B4 - 00

SPECIAL REPORT FOR SC B4
(HVDC and Power Electronics)

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Special Reporters

INTRODUCTION

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

A total of 26 papers have been selected in accordance with the three preferential subjects for the 2012 session. These papers introduce state-of-the-art practices of great interest regarding HVDC and FACTS system technologies. There is every reason to expect that recent progress on VSC topologies and HVDC grid concepts open up a new era of HVDC and FACTS applications. The information provided in the selected papers makes a valuable contribution to the continuing improvement and development of the HVDC and power electronic industry.

The preferential subjects decided by the Study Committee for the B4 2012 Sessions are:

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 A total of 13 papers were accepted for this subject, but paper **B4-104** was withdrawn.

1.1 Project planning, including environmental and regulatory issues

B4-103 "Planning the Next Nelson River HVDC Development Phase Considering LCC vs. VSC Technology" examines the technical feasibility of using voltage sourced converters (VSC) technology using 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, when considering the total injection of power by means of HVDC. The study was performed in PSS/E using a generic transient stability model and indicated that VSC technology is feasible and would not require synchronous condensers. As a consequence, it would save capital cost; operating and maintenance expenses. On the other hand, studies also indicated that DC fault recovery is slower and the frequency variation at the inverter due to rectifier AC faults is higher compared with LCC results. Some mitigation actions are recommended, including control modifications.

B4-110 "New French-Spanish VSC link" describes in detail the characteristics of the future VSC HVDC interconnection between France and Spain, the reasons that have led to the implementation of VSC technology, the conclusions obtained from the studies conducted to determine the future exchange capacities, the control strategies that will be adopted and the behaviour and operation of the DC link embedded in an AC network. The link, which is projected to cost 700M€, is scheduled to be in commercial operation in 2014 and will increase the exchange capacity between France and Spain from about 1200 MW to 3200MW.

Question 1.1:

For **B4-103** VSC technology was considered because it can operate in a much weaker network compared to traditional LCC HVDC systems. For **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?

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 frequency caused by remote rectifier AC faults for 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?

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?

1.2 Schemes recently completed or under construction

B4-105 "New Fenno-Skan 2 HVDC pole with an upgrade of the existing Fenno-Skan 1 pole" describes the project of the second pole of Fenno-Skan and the upgrade of the existent one. The 800 MW, 500 kV Fenno-Skan 2 transmits power between Rauma (Finland) and Finnböle (Sweden). The existing HVDC overhead line was upgraded to 500 kV. Due to the characteristics of this project, it has involved construction, upgrade and retrofit of converter stations, and construction and upgrade of the DC transmission line and the submarine cable. The paper discusses the different studies that have to be 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.

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 that can be used in Capacitor-Commutated Converters (CCC) HVDC systems in order to allow the connection 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. With appropriate sizing of the commutating capacitors, the converter can generate or absorb reactive power from the connected AC system. It is shown in the paper 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. Simulation results of Rio Madeira Back-to-Back system is used to illustrate the performance with this control strategy. The paper has concluded that the performance of CCC systems can be enhanced with the new control scheme.

B4-107 "Caprivi Link HVDC Interconnector: Comparison between energized system testing and real-time simulator testing" presents the results obtained from factory system tests and energized system tests. The Caprivi Link HVDC Scheme in Namibia is a 300 MW, -350kV VSC HVDC monopole with 950 km of overhead line. Extensive factory system tests were performed on the control and protection systems interfaced with a real-time simulator. The results are compared and discussed in the paper. The performance of the system during commissioning was similar to those obtained during the factory tests. The benefit of the extensive FST testing was that the commissioning time was minimised as no major change in the control settings were needed.

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. The continuous short–time overload current capacity was 1.5 pu. Some of this overload capability was used in 1989 when the bipole was up-rated to 1920 MW. Due to California's environmental policies, the need to upgrade the Intermountain HVDC system to 2400 MW arose in order to bring additional renewable power resources into the Los Angeles area. All stages of the project, starting with identifying the required modifications and ending with the system commissioning, are presented in the 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. 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. The paper describes the main points related to Bipole 1 and the Back-to-Back supply.

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. As previously discussed, this project involves various utilities and different suppliers. It is the first HVDC scheme in Brazil to be installed under the new regulatory framework granting transmission concessions through a 30 year period. The paper contains most of the data that it is usually needed by the B4 community and will probably be used as reference for future papers about Rio Madeira Project.

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?

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?

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?

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?

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 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?

1.3 Service experience of VSC, HVDC and UHVDC schemes

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 tubing for Bipole 2, replacement of the smoothing reactors for both bipoles and the implementation of a reliability-centred maintenance program. The effects of ageing on the availability are also discussed. Prior to 1998, maintenance works alone were responsible for an unavailability of 4.38%. In order to reduce the unavailability, a reliability–centred maintenance program was adopted. Planned maintenance unavailability was reduced to 0.62%, which is the expected maintenance unavailability of a brand new HVDC system. The main conclusions are:

- After approximately twenty years of service, major life extension measures may be required.
- The effects of the additional outages on the system requirements and the life cycle cost should be taken into account.

B4-102 "Commutation Failure Propagation in Multi-Infeed HVdc Systems" studies the susceptibility of the propagation of the commutation failures in existing HVDC links operating in "wheeling mode", where some of the HVDC terminals are operating as rectifiers while others operate as inverters. The commutation failure is normally associated with the inverter side. For multi-infeed HVDC systems a single AC fault may cause commutation failure in several systems. The paper describes that in "wheeling mode" the failure will propagate through a rectifier and may cause commutation failure in an inverter nearby. In the past, this type of event occurred in the Danish system, while it was operating in "wheeling mode". A detailed transient model of the AC/DC system was developed and validated in PSCAD/EMTDC and then a series of simulated AC faults were applied at the inverter terminals of the HVDC links. The commutation failure propagation was observed and compared against actual recordings obtained from the real system.

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. SGCC has 10 HVDC systems in operation and 3 new projects under construction, in March 2011. 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. The reliability of SGCC HVDC projects based on the frequency of outages is improving.

B4-113 "A survey of the reliability of HVDC systems throughout the world during 2009 - 2010" is a summary of the reliability performance of HVDC systems in operation worldwide during 2009 and 2010. This is the report of SC B4's Advisory Group AG-04 on the data collected annually regarding the reliability and availability of HVDC systems in operation throughout the world. The report contains statistics on frequency and duration of outages. Converter transformer failures continue to contribute a large proportion of the Forced Energy Unavailability (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. Converter transformer outages alone are responsible for 79.0% of the EOH during 2009 and 2010. AC equipment outages without considering transformers outages are responsible for 4.1%. For this period the major EOH was associated with one system.

Question 1.9:

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 (**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?

Question 1.10:

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?

Question 1.11:

In spite of all efforts done by SC B4 in the last years**, 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?

2. Preferential Subject 2: HVDC and FACTS Technology Developments

Preferential subject 2 provides a forum for presentation of new developments in HVDC and FACTS technology. 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.

2.1 HVDC converter stations

B4-201 "R&D Progress of ±1100 kV UHVDC Technology" presents the results of feasibility studies on the 1100 kV UHVDC system in China. The basic design concept of the main circuit including insulation coordination is discussed. According to the study results the 1100 kV HVDC station will consists of two 550 kV converter groups connected in series, which is the same topology as in existing 800 kV UHVDC system. In general the 1100 kV HVDC system including the overhead lines and station equipment has been considered as technically feasible.

B4-202 "Computationally Efficient Sub-Module Selection Scheme for Voltage Balancing Controller of Modular Multilevel Converter" addresses one of the most challenging aspects with regard to the control concepts for a VSC HVDC system based on the Modular Multilevel Converter. There are several methods to control and to balance the capacitor voltage at each individual sub-module to achieve the required performance at each control instant. With increasing operating voltage and thus the number of sub-modules, the computational intensity of controls will become very time-consuming and would be a bottleneck for dynamic performance. This paper proposes a sorting algorithm which minimizes the state change of sub-modules and improves the computational efficiency in terms of CPU time.

B4-204 "Requirements of DC-DC Converters to Facilitate Large DC Grids" presents a number of possible configurations for DC-DC converters, which may be helpful in realization of large DC Grids. According to this paper DC-DC converters may have potential use in following applications:

- Interconnection of two DC grids which have been independently developed with different operating characteristics.

- Connecting a common DC collector bus in a large offshore wind park directly to a DC transmission system at higher operating voltage
- Connecting existing LCC HVDC systems to future VSC DC Grids

Some of these situations may require DC-DC converters, which as explained in this paper can be realized with modular multilevel converters.

B4-205 "A 24 MW Level Voltage Source Converter Demonstrator to Evaluate Different Converter Topologies" presents a 24 MW Back-to-Back voltage sourced converter demonstrator at one manufacturer's facility. The purpose of this full-scale demonstrator is to validate the design of modular multi-level converter or its possible variants. Various design details of this demonstrator are explained in this paper. Possible future extension of test facilities for testing other converter concepts is also described in the paper.

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?

2.2 FACTS equipment

B4-203 "Development of High Efficiency D-STATCOM Using SiC Switching Devices" presents an investigation of circuit topologies suitable for D-STATCOM in the power range of 100 kVA. The prototype D-STATCOM uses a modular multilevel converter with three levels of H-bridges. The switching devices are 1.2 kV SiC J-FET, which enables a high switching frequency of modules in order to achieve required voltage output without harmonic filters. Based on the results from a prototype system the authors of this paper estimate that a 100 kVA, 6.6 kV D-STATCOM can be realized with 3.3 kV SiC components in the same system configuration, and that it can be directly mounted on a distribution pole due to its light weight and small volume. The purpose of such D-STATCOM is to control voltage quality in a distribution network with increased use of distributed generators.

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?

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?

2.3 UHVDC equipment

B4-201"R&D Progress of ±1100 kV UHVDC Technology" presents the challenges and possible solutions in connection with 1100 kV UHVDC equipment. The R&D activities mainly focused on the high-end converter transformers and wall bushings. The feasibility of an 1100 kV HVDC transformer will be demonstrated with a mock-up configuration, which will go through type tests in year 2012. Due to the limitation of access roads it is not feasible to transport large equipment such as an 1100 kV transformer to the site. Therefore a solution with on-site assembly and testing is proposed for the converter transformers. The converter hall will be used for this purpose prior to the installation of the thyristor valves.

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?

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.

3.1 HVDC grids and multi-terminal HVDC systems

B4-301 "Multi-Terminal HVDC Grid with Power Flow Controllability" presents the concept of the DC power controller used in a multi-terminal dc grid. The power flow controller is a converter with bidirectional thyristors, which is inserted along a dc line to control the power flow within the dc grid. The features and benefits of the power flow controller have been evaluated in a 3 terminal grid. Then the demonstration progresses with a 7 terminal meshed VSC HVDC grid. The proper and stable operation of such DC grids has been validated through digital simulations.

B4-307 "Technical Guidelines for First HVDC Grids – A European Study Group based on an initiative of the German Commission for Electrical, Electronic & Information Technologies", dealing with the technical guide lines for HVDC grids, presents their first findings. The work of this study group focuses on the radial DC network (multi-terminal DC) consisting of VSC only. This paper provides a functional description of the study results developed in the study group covering areas such as principle of DC load flow, short-circuit current, fault detection and fault clearing.

B4-308 "HVDC Meshed Grid: Control and Protection of a Multi-Terminal HVDC System" presents results from digital simulation studies on meshed DC grids with focus on control and protection. The study has been performed with 5 terminals in a meshed grid structure. Study results demonstrated the feasibility to control a meshed dc grid both in steady state and dynamic conditions. Assuming that high speed telecommunication is available, a protection scheme based on differential criteria seemed to be one of the promising solutions in a multi-terminal dc grid.

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?

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?

3.2 FACTS equipment for increased AC network performance

B4-305 "Grid Code Compliance Support for Connecting Renewable Energy into Transmission Line Using D-STATCOM System" presents the capability of D-STATCOM to support grid code compliance at the connecting point of renewable energy systems in distribution networks. This is demonstrated in a project with a wind farm connecting to an existing distribution network. Only with the help of a ± 6 Mvar D-STATCOM could the grid code of local utilities be fully met.

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?

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

B4-303 "Application of HVDC to the Emergency Control of the Hybrid DC /AC ENTSO-E – IPS/UPS Network Interface" presents results from a study, which focused on the operation and emergency control utilizing special features of the HVDC interconnections. The study was performed for the interconnected ENTSO-E and IPS/UPS networks with embedded HVDC systems. Especially the benefits of the VSC HVDC during fault / voltage sags (immunity to commutation failure and providing voltage support) have been fully demonstrated in the digital simulations. With the help of wide area measurements and a special control algorithm it can be demonstrated that system stability can be effectively improved by active power modulation of the HVDC systems.

B4-304 "An Integrated AC-DC Multi-terminal Grid in the Western Mediterranean Basin – Development, Planning and Design Challenges" reports the results from studies on the development of a hybrid AC-DC grid across the Mediterranean area connecting the North African electricity system with the ENTSO-E. The system planning aspects of the networks involved have been discussed in detail. The need for further studies of technical and technological aspects has also been highlighted in this paper.

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?

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

B4-306 "Projects BorWin 2 and HelWin1 – Large Scale Multilevel Voltage-Sourced Converter Technology for Building of Offshore Windpower" gives an overview of the design aspects and electrical parameters of two large VSC HVDC projects under implementation. These systems connect large offshore wind parks in the North Sea with on-shore AC grids. Besides the modular multilevel converters there are also other new concepts highlighted in this paper. One example is a braking chopper utilizing a modular multilevel converter to absorb the wind energy during transient grid faults. Another example is a parallel connection of offshore transformers for the purpose of increased system availability.

B4-309 "Tres Amigas: A flexible gateway for renewable energy exchange between the three asynchronous AC networks in the USA" describes a multi-stage project with 6 HVDC Back-to-Back converter stations. The project under development will start with HVDC stations using VSC HVDC technology. In later stages, with increased system strength, the Back-to-Back converter stations will use the LCC technology. One of the key justifications for this project is to utilize the flexible interconnections for maximum use of renewable energy throughout the regional 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"?

Question 3.6:

One of 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?