configured to provide (thinking outside the box) solutions to problems in the power systems?

1.4 New HVDC Projects

Working group WG B4-45 is dealing with assessment of 800 kV HVDC applications. The 800 kV developments mentioned in papers **B4-106** and **302** require increased ratings of thyristors presently available. The development is expected to follow a well-established path and may be treated as an organic development of this technology. Following any such development will be the need for testing assemblies of ever increasing ratings, in order to simulate the operating conditions as closely as possible. Paper **B4-309** describes some development by one manufacturer to help test valves for increased ratings. The applications of 800 kV would require further development the technology and of course new test systems. More importantly, the overall system reliability will be a major consideration, as the unavailability or forced outage of a pole will have greater consequences given the relatively large percentage of power that would be carried by a single pole.

Question 1.4-6:

There are important potential 800 kV UHVDC applications for long distances and high power transfer levels being evaluated in India, China, Southern African countries and in Brazil. One relevant issue, concerning these projects is how the new market frameworks would affect the planning & design (technical), configuration & reliability (economic), equipment supply market

as well as the technological development aspects of HVDC. Comments on these issues or for another considered critical would be welcome.

Paper B4-309 reports on a new facility designed for the testing of thyristor valves for HVDC and SVC applications. The test facility has so far been developed for HVDC, and, in the next phase, it will be upgraded for testing thyristor valves for the SVC applications. The test facility is using the synthetic testing approach, and it is able to test high-performing thyristor with high-voltage blocking capability (> 8 kV) and high current capability of several kA. The test facility has the capability to test a complete valve section consisting of up to six 8.5 kV thyristors which are connected in series. The function of the test facility as well as how it is used to test valves for HVDC and SVC applications are described in details, and curves with test results are included in the papers. The test facility has been used to test thyristor valves for the first commercial project.

Question 1.4-7:

With deregulation of the electricity market the way power systems used to be operated has changed a lot where rescheduling of generation can change with short notice depending on the market signals. This may stress the equipment in a different way than it used to. In B4-301, it is stated that the Cigré cycle cable testing was modified due to changed market conditions. Does the change in the market conditions also require new test procedures for HVDC and FACTS equipments? What about the new foreseen 800 kV applications? Besides reduction in testing time, what are the technical benefits from the new test facility? Can better tests be implemented, and do other similar test facilities offer the same possibilities?

Paper **B4-104** describes the feasibility studies carried out for the proposed HVDC link between the Spanish Peninsula and the Balearic Islands. This paper describes specific challenges faced with the projects with respect to cable route selection, environmental assessment, reserve consideration and the connection to a weak network in Mallorca. In planning the link, several scenarios – including the variations of power rating, utilisation, VSC vs. “traditional” (LCC) HVDC, monopolar vs. bipolar options, station locations and cable routes – were compared. A low ESCR value of 1.6 may result in the case of 2x300 MW rating of the link requiring the adoption of a non-standard design (e.g. the use of SVC). Overall, a bipolar “traditional” HVDC, rating 2 x 200 MW has been selected as the preferred solution. The submarine cable design and laying depth envisaged is 1500-1600 m, with emphasis on limiting the number of laying campaigns. The benefits from the link – such as reduction in generation costs (capital and fuel), green house emission, unserved energy, while resulting in better frequency regulation – were attributed to the presence of HVDC link. Apart from the latter, all other benefits were quantified in some form to justify the project. This paper will be discussed further under preferential subject 2.

The generation development scenarios play an important role in determining the future economic benefit from any new investment. HVDC presents an ability to stage the development, hence maintaining deferral of capital or maintaining the option value of investment. A careful consideration of scenarios is critical in order to capture all likely scenarios and to attribute realistic benefits and option values to projects. This type of planning is carried out often well before the proposal reaches the HVDC designers, requiring the HVDC engineers to have an early input into planning studies.

Question 1.4-8:

The authors of B4-104 mention that a low ESCR value of 1.6 may result in the case of 2x300 MW rating of the link requiring the adoption of a non-standard design (e.g. the use of SVC). Can the authors elaborate on the design considerations? Also, the authors claim that better frequency regulation, although known as a benefit from the link, was difficult to quantify in

economic values. Are there any constructive suggestions as to how such ancillary service benefits can be quantified? How may the HVDC community help the planners and decision makers attribute accurately the benefits from HVDC technology for project economic comparisons? How may the HVDC community quantify and articulate all the identifiable benefits from HVDC and FACTS projects to the decision makers?

What experience can be reported on the use of SVC's near HVDC converter stations, similar to B4-203? Traditionally, the use of synchronous condensers has been the device of choice for strengthening the a.c. fault level or performance with low ESCR levels. What new developments or reliable, cost-effective solutions are available that do not interfere with HVDC control performance?

Question 1.4-9:

Both projects described in papers 104 and 205 require cable laying depths of about 1600 m. In these cases, the ability to secure a viable cable route in advance is critical, as illustrated in both feasibility studies. The cables form a vital and most complex part of the project and present challenges, for installation, and in the event of deep-sea repairs are required. What special measures and design requirements are necessary to ensure the reliability and to manage repairs for such deep-sea installations?

Question 1.4-10:

Paper 105 describes the new development in terms of polymeric extruded cables able to reach laying depths greater than 2000 m. Allowing a laying depth over 1500 m with an extruded cable is supported with a progressive interpretation of the recommendation published in Electra No. 171, April 1997. Are there any opinions from the readers on the progressive interpretation by the authors allowing permanent deformation of conductor joints?

2. Preferential Subjects 2 - Issues Concerning HVDC and Power Electronic Projects

A total of 10 papers were accepted in response to this preferential subject which deals with environmental issues, fault diagnosis as well as studies on and experiences with cost reductions. B4-104, which amongst other thing is dealing with environmental and economic issues, is also relevant for a discussion under this subject.

2.1 Environmental Requirements for New Applications and Upgrades

Paper **B4-205** describes the environmental issue regarding a new HVDC submarine project between Sardinian Island and the Italian Peninsula (SAPEI). The new HVDC submarine system will be a 1000 MW bipolar system with land and sea cables. The first 500 MW HVDC monopole is planned to be commissioned in 2008, subsequently to be upgraded to a 1000 MW bipole. The existing anode for the existing SACOI2 HVDC link will be upgraded and used in common with the new SAPEI HVDC link, and a new cathode will be installed at a suitable location at the coast line of Italy. The environmental issues covered are the methodology used for the sea cable route survey study and corrosion issues for establishment of the electrodes i.e. upgrading of the existing SAPEI anode, from 1500 A to 2500 A and a new cathode of similar design as the cathode used for SACOI 2. A particular concern is that each electrode is not designed for reverse anode/cathode operations. Therefore, it has been proved at laboratory tests. The paper also gives a review of how issues regarding electromagnetic compatibility and audible noise are dealt with.

Paper **B4-207** addresses radio interference (RI) issues for high-voltage substations with HVDC and FACTS equipment which are generally not covered by existing standards or recommendations. An important difference regarding RI for HVDC and FACTS equipment is that RI cannot be verified in laboratories, but requires on-site measurements where background noise interferes with the measurements. The characteristics of the emission sources are discussed. In high-voltage substations, RI emitted noise are mostly caused by corona discharge and sparks. RI emission propagates by direct radiation, but may also propagate via connecting lines. In HVDC and FACTS equipment, the commutating process is causing high-frequency current circulating in bus work and ground system which may act like dipole antennas. Even by small currents, the radiation can be significant due to the large "antenna" area. For forced commutated converters, the high switching frequency may cause resonant peaks for frequencies up 10 MHz due to parasitic capacitances and inductances. The attenuation increases with the distance from the equipment. However, at distances smaller than the physical size of the installation, the field level may be very irregular with significant variations. The RI impact and limits are discussed. It is pointed out that the risk of interference is not the field level at the source but at location at the receiver. The measurement distance for RI verification is discussed.

Results from several measurements at HVDC and FACTS installation are presented in the paper and based on the authors' experiences an approach for RI verification is proposed. The paper finishes with some important discussions and a conclusion regarding RI requirements and verifications for substations with HVDC and FACTS equipments, as well as needs for further investigations in relation to existing relevant standards.

Environmental issues are of great public concern and HVDC transmission may have the advantage to be considered as environmentally friendly in several respects compared with long a.c. transmission lines. Monopolar HVDC with earth or sea return is a cost-effective solution. However, as reported in B4-104, it can be difficult to get a permission to build, which is why only metallic return is considered for this project. Several other new HVDC projects under construction and planning are only considering metallic return in order to avoid uncertainties in the environmental approval process (B4-301).

Several new HVDC schemes recently completed or in progress are only considering metallic return, whereas B4-205 reports a new bipolar scheme which will be built for earth return. It may be argued that in some projects, there may be commercial justifications to speed up the licensing process and therefore to accept the additional cost of metallic return cables. With a few links following similar lines precedence may be set that could well make the metallic return the de-facto standard configuration for future HVDC links. This area needs a careful consideration by the HVDC community prior to accepting a viable standard approach.

Question 2.1-11:

What are the most critical environmental obstacles in getting permission to build a new HVDC project? What are the life time costs for a return cable compared with the environmental monitoring and additional maintenance of HVDC schemes for continuous earth return operation?

Question 2.1-12:

B4-207 states the need for a new standard regarding RI requirement for HVDC and FACTS installation. Has RI been a problem caused by HVDC and FACTS using voltage sourced converters in practice, and how has it been dealt with? Is there also a need for standards with respects to the power quality on the line side? Could any existing national guidelines or standards be used as basis for a new RI standard? Which body should undertake to prepare guidelines?

2.2 Environmental Monitoring Programs for Existing Schemes

Paper **B4-204** deals with problems with monopolar ground return operation of the Talcher - Kolar bipolar HVDC system with a transmission capacity of 2000 MW at ±500 kV. During commissioning, a humming sound from the Kolar converter transformer and other nearby power transformers was heard. An investigation revealed that the ground electrode design was within design limits, but that grounding resistance and potential deviated at a radius above 1.9 km from the electrode station. It was concluded that the unexpected deviation was due to special geological conditions at a distance from the electrode station. Consequently, the maximum permissible power transmission at monopole operation was reduced to 150 MW. It was found that the phenomena was due to ground potential differences between transformer grounding in the area caused by the ground return current at monopolar operation of the HVDC link. In order to block the d.c. neutral current, blocking devices were developed for installation in the affected power transformer neutrals. In total, nine blocking devices have been installed in the nearby power transformer neutrals, and the maximum return current at monopolar operation could be raised from 300 A without blocking device to 1000 A with the blocking devices installed.

Paper **B4-206** reports on comprehensive environmental experiences over 40 years, since the first commissioning in 1965 and the later capacity upgrading in 1992 of Benmore-Haywards HVDC link between North and South Island of New Zealand. The cathode is a land electrode, and the anode is a shore electrode, but both were designed for reversible anode/cathode mode. The environmental aspect taking into account the original electrodes from 1965 and the later upgrading in 1992 are discussed. The aspect applies mainly for bipolar operation with occasional d.c. earth current return due to unbalance operation of the bipolar or monopolar operation. It is pointed out that the findings are not directly applicable for HVDC monopolar links with earth returns. The important aspects considered for the electrode design are safety for humans, animals and marine life, d.c. stray current corrosion, touch voltages on metallic structures, interaction with the a.c. grid and lifetime for the electrodes. Based on the experiences, the paper also gives important conclusions with respect to periodic monitoring of step voltages, the earth resistivity and other measures.

Operation of HVDC links with ground current return is not only a challenge during planning as reported in B4-205, but also during the lifetime of a project, as reported in B4-206, because ground return current may influence new installations built later by third parties. B4-204 report on unwanted d.c. current flows in the nearby a.c. systems power transformer. The problems was discovered by changes and solved by installing d.c. blocking devices in the affected a.c. power transformer neutrals.

Question 2.2-13:

Would such measures, as widespread applications of d.c. current blocking devices, be acceptable for new HVDC schemes with continuous earth current return?

2.3 Fault Diagnosis and Lifetime Prediction at Operation and Maintenance Levels

Paper B4-201 is an important report on faults experienced on nearly all converter transformers in the Itaipu system, which consists of two ± 600 kV bipoles with a transmission capacity of 6000 MW. In total, the system is provided with 24 single-phase 3-windings converter transformers. Over a 20 years operating period, since 1985, 22 converter transformers have had seriously faults during operation of which only one fault was due to external reasons. All other faults were caused by internal faults in the converter transformers themselves. The failures fell in two distinct periods. In the first period from 1985 to 1990, 12 faults occurred, and according to the manufacture's analysis and opinion, the faults were mainly due to low quality in the manufacturing process. After 7 years without faults, the second period began from 1997 to 2004 in which 10 converter transforms failed due to new type of faults. The paper includes an important description of the faults and their causes as well as a recommendation regarding how to operate the system by not operating the rectifier in high gamma mode for high Mvar uptake in the converters and recommendation regarding modification in converter transformers, which should be implemented by the manufacturer.

The performance of HVDC transmission is mostly affected by the reliability of converter transformers, because it requires long down times in case of serious faults in converter transformers. This is also reflected in B4-202, where 83 per cent of the Forced Energy Unavailability is caused by faults in converter transformers.

Question 2.3-14:

Are converter transforms more vulnerable to failures than a.c. power transformers? Is design or materials composition the critical parameter that is determining their high failure rates? Are there any differences with respect to performance between 3-phase converter transformers with 3 windings and 2-phase converter transformers with 3 windings? What would be the most cost-efficient solution when a spare converter transformer is required for improvement of the overall reliability? These questions also apply for 800 kV applications, as described in B4-106 and B4-302.

2.4 Operating Experiences of Projects

Paper **B4-202** is the biannual report which is prepared on behalf of the study committee B4 by the Advisory Group B4.04. The paper is a summary of the survey on reliability of the HVDC systems world wide based on data gathered from owners of HVDC systems. The report brings valuable information where performance of HVDC systems can be compared and evaluated. The reporting protocol is regularly updated based on experiences, and the last revision was made in 1997. The data is the memory of the worlds HVDC community, and it represent a reporting period of 33 years covering 23 thyristor valve systems and three mercury arc valve systems – the latest representing the first generation of HVDC systems which are still in operation. The report defines important parameters for the HVDC performance. Two important parameters are the Forced Outage Rate (contributing to FEU), and the Energy Availability (EA). The average Energy Availability for all links in operation in 2003 was 92.9 per cent, and in 2004 it was 94.6 per cent. Approximately 93 per cent of the FEU for 2003-2004 are due to equipment on the a.c. side where converter transformers account for 83 per cent and other equipment accounts for 10.7 per cent. It is also remarkable that the contribution from a.c.

equipment to the average FEU for 2003 and 2004 has increased significantly compared to the FEU accumulated from 1983-2002.

Paper **B4-203** is a report on the performance of the Cross-Channel HVDC link over its 20 years of operation since 1987. The average Energy Availability has been more than 97 per cent, and the two converter stations were built by different contractors with different converter station design. The HVDC system consists of two 1000 MW bipoles with eight sea cables between the French and British national power systems. The French converter station "Les Mandarin" is an outdoor installation, except for the converter, and it is only manned during working hours. The British Converter Station "Sellindge" is provided with indoor GIS substations and two +/- 150 Mvar SVC's. Sellindge is continuously manned. In Sellindge, the thyristor failures are few – only 5 thyristors in total out of 12,000 are replaced per year. In "Les Mandarin" the thyristor failure rate is of the main concerns with a rather high failure which in 2004 was about 1.06 per cent. The converter transformers in the two ends of the links are different. In Sellindge, two 3-phase, 3-winding transformers per pole are used, where the main issue has been a few bushing failures due to inappropriate shielding of the bushings.

This has now been solved by using new stress shields. In "Les Mandarin", single-phase 3-windings transformers are used, and they have performed satisfactory with only one major transformer fault due to the gas generation caused by a hot spot. The pollution levels have also caused problems which have led to degradation of filter reactor faults and to the reduction of efficiency of cooling systems for the converters, which are air-cooled. The control electronics, which is based on analogue technique, have been very reliable. However, due to lack of spare parts, replacements may eventually be necessary. It is concluded in the paper that the high availability is achieved due to close cooperation and exchange of experiences between the French and British operators.

Paper **B4-208** reports on operating experiences with the Three Gorges-Changzou (3GC) and the Three George-Guangdong (3GG) HVDC bipolar links. Both links have a nominal rating of 3000 MW, ±500 kV. They have been designed for a continuous overload capability of 3480 MW and 5-seconds overload capability of 4500 MW. The main circuit layouts for the two links are identical except for the reactive power equipment. Stability has been ensured by optimal utilisation of reactive power capability of generators of the Three Gores hydro power system. One-and-a-half breaker configuration has been applied on the a.c. side of the converter stations. The links are designed for monopolar operation with either ground or metallic return. The links went into commercial operation in 2003 (3GC) and 2004 (3GG). The links have performed better than required with respects to availabilities, outage rates and annular failure rates. Some running-in problems were encountered after commissioning of the first bipole in 2003 (3GC) with respects to hardware and software for control & protection. However, none of these problems caused trips of the link. Only a few similar problems were experienced in the 3GG link in 2004. Based on the experiences gained, corrective measures have been implemented for increased performance of the links.

Paper **B4-210** describes the design and implementation of an Operator Training Simulator (OTS) which can be used for offline simulation of FACTS controllers. The OTS is designed in such a way that it can be used to simulate multi-functional VSC-based FACTS Controllers and so that it can be customised to the Convertible Static Compensator (CSC) in the New York Power Authority (NYPA) system. The CSC consists of two 100 MVA VSC which can be configured as a Static Synchronous Compensator, Static Synchronous Compensator Unified Power Flow Controller or an Interline Power Flow Controller. In total, the CSC can be configured in 11 different configurations. The mimics of the OTS and the Station one-Line Diagram is similar to the real mimic of the CSC installation. The OTS software is developed in MATLAB. In the paper, the use of the OTS is demonstrated by an example where two SSSC are used to reduce the flow in the lines downstream from the FACTS controllers. The OTS can be used to train control room operators, and it is possible to adapt the OTS to other types of FACTS Controllers.

Power systems are rather complex, and the complexity will certainly increase over the years due to more distributed generation, lacking development of the grids and consequently closer operation to its limit. In order to operate the power system, more FACTS controllers may be required, and this makes power system operation more demanding. Paper B4-210 reports on an Operator Training Simulator (OTS). The OTS can be used by operators to gain experiences before the commissioning of new FACTS controllers.

Question 2.4-15:

How do HVDC designers use the performance report to improve their design? To what extent is the availability important for HVDC planners? Is the availability for HVDC transmission comparable with the availability of a.c. transmission, and how could it be achieved. Are any improvements of the performance report planned for, and do the readers have any proposals/wishes for improvements in order to make it more applicable for planners and maintenance staff?

Question 2.4-16:

In what way has the OTS been used in training operators? Can the OTS be operated in real time, specifically in the control room to test operations before they are executed on the real power system? What are the operator experiences with the OTS, and what are the future perspectives for using OTS for other power systems with multiple HVDC and FACTS devices?

2.5 Studies and Experiences on Cost Reduction

Paper **B4-209** presents a new tool designated "Life Cycle Environmental and Economic analysis of Transmission Systems (LEETS)" for environmental and economic analysis of transmission systems. The tool is implemented in software, and its use is demonstrated with a study case. LEETS, with its acronym, is a key outcome of a larger project for evaluation of HVDC Systems, which is financed by the European Union. Its purpose is to asses the benefits and impacts of HVDC embedded in large HVAC electrical power transmission systems. LEETS can be used to evaluate the construction, operation and end of life phases of a HVDC project. According to the paper, saving at full integration of the European power systems with HVDC links is estimated to be 10 per cent of the totally installed thermal generation. At present, most transmission is by HVAC. By using embedded HVDC systems, significant reduction in CO_2 emission could be achieved. The drives for applying HVDC are liberalisation, additional flexibility, environmental issues, a.c. system security etc. The paper presents a study case of a link upgrade between France and Spain in which three scenarios are considered, and the results of the scenarios are presented. LEETS can be used by TSOs and adapted to their practices. However, it is necessary to gain experiences, general acceptance and confidence with the approach.

Question 2.5-17:

To what extent the HVDC and FACTS devices, embedded in a.c. systems, can improve the overall performance and costs of a power system? In B4-209, it is presumed that LEETS eventually will be used by TSOs for the evaluation of HVAC and HVDC transmission projects. When will LEETS be available as a planning tool for the TSOs? Can the authors elaborate on the scenarios in the example case with respect to promoting HVDC?

3. Preferential Subject 3 - Role of HVDC and FACTS to Assist System Performance

Preferential subject 3 is intended to capture the role of HVDC and FACTS to assist the dynamic performance of power systems aided by the ability to actively control real and reactive power flow, voltage and frequency. A total of 10 papers were submitted in response to this subject.

3.1 Dynamic Design Requirements of Projects for severe Operating Conditions

The paper **B4-301** describes the interconnection of Tasmania to mainland Australia via a 630 MW HVDC link. The 290 km long cable makes it the longest submarine cable link in the world in 2006. The introduction of a 630 MW HVDC connection to a weak Tasmanian system requires careful consideration of managing the transmission network under contingencies. The application of a special protection scheme (SPS) has been the choice for managing security constraints in order to avoid large investment in the a.c. grid reinforcement. Without the SPS, transfer will be limited to less than 200 MW, and the link would not be commercial viable. The Basslink frequency controller is an essential element in the design of SPS and enables Tasmania to be part of a single frequency control ancillary service (FCAS) market. HVDC runback and ramp up are commonly applied to cope with a.c. system constraints. However, the SPS proposed extends well beyond the HVDC control area.

The electricity market operation requires a quick change of power flow, where the market operates with a 5-minute dispatch interval. To achieve fast power reversal, a fast 2-minute deionisation time has been achieved for the cable.With growing demand, power systems are developing rapidly stretching the stability limits in most countries. The impact of a new infrastructure on the existing power system needs critical assessment prior to any new interconnections can be implemented.

The paper **B4-302** describes the preliminary investigations into the use of ±800 kV and discusses optimum line and converter ratings as well as system configurations, taking into account the relative size of the receiving network. Based on steady state studies, it is concluded that UHVDC at 800 kV d.c. is very attractive for integration of remote hydro power plants. HVDC provides definite advantages compared to an a.c. transmission. For transmission distances over 2000 km, power losses is of major concern, where the (N-1) transmission system planning criteria may be used to ensure with a loss of one element there is no loss of transmission capacity. A short term overload for 30-minute duration is permitted. The loss of a bipole may not be tolerable due to the difficulty in managing transient overvoltages and frequency excursions. With two bipoles terminating in the receiving end, it is much easier to maintain reliability. An overload value of 33 per cent is added to cover for a single pole outage. This enables covering for a single pole outage by the remaining three poles without significant impact on the receiving a.c. system. Converter topologies, transformer size, transmission line outage relevant to provide required reliability were discussed.

Paper **B4-304** describes the advantages of HVDC and FACTS for interconnections to effectively control power flow and enhance system stability. The authors propose a benchmark model, with data similar to existing and future systems, to study the integration of HVDC system into the a.c. system.

Paper **B4-305** describes the studies and testing of thyristor-controlled series capacitor (TCSC) damping controller to enhance the stability of a tie line interconnecting two large regions in India through a 400 kV line. Based on the studies, 40 per cent fixed series compensation along with 5-15 per cent variable compensation through TCSC has been found necessary. The methodology of field testing as well as the test setup to create a temporary single line to ground fault in the field has been described. The field tests confirm the findings from system studies, the necessity for a damping controller to damp out low frequency inter-area oscillations that may appear during certain network contingencies.

Paper B4-310 describes the two TCSCs installed for Power Oscillation Damping (POD) in the 400 kV double circuit 412 km a.c. transmission lines which interconnect Raipur and Rourkela in India. At high power exchange and at certain contingencies, a poorly damped low frequency inter area oscillation was observed. In order to cope with these low frequency oscillations, 40 per cent compensation with Fixed Series Capacitors (FSC) and 5 per cent compensation with TCSC were installed in each of the double transmission lines. Design consideration, with respect to the TCSC main circuit configurations, operation range, operating range and fault handling, is being discussed. In addition, the important requirement that the POD function shall comply with are described. Curves recorded during commissioning showing damping of power oscillation with and without the POD are included in the paper.

Question 3.1-18:

In general, HVDC and FACTS can improve the performance of the power system. However during an HVDC outage, special protection systems may need to be employed to exploit the full potential of the HVDC system. Could the authors of paper B4-301 comment on the reliability requirements for the special protection scheme (SPS) and the consequences of a failure of SPS during operation? Are there any SPS schemes in operation or under consideration for other HVDC links, similar to the Tasmanian scheme?

Q 3.1-19

Besides the damping of power oscillation, what other technical advantages were achieved with the TCSC described in paper B4-310. Is a coordinated control of the two TCSC required to obtain optimal performance? How does a trip of one of the lines influence the operation of the remaining line?

Question 3.1-20:

What dynamic studies are required to fully explore the advantages from fast power flow control? With the increase in bipole power capacity in excess of 3000 MW, is the N-1 planning criteria still appropriate? What level of short term (30-minute) overload is practically achievable without having to oversize the converter poles? What are the considerations for using two bipoles (four poles) as opposed to having one large bipole? How would this impact on the HVDC main circuit design especially d.c. line or cable design in terms of cost and securing routes?

Question 3.1-21:

In a deregulated electricity market, the power flow in lines can change very often in both size and direction. In some deregulated electricity markets, it is possible to re-dispatch generation down to 15 or 5 minute intervals. How does this influence the design of HVDC transmission, and what are the critical components? What trade-off is possible, if the generation re-dispatch times are reduced to below 30 minutes?

Question 3.1-22:

In paper B4-301, it is stated that the Cigré cable load cycle test was altered to reflect expected power flows under market conditions. Which changes have been made by the authors? Should changes be recommended to reflect long HVDC cables and changing market operating conditions in Cigré load cycle tests?

3.2 HVDC and PE technologies contributions to system restoration

None of the papers address this important subject on system restoration. As some remarkable occasions over the last years have revealed, system blackout cannot be completely avoided. As it has been demonstrated in HVDC, interconnections between a.c. systems can prevent cascading blackouts. After an eventual blackout, quick restoration of a power system is crucial.

3.3 Studies and experiences on how to incorporate HVDC and PE modelling into system planning

Paper **B4-303** describes the study of Multi-Infeed Direct Current (MIDC) system in China Southern Power Grid (CSG), where the a.c. and d.c. systems are operated in parallel. With the Three Georges-Guang and Gui-Guang HVDC transmission systems by 2004, three HVDC systems are feeding into Guandong with capacities of 1800, 3000 and 3000 MW, respectively. By 2007 and 2010, in addition two more systems will be put in place and fed into Guandong , that is Gui-Guang II of 3000 MW and Yun-Guang, 800 kV UHVDC of 5000 MW. Given the size of these HVDC terminations being in close proximity, the assessment and understanding of any adverse interactions is critical to the successful operation of CSG. The paper explains the nature and extent of the model built to study the MIDC interaction. The a.c.-d.c. interaction has been assessed by the commutation and recovery performance of the three d.c. converters to a fault applied at selected locations in the 500 kV a.c. network. The dynamic performance is assessed by commutation failure duration (CFD), lowest commutation voltage (LCV) and recovery time (RT) of d.c. power to 90 per cent of pre-fault level. The authors identified several measures to improve the dynamic performance and stability of the MIDC system. This includes the use of HVDC control, reserve management, enhanced reactive support, dual modulation controls, and run-ups and runbacks.

Paper **B4-305** describes the modelling details applied in reproducing TCSC dynamics and low frequency oscillations in the power system. A total of 766 buses, 2008 branches including transformers and 146 generating plants were modelled. For load flow studies, the load models were based on constant power. For dynamic stability studies, constant current and constant impedance models were used for active and reactive power models, respectively.

Paper **B4-306** discusses the application of an 80 MVA Unified Power Flow Controller (UPFC) which was commissioned in 2002 in the Korea power systems. The reasons for installing the UPFC were to cope with dynamic problems due to oscillations during contingencies in the grid, and because permission to build a new 345 kV line was delayed for several years. The dynamic problems and interaction between the UPFC and a HVDC link were investigated for different disturbances and different severity. The studies were carried out in PSS/E. The ability of the UPFC to perform voltage and power control and to damp oscillation is demonstrated for several scenarios in the paper.

Paper B4-307 discusses the operational principles for a Magnetically Controlled Shunt Reactor (MCSR). Based on practical experiences with other MCSR installations, it is planned to install a 180 MVA in a 500 kV 1000 km a.c. transmission line followed by other MCSR installations in long a.c. transmissions lines. The paper also has a theoretical discussion based on simulations of control strategies and transient and small signal stability for long a.c. transmission lines using MCSR. It is concluded that the application of MCSR with suitable controls can improve the stability for long a.c. transmission lines.

Paper B4-308 discusses how the transmission capacity on an existing tie line together with a new line between Swiss and Italy can be increased by using Thyristor Regulated Series Capacitor (TRSC). The new tie line has been constructed quickly after the blackout incident in September 2003. Three alternative TRSC schemes are being discussed – namely one TRSC in series with a Fixed Series Capacitor (FSC) and two other alternative with smaller TRSC in series with one or two Mechanical Switched Capacitor (MSC). The operating range and characteristics of the schemes are being discussed. In addition, the Static Series Synchronous Compensator using Voltage Sourced Converters are also being discussed and compared. A relative economic comparison between the discussed alternatives is conducted. TRSC solutions are favoured because it is more matured than the SSSC solution.

Question 3.3-23:

Paper B4-303 reports a Multi Infeed HVDC system (MIDC). How do interactions affect the HVDC control performance? How could a solution be incorporated, if an interaction problem is caused by an existing HVDC system with a different owner? WG B4-41 is currently carrying out some pioneering work in MIDC systems? What new developments can be reported that enable a better understanding of MIDC problems and remedial measures to be implemented?

Question 3.3-24:

Have the findings described in the paper B4-306 been confirmed either by practical experiments or at incidents which have happened in the grid? How has the UPFC performed, and what were the greatest challenges and the most severe problems, if any?

Question 3.3-25:

Can the theoretical findings of using MCSR in long a.c. transmission lines be confirmed with practical experiences from existing MCSR installations? In general, how do controlled shunt compensation and controlled series compensation compare with respect to angular stability and how does the performance of MCSR compare with TCSR? What are the pros and cons, technically and economically?

Question 3.3-26:

Has the TRSC solution (B4-308) been decided for improvement of the transmission capacity between Swiss and Italy? To what extent would the proposed TRSC improve the power system security? What are the general views on TRSC's with respect to performance and costs? Are they in general an economical alternative to phase-shifting transformers?

Question .3.3-27:

Although the power of computing increases rapidly, appropriate selection of tools and the necessary modelling details still remains. What developments can be reported by working group WG B4-38 or others that capture the state-of-the-art in HVDC and FACTS modelling to adequately capture system issues? What are the modelling requirements for long cables for vital links as reported in B4-301? What control and practical steps are needed to manage transient behaviour of long cable links?

The effect of load modelling will have significant influence on the dynamic response. What level of accuracy and effort is necessary to represent network load for HVDC and FACTS studies?

3.4 Technical and economic benefits experienced (already addressed in previous questions)

Appendix 1: Summary by the Special Reporter

DISCUSSION MEETING

for SC B4, Cigre 2006 session

SUMMARY

GROUP B4

HVDC AND POWER ELECTRONICS

31st August 2006

Chairman : **Marcio Szechtmann** Secretary : **Bill Long**
Special Reporters: **Mohamed Zavahir** and **Kent Søbrink**

The session was attended by about 150 delegates. 27 papers were covered by Study Committee B4. The discussion included 47 prepared contributions and 43 spontaneous contributions, thus reflecting the actuality of the preferential subjects and the large interest for the area of HVDC and Power Electronics.

The Mission of SC B4 is “To facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of HVDC and power electronics. To add value to this information and knowledge by synthesising state-of-the-art practices and developing recommendations”. 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.

Three preferential subjects were covered in the Technical Session:

1. New HVDC and Power Electronic (PE) Technologies and Projects

- 1.1 Enhanced Voltage Sourced Converter Applications
- 1.2 Advances in PE Devices
- 1.3 Novel PE Applications
- 1.4 New HVDC Projects.

2. Issues Concerning HVDC and Power Electronic Projects

- 2.1 Environmental Requirements for New Applications and Upgrades
- 2.2 Environmental Monitoring Programs for Existing Schemes

2.3 Fault Diagnosis and Lifetime Prediction at Operation and Maintenance Levels
2.4 Operating Experiences of Projects
2.5 Studies and Experiences on Cost Reduction.

3. Role of HVDC and Facts to assist System Performance

3.1 Dynamic Design Requirements of Projects for Severe Operating Conditions
3.2 HVDC and PE Technologies' Contributions to System Restoration
3.3 Studies and Experiences on How to Incorporate HVDC and PE Modelling into System Planning
3.4 Technical and Economic Benefits Experienced.

A poster session of B4 papers was held a day prior to the technical session on Wednesday. A majority of papers were presented at this session. The Special Reporters could not report on the poster session due to conflict with receiving spontaneous contributions at the same time. However, the general feedback received from the paper authors who were available to be present at the poster session was very positive.

PS 1: New HVDC and Power Electronic (PE) Technologies and Projects

There were 7 regular papers and 8 special report questions discussed by 15 prepared contributions and 14 spontaneous contributions. As a result the following can be concluded:

This session has brought some new ideas and innovative applications of HVDC and PE devices. The application of Static Var Compensator as a de-icer and the use of Tri-pole HVDC converters for converting AC lines to DC were two innovative ideas presented. Two new developments were discussed that push the boundaries of existing technologies through new technological developments. These are in the increasing capacity applications of Voltage Sourced Converter transmission to 1000 MW and Line Commutated Converter technology to UHVDC at 800 kV.

The use of bi-directional valves was presented as a means to assist the Tri-pole DC implementation. In addition both series and parallel converter configurations for 800 kV UHVDC were discussed.

Prior to HVDC community is able to promote UHVDC, the problem with the DC Converter transformer failures need to be resolved. In spite of some concerns raised, the general consensus was that the HVDC community is getting ready to deploy UHVDC applications. Polarity reversal of HVDC cables was another concern addressing the need for modifying the load cycle test within existing standards.

Need for VSC transmission with overhead lines was raised especially where applications with overhead lines are still economically and environmentally acceptable or when converting the existing AC lines to DC. Discharge from DC faults can be detrimental to the valves in a VSC converter and hence most projects implemented to date have been with underground cables.

PS 2: Issues Concerning HVDC and Power Electronic Projects

The Special Reporter summarized the papers and questions on the preferential subject, followed by a discussion on specific developments.

There were 14 prepared contributions and 9 spontaneous contributions at this session.

Converter transformer failures and possible comparison with AC transformer failure performance statistic where discussed. The need for improvement of converter transformers performance was emphasised. As per the general opinion, copper sulphide (Cu_2S) is a problem but is not a new phenomena and not the only cause of failures. It was argued that the consequence of converter transformer failure is greater than ac power transformers because ac systems are designed with redundancy to provide (n-1) security. Proper comparison with AC power transformers was considered not possible due to lack of power transformer failure statistics. However some interesting statistics covering approx. 1500 transformers were pointed out to be available in a North American study.

Environmental monitoring / approval process has been recognised as one of the critical element in any HVDC project implementation. Some companies have developed greater understanding and proactively managing stakeholder relationships thus having positive results. Monopolar ground return has been avoided in some projects for commercial reasons to expedite the approval process. A serious concern was raised that these decisions may set undue precedence. Cigre SC B4 has initiated an Advisory Group and a WG aimed at providing environmental planning guidelines for HVDC projects that will address these issues.

The lack of a consistent or clear standard relating to radio interference was raised. This requires new standards to be developed by the HVDC community.

Commissioning in the new market environment is a commercial and technical challenge. A greater co-operation and stakeholder management with associated system and commercial impacts need to be addressed with future projects. Some of the issues relating to spinning reserve management, power flow variability (within 5 or 30 min dispatch periods) and polarity reversal, cable load cycling / test requirements were raised as major concerns.

Management of forced outages under 800 kV UHVDC transmission, where the block sizes could be of 3000 MW pole or 6000 MW bipole, need to be addressed in the design very carefully. Several options presented for minimising the impact of outages including series / parallel converter configurations, and transformer winding arrangements. The ability to use overload on the remaining poles were also considered as an option. Environmental concerns and/or practical difficulties in getting right of ways in some transmission routes would necessitate development of 800 kV UHVDC cables.

SC B4 has a joint working group with the transformers committee has initiated some activities towards preparing appropriate test standards for HVDC converter transformers. The urgency and importance of resolving this issue was considered a critical to the future of HVDC applications.

PS 3: Role of HVDC and Facts to assist System Performance

The Special Reporter summarized the papers and questions on the preferential subject, followed by a discussion on specific developments.

There were 18 prepared contributions and 20 spontaneous contributions at this session.

The use of HVDC for avoiding cascade failures and to aid system restoration was discussed. For example, a back to back HVDC converter within a large AC system could decouple the AC system and arrest cascading system failures, and with VSC converters it is possible to provide black start capability.

The application of special protection schemes (SPS) with HVDC have been applied for many years. A recent application of SPS in Tasmania has been extended to provide frequency control in addition to managing system o overloads.

The extensive discussion on the impact of fast changing power flow (under all three preferential subjects) indicated the widespread concern of the deregulated market on HVDC operation.

The operation of static var system (SVS) in the vicinity of or with HVDC converter stations were considered quite acceptable with a few working examples.

The operation of multiple HVDC converters in the same vicinity has already been recognised by the HVDC community. WG B4-41 has introduced multi-infeed interaction factors that enable the understanding of interaction between multiple converters.

Session Closing Remarks by SC B4 Chairman

The Chairman of SC B4 summarized the discussion into 13 main topics and thanked all contributors and attendants for valuable contributions and their interest in the session.

The 13 main topics were:

1. 800 kV Schemes
2. Converter transformers failures/HVDC performance
3. Ground return /electrodes
4. Environmental issues (incl. RI)
5. Polarity reversal in HVDC
6. Converting AC to DC lines
7. Experiences with FACTS/PE (STATCOM, UPFC, etc)
8. VSC with OH lines
9. B-t-B integrated in AC system
10. Overload characteristics/design of HVDC
11. TCSC applications
12. HVDC cable modeling/requirements
13. 800 kV DC cables

Conclusions

Overall the sessions were well attended and the discussions were timely. The prepared contributions generated a lot of spontaneous contributions, leading to a healthy technical session.
There is an increasing scope for HVDC applications with the demand for high power long distance transmission from fast developing countries.

The challenges facing the HVDC community are both from equipment and system performance issues. The community is learning to cope with the increasing demands placed on it due to deregulation, resolving transformer failures and the need to implement UHVDC solutions. Cigre is playing an important role in all these aspects and is helping the HVDC and Power Electronics applications to improve overall power system performance from environmental, technical and economical aspects.

Appendix 2: General Report by the Special Reporters

DISCUSSION MEETING

for SC B4, Cigre 2006 session

GENERAL REPORT

GROUP B4

HVDC AND POWER ELECTRONICS

31st August 2006

Special Reporters: **Mohamed Zavahir** and **Kent Søbrink**

Chairman : **Marcio Szechtmann** Secretary : **Bill Long**

The session was attended by about 150 delegates. 27 papers were covered by Study Committee B4. The discussion included 47 prepared contributions and 43 spontaneous contributions, thus reflecting the actuality of the preferential subjects and the large interest for the area of HVDC and Power Electronics.

The Mission of SC B4 is "To facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of HVDC and power electronics. To add value to this information and knowledge by synthesising state-of-the-art practices and developing recommendations". 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.

Three preferential subjects were discussed at the Technical Session:

1. New HVDC and Power Electronic (PE) Technologies and Projects

- 1.1 Enhanced Voltage Sourced Converter Applications
- 1.2 Advances in PE Devices
- 1.3 Novel PE Applications
- 1.4 New HVDC Projects.

2. Issues Concerning HVDC and Power Electronic Projects

- 2.1 Environmental Requirements for New Applications and Upgrades
- 2.2 Environmental Monitoring Programs for Existing Schemes
- 2.3 Fault Diagnosis and Lifetime Prediction at Operation and Maintenance Levels
- 2.4 Operating Experiences of Projects
- 2.5 Studies and Experiences on Cost Reduction.

3. Role of HVDC and Facts to assist System Performance

- 3.1 Dynamic Design Requirements of Projects for Severe Operating Conditions
- 3.2 HVDC and PE Technologies' Contributions to System Restoration
- 3.3 Studies and Experiences on How to Incorporate HVDC and PE Modelling into System Planning
- 3.4 Technical and Economic Benefits Experienced.

A poster session of B4 papers was held a day prior to the technical session on Wednesday. Seventeen of the twenty seven papers were presented at this session. The Special Reporters could not report on the poster session due to conflict with receiving spontaneous contributions at the same time. However, the general feedback received from the paper authors who were available to be present at the poster session was very positive.

PS 1: New HVDC and Power Electronic (PE) Technologies and Projects

There were 7 regular papers and 8 special report questions for discussion. A total of 15 prepared contributions and 14 spontaneous contributions were made. As a result the following can be concluded:

Question 1.1-1:

A strong feature of FACTS devices proposed is the ability to improve power quality in the transmission system. However, very few utilities have embraced FACTS technology for widespread application. Are there any enhanced VSC applications similar to that described in B4-103 used for power quality improvements in large scale?
The VSC-based compensation (FACTS devices) was compared to traditional SVCs from the introduction of other FACTS devices. The main emphases were on investment costs and equipment reliability. What developments have taken place during the last decade that could make VSC-based devices more attractive or otherwise?

A major advantage of VSC (voltage source converter)-based FACTS devices is the fast controllability of voltage and current on a waveform level. The fast controllability, achieved with the PWM operation, enables a VSC-based FACTS device to mitigate voltage sag, which is difficult to compensate with a conventional LCC (line commutated converter)-based or thyristor-based devices.

VSC based FACTS devices are used for voltage stability and power quality improvement. Some example cases discussed were for flicker mitigation applications in arc furnaces (for example in Germany, Finland and Norway), voltage unbalance in railway applications (France) and for voltage stability improvement in transmission systems (Japan).

An example of voltage sag compensation effect of a 80 MVA STATCOM was demonstrated in an actual power system at Kanzaki substation in Japan. The decision was based on system analysis that revealed a voltage collapse will occur in the contingency of a single circuit trip of a 154kV double circuit transmission line. Measurements have shown that in addition to the primary voltage stability improvement the statcom also provides a voltage sag mitigation effect during system faults.

In the case of unbalance compensation the authors of B4-103 have not adopted the SVC solution since the short circuit power is too low. The VSC based device was considered an innovative solution for multiple applications : unbalance, reactive compensation and as an active filter.

The unbalance application used a VSC device built with GTO (gate turn off) devices whereas the Kanzaki statcom was built with GCT (gate commutated turn off thyristors). The GCT based VSC devices may be produced with lower number of devices, lower losses and reduced foot print compared to a GTO based equivalent. The authors of B4-103 believe that VSC will become attractive than SVC solutions for two reasons: less passive components than SVC and the reduction of the semiconductor cost.

Question 1.1-2:

What other developments are required to make VSC transmission a technically and economically viable alternative against traditional HVDC or ac transmission? Are there any examples of life cycle cost-benefit analyses comparing the use of VSC on overhead lines against cable transmission or a.c. transmission lines?

A case was presented in favour of VSC with cables as the most economical alternative for long distance underground transmission. The reason is partly due to the possibility to use polymeric extruded cables, which are easy to install and to join. To make the VSC transmission technology technically and economically viable in all applications may not be considered a reasonable goal.

The authors of B4-105 emphasised that it is better to use each technology in its most suitable application. In back to back applications, maximum current in the converter usually gives the best economy. As the technology stands today, VSC Transmission has certain limitations in current and voltage, leaving the field for the multi GW HVDC transmissions to the thyristors.

VSC may be favoured over classic HVDC for economical reasons when for instance AC-net parameters, total delivery time, operational flexibility, site space requirements or possibility to get building permits for a transmission would count in favour for VSC.

<u>Tri-pole transmission and ac to dc Conversion</u>
At the 2004 B4 meeting a means was introduced whereby three, rather than two conductors could be fully utilized for transmission of HVDC thus increasing the viability of ac to dc line conversion.
In the "Tri-pole" scheme, the third pole must be reversible both in voltage and current. But since poles 1 and 2 remain at constant polarity, there appears to be no reason, in principle, why they can not be comprised of VSCs rather than traditional thyristor valves – thus extending the usefulness of the tripole idea to systems of very low short circuit ratio.

<u>VSC on overhead lines</u>
There is ample precedence for VSC transmission application on cable systems. VSC has been in operation on an overhead line since 1997, albeit in a small 10kV, 3MW scale, at the Hellsjön-Grängesberg transmission in Sweden.

The issues to be resolved for overhead line applications include:
1. Clearing of a VSC pole fault to earth that might require clearing by ac circuit breaker
2. Slower post pole fault restoration to full power on successful clearing of fault.

The acceptable use of VSC transmission for overhead lines will provide an added value for tripole HVDC application. The problem of turning off the dc-current after a line fault is taken care of by a dedicated series connected semiconductor valve, called a line switch.

In other areas, there could be an advantage if existing lines are upgraded to VSC transmission, otherwise the cost and the time needed for a new OH-line would be essentially the same as for an ordinary AC-line project, plus the terminal costs for the VSC.

Question 1.2-3:

What is the typical product development time for new PE devices? What measures can be used to ensure that the new installations are supported in the long run, or replaced without resorting to significant change or total replacement of the installation? What life cycle and reliability assessments are available for new PE devices? What are the potential advantages expected from the developments described in the papers B105 and B4-107?

<u>Product development time</u>
The product development time for new PE devices is usually 3-5 years. In the case of the devices used for the main part of the VSC transmission projects, there has been a continuous development over the years. The new devices are better and a replacement strategy is relatively easy to establish, even where strict one-to-one backward compatibility has not been ensured.

<u>Product Support in the long run</u>
It is possible to manufacture enough spare parts to last the life of the VSC transmission. However, this may be uneconomical due to initial cost, cost for storage and difficulty to estimate future failure rate.

Three possible ways to ensure that the converter does not run out of PE devices are:

1. The **reduction of failure rate** is partly the responsibility of the supplier, that the devices and their supporting systems have good quality, and partly the responsibility of the user, that the plant is run within specifications and correctly maintained.
2. **New spare parts** of compatible mechanical design may be usable as direct replacement even if all electrical parameters are not exactly the same as for the original device. In this case the components are for practical purposes compatible and may be mixed into the converter freely.
3. A **partial exchange**, for instance one valve in a converter consisting of 18 valves frees a number of old components that can be used as spares in the rest of the VSC. The new switch then consists of new components that may be mechanically incompatible to the old components but works well electrically together with the remaining parts of the converter.

Reliability assessment

New components are tested to find out their life expectancy. It is done through accelerated tests of different types. Two of the most important ones are:

- IOL, Intermittent Operating Load
- SCFM, Short Circuit Failure Mode

In IOL tests the components ability to withstand a large number of temperature/load cycles with very high amplitude is verified. In SCFM tests, we verify the ability of the PE device to keep conducting current safely even though it is short circuited and has ceased to function as a switch.

Question 1.2-4:

Do most series compensation projects allow for future dynamic compensation in order to preserve the future option value of not investing immediately? If so, what design considerations are made at the first stage of the project?

There were no respondents to Question no 1.2-4.

Question 1.3-5:

Power Electronics and FACTS technology has been available for more than a decade. What are the obstacles that limit the application of non-conventional ideas in the power system as in B4-101? Are there any other new and interesting applications where PE devices can be configured to provide (thinking outside the box) solutions to problems in the power systems?

Main obstacles to PE applications

The main obstacles to widespread use of FACTS devices are the novelty of the installations, cost relative to conventional solutions and perceived unreliability.

However as more installations come on line, based on the same Power Electronic Building Block (PEBB), these concerns should ease and VSC based installations will be considered as the preferred solution to system control problems. Although VSC installations on power systems are relatively new, VSC as a technology has been used in drives, frequency converters and special power supplies in industrial applications for many years.

Reduced cost, increased device efficiency and ratings may also allow other FACTS devices which are only at a proof-of-concept or model stage to be cost effective in the future.

New Applications

Some of the new applications of PE devices are:

1. De-icer,
2. Bi-directional vales
3. Tri-pole AC-DC conversion

De-icing of transmission lines

In the Lévis De-icing application discussed in B4-101, P.E. has allowed technical and economic solutions with more advantages than other technical solutions. The recent advance in P.E. has provided a great adaptability to meet Hydro-Quebec requirements not only for de-icing purposes but also in the SVC mode. The PE technology has great adaptability for new network applications. The high level of dc current in de-icing mode and the loss penalty in SVC mode have dictated the optimal valve arrangement in the De-icer project.

Bi-directional vales

The use of a bi-directional valve design should enable fast reversal of power flow in a multi-terminal tap. A dc tap's ability to reverse power rapidly will often allow greater (n-1) compliant loading on the parallel ac system. Power reversals by continuous-acting power electronics are acceptable as a condition of (n-1) compliance within most standards whereas reliance on mechanical switching is not.

Bidirectional converters may also be used to replace conventional converters in Tri-pole HVDC systems where the third (modulating) pole must periodically reverse current.

Tri-pole AC-DC conversion

With the tri-pole solutions it is possible to reduce power losses and improve (n-1) capability of the AC/DC transmission system. It is possible to achieve high utilization and effectiveness of the line reducing the need for construction of new lines.

Question 1.4-6:

There are important potential 800 kV UHVDC applications for long distances and high power transfer levels being evaluated in India, China, Southern African countries and in Brazil. One relevant issue, concerning these projects is how the new market frameworks would affect the planning & design (technical), configuration & reliability (economic), equipment supply market as well as the technological development aspects of HVDC.

The application of 800 kV has raised a lot of interest within the power industry and particularly within the HVDC community as an attractive means of transmitting large blocks of power. SC B4 has initiated a WG on 800 kV that will address relevant technical issues. Manufacturers and system designers are actively finding solutions that will address known and expected issues of concern.

The choice of series or parallel configurations of valve groups and transformer configurations were discussed. The decision to choose one configuration over the other will depend on:

- Staging consideration of the project
- The amount of power to be transmitted at the different stages of the project
- Reliability and availability requirements
- Loss evaluation
- Size and weight of the converter transformers for transport

Other system related performance criteria that will dictate the type of solution are:

- Relative size of the dc pole/link to the connected ac system
- Overload requirements – post fault (contingency) ratings
- Performance incentives/penalties

Series and parallel converter configurations

The question about series and parallel converter configurations has several dimensions. One is the question of ground current operation. If ground currents are not permitted, then series connection of the converters may be better than parallel connection because it is possible to operate one pole at 400 kV and the other at 800 kV with no ground current if two 400 kV series connected converters per pole are used. It should be noted that continuous ground current operation is not allowed by the National Electric Safety Code (NESC), which US utilities have to follow (this restriction is an extreme case and is not universal). In case of parallel converters, a loss of one converter would require overload operation by the other in the same pole, which costs money. The alternative is to shut down or reduce the load in the parallel pole to 50% of rated power. Thus, the firm power assumption in case of parallel converters might be reduced to 50% of the rated bipole power whereas it might be 75% of the rated bipole power for series connected converters.

Question 1.4-7:

With deregulation of the electricity market the way power systems used to be operated has changed a lot where rescheduling of generation can change with short notice depending on the market signals. This may stress the equipment in a different way than it used to. In B4-301, it is stated that the Cigré cycle cable testing was modified due to changed market conditions. Does the change in the market conditions also require new test procedures for HVDC and FACTS equipments? What about the new foreseen 800 kV applications? Besides reduction in testing time, what are the technical benefits from the new test facility? Can better tests be implemented, and do other similar test facilities offer the same possibilities?

Power flow under market conditions

The deregulation of the electricity market can result in frequent load changes, and even require power direction reversals with a short zero load interval in-between. The South-East Australian market operates with a 5 minutes dispatch interval. This means a possibility of frequent changes in power flow direction equirement for at least 1000 reversals per annum with multiple reversals in a day. Practical experience indicate at least 4 power reversal a day.

The effect on the dc equipment are better managed if the mode of operation is known during the specification stage. Failure to do so might impose unnecessary operational stresses on equipment. An increased number of filter switching was presented as an example from the New Zealand experience. The frequent power reversal due to market conditions has also caused increased arc backs with the mercury arc valve pole forcing some operational restrictions.

Commissioning under market conditions

An important change to traditional procedures is commissioning of HVDC under market conditions, where power flows must be secured through the market. This could be very expensive as on occasions counter-price flows must be procured. Also, the commissioning requires long period of constant flow and market conditions may not be conducive to satisfy such requirements. Other implication can be a significant extension of commissioning time due to market and system limitations inhibiting achieving required test conditions.

Power reversal tests

The effect of power reversal on HVDC equipment was discussed. The Australian experience suggested that current CIGRE tests load cycle and polarity reversal test is not adequate. Additional accelerated load cycle polarity reversal test was added in their case. This was based on concerns that the present equipment (in this case the HVDC cable) tests may not adequately capture the conditions during frequent power reversals.

It was argued that the de-ionization time is not very critical as the electrical time constants in the insulation material used is much longer than that. The withstand capability for stresses at transient fast polarity reversals is verified by the superimposed impulse voltage tests defined in section 3.9 of the recommendation in Electra No. 189. The testing procedures must also be practical regarding facilities in the test labs. Thus, it was argued that there is no need to revise the test recommendations.

Another point of view raised in regards to voltage reversal testing of cables and transformers is that the state of the equipment under test prior to the voltage reversal test has to be considered. It was shown that the relaxation time for oil and pressboard insulation systems in transformers at 20^0C, the relaxation time is about 2 hours, which means that the pressboard will not be fully charged until after 4 to 6 hours. Any voltage reversal performed prior to that time, will not lead to maximum stress on the paper dielectric systems when the voltage is reversed. If there are problems associated with charge redistribution after reversal, then the voltage of the opposite polarity should be maintained for a couple of hours. Cables are in some respect simpler because the cable insulation system is homogeneous. However, the maximum dielectric stress is temperature dependent so the maximum stress point in the cable insulation is some distance away from the conductors. The probability for partial discharges in the dielectric system may therefore be difficult to estimate but a cold cable should have the highest electric fields in the conductor region so this may be the worst case test. In regards to the frequency of voltage reversals, there is not enough knowledge to assess the potential reliability impacts. What we do know is that partial discharges are normally associated with voltage reversals. However, the damage to the insulation system from such partial discharges although assumed to be relatively benign, is largely unknown. Some further research was recommended.

800 kV UHVDC tests

As for 800 kV tests, it was pointed out that UHVDC will primary be used for bulk power transmissions where the power is unidirectional, even if it will be possible to operate in reverse power direction.

For a single 12-pulse bridge per pole, single valve tests for 800kV represent an increase by a factor of 1.6 compared to the highest rated valves of today. The problems with valve dielectric testing for 800kV are substantially eliminated by using two 12-pulse bridges per pole.

Question 1.4-8:

The authors of B4-104 mention that a low ESCR value of 1.6 may result in the case of 2x300 MW rating of the link requiring the adoption of a non-standard design (e.g. the use of SVC).
Can the authors elaborate on the design considerations? Also, the authors claim that better frequency regulation, although known as a benefit from the link, was difficult to quantify in economic values. Are there any constructive suggestions as to how such ancillary service benefits can be quantified? How may the HVDC community help the planners and decision makers attribute accurately the benefits from HVDC technology for project economic comparisons?
How may the HVDC community quantify and articulate all the identifiable benefits from HVDC and FACTS projects to the decision makers?

What experience can be reported on the use of SVC's near HVDC converter stations, similar to B4-203? Traditionally, the use of synchronous condensers has been the device of choice for strengthening the a.c. fault level or performance with low ESCR levels. What new developments or reliable, cost-effective solutions are available that do not interfere with HVDC control performance?

Highlighting economic benefits of HVDC technology
The great difficulty in convincing decision makers concerning HVDC transmission in Brazil is much related to the following aspects:

- **costs**; widely varying information related to dc costs has been causing some concerns among the decision makers.
- **social development in the region** crossed by the link (tap-off small loads); e.g. rural electrification projects may be relevant may be necessary to win public support
- **new generation connection**; some form of weak parallel ac system may be necessary in these cases
- **converter transformer failures**; better understanding, communication and resolution of such failure modes will help ease decision makers concerns. In addition better spares and asset management strategies can improve investor confidence.
- **environmental impact related to the electrodes**; clear explanation that the ground return operation has a small rate of use along the dc link lifetime besides showing the effectiveness of mitigation measures.

Economic valuation of HVDC benefits
In the case of SA.PE.I. link several of benefits have been estimated for the new link such as:

– the reduction of transmission losses between Sardinia and Mainland
– the possibility to accept a larger total capacity of wind power plants in Sardinia
– the reduction of the production costs, and
– the reduction of the "Energy not Supplied" for the relatively weak Sardinian system.

As an example, this last benefit has been evaluated with a rather simplified approach, starting from the results of the dynamic security analysis, that showed, in isolated condition of Sardinia, the need of a load shedding of about 240 MW in case of sudden loss of one of the two largest generation units (320 MW each) at peak load condition. This result could be even worse in case it is coupled with the further tripping of wind power plants, if they do not have sufficient ride-through capability to face the transient. The same event in light load conditions, or the loss of smaller generation units would not be so critical.

The evaluation of the benefit has been carried out considering the frequency of unit tripping (a data coming from previous operating results of those groups) coupled with critical network conditions, the average duration of the load shedding (assumed to be 1 hour), and the cost of Energy not Supplied (assumed to be a 5 €/kWh). The presence of the HVDC link would avoid completely the load shedding, by making use of its fast power controllability, allowing effective frequency control of Sardinian network, and, if needed, the fast power reversal (in less than 1 sec).

With reference to the extreme situation of "Sardinian Network Isolated" a benefit of about 14 millions Euro per year has been estimated.

SVC near HVDC stations

The use of SVCs near HVDC converter station is rare but the recent experience has been good. Since June 1995 a +/-200 Mvar SVC has been in operation at Kristiansand, the Norwegian station of Skagerrak HVDC link. Also in the German station of the Baltic HVDC link an SVC is installed.

Some coordination between HVDC and SVC control is needed for avoiding hunting etc. It is not too complicated and would have no impact on the overall performance.

An SVC and a synchronous condenser do not have the same effect. An SVC gives good support of the a.c. network voltage stability. A synchronous condenser reduces the impedance of the a.c. system. It also adds some inertia to the system. But its voltage control is slower than that of an SVC.

HVDC for low ESCR

With low ESCR levels the Capacitive Commutated Converters (CCC) are a good option. Six blocks of CCC HVDC with a total capacity of 2 400 MW have been in operation with good experience during some years now. The ESCR level in the largest scheme is below 1.5. Besides, the characteristic of a CCC HVDC is favourable with long HVDC cables.

Furthermore, an HVDC link based on VSC technology is its own SVC. A VSC HVDC can operate on an ESCR level theoretically down to zero..

Question 1.4-9:

Both projects described in papers 104 and 205 require cable laying depths of about 1600 m. In these cases, the ability to secure a viable cable route in advance is critical, as illustrated in both feasibility studies. The cables form a vital and most complex part of the project and present challenges, for installation, and in the event of deep-sea repairs are required. What special measures and design requirements are necessary to ensure the reliability and to manage repairs for such deep-sea installations?

Deep cable design considerations

In the case of SAPEI deep sea cable installation, a Preliminary Marine Survey (PMS) prior to tender stage has been believed necessary to obtain sufficient and safe information to minimise technical and economical risks. The PMS activities have been mainly devoted to obtain sufficient information on the most critical sections along the route, foreseeing a relatively reduced utilisation of high resolution equipment. In such a way it has been possible to limit the cost to about 1/4 - 1/5 with respect to a complete detailed Marine Survey, that will be performed as part of the cable laying contract.

Considering the challenge of high depth cable laying, main cable manufacturers have been consulted during early stage of the project with respect to laying feasibility.

To ensure the reliability and to manage repair of the cables, a sea trial (similar to the Italy – Greece HVDC submarine cable) has been adopted, properly customised to the SA.PE.I. Project.
Therefore, in the frame of engineering activities to be performed by the contractor, the execution of a complete sea trial has been required for both cable types foreseen in the project (cables for shallow/medium and high sea depth), aimed to verify:

- the suitability of the cable systems (cable, repair joint, transition joint between cable sections) for laying, recovering and repairing;
- the suitability of the equipment for laying and recovery of cables and accessories;
- the suitability of the procedures relevant to laying and recovery operations;
- the operation of the embedding machine for the mechanical protection of the cables

Question 1.4-10:

Paper 105 describes the new development in terms of polymeric extruded cables able to reach laying depths greater than 2000 m. Allowing a laying depth over 1500 m with an extruded cable is supported with a progressive interpretation of the recommendation published in Electra No. 171, April 1997. Are there any opinions from the readers on the progressive interpretation by the authors allowing permanent deformation of conductor joints?

This question did not attract any response from the audience or the authors of the paper B4-105.

PS 2: Issues Concerning HVDC and Power Electronic Projects

The Special Reporter summarized the papers and questions on the preferential subject, followed by a discussion on specific developments. There were 14 prepared contributions and 9 spontaneous contributions at this session.

Question 2.1-11:

What are the most critical environmental obstacles in getting permission to build a new HVDC project? What are the life time costs for a return cable compared with the environmental monitoring and additional maintenance of HVDC schemes for continuous earth return operation?

The most critical obstacles for new HVDC project are overhead lines, electrodes installations, and routing of submarine cables. In general it is difficult to get permission to build new overhead lines in Europe and USA. Several newer HVDC project have therefore been buildt with dc cables which are much easier to get permission to build. Similarly it is also difficult to get permission to build new electrode installations leaving return cables as the only alternative. It is well known that pole cables are more expensive than overhead lines. In favour of earth return is that investment cost of electrode installations is only about the same costs as a few tenth of a return cable and that the transmission losses in return lines are twice the losses in electrode lines and the electrodes. The maintenance cost has no significant influence on the over all project economy. It was reported that for the SAPEI HVDC project no real obstacles was experienced because it was decided to use underground and submarine cables for the pole line and because the existing anode for the SACOI could be used. In case of the Baleares HVDC link, crossing of the shore line was the critical obstacle. Earth return was disregarded on an earlier stage of the planning of the link as it was considered to be an insurpassable obstacle. The environmental advantages of using VSC HVDC with cables as an alternative to ac overhead lines was pointed out.

Question 2.1-12:

B4-207 states the need for a new standard regarding RI requirement for HVDC and FACTS installation. Has RI been a problem caused by HVDC and FACTS using voltage sourced converters in practice, and how has it been dealt with? Is there also a need for standards with respects to the power quality on the line side? Could any existing national guidelines or standards be used as basis for a new RI standard? Which body should undertake to prepare guidelines?

There were no reports on practical RI problem for HVDC and FACTS and applied measures to limit RI levels have been reasonable. Applicable standards were mentioned, ENV 50121-6: 1996 up to 30 MHz and CISPR 11 above 30 Mhx. Limits of 100 µV/m at 450 m has been applied. A comparison of requirements from different applicable standards was presented. The comparison showed that the various requirements, recalculated to the same distance, was quit different. With respect to a new standard regarding RI for substaions with HVDC and FACTS it was pointed out that the harmonised standard EN 50121-5 would be a good basis. For VSC the standards for HVDC and FACTS are also applicable. For telephone interference the harmonics up to 5 kHz should be considered. A Cigre/CIRED working groupe JWG C4.202 is preparing a ‘Guide on Measurement of Radio Frequency from HV and MV Substations’. It was mentioned that new contributors may joint the working group. The guide is expected to be ready by mid 2008 to be published as a Cigré Technical Brochure

Question 2.2-13:

Would such measures, as widespread applications of d.c. current blocking devices, be acceptable for new HVDC schemes with continuous earth current return?

Earth conductivity between ground electrodes depends on the earth geology and geomorphology. For future HVDC projects using ground return this knowledge is very important, but difficult to be obtained, in order to identify local areas with high and low conductivity. It was shown how the voltage rise depends on the distance to electrode and the conditions of the soil. It was reported that blocking devices have been used with success in New Zealand without any problems. The losses in blocking devices are very low so contionuus current is not a problem. In New Zealand modified rail traction locomotive resistors are used as blocking resistors which are sufficient robust. The blocking resistors are bypassed during ac fault conditions to avoid high neutral voltages. Operating experiences to date have been good. It was emphasized that studies have shown that it is quit easy to protect reinforced concrete foundations from catalytic corrosion at little cost by design and with moisture barriers. The major problem is the lack of public understanding.

Question 2.3-14:

Are converter transforms more vulnerable to failures than a.c. power transformers? Is design or materials composition the critical parameter that is determining their high failure rates? Are there any differences with respect to performance between 3-phase converter transformers with 3 windings and 2-phase converter transformers with 3 windings? What would be the most cost-efficient solution when a spare converter transformer is required for improvement of the overall reliability? These questions also apply for 800 kV applications, as described in B4-106 and B4-302.

Comprehensive investigations of 22 major converter transformer failures were presented and the conclusion was that the failure causes were a combination of factors relating to design, manufacturing and material. It was pointed out that converter transformer are more sensitive to environmental factors such as humidity, contamination particle etc. Although the general opinion was that the performance of converter transformers are the same as for ac. transformers, the consequences of converter transformer outages are much greater because the power cannot be rerouted. The performance of converter transformers is very well documented, but the same is not the case for ac power transformer. It was mentioned that statistics for ac power transformers is in fact available in North America from where it should be possible to obtain such statistics for comparison. The repair time is very long so without a spare transformer available right away it will take a long time before the associated pole is back in operation after an outage. For new projects it was recommended to provide one spare transformer of each type at each station, and the design of the switchyard is such that the transformer can be removed fully assembled. In addition it was recommended to make improvements on the specification and test requirements, to perform a thorough design review and finally it was recommended to provide on-line monitoring and fiber optic probes at anticipated hot spots. Corrosive oil due to copper sulphide was pointed out to be the most common reason for transformer failures. Therefore WG A2-32 has proposed new test methods which are aimed at eliminating the problem for new transformers caused by oil contermination and cupper sulphide.

Question 2.4-15:

How do HVDC designers use the performance report to improve their design? To what extent is the availability important for HVDC planners? Is the availability for HVDC transmission comparable with the availability of a.c. transmission, and how could it be achieved. Are any improvements of the performance report planned for, and do the readers have any proposals/wishes for improvements in order to make it more applicable for planners and maintenance staff?

The biannual HVDC performance report can be used by HVDC designers to improve their design of hardware and software, and to review the spare part strategy in order to obtain the required performance. It also provides the necessary basis for comparing the performance of various designs. For planners the report can help make the right technical and commercial decisions for new projects regarding system reliability, redundancy and performance guarantees. It was argued that it is difficult to compare HVDC with ac transmission for various reasons and that the impacts on end consumers are different. A significant factor in the design of ac circuit compared to HVDC links is that most ac systems are built to maintain system security under most contingencies. Whereas most HVDC links are designed to perform as energy links, which can be operated at reduced capacity to suit system conditions, rather than providing redundancies to maintain transfer capacity under all contingencies. This is also dictated by the cost and the ease of providing redundant capacity in either system.

With respect to improvements of the performance report it was emphasised that consistent data reporting is important, more analysis using the performance data can be done and that increased feedback with HVDC owners should be ensured. It was proposed that the performance reporting also should include availability data for the dc lines and a rough division of reasons for cable and bipole fault, the ability to ride through ac faults i.e. commutationm failures and information on possible interaction between ac and dc would also be useful.

Question 2.4-16:

In what way has the OTS been used in training operators? Can the OTS be operated in real time, specifically in the control room to test operations before they are executed on the real power system? What are the operator experiences with the OTS, and what are the future perspectives for using OTS for other power systems with multiple HVDC and FACTS devices?

The Operator Training Simulator (OTS) reported in the paper B4-210 has been developed for the NYPA Convertible Static Compensator (CSC). The CSC has many operating modes which the operator needs to exercise in order to familiarise with the operational possibilities. The training simulator enables the operator to start up and shut down in all possible operating modes of the CSC. The OTS has not been configured to operate in real time but this is a possibility that will be explored in the future. An additional perspective of the OTS is that with its accurate representations of capacity ratings in the various operating modes it is the ideal planning tool for sizing of the VSCs for possible applications.

Question 2.5-17:

To what extent the HVDC and FACTS devices, embedded in a.c. systems, can improve the overall performance and costs of a power system? In B4-209, it is presumed that LEETS eventually will be used by TSOs for the evaluation of HVAC and HVDC transmission projects. When will LEETS be available as a planning tool for the TSOs? Can the authors elaborate on the scenarios in the example case with respect to promoting HVDC?

The LEETS software is already available for TSOs as a tool for planning of HVAC and HVDC. Each TSO may have a different approach to economics and environmental analysis. LEETS is therefore designed as an open and flexible tool which can be tailor-made for different TSO practices. The LEETS project includes technical, economic and environmental investigation of mixed HVDC/HVAC systems. For example, the HVDC benefits from an environmental perspective usually stems from the elimination of visual impact from overhead lines by using HVDC cable solutions. LEETS can also be used for optimised design of substations by minimising the life-cycle environmental impact and economy.

The initial investment costs in HVDC converter stations is high, however if this solution is chosen in order to obtain public acceptability then the length of the dc line is less important compared with ac overhead lines. It was also argued that in many countries it is difficult and time consuming to obtain permission to build new ac overhead lines. It was argued that for distances around 50 km HVDC cable transmission may be an alternative to ac cables. FACTS or HVDC may also be a good alternative to solve bottlenecks in ac grids.

PS 3: Role of HVDC and Facts to assist System Performance

The Special Reporter summarized the papers and questions on the preferential subject, followed by a discussion on specific developments. There were 18 prepared contributions and 20 spontaneous contributions at this session.

Question 3.1-18:

In general, HVDC and FACTS can improve the performance of the power system. However during an HVDC outage, special protection systems may need to be employed to exploit the full potential of the HVDC system. Could the authors of paper B4-301 comment on the reliability requirements for the special

protection scheme (SPS) and the consequences of a failure of SPS during operation? Are there any SPS schemes in operation or under consideration for other HVDC links, similar to the Tasmanian scheme?

Special Protection Schemes (SPS)
Various special protection schemes are in operation in conjunction with a number of HVDC schemes. Each protection scheme is tailor made for adaptation to the specific conditions. Typical events to be considered are: Loss of HVDC transmission capacity, loss of generation capability and split of the a.c. System.

A SPS installed in the Tasmanian system enables higher transfers along Basslink and made the link economically viable.

In another example, the installation of SPS has allowed the maximum power transfer capability between Manitoba Hydro and the U.S. system to be increased from a few hundred megawatts to over 2000 MW. These SPS help maintain the stability of the interconnected system and prevent system separation.The alternative would have been to build additional interconnected ac transmission to maintain system stability under high exports.

Reliability of SPS systems
The operation experiences of those protective systems are good. The reliability requirement for such SPS, dependability and security, may be quite stringent depending on the consequences of maloperation. As for all protective systems at least two lines of defence is needed, primary and back up protection.

In the case of Manitoba Hydro, in order to ensure very high reliability the SPS circuits are triplicated, and a two out of three voting system is used. All the communication channels for transmitting various trip and power flow signals are duplicated. Every year one of three circuits is taken out of service to perform maintenance while the other two circuits remain in service. The Special Protection Scheme has been in service for 24 years and has operated very reliably.

In the Basslink (Australia) case, the availability of the central SPS assets must to meet 99.99%. Number of outages of the SPS central assets is limited to 1 per annum. Protection practices are applied to define the maximum time when the scheme can operate without redundancy under maintenance conditions.

Question 3.1-19:

Besides the damping of power oscillation, what other technical advantages were achieved with the TCSC described in paper B4-310. Is a coordinated control of the two TCSC required to obtain optimal performance? How does a trip of one of the lines influence the operation of the remaining line?

This question was addressed by the authors of paper B4-310 with respect to the TCSC's installed in India. There are identical TCSCs on each circuit of the double circuit 400 kV transmission line between Raipur and Rourkela. The power oscillation damping controllers are fed with the same input signal which is the sum of the power flow in both circuits and the reactance controllers are identical which means that both TCSC’s will have the same response to a power oscillation. This means that the POD controllers are coordinated by using identical systems fed with the same input signal which should guarantee optimal synergy between the two TCSC’s in terms of power oscillation damping performance.

A trip of one circuit will change the power flow and the TCSC in the remaining circuit will continue to operate with the same setting of control parameters.

Question 3.1-20:

What dynamic studies are required to fully explore the advantages from fast power flow control? With the increase in bipole power capacity in excess of 3000 MW, is the N-1 planning criteria still appropriate? What level of short term (30-minute) overload is practically achievable without having to oversize the converter poles? What are the considerations for using two bipoles (four poles) as opposed to having one

large bipole? How would this impact on the HVDC main circuit design especially d.c. line or cable design in terms of cost and securing routes?

Dynamic studies
As for any other large system, dynamic studies have to be performed to be able to know the possible constraints, if any, along the years when the ac system grows. At the same time, through the studies, it is possible to see the benefits that an HVDC link gives to the system, besides the obvious one of just transmitting power. The dynamic benefits will usually allow a more economical overall dispatch, resulting in significant savings.

A much more complex issue is how to evaluate these benefits (the savings mentioned above) and even more complex, how to assess their allocation to the HVDC owner/operator and other beneficiaries.

HVDC bipole power consideration
For bulk power transfer links, the consideration of a single versus two bipoles were addressed. For overhead lines Itaipu HVDC system is a good demonstration of both alternatives. Two bipoles are used for transfer of 6300 MW, i.e. four poles. In addition, there are two converters per pole.

By having two converters per pole the power loss for most station contingencies is limited to 25 % each bipole. By proper deign of the towers, the risk for a permanent line pole fault is limited. However it can not be disregarded.

The base for selection of the alternatives is the economic consideration, including the cost for coping with the larger power blocks. On one hand, the analyses involve spinning reserves for coping with loss of the largest block, and integrated times for the different conditions. On the other hand, the investment costs. The latter are probably easier to calculate, with the possible exception of the costs for securing ROW for one vs two bipoles.

In the Brazilian example of Madeira River hydroelectric power project the solution envisaged is composed of two ± 600 kV bipoles, 3150 MW each, 2500 km long, connecting the collecting substation in the Porto Velho region to the load center at São Paulo state.

Overload consideration
Any overload requires uprating of equipment, unless related to favourable external conditions such as low ambient, availability of redundant coolers etc. For the valves, 30 minutes is a long time, more or less equivalent to the continuous rating. Transformers, smoothing reactors, etc. have a much longer time constant, meaning lower uprating. Thus, the uprating can be limited, compared with continuous rating. However an uprating is always needed.

The necessary levels of overload for coping with, for example,(n-1) criteria may be placed on HVDC transmission, in the form of overload. A more usual form is in pure ac systems, where the overload is put on the transmission (the design has to allow for loss of a line, stability wise and thermally), or in the generation dispatch (spinning reserve means loss of a generator results in higher powers in the remaining ones). Therefore, it was recognised that the overload is not free and the cost may lie depending on the power system and market mechanisms in practice.

An estimate from the Brazilian project indicates that to keep a 33 % continuous overload with two bipoles would result in a 27 % cost increase. By incorporating a generation re-dispatch within 30 minutes means the cost increase would be limited to about 10 %. It is recognised that this additional cost can be further reduced by integrating the control of generation dispatch with HVDC controls. In addition to the above SPS considerations, it was recognised that some torsional stress mitigation measures need to be implemented to protect close in generators connected to the parallel weak ac system.

Question 3.1-21:

In a deregulated electricity market, the power flow in lines can change very often in both size and direction. In some deregulated electricity markets, it is possible to re-dispatch generation down to 15 or 5 minute intervals. How does this influence the design of HVDC transmission, and what are the critical

components? What trade-off is possible, if the generation re-dispatch times are reduced to below 30 minutes?

HVDC under fast dispatch
The converters of most HVDC links in northern Europe are design for full power reversal, i.e. full load in one direction to full load in the other direction, within one second. Thus for the HVDC equipment re-dispatch down to 5 minutes intervals is not a problem. The cable have very long thermal time constant and re-dispatch at 5 minutes intervals are hardly worse than redispatch each 30 minutes.

Depending on the amount of load variation it may be necessary to review the strategy for tap changer control and filter switching for avoiding excessive number of operation. Two steps each five minutes means more than tap changer 200 000 operation per year. To switch filter or shunt capacitor banks each five minutes means 100 000 operation per year. Besides, both capacitor switching and power variation will impact the power quality (flicker). Thus, at frequent and large power variations, an SVS (Static Var System) can be a good option.

Minimum current requirements means that a monopolar scheme may be stopped at lowe power levels (say -50 to +50 MW for Basslink). Each start and stop means a step of about 10 % in power, which might be disturbing for the connected networks if it happens to often, especially if combined with ac filter switching. A solution could be in the form of round power in a bipole scheme. A different solution may need to be found for a monopolar scheme.

A Capacitive Commutated Converters (CCC) has a much less Mvar variation at MW load variation it should be favourable considering the power quality aspect, when the HVDC load varies very frequently. In addition, no filter switching is required in order to compensate for reactive power variation.

For a VSC based HVDC scheme there is no limit regarding frequency of power reversals as no blocking is needed for power reversal. There is no voltage polarity reversal required to reverse the power flow. Besides the VSC converters acts as its own SVC for a.c. voltage control.

Question 3.1-22:

In paper B4-301, it is stated that the Cigré cable load cycle test was altered to reflect expected power flows under market conditions. Which changes have been made by the authors? Should changes be recommended to reflect long HVDC cables and changing market operating conditions in Cigré load cycle tests?

Cigre cable load cycle test
The question has been well addressed at the session with several interesting discussions. The authors of B4-301 considered that the original CIGRE load cycle and polarity reversal tests do not sufficiently reflect anticipated mode of HVDC operation under market conditions. To respond to fast changes in market spot prices, generators in Tasmania require availability of fast power reversal and fast ramping. Test based on a change of voltage polarity every 4 hours does not provide sufficient confidence about future cable performance under market operations.

The lack of experience in fast power reversal on large HVDC cable links and the lack of understanding of the insulation behaviour under frequent voltage reversal call for further work in this area. Such findings may be necessary to devise any recommendations to improve equipment testing. This could be a subject for future study by SC B4 in conjunction with other relevant study committees.

Sub topic 3.2

None of the papers addressed this important subject on system restoration. As some remarkable occasions over the last years have revealed, system blackouts cannot be completely avoided. As it has been demonstrated in HVDC, interconnections between a.c. systems can prevent cascading blackouts. After an eventual blackout, quick restoration of a power system is crucial.

There were two spontaneous contributions were at the sessio dealing with HVDC and system restoration.

HVdc systems operation during and after a major system disturbance is of great interest to the ac system operators. In the case of the Pacific HVdc Intertie between Oregon and Los Angeles in the US, it has stayed in operation during several large area blackouts feeding power into the Los Angels area. In that sense, it has been beneficial for the owners of the dc system and probably contributed to restoring the system. However, this is probably not a general conclusion because if the dc link lacks reactive power support in the receiving end, it can not stay in operation. So, it has to be studied on a case by case basis.
Unlike the LCC based HVDC the reactive power needs of a VSC converter is not dependent on the connected ac system and is likely to aid system recovery.

<u>HVDC back to back</u>
Size of interconnected systems is growing. With generation capacity exceeding 250 GW connected synchronously, grid disturbances would have severe implications. Probability of grid collapse of once in 10 years or so as at present, may not be acceptable. One solution to address this could be to split the inter-connected ac network in two layers connected to each other at suitable locations through HVDC back to back. This would reduce the probability of total grid collapse to much lower levels – from p to p^2, where $p<<1$.

The ac network split in two layers and having parallel power transfer corridors with HVDC back to back connections at suitable locations would allow transfer of loadings from one system to other in case of contingencies of outage in either of the systems. Due to inter-connections being HVDC back-to-back, the two systems would be isolated from each other for any spread of disturbance.

The design could also help to mitigate the problem of increasing short circuit levels in closely connected ac network.

Question 3.3-23:

Paper B4-303 reports a Multi Infeed HVDC system (MIDC). How do interactions affect the HVDC control performance? How could a solution be incorporated, if an interaction problem is caused by an existing HVDC system with a different owner? WG B4-41 is currently carrying out some pioneering work in MIDC systems? What new developments can be reported that enable a better understanding of MIDC problems and remedial measures to be implemented?

Practical results from several multi infeed studies of which the biggest study was for the China South network were presented. The Southern China Network study with up to five HVDC links revealed that sympathetic commutation on all the HVDC links causes a short (for 100 - 200 ms) simultaneous loss of power transmitted on the HVDC links, however after the fault clearance all links restarted without any problems. Based on the study results, the conclusion was that the HVDC links themselves are not the problem. However, parallel ac lines can be a problem. However, with a carefully designed system for tripping of generators this can be solved. The many HVDC links in the vicinity to each other is not be a problem, on the contrary, advantages can be gained by using the HVDC overload capability and the fast HVDC power control to improve the resulting performance of the parallel ac lines. Another study for the coming HVDC link between Norway and Nederlands (Norned) and the existing HVDC links between Norway and Denmark (Skagerrak) has revealed that strong interaction is possible between the HVDC links in weak grid situations. In such cases restrictions on the operation of the links may be necessary in order to obtain secure operations. For safe fault recovery after ac faults in weak grids it may also be necessary to coordinate recovery times between the links.

Multi Infeed Short circuit Ratio and particpation factors have been defined to assess the interaction and sensistivity (for commutation failures) between the multiple HVDC links. CIGRÉ SC B4 has an active WG to study these matters in gretaer detail.

Question 3.3-24:

Have the findings described in the paper B4-306 been confirmed either by practical experiments or at incidents which have happened in the grid? How has the UPFC performed, and what were the greatest challenges and the most severe problems, if any?

Due to delays in getting permission to build a new ac transmission line, a UPFC has been installed by KEPCO in order to combat severe voltage and power oscillations during critical contingencies in the grid. The obtainable improvements by using the UPFC at various types of contingencies have been studied. The control modes for the

UPFC have been determined. For the series part of the UPFC, the power flow control mode has been selected instead of the voltage injection control mode. For the shunt part of the UPFC the voltage control mode has been selected instead of reactive power control mode. An optimised algorithm for automatic UPFC operation is under development. For the moment the UPFC is operated in manual mode. The next step is to operate the UPFC in manual mode but using optimized control algorithms. Finally the automatic operation of the UPFC will be implemented. Since commissioning six major internal faults in the UPFC were experienced. However the availability has since improved and is now above 97%. A high level of availability must be kept in the future in order to maintain high system reliability.

Question 3.3-25:

Can the theoretical findings of using MCSR in long ACtransmission lines be confirmed with practical experiences from existing MCSR installations? In general, how do controlled shunt compensation and controlled series compensation compare with respect to angular stability and how does the performance of MCSR compare with TCSR? What are the pros and cons, technically and economically?

The theoretical findings in paper B4-307 have not yet been confirmed by practical experiences, only one 180 MVAr MCSR has been installed in a 500 kV, 1000 km ac transmission line. Comparative studies of a transmission line compensated with TCSC alternatively with a theoretical MCSR shows that the variation in the voltage profile along the transmission line is quit less with a MSCR than with the TCSC. Transient studies have shown that compared with a TCSC, the MCSR provides less damping in the beginnig of a transient event but more damping in the subsequent oscillations. The material consumption for the MCSR is estimated to about 2.8 kg per kVA.

A counterarguement was that series compensation is superior compared with shunt compensation on many points. Series compensation directly reduces the line reactances and the angular voltage differences between the line ends. Shunt compensation needs much more reactive power in order to provide the same performance with respect to angular stability as series compensation. For power oscillation damping the performance of a TCSC is much more independent of its location than a SVC and the rating of a TCSC only needs to be 12-20% of the rating of a SVC. For system stability synchronicing power is important and because the TCSC offers much better first swing damping the TCSC is better than shunt compensation using MCSR. It was pointed out that is is not possible to make a meaningfull comparison of MCSR with TCSC because there are only a few MCSR installations (above 400 kV). It was argued that the main reason being that TCSCs are technically and commercially better than MCSRs.

Question 3.3-26:

Has the TCSC solution (B4-308) been decided for improvement of the transmission capacity between Swiss and Italy? To what extent would the proposed TCSC improve the power system security? What are the general views on TCSC's with respect to performance and costs? Are they in general an economical alternative to phase-shifting transformers?

The decision regarding a TCSC solution in the tie lines between Italy and Switzerland has not yet been taken. The power system security can be improved by using TCSC wich has been investigated through three different scenarios with and without TCSC. In a scenario similar to the event that caused the Italian black out in 2003 it was reveald that with a TCSC in the problematic tie-line, the system security would have been maintaned after the critical incident. It was pointed out that generation managements or line switching outside the Swiss network can also lead to overload on the tie line to Italy. In addition to improve the dynamic security the TCSC is therefor to be provided with a functions that can dynamically limit the flow on the tie line so the operator will have time to manage acute situations that could lead to termal overload of the tie-line. On the ground that the performance of phase shifting transformer was judged to be poorer than a power transfomer with onload tap changer, it was argued that the TCSC maintenance cost is less than the phase shifting transformer cost and that the overall cost including maintenance cost would be in favour of a TCSC solution compared with a phase shifting transformer solution.

Question .3.3-27:

Although the power of computing increases rapidly, appropriate selection of tools and the necessary modelling details still remains. What developments can be reported by working group WG B4-38 or others that capture the state-of-the-art in HVDC and FACTS modelling to adequately capture system

issues? What are the modelling requirements for long cables for vital links as reported in B4-301? What control and practical steps are needed to manage transient behaviour of long cable links?

The effect of load modelling will have significant influence on the dynamic response. What level of accuracy and effort is necessary to represent network load for HVDC and FACTS studies?

Two approaches to modelling dc cables were discussed. One approach using multiple π sections to model long cables. The other approach was to use general cable models in commercial software. For both approaches it is important to evaluate that the models are sufficient representations of the actual dc cables. Cable models for specific frequencies are straight-forward whereas this is not the case for frequency dependent models. It was argued that frequency dependent cable model in commercial software can be too simplistic. In addition it can also be difficult to use the software as it is not obvious how data for the cable model is derived from the physical cable. Regarding modelling requirements it was mentioned that for HVDC dynamic studies it is important that the total cable capacitance is correct, the travelling time is correct, earth return and cable sheath modes to be reasonable and the cable model is correct for higher frequencies. Regarding transient managements of HVDC with long dc cables it was said, that it is important to ensure stable inverter dc voltage, that risk of commutation failures should be kept at an appropriate level, as well as management of power recovery (inverter side) and management of ac voltage fluctuations at recovery (rectifier side) after faults.

For the Basslink project EMTDC was used intensively and it was revealed that 2 seconds simulations matched well to measurements. EMTDC simulation with an updated frequency depended cable model matched very well with the behaviour of the physical cable. The strong ac system (Australian mainland power system) was represented by a reduced ac equivalent whereas for the weak ac systems (Tasmanian power system) a more detailed ac equivalent was required. The Basslink recovery after ac or dc faults was improved by using a control loop for phase angle damping modulation and by using another control loop for Udref reduction.

Session Closing Remarks by SC B4 Chairman

The Chairman of SC B4 summarized the discussion into 13 main topics and thanked all contributors and attendants for valuable contributions and their interest in the session.

These 13 main topics were:

- 800 kV Schemes
- Converter transformers failures/HVDC performance
- Ground return /electrodes
- Environmental issues (incl. RI)
- Polarity reversal in HVDC
- Converting ac to dc lines
- Experiences with FACTS/PE (STATCOM, UPFC, etc)
- VSC with OH lines
- B-t-B integrated in ac system
- Overload characteristics/design of HVDC
- TCSC applications
- HVDC cable modeling/requirements
- DC cables for 800 kV applications

Conclusions

Overall the sessions were well attended and the discussions were timely. The prepared contributions generated a lot of spontaneous contributions, leading to a healthy technical session. There is an increasing scope for HVDC and Power Electronic applications with the demand for high power long distance transmission from fast developing countries and with the need for improved power system performance in all parts of the world.

The challenges facing the HVDC community are both from equipment and system performance issues. The HVDC community is learning to cope with the increasing demands placed on it due to deregulation, resolving transformer failures and the need to implement UHVDC solutions. Cigré is playing an important role in all these aspects and is helping the HVDC and Power Electronics applications to improve overall power system performance from environmental, technical and economical aspects.