

Cigre and Trends in Power Electronics for the Grid

Bjarne Andersen
Chairman of Cigre Study Committee B4
HVDC and Power Electronics



Contents

- **SC B4 Activites**
- **Present Status of HVDC System Technology**
- **Active SC B4 Working Groups**
- **SC B4's Contributions to HVDC Grids**

Abbreviated scope of B4



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

HVDC: Economics of HVDC, applications, planning aspects, design, performance, control, protection, control and testing of converter stations, i.e. the converting equipment itself and the specialist equipment associated with HVDC links.

Power Electronic for AC systems and Power Quality Improvement: Economics, applications, planning, design, performance, control, protection, construction and testing.

Advanced Power Electronics: New converter technologies including controls, new semiconductor devices, applications of these technologies in HVDC, Power Electronics for AC systems and Power Quality Improvement.



Strategic Direction of SC B4

- **Provision of unbiased information concerning research, development, design, performance, and life time management of HVDC Systems, FACTS systems and Power Electronics for AC networks and generation.**
- **Applications of HVDC and FACTS systems**
- **Creation of technical information to facilitate the development of HVDC Grids**

Active and recently completed WG's in SC B4

HVDC Grid related WGs omitted.

WG B4-38 -Simulation of HVDC systems. Completed -TB 563

WG B4-47 - Special Issues in AC filter Specification for HVDC. Completed - TB 553

WG B4.49 - Performance evaluation and Application Review of existing TCSCs. Completed – TB 554

WG B4.51 -Study of Converter Voltage Transients Imposed on the HVDC Converter Transformers.

WG B4.53. - Guidelines for procurement and testing of STATCOMs.

WG B4.54 - -Guidelines for Life Extension of Existing HVDC Systems.

WG B4.55 - HVDC connected Wind Power Plants.

WG B4.61 - General Guidelines for HVDC Electrode Design.

WG B4.62 - Connection of Wind Farms to Weak AC networks.

WG B4.63 - Commissioning of VSC HVDC Schemes.

WG B4.64 - Impact of AC System Characteristics on the Performance of HVDC schemes.

WG B4.38 Studies for HVDC systems

"Studies for Planning and Preparation of Technical Specification of an HVDC project" including

- Pre-project studies
- Studies required for development of technical specifications

"Studies performed during bid process"

"Post award studies" including

- Equipment rating studies
- System integration studies
- Factory Acceptance Test (FAT) studies

"Studies performed for commissioning"

"Studies over the Normal Operational Use of the HVDC system" including

- Transmission network planning and operational studies
- Post-disturbance analysis and remedial actions
- Pre-Specification and specification studies for new transmission or generation equipment

WG B4.47 Special Issues in AC Filter Specifications for HVDC



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

This report is An Addendum to

**GUIDE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS FOR
HVDC SYSTEMS- (Technical Brochure 139, 1999)**

- **Specification of network harmonic impedance**
- **Performance and rating of filters in the presence of pre-existing harmonics**
- **AC side – DC side harmonic interaction across the converter**
- **Current-based harmonic interference criteria such as IT product**



WG B4.49 - Performance evaluation and Application Review of existing TCSCs



- Fifteen TCSCs installed and in commercial operation were identified and evaluated.
- Most of the systems have been installed in new, long line applications to damp some unstable or marginally stable modes.
- It was found that the reliability of the installed systems for which reliability/availability information was made available has been remarkably good



Active WG's in SC B4 – 1

(not including HVDC Grid related WGs)



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECARAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

WG B4.51 -Study of Converter Voltage Transients Imposed on the HVDC Converter Transformers.

This WG was preceded by a JWG between B4 and A2 (transformers) which investigated the cause of a sudden and significant increase in the number of converter transformer failures. The JWG produced a design review guide and a document reviewing the failures and the exiting test requirement.

This B4 WG was initiated to re-examine the stresses experienced by converter transformers in LCC HVDC schemes.

The WG has performed a number of studies of steady state, dynamic and transient events.

The draft TB is currently in the SC review cycle.



Active WG's in SC B4 – 2

(not including HVDC Grid related WGs)



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECHEMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

WG B4.53. - Guidelines for procurement and testing of STATCOMs.

- This WG has gathered the knowledge of technical experts concerning the procurement and testing of STATCOMs.
- They are finalising a TB that will allow planners and utility engineers to specify and test the STATCOM such that it will offer safe, efficient and reliable operation.
- The TB is likely to be available in 2014

WG B4.54 - Guidelines for Life Extension of Existing HVDC Systems.

- Life assessment and life extension measure of equipment
- Guideline for identifying Techno-Economic life of major equipment
- Recommendations for Specification of Refurbishment of HVDC systems
- Testing of Refurbished/Replacement Equipment
- Environmental and Regulatory issues. Techno- Economic Analysis
- The TB is likely to be available end 2014



Active WG's in SC B4 – 3

(not including HVDC Grid related WGs)



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRAAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

WG B4.55 - HVDC connected Wind Power Plants.

Over-views of HVDC and wind turbine & power plant technologies and conceptual designs

Integration of HVDC and WPP, and Requirement specifications for HVDC and WPP

Study requirements, data, modelling & simulation requirements

Overview of HVDC connected off-shore WPPs

WG B4.61 - General Guidelines for HVDC Electrode Design.

An update of previous SC B4 work, taking into account new survey technologies and the experience gained on electrodes already in service.

Final WG editing and review of chapters in progress. TB expected to be available end 2014.



Active WG's in SC B4 – 4

(not including HVDC Grid related WGs)



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECARAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

WG B4.62 - Connection of Wind Farms to Weak AC networks.

- WG established in 2013. Will address concerns regarding reliable operation of PE driven wind generators , e.g. interactions with other PE based systems.
- Will look at classical and FACTS based solutions continuing previous work in Cigre.
- Will also look at tools and models for assessment of the impact of wind farms.

WG B4.63 - Commissioning of VSC HVDC Schemes.

- WG established 2013. The WG will review previous work by CIGRE and other relevant bodies. Focus on the VSC HVDC converter station and HVDC system.
- Identify and develop the stages, sequence and structure of commissioning, developing guidelines and recommendations for the complete process.



Active WG's in SC B4 – 5

(not including HVDC Grid related WGs)



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECARAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

WG B4.64 - Impact of AC System Characteristics on the Performance of HVDC schemes.

- WG initiated in 2013 in response to new HVDC technologies (LCC, CCC, VSC) and increasing use of HVDC and other PE within ac networks. Are SCR and ESCR still relevant measures?
- The WG will perform studies to assess the impact of SVCs, STATCOMS, TCSC and SC and the relevance of the traditional measures in different situations. The WG will also review previous work done, including multi-infeed studies. The WG may propose additional and/or alternative methods for the initial assessment of the impact of new installations.



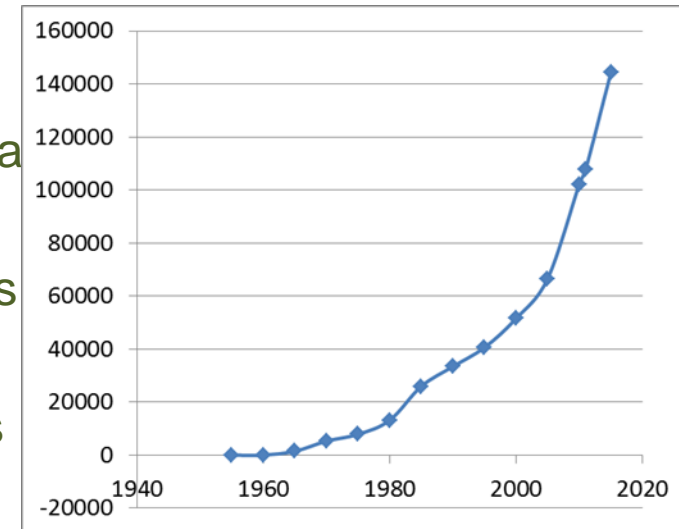
HVDC Technology - 1

HVDC Market is growing rapidly

- Growing electricity demand in India, China, Brazil and Africa
- Connection of Offshore and remote wind farms
- International power connections
- Increasing capacity in existing power corridors

Two HVDC Technologies

- Line Commutated Converters, based on thyristors and now being implemented at $\pm 800\text{kVdc}$, 7200MW, with $\pm 1100\text{kV}$, capable of >10GW being developed in China.
- Voltage Sourced Converter HVDC, based on IGBTs, now in Service up to $\pm 320\text{kVdc}$, 800MW and capable of up to 1200MW.
- There would be no insurmountable difficulties in the design of VSC HVDC converters for higher dc voltages.



Thyristor Valve and Converter Transformer for LCC HVDC

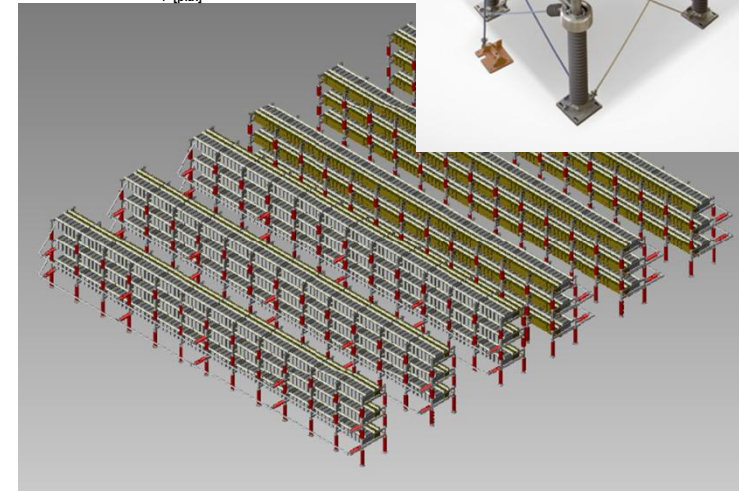
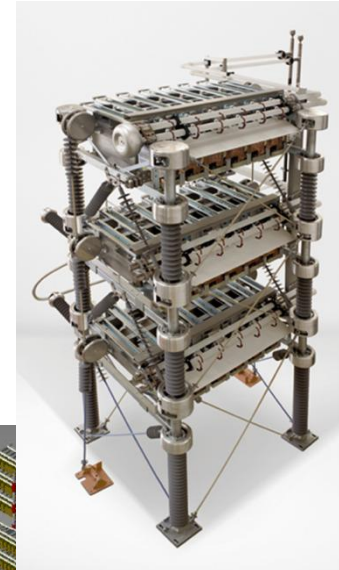
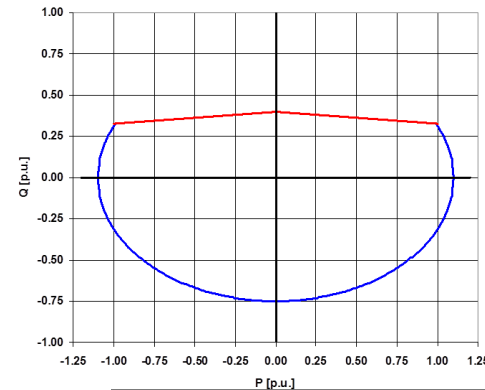
11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA



Elecrama, Bengaluru, January 2014

VSC HVDC Technology

- VSC HVDC provides independently controlled reactive power.
- VSC HVDC can operate into a passive ac network.
- Early generations of PWM VSC HVDC converters have been superseded by Multi-level converters, with lower power loss (~1%)
- Two multi-level topologies are possible, with cells using half or full converters, impact is on performance during dc side faults.
- Higher dc voltages can be implemented, and converters or IGBTs can be used in parallel to give higher MW rating.
- VSC HVDC is well suited to HVDC Grids, provided very fast dc breakers are available.

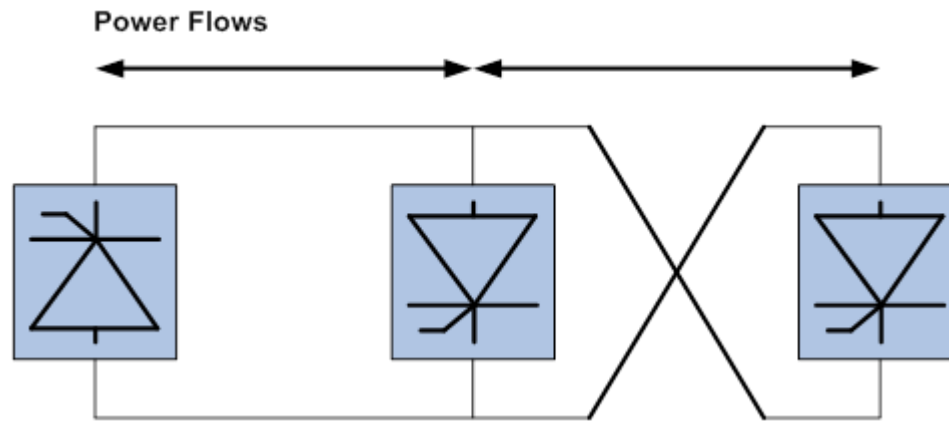
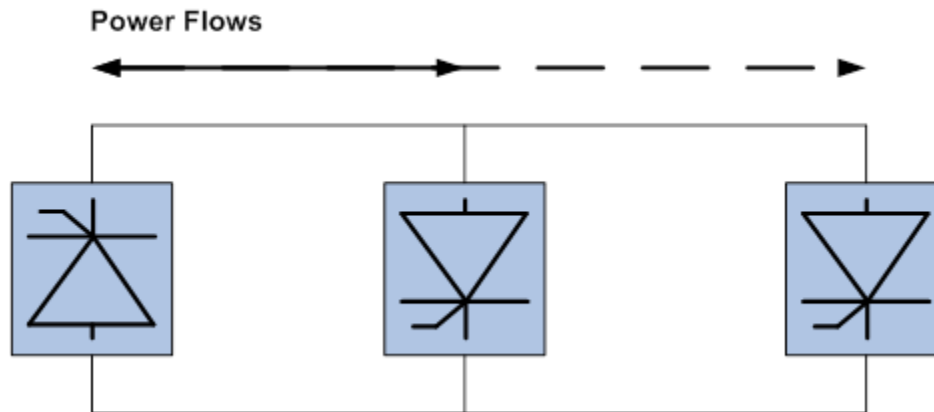


HVDC Systems

- Almost all HVDC systems are point to point schemes (OHL, cables or BtB).
- Two multi-terminal HVDC schemes with three terminals are in service. A further scheme is in construction in India –North East to Agra, 800kVdc, 6000MW.
- Why not more multi-terminal schemes?
 - LCC technology will suffer commutation failures for large ac network disturbances at the inverter terminal, resulting in brief interruption of power flow (about 100ms).
 - Power reversal for LCC HVDC schemes requires a dc voltage reversal – so some stations may need full HVDC withstand of both ends of each converter arm.
 - Whilst VSC HVDC does not suffer from commutation failures and do not require voltage reversal when power reverses, VSC HVDC technology is relatively new.

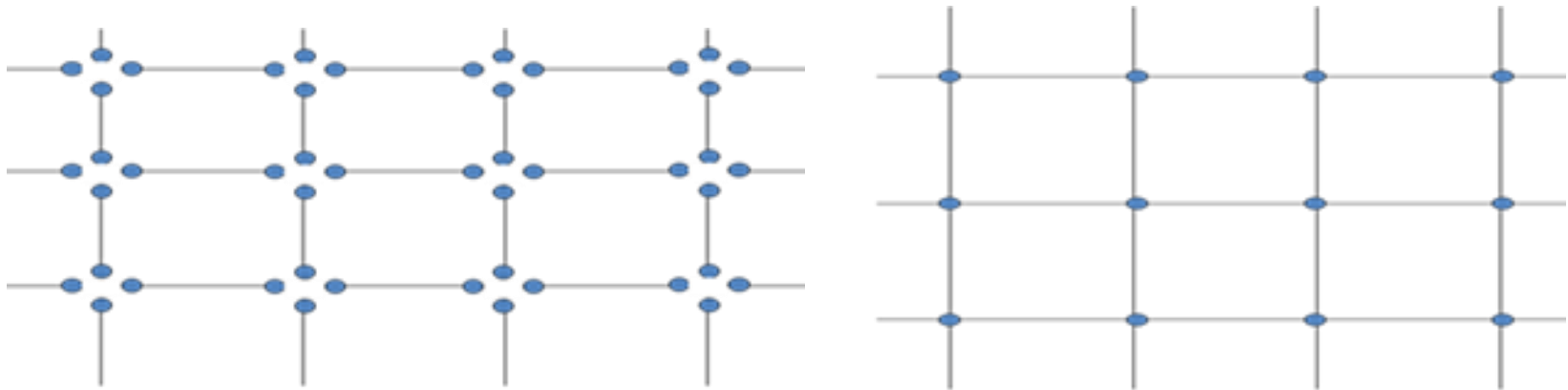


Multi-terminal with LCC HVDC



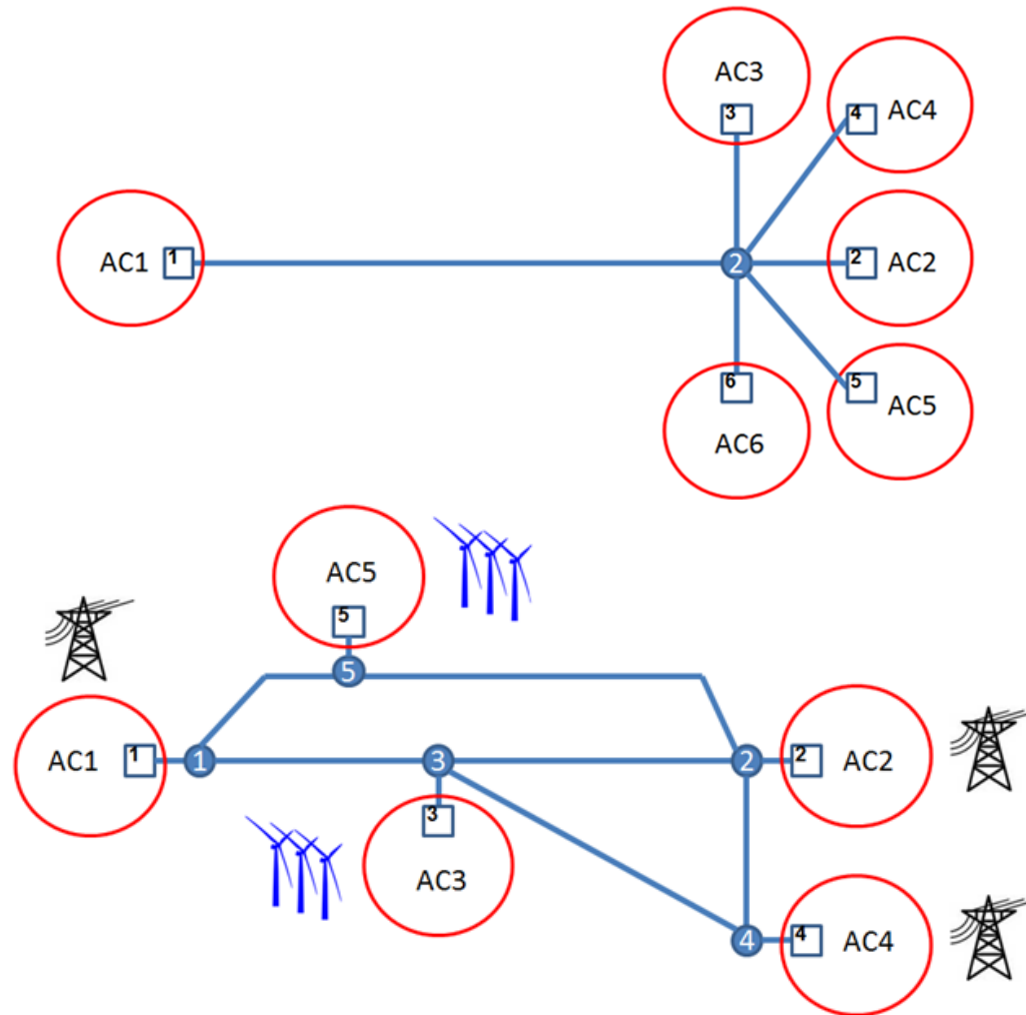
HVDC Grids

Because of the growing number of HVDC schemes and with many of the terminals for these in close proximity the idea of a HVDC Grid was born.

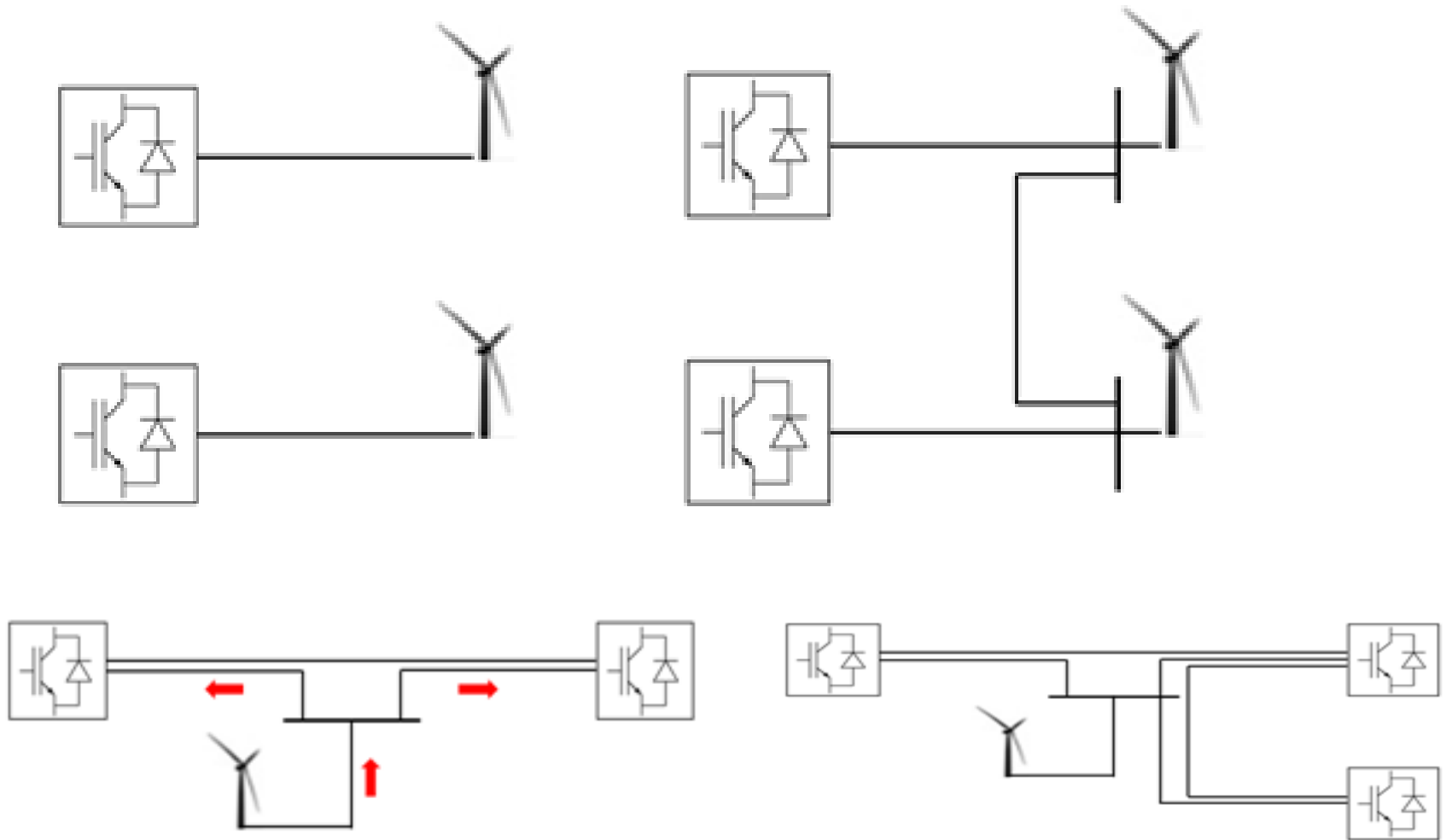


An HVDC Grid is defined in Cigre as an HVDC system consisting of at least three converter stations and at least one mesh formed by transmission lines.

Multi-terminal and HVDC Grid

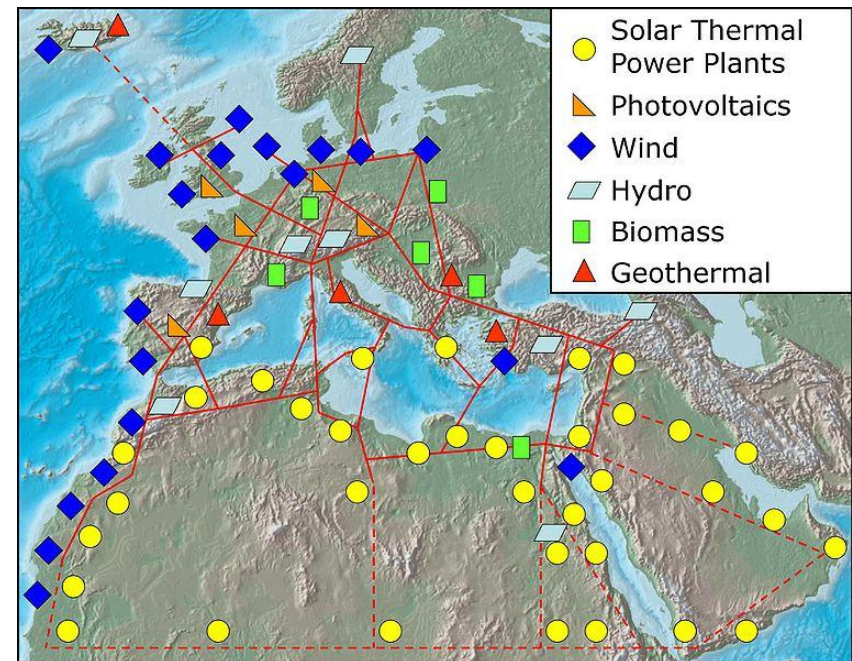


From Point to Point to HVDC Grid



HVDC Grids

- Several HVDC Grids have been proposed and are being investigated in Europe.
- The purpose of all of these are to increase the amount of renewable energy.
- Projects include:
 - The European SuperGrid
 - The North Sea Grid
 - The MedGrid
 - Desertec



HVDC Grids

- Cigre WG B4.52 studied the feasibility of HVDC Grids, resulting in Technical Brochure No 533, which concludes:
 - There are no insurmountable technical obstacles to building HVDC Grids.
 - HVDC Grids would provide a highly controlled overlay on AC grids, for the transmission of renewable energy and sharing of energy storage.
 - Special protection is needed in case of dc side faults to identify the faulty elements and disconnect the fault, before the dc grid collapses.
 - A Grid Code covering operational and performance aspects of HVDC Grids is necessary.



Challenges of a HVDC Grid

TB 533 identifies that the building of meshed HVDC Grids will result in a number of technical challenges. Examples of issues that have to be resolved include:

- The protection of the HVDC Grid.
- Functional control strategies for the HVDC Grid.
- Development of Central Co-ordinating Controllers.
- Development of modelling tools and generic converter models.
- The selection of a set of preferred DC Voltages for HVDC grids.
- The development of Grid codes for HVDC Grids.
- The development of benchmark tests for additional converter stations.
- The development of efficient DC/DC converters.

SC B4 WGs in the area of HVDC Grids



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECARAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

- WG B4.56 - Guidelines for the preparation of “connection agreements” or “Grid Codes” for HVDC grids.
- WG B4.57 - Guide for the development of models for HVDC converters in a HVDC grid.
- WG B4.58 - Devices for load flow control and methodologies for direct voltage control in a meshed HVDC Grid.
- JWG B4/B5.59 - Control and Protection of HVDC Grids.
- WG B4.60 - Designing HVDC Grids for Optimal Reliability and Availability performance.
- JWG B4/C1.65: Recommended voltages for HVDC grids.
- JWG A3/B4.34: Technical requirements and specifications of state-of-the-art DC Switching Equipment.



WG B4.56 - Guidelines for “Grid Codes” for HVDC grids.



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

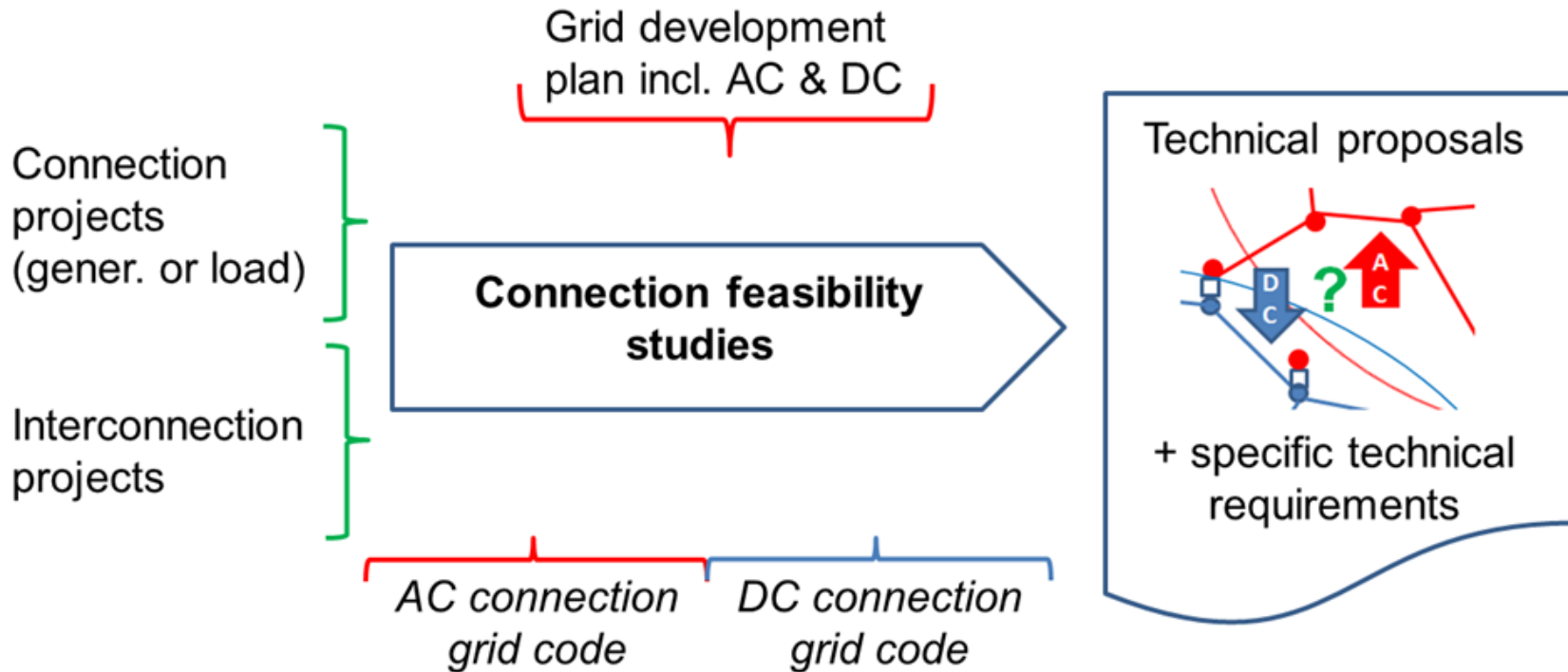
The TB will provide guidelines for the studies and documents necessary to prepare the following activities:

- The grid development plan of a power system including HVDC Grid solutions;
- The technical specifications of a HVDC Grid control and protection system;
- The technical performances of a HVDC Grid guaranteed to its users;
- The technical requirements for new equipment to be connected to a HVDC Grid, including high voltage and control and protection specifications;
- The requirements for the connection, testing and operation of new equipment to be connected to a HVDC Grid;
- The specifications of the data to be exchanged between individual equipment and the HVDC Grid central co-ordination control system.

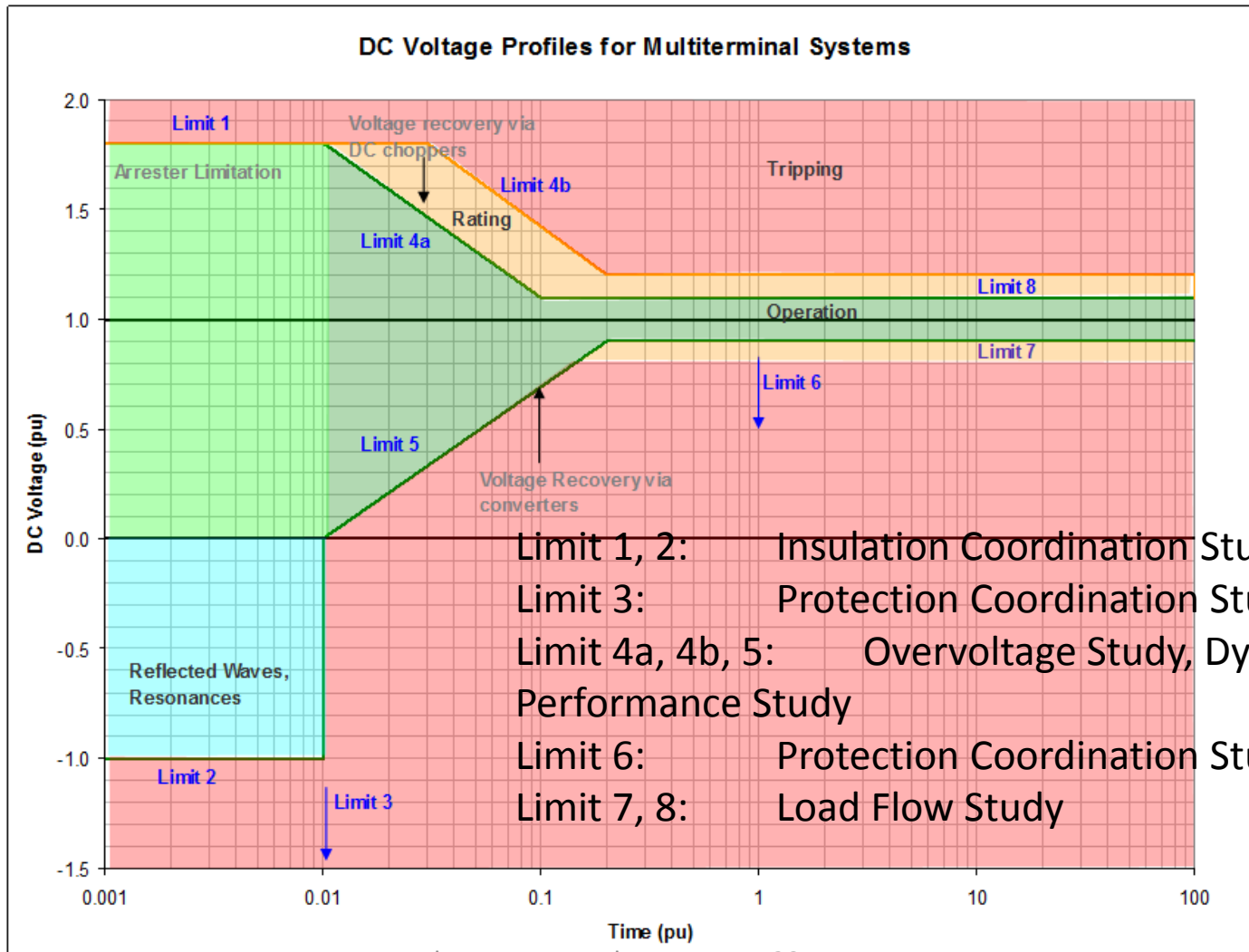
The WG is expecting to complete its activities in 2014



AC grid code and DC grid code from the TSO connection point of view.



Temporary DC Voltage Limits

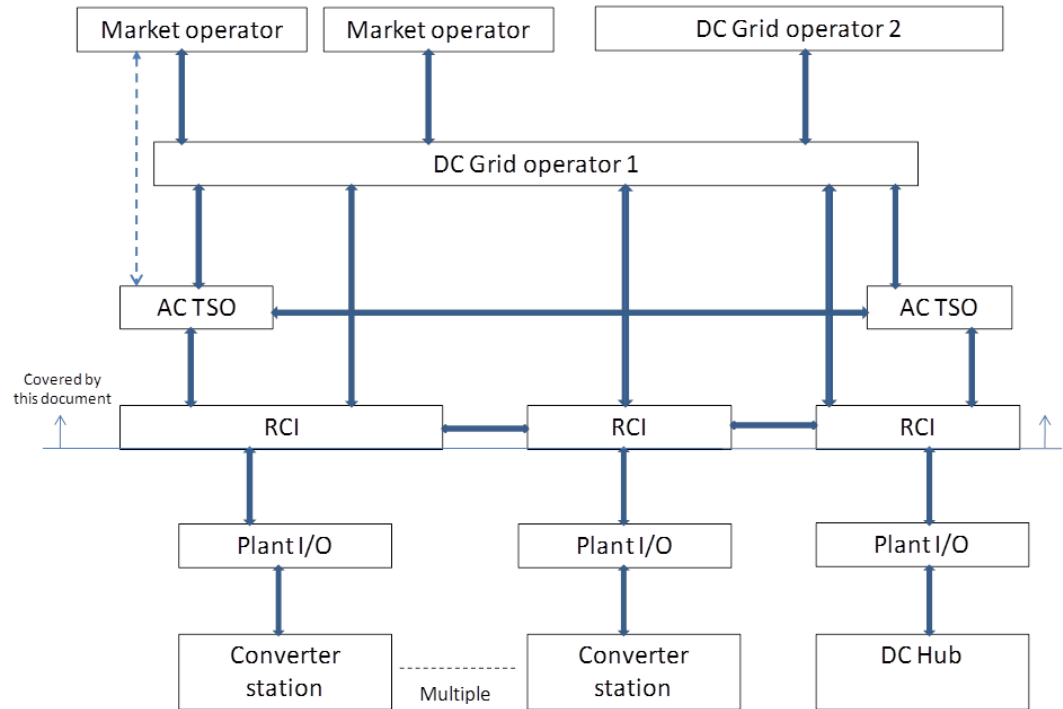


- Limit 1, 2: Insulation Coordination Study
- Limit 3: Protection Coordination Study
- Limit 4a, 4b, 5: Overvoltage Study, Dynamic Performance Study
- Limit 6: Protection Coordination Study
- Limit 7, 8: Load Flow Study

Data Exchange Requirements

Converter station/DC Hub – example signals

- Active power MW setpoint
- Reactive power MVar setpoint
- Active power MW actual
- Reactive power MVar actual
- Frequency
- DC voltage
- DC current
- Voltage Droop set point
- AC Circuit Breaker between HVDC subsystem and TSO status
- Converter deblocked/blocked status
- DC switchyard open/closed status
- Critical alarm status
- AC grid fault
- Maximum Station Capability status (MW & MVar)
- Transformer tap position (if applicable)



From: DC Grid operator

- DC grid Setpoints (Voltage & Current)
- Operational profile
- Maintenance outage
- Master/Slave to converter stations

From: AC TSO

- Active & reactive setpoints
- Emergency¹ frequency setpoint
- Emergency¹ Voltage setpoint (could be MVar setpoint)
- Emergency¹ MW setpoint

WG B4.57 - Models for converters in a HVDC grid.

- Modelling of the HVDC Grid and its converters and components, and studies using these models are an essential part of the planning of an HVDC Grid.
- Models will be needed for steady state dynamic and transient studies. Thus Phasor and EMT models will be discussed.
- It is recommended that models be separated into upper and lower level controls. These upper level controls are independent of the PE topology. The lower level controls system is very dependent on the PE topology.
- Models will need to be provided by different manufacturers, who will want to protect their IPR. The WG will be covering the protection of IPR.
- An HVDC Grid test system has been developed jointly with B4.58. The test system will be used by all WGs for their studies. Academics and researchers in HVDC grids are encouraged to use the test system.

Model Types

- Type 1 - **Full Physics Based Models**
- Type 2 - **Full Detailed Models**
- Type 3 - **Models based on simplified switchable**
- Type 4 - **Detailed Equivalent Circuit Models**
- Type 5 - **Average Value Models based on switching functions** - harmonics
- Type 6 - **Simplified Average Value Models** - controlled current and voltage sources.
- Type 7 - **RMS Load-Flow Models** steady-state converter outputs..

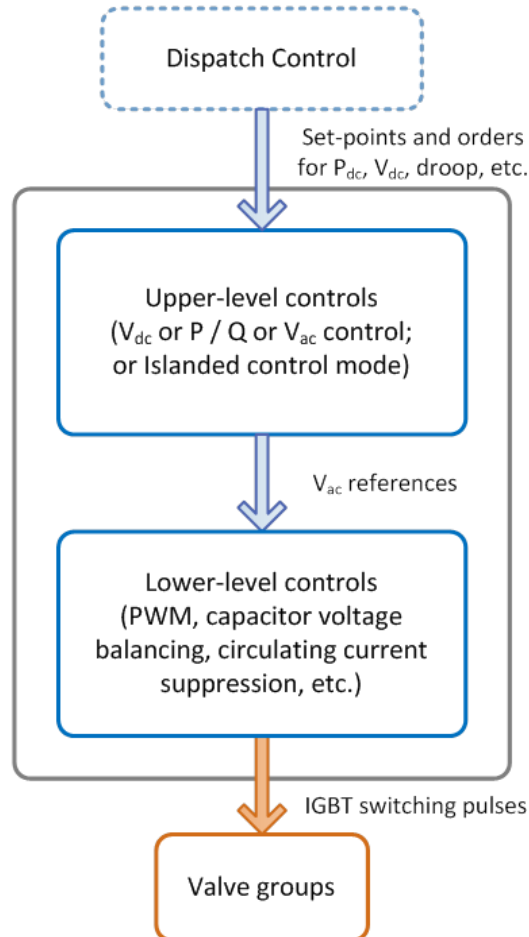
Models/Types of Studies

Detail of Model	Type of Studies	2 or 3 level PWM VSC	Half Bridge MMC (NLS)	Half Bridge MMC & phase shifted pwm	Full Bridge MMC	Hybrid Half & Full Bridge
Type 2/3 Traditional	Full EMT Transient	YES	NO EMT too slow			
Type 4 Detailed Equiv.	Full EMT Transient	NA	YES *	YES *	YES *	Topology and controls Need to be defined
Type 5 RMS with Gate Pulse	Fault and Harmonics	YES	YES	YES	YES	
Type 6 RMS	Fundamental Frequency only	YES			YES	Yes
Type 7 Phasor	Fundamental Frequency only	YES			YES	

Hierarchy Structure of VSC MMC Control Systems



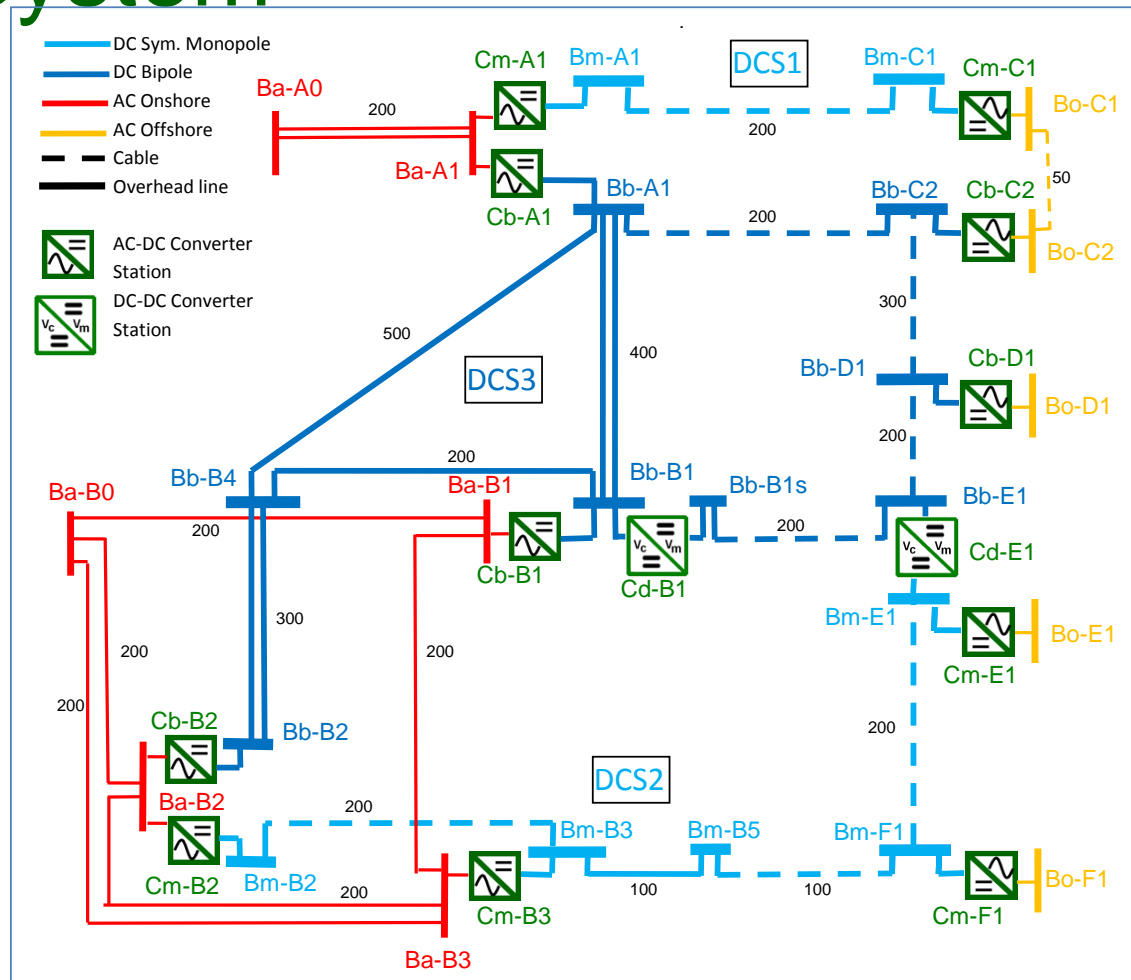
11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECHEMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA



The CIGRE B4 HVDC Grid Test System



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELEC RAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA



b4.cigre.org/Publications/Documents-related-to-the-development-of-HVDC-Grids

, Bangalore, January 2014

Model Security - Options

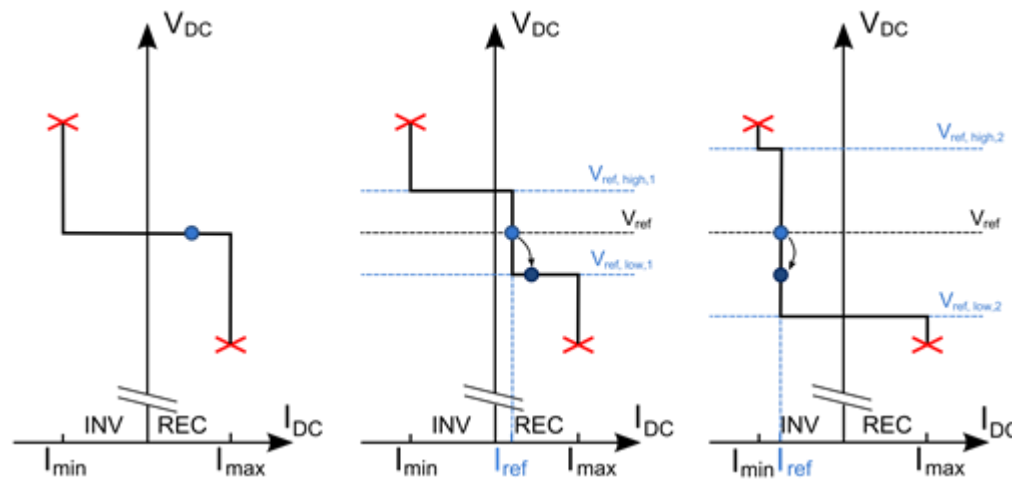
- Manufacturers provide open (generic) models of their particular systems for multiparty study. (Black Box)
- Password protection: locking system detail access with passwords or other authentication methods.
- Co-simulation: each owner/vendor simulates only a specific part of the system and this part is incorporated in a master simulation.
- Real-time HVDC grid simulator: a real-time simulator, connected to physical control system replicas,
- HVDC grid code: by establishing an HVDC grid code, model security is indirectly preserved as model sharing is not required, only compliance to the grid code.

WG B4.58 - Load flow control devices and dc voltage control methodologies

- DC Voltage control in a HVDC Grid is critical and must be fast, because of relatively low energy storage.
- Various dc voltage control strategy are being considered, with dead bands and the duty shared using droop controls.
- The branch power flow depends on the voltage difference across the branch, and the branch resistance. It is not possible to control all branch power flows.
- Branch power can also be controlled by insertion of resistance (power loss) or DC/DC converters. The WG is examining different types of DC/DC converters

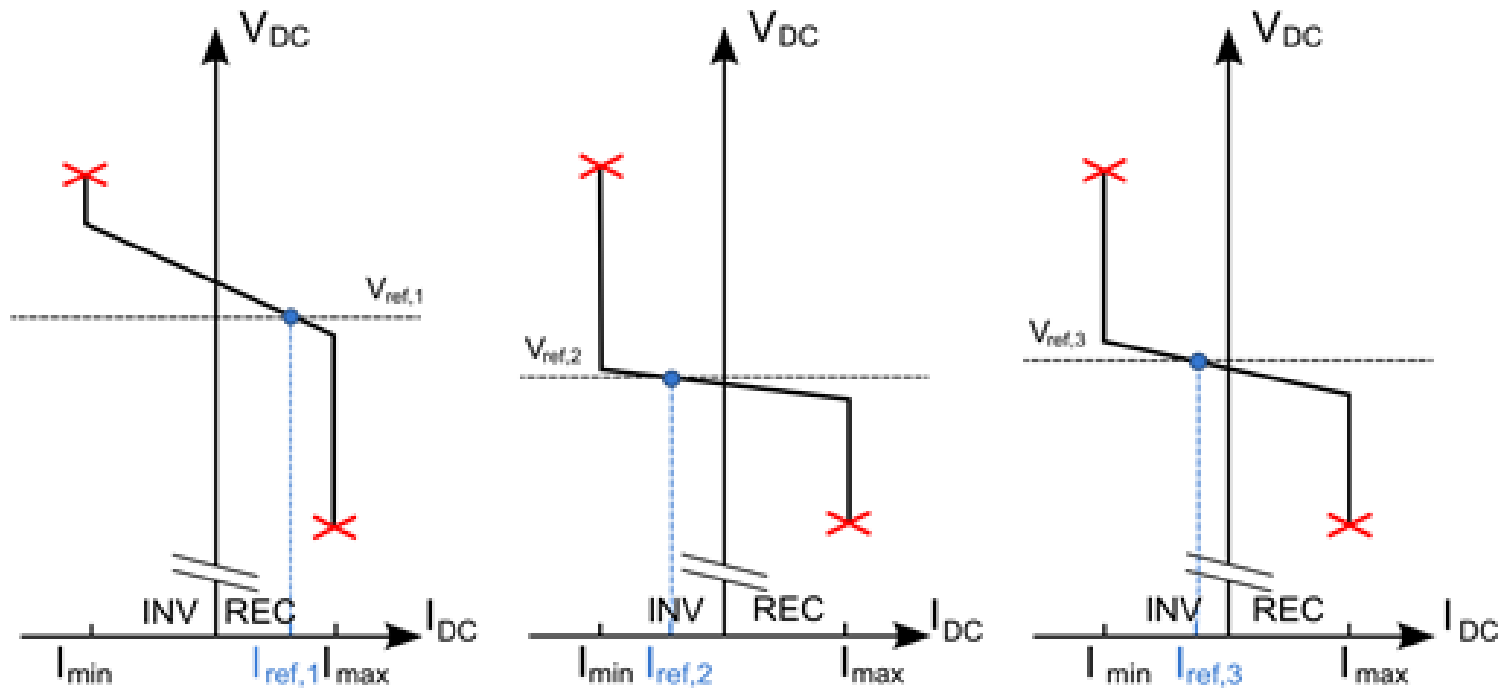
Voltage Margin Control

- Idc - Vdc characteristics of Voltage Margin Control.



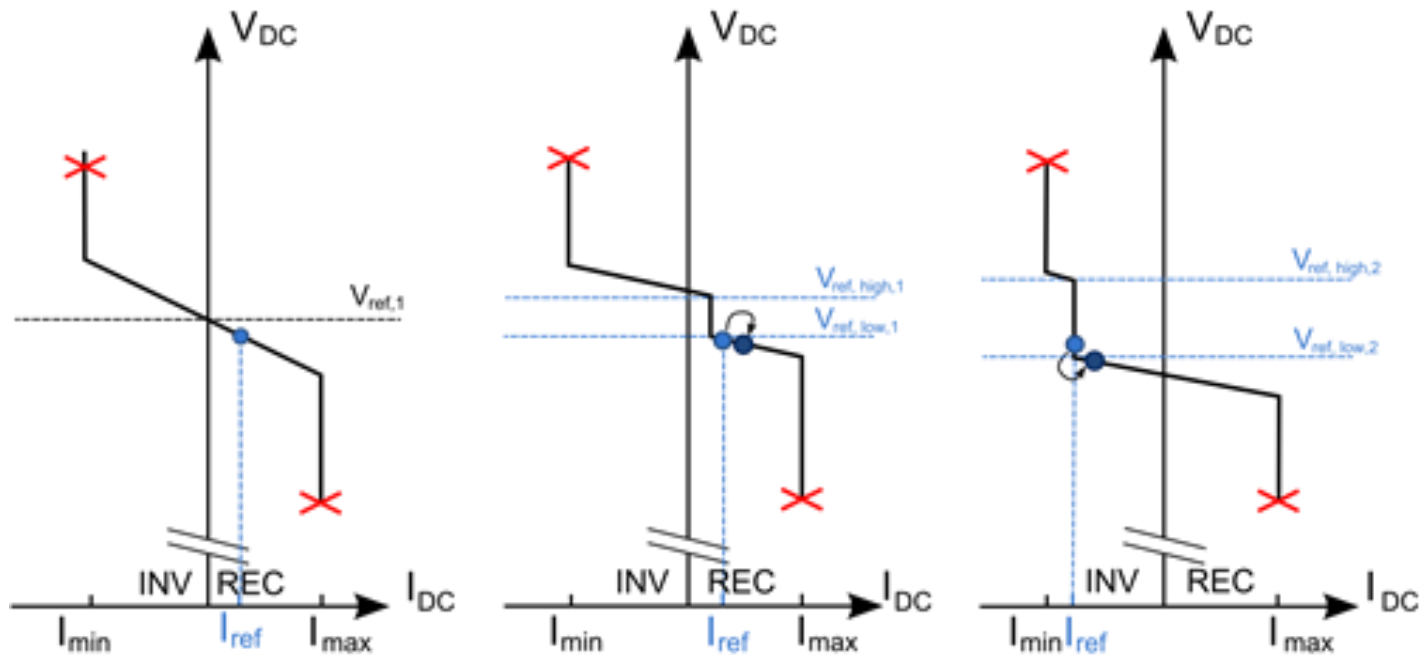
Voltage Droop control

I_{dc} - V_{dc} characteristics of the Voltage Droop Control.



Voltage Droop with Margin

I_{dc} - V_{dc} characteristics of the Voltage Droop Control with a voltage margin.



JWIG B4/B5.59 - Control and Protection of HVDC Grids

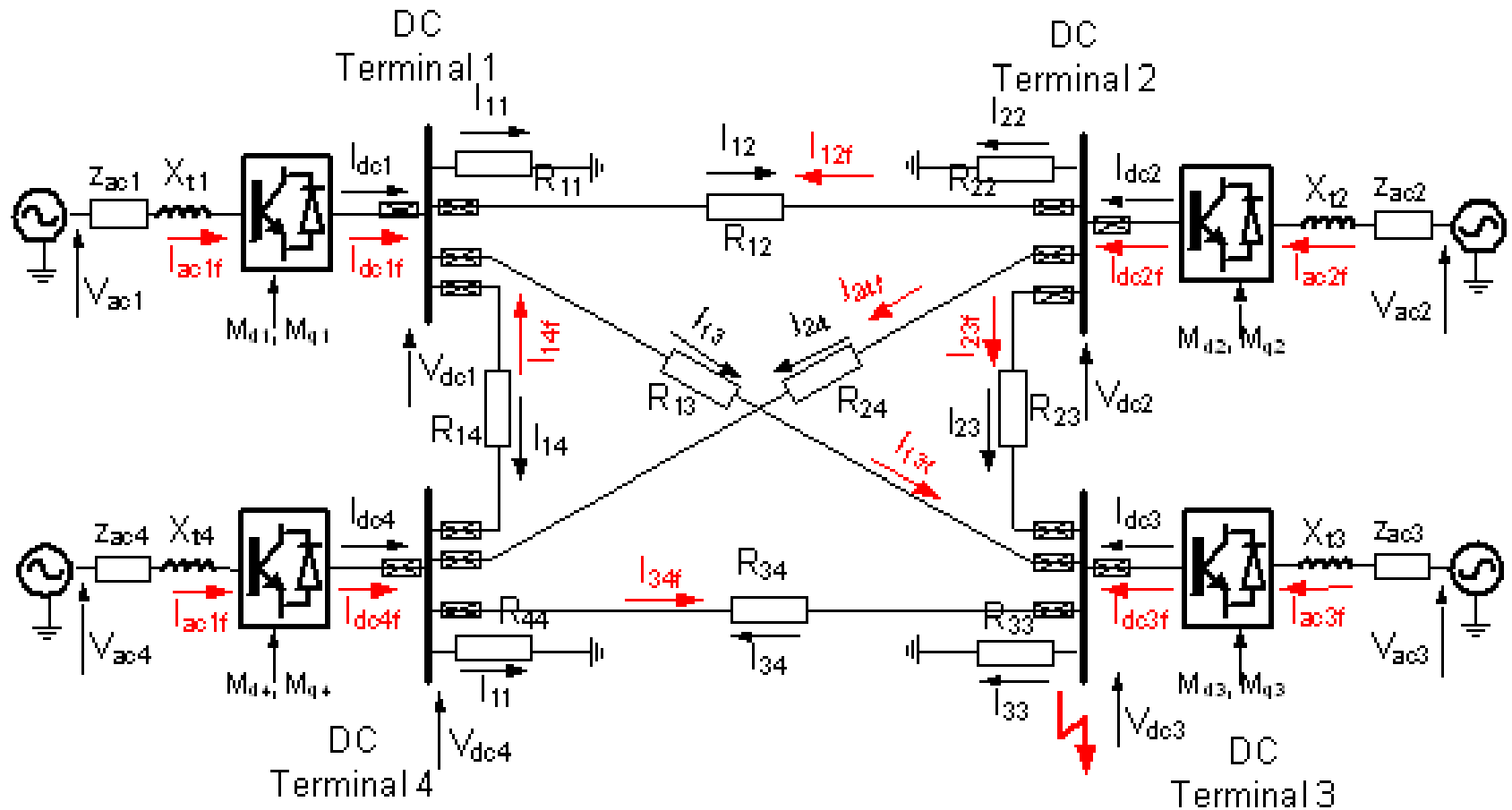


11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECARAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

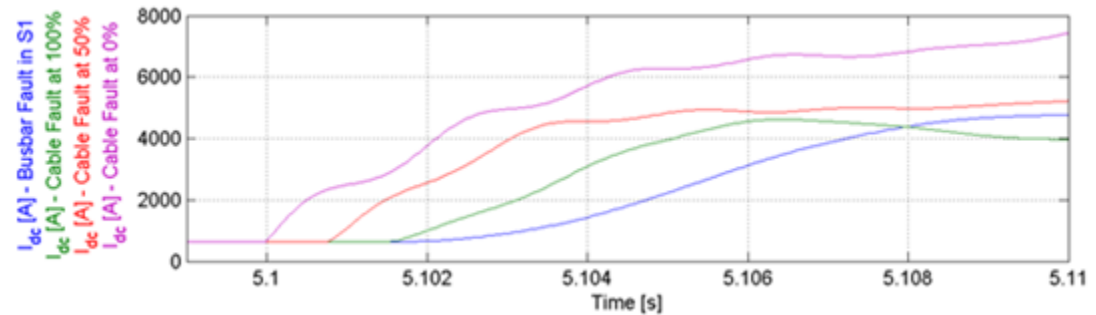
- Similar to an AC network selective, fast and reliable protection is key to good performance and high availability of an HVDC Grid.
- The protection of the converter station equipment is likely to remain unchanged.
- Typical Voltage Sourced Converters turn into a diode rectifier during faults on the dc side. Therefore dc side fault current can become very high. Cable section in the HVDC Grid can also contribute to high dc side fault currents.
- It is expected that faults on the dc side need to be cleared within 5ms, to prevent a collapse of the HVDC grid. This require power electronic devices. To reduce the power loss hybrid switches, including ultra fast mechanical switches may be used. Other alternatives are also being investigated.
- Alternative converter topologies, capable of blocking dc side fault currents, are being proposed for HVDC grids.
- Reactors may be used strategically within the grid to slow down the fault current increase, but result in additional power loss.



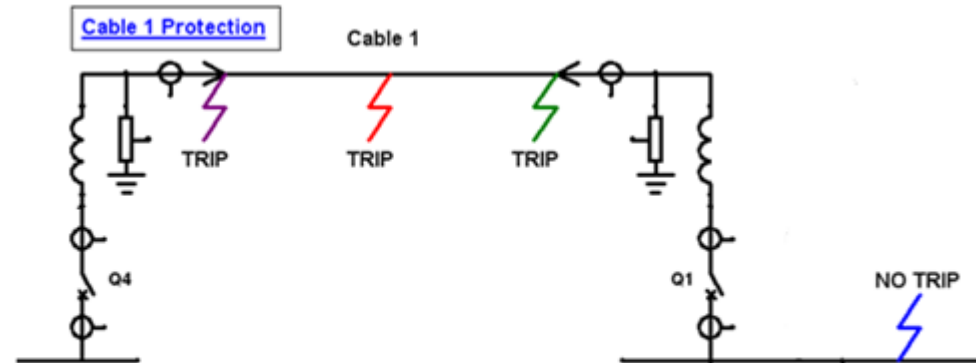
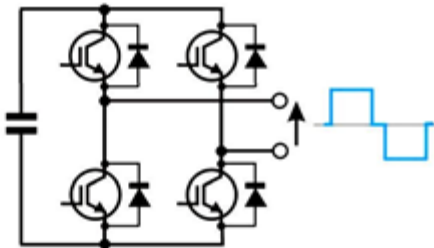
Short Circuit in HVDC Grid



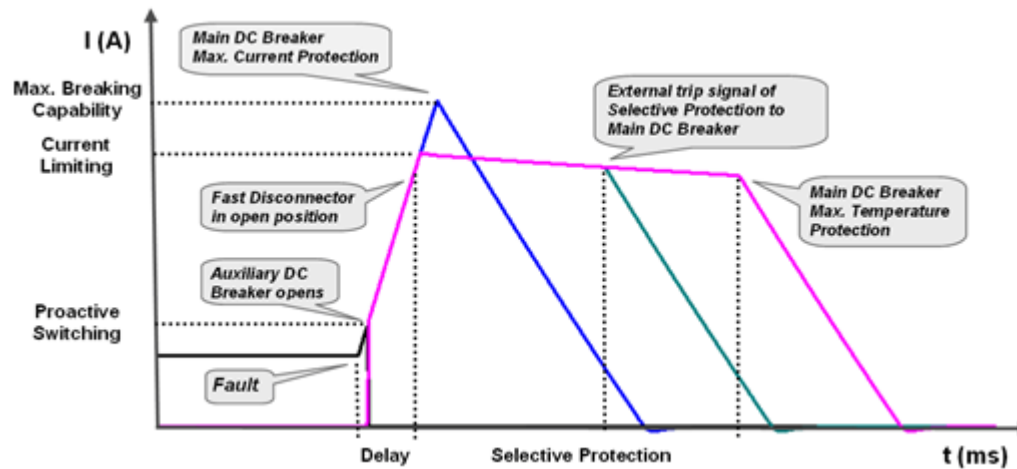
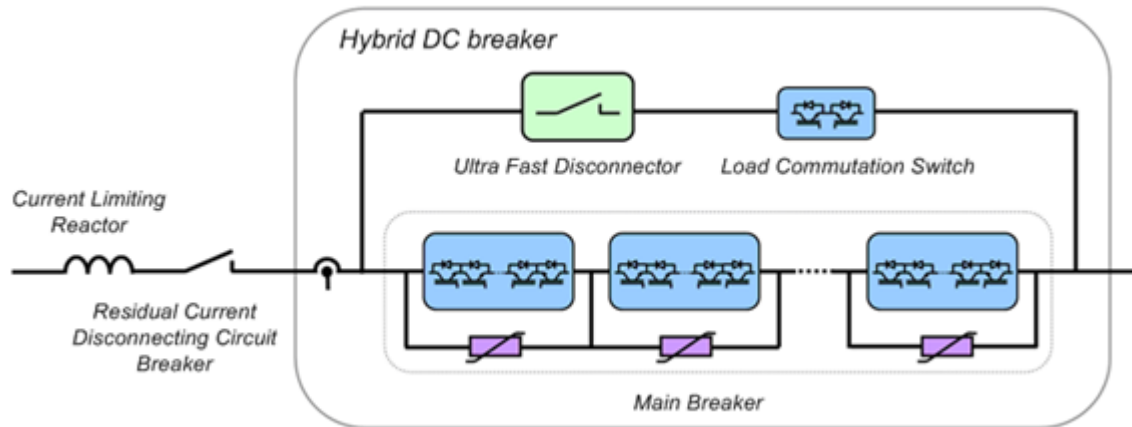
Fault Location Detection



Full-bridge module



Fast HVDC Circuit Breaker



WG B4.60 - Designing HVDC Grids for Optimal R&A performance

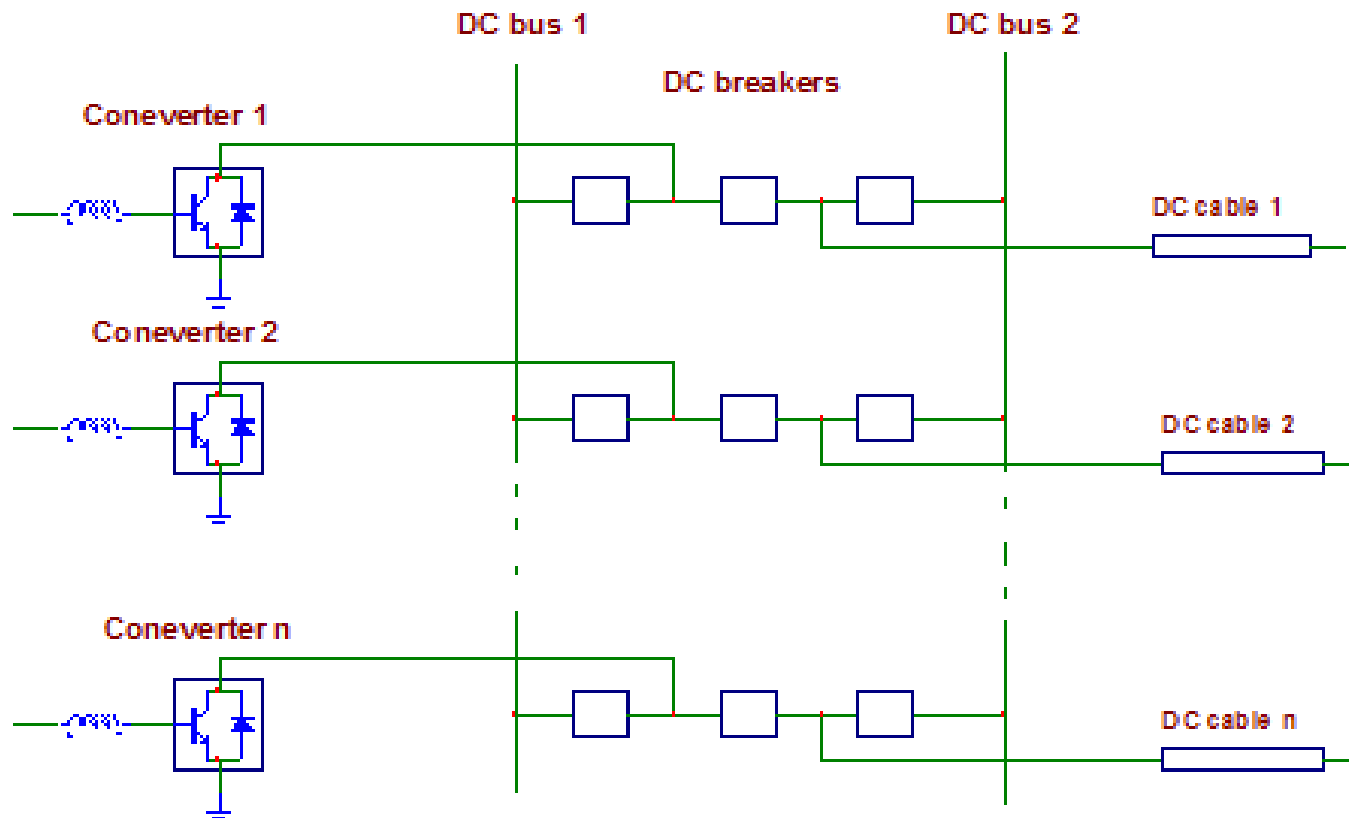


11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECRAMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

- **HVDC** Grid Reliability and Availability concepts will be quite different from those considered for point to point HVDC schemes. The WG will propose criteria derived from those used for ac networks.
- This WG is reviewing the impact on R&A of different HVDC Grid and converter topologies.
- Operating strategies, including spares holdings and maintenance is being considered.
- The impact of HVDC Grid protection strategies is being considered.
- The impact of converter and line outages is being considered.



HVDC Switchyard



SC B4 WGs in the area of HVDC Grids



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECHEMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

JWG B4/C1.65: Recommended voltages for HVDC grids.

- This JWG was established in 2013. It is considering only the pole to pole and pole to ground dc voltage.
- Recommended voltages may benefit HVDC developers wanting to future proof their investment. However, when it is unlikely that a scheme would become part of an HVDC Grid, the optimum dc voltage, and not the preferred dc voltage should be used.
- The JWG is expected to complete its work in 2015.

JWG A3/B4.34: Technical requirements and specifications of state-of-the-art DC Switching Equipment.

- The JWG was established in 2013. It will look at the mechanical parts of the dc side switchgear, including isolators, disconnectors, earth switches, and fast dc load switches and ultra fast dc circuit breakers.



Will HVDC Grids be Implemented?

- There is much lobbying from manufacturers and high political interest in Europe.
- HVDC Grids will be driven by increasing amounts of renewable energy, and the need for additional electrical transmission, and opposition to new OHL.
- Some of the issues delaying HVDC Grids include:
 - The magnitude of the investment which will be needed whilst economies are only slowly emerging from a recession.
 - Fragmented ownership of the existing HVDC schemes.
 - Uncertainty resulting from energy policies which in many countries are relatively short term.
 - Political issues associated with an HVDC Grid potentially covering many different countries, which may have different energy policies and security concerns.
 - The fact that an actual HVDC grid has not yet been built, even though the technical experts agree that there would be no insurmountable difficulties.



What can be done instead of/as well as HVDC Grids?



11TH INTERNATIONAL EXHIBITION OF ELECTRICAL AND INDUSTRIAL ELECTRONICS INDUSTRY
ELECHEMA-2014
8-12 JANUARY 2014, BIEC, BANGALORE, INDIA

- The transmission capacity on existing OHL corridors can be increased by the use of Flexible AC Transmission system (FACTS) devices. OHL capacity may also be increased by replacing conductor with higher ampacity conductors.
- Increasing power flow on lines is likely to result in the need for more dynamic reactive power control.
- FACTS devices provide a fast dynamic response, which can prevent ac system collapse or brown out.
- FACTS devices to be considered includes:
 - Static Var Compensator (SVC) – thyristor based – TCR/TSC solutions
 - Static Synchronous Compensator (STATCOM)– GTO/IGBT based – faster response, better low voltage support.
 - Thyristor Controlled Series Capacitor (TCSC) – Thyristor based – enable higher percentage compensation without Sub-Synchronous Interaction compare with Series Capacitor.



Other devices, e.g. SSSC, UPFC, etc are also available, but less commonly used.

Elecrama, Bengaluru, January 2014

Thank you very much for your attention!

Any Questions?

Dr Bjarne Andersen
Chairman of Cigre SC B4
Bjarne@AndersenPES.com

