B4 - 00

GENERAL REPORT FOR SC B4
(HVDC and Power Electronics)

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The B4 session was very well attended with between 300 and 400 delegates. 24 papers were covered by Study Committee B4. The discussion included 71 prepared contributions from 12 countries and around 30 spontaneous contributions, thus reflecting the actuality of the preferential subjects and the large interest for the area of HVDC and Power Electronics. The attendance during the session indicates that HVDC technologies and AC power electronic systems are topics of high interest to the CIGRE community.

The preferential subjects discussed during the B4 2012 Session were:

1. HVDC and FACTS Schemes
   - 1.1 Project planning, including environmental and regulatory issues
   - 1.2 Schemes recently completed or under construction
   - 1.3 Service experience of VSC HVDC, LCC HVDC and UHVDC schemes

2. HVDC and FACTS Technology Developments
   - 2.1 HVDC converter stations
   - 2.2 FACTS equipment
   - 2.3 UHVDC equipment

3. Applications of HVDC and FACTS
   - 3.1 HVDC grids and multi-terminal HVDC systems
   - 3.2 FACTS equipment for increased AC network performance
   - 3.3 Embedded HVDC systems, including AC lines converted to HVDC operation, for increased network capacity and performance
   - 3.4 Use of Power Electronics to facilitate the integration of large renewable energy sources into AC networks

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1. Preferential Subject 1: HVDC and FACTS Schemes

Preferential subject 1 deals with HVDC and FACTS schemes. It covers new projects, including projects under construction, and experiences from existing projects. A total of 13 papers were accepted for this subject, but paper B4-104 was withdrawn.

There were 11 questions in the Special Report. 41 prepared contributions were received for the discussions at this session. 16 spontaneous contributions were received.

1.1 Project planning, including environmental and regulatory issues

Question 1.1:

For paper B4-103 VSC technology was considered because it can operate in a much weaker network compared to traditional LCC HVDC systems. For paper B4-110 HVDC was a social requirement, as the HVDC underground cable solution is 8 to 10 times more expensive than the AC overhead line alternative, but the use of an overhead line is unacceptable in this area. As the papers were prepared about eight months ago, what are the latest information and decisions regarding the Nelson River Bipole 3 and the French-Spanish link? Are there any other VSC HVDC project being planned with a rating above 1000 MW? Are there any projects in the world being planned using LCC technology to be terminated at weak ac system? What are the main reasons for selecting VSC or LCC?

VSC is still being called a new technology however the number of new projects using this technology is impressive. Papers B4-103 ("Planning the Next Nelson River HVDC Development Phase Considering LCC vs. VSC Technology") and B4-110 ("New French-Spanish VSC link") are good examples of this situation.

The first paper examines the technical feasibility of using voltage sourced converters (VSC) technology along with overhead lines for the third Bipole of Nelson River. A traditional line commutated converter (LCC) solution would require 1000 Mvar of synchronous condensers, due to the weak AC system at the inverter side. In the SC B4 Technical Session, Manitoba Hydro reported that the third Bipole is planned to be tendered in 2013 with LCC as the base bid and VSC as an optional bid.

The second paper describes the characteristics of the future VSC HVDC interconnection between France and Spain, the reasons which have led to the implementation of VSC technology, the conclusions obtained from the studies conducted to determine the future exchange capacities, the control strategies which will be adopted and the behaviour and operation of the DC link embedded in an AC network. The French-Spanish link is under construction and the expected date for commissioning works is 2014.

There are several VSC projects above 1000 MW planned:

- South-West Link in Sweden - Two 720 MW, 300 kV symmetrical VSC monopoles. Transmission link includes a 10 km and 179 km cable split by a 62 km overhead line segment. The order has been placed and the expected in-service date is the end of 2014.
- Scotland 1200 MW HVDC Hub – It is planned to change the previously planned 600 MW link between the island of Shetland and the Scottish mainland to a multi-terminal scheme by adding an intermediate dc switching station, adding a 800MW link from Caithness, and increasing the cable capacity and the southern converter station rating to 1200MW.
- Germany 1.3 and 2 GW project blocks, with 12 GW by 2022 (7 links in 4 corridors, 2000 km new DC lines) and 18 GW by 2032 (8 links in existing corridors, 1000 km new DC lines). The 2 GW blocks will initially use parallel converters until the technology develops further.
- Atlantic Wind Connection (AWC), between New Jersey and Virginia – In final stage is planned to be composed of four 500 MW plus four 1000 MW converter stations. Each block of 1000 MW, composed of two 320 kV symmetrical VSC monopoles, would consist of two HVDC cable systems and one fibre optic cable system.
- Mid-Atlantic Power Pathway (MAPP) - is a 2x1000 MW Project using VSC technology planned for the 2019-2021 with a 152-mile transmission submarine cable between Southern Maryland and the Delmarva Peninsula.
- Dalian VSC-HVDC Project in China - Two 500 MW, 320 kV symmetrical VSC monopoles. The feasibility study, system analysis and preliminary design scheme for the project were completed last June. Commissioning is planned by late 2013.

Two planned VSC projects between 500 MW and 1000 MW were also cited:

- Eirgrid East West VSC link – this project has a capacity of 500 MW, is already being commissioned. It interconnects Ireland and Great Britain.
- Tres Amigas Project in New Mexico - this is the planned interconnection of the 3 southwestern US networks. It will be built in different stages between 2014 and 2020, and will mix LCC and VSC technology. The maximum VSC links will be rated at 750 MW.

Regarding LCC projects terminating in weak systems, there are the following projects:

- Skagerrak 1-3 is a multi-infeed LCC HVDC system that interconnects Denmark with Norway. Under some operating conditions, the HVDC converters will feed into a rather weak ac system. This project will be reinforced with a parallel VSC, the 700-MW 500-kV Skagerrak 4. The planned in-service date of Skaggerak 4 is 2014.
- Rio Madeira project, in Brazil (2x 3150 MW) has LCC terminating in weak systems at the north end.
- Belo Monte in Brazil, currently in the planning stages, will terminate in a weak northern end, which will receive power during the dry winter months.

- Newfoundland to Labrador Island HVDC link, 900-MW ±320-kV LCC Bipole, will be terminated in a weak southern system that will be supported with three 150-MVAr high-inertia synchronous condensers. Planned in service date is 2017.

Question 1.2:

Paper B4-103 reports the necessity to investigate solutions for quick clearance of DC line faults and to reduce the impact in the inverter ac network frequency caused by remote rectifier AC faults for the VSC HVDC alternative. What alternatives are available and what are the latest advancements in the OHL fault clearing technology? What research and development is being done in the area of control solutions to solve the problems presented by the authors?

One of the difficulties to transmit energy through VSC HVDC links using overhead transmission line is how to clear a DC line fault. Even considering that solutions are already available, as it is proved by Caprivi link; there is a necessity for new equipment in order to have more efficient DC line fault clearance. One example of this requirement is the DC grid that is being studied for Europe which requires very fast DC breakers.

The reasons for requiring fast DC line fault clearing can be summarized as follows:

- To prevent excessive transient underfrequency.
- To minimize mechanical stresses on overhead DC line. Fault current and DC capacitor discharge current could impact space damper design on a bundled overhead DC line.

Possible alternatives to clear the fault are:

- Half bridge converter with AC breaker clearing the fault (current technology);
- Half bridge converter with DC breaker (mechanical breaker with electrical resonance circuit, full IGBT breaker or hybrid DC breaker with IGBTs and mechanical (ultra) fast disconnector) clearing the fault;
- Full bridge converter capable of clearing the fault;
- Hybrid converter comprised of full bridge and series connected IGBTs.

However, it is important to note that some technologies are still under development.

The Caprivi link, in Namibia, is the first commercial application of VSC with overhead lines. It adopts the following procedure to clear a DC line fault:

1- Opening of AC breaker
2- Fault arc de-ionization
3- Clearing of the residual dc current by conventional dc circuit breaker
4- Closing of AC breaker and fast re-start.

For the South-West VSC interconnection a sequence similar to that used by Caprivi link is proposed:

1- Blocking IGBTs
2- Opening of AC breaker;
3- Closing of discharge resistor

4- Opening of discharge resistor and closing of AC breaker
5- Restarting of converter

Regarding research and new developments in this area, the advancement in DC Breaker technology has opened up the possibility of low loss and low cost solutions for fast auto-re-closure without power interruption in parts not affected by the fault.

Question 1.3:

HVAC and HVDC networks perform very differently, because of the controllability of HVDC and the natural response to changes of the HVAC network. Paper B4-110 describes that the project will have a control to emulate the behaviour of an AC line. What are the advantages of emulating AC behaviour using an HVDC system? Are there any other HVDC system that intends to emulate AC system behaviour?

There are two methods for AC line emulation:

- Modify the HVDC power as a function of the amount of active power which is transmitted by a parallel AC line;
- Increase/decrease the HVDC power as a function of the difference of the phase angles at the ac terminals at the two HVDC converters.

Some advantages were presented in emulating AC lines in the post-disturbance period:

- Increase power transfer up to the maximum rating of the HVDC scheme;
- Automatic reduction of the transmitted power;
- Reduced possibility of overloading in adjacent AC lines;
- Reduced amplitude of the first active power swing in the adjacent AC lines.

For dispatch, the automatically control of the HVDC scheme as a pseudo AC line not requiring frequent schedule decisions from the operator can be considered as an advantage in some situations.

For the French-Spanish VSC interconnection, AC emulation facility could allow the use as tertiary control, providing that the commercial exchange between France and Spain is known.

The possibility of an automatic control emulating the behavior of an AC line is currently under study in the French-Spanish VSC interconnection. However, there were no reports of any existing scheme that uses this automatic control.

1.2 Schemes recently completed or under construction

Question 1.4:

Paper B4-105 describes the challenges associated with obtaining permission to perform needed system tests due to the electricity market restrictions. A lot of effort is spent in negotiating permits for the tests. This situation is not likely to improve. Since the number of HVDC systems is increasing the chances of multi-infeed systems with

different owners and using different technologies are increasing. In this situation, system tests may be the only opportunity to confirm the performance of new systems considering interactions with the existing systems and to make final adjustments in the control. What is the experience on other projects related to the process required to get the approval to perform the needed system tests? Are there any examples of operational performance discovered after commissioning, which might have resulted from inability to do the appropriate tests during commissioning? What can be done to reduce the risk of the prospective issues?

Paper B4-105 ("New Fenno-Skan 2 HVDC pole with an upgrade of the existing Fenno-Skan 1 pole") presents the project of the second pole of Fenno-Skan and the upgrades of the overhead line and pole. The 800 MW, 500 kV Fenno-Skan 2 transmits power between Rauma (Finland) and Finnböle (Sweden). The paper discusses the different studies that have been performed, including those related to HVDC transmission lines, AC filter interactions between poles, electrode line unbalance supervision, sub-synchronous interactions, electrode replacement and difficulties encountered in conducting the system tests. The project was finished last year and has been in commercial operation since December 15, 2011.

The following rules were suggested to facilitate permissions to perform the tests:

- Clear and exact rules must be established beforehand to meet the rules of the market
- Early agreement on testing plan with transmission owner
- Early announcement of timing schedule and power level through transmission owner to the market
- Information exchange through only one person appointed by the company
- Propose weekly plan for requested test power levels with updates one week in advance
- Request transmission plan for the following day
- Adapt the testing schedule based on market constraints

One contribution from Japan informed that at the Kii-channel HVDC Link the performance tests of some control and protection functions related to commutation failure prevention were not allowed. So those functions have to be verified during commercial operation, examining plots of actual AC line faults and changing the settings whenever needed. In order to reduce the risks of a degraded performance of the function in the early stage of operation, the control & protection system was previously tested using real-time power system simulator.

Question 1.5:

What is the influence of the capacitor size on the performance of the CCC system using the new control scheme presented in paper B4-106? The paper suggests a lot of "pros" but are there any "cons"? What similar research is being done by others on CCC and LCC control systems?

Paper B4-106 ("A new control scheme for an HVDC transmission link with capacitor-commutated converters having the inverter operating with constant alternating voltage") presents a new control strategy to enhance the performance of Capacitor-Commutated

Converters (CCC) HVDC systems whenever connected to AC systems with low short-circuit ratio. The main control strategy consists of using the CCC to control the AC bus voltage at the inverter side. If the commutating capacitors have a suitable size, the converter can generate or absorb reactive power from the connected AC system. Simulation results, using Rio Madeira Back-to-Back system as reference, show that the HVDC system operates satisfactorily even if it is connected to an almost passive AC network, with the inverter emulating the operation of a Voltage Sourced Converter.

The Capacitor Commutated Converter (CCC) is a classic HVDC converter with thyristor valves which has commutation capacitors between the converter transformer and the valves.

The major advantage of the CCC concept is the reactive power characteristics:
- It extends the operating range of the converter.
- It can produce reactive power, depending of the sizing of the capacitor. This characteristic can be used to stabilize the converter and control the AC voltage at the converter ac bus.

To maximize the performance [at the converter ac network] under extreme weak conditions of connected AC system the new control strategy proposes that the inverter has to operate with constant alternating voltage and independent control of P and Q while the rectifier controls the direct current. This operation mode at the inverter side, is analogous to the control of VSC HVDC links, and is useful whenever the SCR is lower than 1.0.

Regarding the size of commutating capacitors, some design aspects of the converter has to be considered:
1) Rating of the converter transformer;
2) Design of the AC and DC filters;
3) Valve voltage insulation level;
4) Valve voltage stresses;
5) Converter transformer valve side insulation level.

Question 1.6:

Paper B4-107 states that the dynamic performance results of real-time tests were similar to the results obtained from actual operational tests for the Caprivi Link HVDC Interconnector. Differences between the results were caused by the simplified representation of AC protections used in the real-time simulations. Considering that the network representation capability and the models available in a real-time simulator are very good and that there are significant risks and difficulties associated with performing actual staged fault tests during commissioning, what improvements have to be made to the Factory System Tests in order to further minimise the extent of the actual system tests?

Paper B4-107 (“Caprivi Link HVDC Interconnector: Comparison between energized system testing and real-time simulator testing”) presents the results of factory system tests and energized system tests for the Caprivi Link VSC HVDC Scheme in Namibia. The control and protection systems were interfaced with a real-time simulator for the factory system tests (FST). The performance of the system during commissioning was similar to that obtained during the factory tests. The paper concludes that extensive FST testing has some benefits: the commissioning time was minimised and no major change of control settings were needed.

Based on the contributions received, the consensus was that the simulations have improved considerably, but they do not cover everything. Even with detailed FST, some tests have to be performed, or repeated, during System Test stage. They are important for final verification and tuning.

Caprivi Link has informed that FST was performed with real-time digital simulator using reduced AC network models and Energized System Test was in line with FST.

For Rio Madeira Back-to-Back System, the various configurations considered by the project have been rigorously tested both in digital simulations and during the FST.

For Japan, one possible improvement for FST would be the incorporation of actual telecommunication system.

Question 1.7:

Paper B4-108 describes an experience where the implementation time for a control upgrade was only three weeks per pole. Are there other upgrade experiences where similar schedules have been achieved? What is the unavailability period that is being considered for future upgrade projects, and what activities are on the critical path of these projects?

Paper B4-108 (“Upgrading the Intermountain HVDC Project to handle 480 MW additional Wind Power”) describes the upgrade of the Intermountain HVDC Project. This project was originally commissioned in 1986 to transmit 1600 MW at ±500 kV with a continuous short–time overload capacity of 1.5 pu. The bipole was up-rated to 1920 MW in 1989 and then, in recent years, to 2400 MW. All stages of up-rating project are presented in the paper.

In general, a typical achievable outage time is 2-3 weeks per pole (block). Factors for success of the project are the detailed planning of the activities during the outage and the extensive factory system testing of all control equipment. Critical paths are the works for switching over of C&P facility and commissioning tests.

The experiences related to control system upgrade for other projects are presented in the following table.

Project	Type	Outage time
CU	Bipole	2 weeks per pole
Square Butte	Bipole	6 weeks total
Skagerak 1&2	Bipole	15 days total
Blackwater	Bipole	21 days total
Chateauguay	BtB 2 blocks	4 weeks per block
IPP	Bipole	3 weeks per pole
Hokkaido-Honshu	Pole	10 weeks per pole

Question 1.8:

Rio Madeira project involved several utilities and suppliers, as described by papers B4-111 and B4-112, and this model probably will be applied in other projects, not limited to Brazil. The competition reduces the price; however, it affects the engineering solutions and an optimization of the whole system is not achievable. What are the views of Owners and the Manufacturers, in respect of the challenges and opportunities that arise when more than one manufacturer is involved in the overall project? What are the main areas that require interaction between manufacturers? What exchange of sensitive information is required and how is this exchange handled?

Paper B4-111 ("The Rio Madeira HVDC System – Design aspects of Bipole 1 and the connector to Acre-Rondônia") discusses the supply of the HVDC parts of Bipole 1 converters and the two back-to-back converter blocks of the Rio Madeira HVDC Project, where various utilities and different suppliers are involved in this project, affecting the engineering solutions adopted and increasing the number of interesting and challenging issues that had to be addressed in this project. Paper B4-112 ("The ±600 kV HVDC Madeira River Transmission System Design") presents the main technical characteristics of the Madeira River HVDC Transmission System derived from the completion of the project's design review stage. It is the first HVDC scheme in Brazil to be installed under the new regulatory framework granting transmission concessions through a 30 year period.

Discussion Contribution from a manufacturer involved in the Rio Madeira Project states that the coordination has required several actions:

- The information ranges from space requirements through equipment data to the details of control systems.
- HVDC manufacturers have a common understanding of the issues involved, even though the details of their solutions may vary. In the case of Rio Madeira the multiple parallel configurations make the coordination essential.
- AC Filters are treated on a bipole basis, while Master Control located in Bipole 1 addresses this as well as active power dispatch and reactive power control.
- An optimised HVDC system should use reactive power from the generating plant, thus reducing overvoltages and the risk of self-excitation.

In order to improve the process, the following comments and suggestions were made:

- A certain degree of optimisation of the system is possible, but this increases the complexity of the bidding documents for the concession.
- The HVDC manufacturers can cooperate to ensure a satisfactory system design, however there are many other sources of uncertainty during the design phase.
- Data and models should be frozen for design phase and adapted when operational studies are made.
- Generic control system models can be used for the early studies, but actual models must be used when finalising the design.

A Contribution from UK has commented that multi-vendor HVDC converters will be the norm in the future and has suggested that a common and independent RTDS facility could be used to connect hardware controllers from multiple vendors, allowing tests and mitigating possible challenges.

For the Brazilian System Operator, the Rio Madeira Project has presented challenges, as different owners and providers share installations, but also opportunities related to cost reductions and knowledge transfer. The most sensitive areas regarding exchange of sensitive information were control system design, real-time models and the requirements of the Master Control.

The Owner Consultant Engineer should be involved in all the stages of the projects, before and after the Contract award, to support TSOs' and TRANSCO engineers not frequently involved in HVDC projects; to prepare specifications and perform studies; to witness acceptance tests and commissioning; and so on.

A Contribution from China presented the strategy used in the country. More than ten schemes, divided into several purchasing package, have been built since 1987. In order to cover sensitive information exchange between entities involved in each project and to reduce the related problems in this area, they are required to make respective contracts or agreements.

Japan informed that multiple manufacture scheme is common in Japan. Projects usually involve two or three converter equipment suppliers and four submarine cable manufactures. The main requirement about this process, in addition to those previously mentioned, is that the owner needs to take a leading role.

1.3 Service experience of VSC, HVDC and UHVDC schemes

Question 1.9:

Paper B4-101 states that, according to an EPRI report, life extension measures are needed after 10-15 years of service and the design life of 50% of the equipment is lower than 25 years. However, identification of equipment end of life is usually not easy. How useful is the data collected for the AG-04 survey (paper B4-113) for this identification?

What criterion was used in the Nelson River system and on other projects? There are a number of thyristor projects over 25 years old. Do they share the same experience regarding life extension measures? What measures are being taken?

Paper B4-101 ("Life extension of Nelson River HVDC system") presents the measures taken to extend the life of the HVDC system and the reasons for implementing the upgrades. The Nelson River HVDC system consists of two bipoles commissioned between 1970 and 1984. The upgrading involved the replacement of Bipole 1 mercury-arc valves, upgrading of the cooling system for Bipole 2, purchase of spare converter transformer, replacement of the thyristor module piping for Bipole 2, replacement of the smoothing reactors for both bipoles and the implementation of a reliability-centred maintenance program. After approximately twenty years of service, major life extension measures may be required.

Manitoba Hydro has presented a contribution informing that there are two forms of life extension: repairing the equipment or replacing it. Repairing is adopted in the following cases:

1. Only some parts are failing;
2. The forced outage time is lower than 6 hrs;
3. The additional outage time to repair is acceptable;
4. Spares are available;
5. Delivery time for spares is short.

While replacement is indicated when:

1. Component has failed;
2. Forced outage time is too long (several days);
3. Spares are not available;
4. Delivery time for spares is long;
5. Repair time is too long.

The decision is affected by many factors like cost of outages, environmental issues, out of date equipment, spares not available and possibility to increase the capacity of the existing equipment.

Brazil has informed that major refurbishment of some SVC's is planned to improve the performance, to reduce the maintenance costs and to solve the difficulty to find spare parts. The equipments are 25 years old or more. In one case, the capacity of the equipment will be increased. The retrofit costs about 30% of the price of new equipment.

China has focused on thyristor lifetime. The ±500kV 1200MW Gezhouba-Nanqiao (GE-Nan) System replaced a complete valve in 2008 after 19 years in service.

Question 1.10:

Paper B4-102 describes a study to reproduce one event associated with multi-infeed terminals that occurred in Denmark. With the increased number of HVDC links in the world, interaction among links will become more and more frequent. What is the

operational experience in this area? Is there any other case of commutation failure propagation through a rectifier? What studies should be done by the Owner and the Contractor, prior to installing a converter station at a location electrically close to existing HVDC terminals, and what models of the existing HVDC scheme(s) are required by the Contractor of the new HVDC scheme? How should the IPR of manufacturers be protected in case of studies involving converters from more than one manufacturer?

Paper B4-102 ("Commutation Failure Propagation in Multi-Infeed HVdc Systems") studies the susceptibility of the propagation of the commutation failures (CF) in existing HVDC links operating in "wheeling mode", where some of the HVDC terminals are operating as rectifiers while others operate as inverters. Some time ago this type of event occurred in the Danish system, while it was operating in "wheeling mode". The AC/DC Danish system was modelled in PSCAD/EMTDC and several AC faults were applied at the inverter terminals of the HVDC links in order to reproduce and understand the disturbance. The results were compared against actual recordings obtained from the real system.

The author of the paper presented a contribution with following statements:

1. The "magnetic" short circuit level will decrease due to the increasing amount of non-synchronous generation. This will increase the spatial propagation of voltage sags causing more concurrent commutation failures on existing LCC HVDC schemes.
2. At least one additional case has occurred in Denmark.
3. The Owner needs to determine if it is even feasible to install the HVDC system (technically and economically) and what type of technology may be required. A detailed model may be set up in order to check possible commutation failure issues. The existing HVDC schemes should represent as closely as possible the actual systems in service. Detailed studies should be done assuming a variety of system configurations, with a variety of load flows in both load flow/stability program and in EMTP-type program.
4. The best way is to provide "black-box" models of the HVDC controls. Alternatively, an approximate model, which gives representative performance of the actual HVDC system, could be provided.

Brazilian Contributions have commented that:

- Commutation failures in multi-infeed systems need to be examined with "net" effects from one HVDC to the other, as system faults may give a systemic effect. So internal faults as well as DC faults would be preferred events to analyse multi-infeed interaction effects.
- Considering the propagation of the commutation failures, the transfer mechanism from a CF at one inverter to the rectifier is an AC voltage reduction at the rectifier end due to the "avalanche" DC current; the AC voltage reduction in the AC system associated to the rectifier side may cause CF at an inverter feeding this system.

- Enforcement of the AC network, installation of Synchronous Condenser, installation of STATCOM, integration of the controls, and use of alternative HVDC transmission are possible ways to mitigate problems.

A Contribution from France has discussed the intellectual property protection in multi-infeed systems, suggesting that real-time tests using replicas of the cubicles could assure and protect the IPR of each manufacturer.

Question 1.11:

In spite of all efforts done by SC B4 in the last years, paper B4-113 reports that converter transformer failures continue to be the major cause of forced outage hours, but seem to affect only a few of the schemes. As 2009-2010 transformer unavailability is mainly associated with one specific system what would be the summary of average FEU without considering this system? Are the causes of converter transformer failures the same as at the start of the higher trend, or are there new reasons because of different operation strategies? What new measures and concepts are introduced into the newest converter transformers to improve the long term reliability and availability? How does the total average Forced Energy Unavailability (FEU) compare with the specified availability for the different projects?

Paper B4-113 ("A survey of the reliability of HVDC systems throughout the world during 2009 - 2010") is the report from SC B4's Advisory Group AG-04 on the data collected annually regarding the reliability and availability of HVDC systems in operation throughout the world related to years 2009 and 2010. Converter transformer failures continue to contribute a large proportion of the FEU. Eliminating converter transformer failures reduced the average FEU from 3.1% to 0.65% and the Equivalent Outage Hours (EOH) from 170.2 to 57.1 hours. For this period the major EOH was associated with one system.

Paper B4-109 ("The Reliability of HVDC Projects in SGCC and the Operation Experience") presents the reliability data of State Grid Corporation of China (SGCC) HVDC Systems in service. The main focus of the paper was the statistics on frequency of outages from 2003 to 2010 but the forced energy unavailability and energy availability indexes in 2010 are also included.

A Contribution from Canada reported that FEU due to transformer failures is 3.1% when all systems are considered and the value is reduced to 0.9% if the data related to the major system is not included, which is still a very high number. It also shows that more than 50% of the failures are caused by internal transformer connection problems for the period 2003-2010. Regarding converter transformers and based on the statistics, the following recommendations for new projects are given:

- Improvement on specification and test requirement;
- Perform thorough design review;
- Install on-line monitoring;
- Include spare for each type of converter transformers at each station;

- Design switchyard so transformer can be moved fully assembled.

Brazil presented the FEU of Furnas (Itaipu) HVDC System between 2001 and 2010 showing that converter transformer have being presenting a better performance in terms of availability since 2001, but are still the major cause of forced outage hours. The number of failures by station was quite similar in the past, although the figure of the last 10 years is very different: There were only two failures at the inverter side while at the rectifier 10 failures were recorded. A repair program is being carried out to mitigate this problem.

2. Preferential Subject 2: HVDC and FACTS Technology Developments

UHVDC and VSC are currently the most interesting developments in HVDC & FACTS technology. Both aspects have been addressed by the 5 papers, which were accepted for this subject.

There were 4 questions in the Special Report. 10 prepared contributions were received for the discussions at this session. 6 spontaneous contributions were received.

2.1 HVDC converter stations

Question 2.1:

VSC HVDC development has been accelerated by the new converter topologies introduced in recent years. More converter concepts along with new methods for control and protection are expected to be available in the near future. How can a new design of HVDC system, in term of a new configuration or a new control concept, be effectively validated? What are the benefits of a cost-intensive full-scale demonstrator for manufacturers and users? How can a complex system like a modular multi-level VSC be efficiently modelled in digital simulation software, whilst still reasonably representing the converter dynamics and control possibilities? Should, and if so how, Cigre develop bench-marking models to help the users of new VSC technologies to understand and to verify the performance and features of the latest developments?

When a new converter technology, such as the modular multi-level VSC, is introduced into market, it is essential for users and suppliers to have adequate tools and procedures to validate the design and the functions. For different purposes there may be different tools and approaches available.

At the beginning, where no experience exists, building a reduced-scaled demonstrator may be an option to gain more confidence in the design and to validate the digital models. Paper **B4-205** reports for example about a 24 MW Back-to-Back voltage sourced converter demonstrator at one manufacturer’s facility.

With increased experience, converter functions shall be tested in other ways, either by digital simulation or by combining component testing and subsystem testing. In many cases digital simulations are sufficient to study relevant phenomena such as control & protection design, load flow and dynamic stability studies. For such studies several tools are already available as reported by many Discussion Contributions.

EMTP-type Simulation Program or Real Time Digital Simulator are frequently used tools for Functional Performance Test / Dynamic Performance Test. During Factory Acceptance Test complete station & converter control hardware and software are often built up, while HVDC station / converter / power electronics are simulated by a Real Time Digital Simulator (RTDS). It is obvious that a complex converter such as modular multilevel VSC may require a very large simulation time with the present RTDS technology, and this makes such real-time applications impossible. As reported in some Discussion Contributions suitable models have already been developed, partly in collaboration between suppliers and users. One Discussion Contribution from China reported that real-time simulation setup can already handle multilevel VSC with up to 451 levels.

It is recommended that B4 address this topic in a future Working Group and develop corresponding Benchmarking Models for modular multilevel VSC.

2.2 FACTS equipment

Question 2.2:

HVDC and FACTS are predominately used in transmission systems till now. With increased integration of renewable energy source like wind and solar in the distribution systems, these systems also need adequate means to maintain the power quality. What are the driving factors for installation of FACTS devices in distribution networks? What synergies exist between FACTS applications in transmission and distributions systems? What will be the main benefits to the distribution systems from the multi-level VSC technologies, which are gaining broad acceptance in transmission systems?

With increased penetration of renewable power generations in the distribution network there is a need for FACTS devices to control voltage fluctuations at the distribution level. The conventional means like OLTC cannot properly response to the step voltage variations. With the help of D-STATCOM a large amount of renewable energy source in distribution network becomes technically feasible and economically viable. Discussion Contributions from Ireland and Japan confirmed such applications.

The advantage of applying multi-level VSCs in the distribution system is increased when a high speed and low loss switching device such as the SiC device is employed. It becomes possible, with a small number of cascaded cells, to pursue simultaneously high output voltage and high switching frequency without increasing the loss, even without an interconnection transformer. The pole mounted STATCOM, as reported in paper **B4-203**, is a good example of the realized benefits for distribution system through the application of the multi-level VSC technologies**.**

Question 2.3:

The performance of power electronic converters used in HVDC and FACTS depends heavily on the features of the power electronic devices. The SiC based switching device is one of many examples of new technologies with potential to impact the development of power electronic systems in the future. Are there other new technologies and devices in the semiconductor industry which have potential to boost the applications of HVDC and FACTS in terms of increased efficiency or cost-effectiveness?

No written Discussion Contribution were received to this question. Two spontaneous contributions were made during the B4 Group Meeting reporting on-going research activities on new semiconductor devices in some research institutes.

2.3 UHVDC equipment

Question 2.4:

HVDC equipment in 1100 kV converter stations have very large dimensions and weight, which require new concept for design, transport and maintenance. On-site assembling of converter transformers in the valve hall has been proposed for an 1100 kV HVDC scheme. What experiences and concepts are available in the industry to perform on-site assembly and testing of large high voltage electrical equipment? What are the required provisions for repair or replacement of the equipment during the useful life of the system? How can a permanent on-site building be reasonably maintained and utilized for other purposes, while it shall be available for assembly and testing as well?

A Discussion Contribution from Japan reported the experience with on-site assembly of large converter transformers gained in Japanese HVDC projects. According to the technology adopted in Japan, the transformers are taken apart into smaller unites suitable for transportation facilities after completing factory tests. The on-site assembly of transformers is not limited to HVDC projects, more experience exists in Japan for AC substation with positive records. The use of a dedicated building suitable for assembly work combined and for testing is recommended for efficient construction work and repair work after commissioning.

According to another Discussion Contribution from Sweden the site assembly concept for the 1100 kV HVDC transformers follows different procedures to those used in Japan. The transformer is not built, tested and dis-assembled before shipping to site, but manufactured at on-site facilities, which is more akin to regular production. Considering the large number of transformers to be produced on site, including spares; the concept on such a larger industrial scale is certainly a challenge.

An on-site repair facility for the transformers is regarded as essential. The test hall, which is built for the on-site assembly during production stage, can be converted to a repair hall in this case. Such repair facility shall be suitable for the repair of failed transformers and even to produce replacement transformer as well. Accordingly, adequate equipment and tools shall be maintained in such a repair facility.

3. Preferential Subject 3: Applications of HVDC and FACTS

Preferential subject 3 addresses the application of HVDC and FACTS in the power grid. Particularly the increasing need for integration of large scale renewable energy sources opens up a new broad application area for HVDC and FACTS. Furthermore, the latest developments of VSC technology accelerate the investigation and discussion of multi-terminal HVDC system and DC grid configurations. A total of 8 papers were accepted for this subject. Paper B4-302 was withdrawn.

There were 6 questions in the Special Report for this Preferential Subject. 19 prepared contributions at this session and 8 spontaneous contributions were received.

3.1 HVDC grids and multi-terminal HVDC systems

A special presentation on "HVDC Grid Feasibility Study" was given by Mr. Gunnar Asplund, the convenor of Working Group B4-52. Major findings from this Working Group have been reported. Although the basic concept of a DC Grid is considered as feasible, there are still a large number of aspects that need further investigation, and this is subjects for other up-coming B4 working groups.

Question 3.1:

Many on-going activities have been reported in the area of HVDC grids and multi-terminal HVDC systems, and SC B4 has 5 active WGs looking at these issues. There are still many concepts evolving for load flow control and transient fault detection & clearing. Construction of a grid requires common rules and design criteria for all of the suppliers and owners. How can the many initiatives running in various international organizations be coordinated and synchronised, to avoid duplication and wasting of valuable effort? What shall be the focus areas of standardization works in the short-term and in the long-term perspective? How can we avoid over-standardization which would be detrimental in view of the rapid development of the VSC HVDC technology?

There were two common understandings among all Discussion Contributions:

- VSC HVDC technology is a new and fast developing technology nowadays. This swift development calls for slow standardization to avoid limitations in foreseen continued increased ratings and functionalities, similar to standardization development of classic HVDC.
- For planning and smooth integration of future VSC-HVDC-Grids some functional standards are necessary and recommended. Describing functional requirements rather than detailed technical solutions will help both the technology and market developments. Some elements of the HVDC Grid must be designed to a specific set of rules for interoperability. These include: topology of grid configuration (symmetrical monopole, monopole or bipole), operating DC voltage range (nominal, steady-state and dynamic range), control and protection principles.

Existing working groups within various institutions such as CIGRÉ, IEC and CENELEC are encouraged to work in close collaboration with focuses on development of guidelines, best practice and test methods taking the two aspects as mentioned above into account.

Question 3.2:

HVDC grids have become a very hot topic. Much research and numerous investigations on this topic are on-going. The potential realization of HVDC grids is, however mainly mentioned in conjunction with Europe. Are there any initiatives or plans for establishing HVDC grids in other regions of the world? Are there any plans to extend a point-to-point HVDC connection into a multi-terminal HVDC system, or to build multi-terminal HVDC systems?

If many point-to-point (PTP) HVDC links are planed in a region, a multi-terminal HVDC (MTDC) system would be a better solution with increased availability and reliability for power supply. MTDC can be further expanded into a future meshed DC GRID. PTP links can be designed to be expandable into a MTDC. The HVDC Project South-West Link in Sweden is an example of this. There are many other projects in planning for MTDC solution up to 5 terminals, not limited in Europe, but also in China, Brazil and USA. Examples are reported:

- Projects in Europe with multi-terminal functionality (all three-terminal): Shetland (UK), COBRA (DK-NL), Kriegers Flak (DK-DE)
- Projects in USA: Atlantic Wind Connector (AWC) 7 GW > 8 terminals
- Projects in China: Nan Ao 200 MW 4-terminal, Zhoushan 400 MW, 5-terminal
- Transmission schemes for large hydropower stations in Tapajos river in Brazil.

3.2 FACTS equipment for increased AC network performance

Question 3.3:

FACTS devices like D-STATCOM can provide significant support in terms of grid code compliance for integration of distributed generation into distribution networks. In addition to reactive power and voltage control, there are also other benefits such as harmonic filtering and flicker control from the use of the power electronics However, the investment cost of FACTS devices is often an obstacle to broader applications of FACTS systems in distribution networks. What is the available experience of commercial installations of FACTS devices in distribution networks? How is the cost-effectiveness of such schemes justified?

Thyristor based SVC and IGBT based STATCOM have been both used in T&D applications. Generally SVCs are still very cost-effective for applications with rated power bigger than 150-200 Mvar, whereas STATCOMs are in favour for applications with lower rated reactive power and faster response time. Another difference is the capability to withstand temporary overvoltages in network, where SVC shows generally higher capability than STATCOMs. On the other hand, overvoltages in distribution are usually lower mainly due to shorter distances compared to the TOV levels in transmission system. Therefore, STATCOMs become more and more an attractive device for distribution solutions, particularly if compliance with grid code for renewables and distributed generation is concerned. This is demonstrated by a project in Ireland as described in the Paper **B4-305**.

3.3 Embedded HVDC systems, including AC lines converted to HVDC operation, for increased network capacity and performance

Question 3.4:

Embedded HVDC systems can improve the stability and performance of interconnected AC networks. The latest development of VSC HVDC and availability of wide area monitoring & control systems opens additional possibilities to improve grid operations. Are there actual examples and operating experiences where improved system performance has been achieved by embedded HVDC systems? How can the features of VSC HVDC, such as immunity against commutation failure and voltage support during voltage drops, be effectively utilized for AC system support? What can be done to increase the trust and confidence in the new VSC HVDC technologies to get these technologies seriously considered during the planning stage of the systems?

Embedded HVDC systems have been often used for enhancing AC system performance. Successful examples exist in many LCC-HVDC schemes over decades. Power oscillation damping and emergency power/frequency controls are frequently used to increase the AC system stability. With improved controllability of VSC, it can be expected that VSC-HVDC can make an even better contribution to stability of interconnected AC systems. Cigre B4 is encouraged to continue to provide the technical guidance in this area.

One Discussion Contribution described the possibility of unsymmetrical polarity configuration in a VSC-HVDC scheme to utilize the different field strength around positive and negative pole conductors.

3.4 Use of Power Electronics to facilitate the integration of large renewable energy sources into AC networks

Question 3.5:

In order to comply with Grid Code requirements, the VSC HVDC schemes connecting large scale wind parks in North Sea are equipped with “braking choppers”, which decouples the offshore wind parks and the onshore AC grid during transient faults in onshore network by absorbing the power generated by the wind parks. What are the major design aspects and requirements for such “braking choppers”? What is the experience from the design, construction, testing and operation of such “braking choppers”?

The dynamic braking systems (DC Braking Choppers) have already been installed in the first generation of VSC-HVDC systems late 90’s. Their purpose is to control the dc voltage within a permissible band during fault events in the AC system. Such systems are usually realized with a combination of braking resistors and power electronic switches, located on the DC side of the onshore converter station. Different configurations have been reported. While a two-level solution uses one high voltage IGBT-switch in series with a resistor, a modular multi-level solution has a series connection of many identical chopper units, similar to the arrangement of multi-level converters. Both solutions have been realized in the latest VSC-HVDC projects in Germany.

Question 3.6:

One of the major advantages of VSC HVDC over LCC HVDC is the inherent capability to operate into a weak ac system. However, the conventional thyristor based LCC HVDC still has the advantage of lower converter cost and losses. A combination of VSC and LCC seems to be an attractive option for integrating large renewable energy sources, where both features are needed. Are there any investigations and considerations for an HVDC scheme utilizing both VSC and LCC converters? How can the control and protection functions be coordinated in a parallel or series connection of LCC and VSC? Are there examples of a STATCOM, rather than a synchronous compensator supporting the operation of LCC with a weak ac system?

Mixed LCC and VSC in the same pole of a HVDC system is technically possible, but is considered not to provide significant benefits, especially in case of connecting of large offshore wind parks. Parallel operation of LCC and VSC converters is, however, a more attractive option. Such configurations are already under construction, e.g. Skagerrak 4 Project (NO-DK) and Tres Amigas Project (USA).

Many examples have been reported about using STATCOM instead of synchronous compensator at a LCC-HVDC system connecting to weak ac system. The capability of dynamic reactive power support enables a stable operation of LCC and fast recovery after faults under weak system condition. Furthermore it provides the possibility to optimise the configuration of AC filters and capacitor banks in the LCC converter stations.

Session Closing Remarks by SC B4 Chairman

The Chairman of SC B4 summarized the discussion and thanked all contributors and attendants for valuable contributions and their interest in the session. Special Reporters expressed their appreciation to the contributors as well and appeals for more contributions & papers about FACTS applications in next Cigre Session.