

**417**

**Technological Assessment  
of  
800kV HVDC Applications**

**Working Group  
B4.45**

**June 2010**



# **Technological Assessment of 800 Kv HVDC Applications**

## **Working Group B4.45**

### **Members**

R N Nayak Convener (IN), R P Sasmal Secretary (IN), Mohammed Rashwan (CA),  
John Graham (BR), Dr. Hartmut Huang (DE), Victor Lescale (SE), Abhay Kumar (SE),  
Norman M Macleod (GB), ZeHong Liu (CN), Mr HongChao (CN), Yanny Fu (NL),  
Ian Grant (US)

### **Copyright © 2010**

*“Ownership of a CIGRE publication, whether in paper form or on electronic support only infers right of use for personal purposes. Are prohibited, except if explicitly agreed by CIGRE, total or partial reproduction of the publication for use other than personal and transfer to a third party; hence circulation on any intranet or other company network is forbidden”.*

### **Disclaimer notice**

“CIGRE gives no warranty or assurance about the contents of this publication, nor does it accept any responsibility, as to the accuracy or exhaustiveness of the information. All implied warranties and conditions are excluded to the maximum extent permitted by law”.

**ISBN: 978-2-85873-104-6**

TABLE OF CONTENTS

1.0	Introduction.....	1
1.1	Technology status and development.....	2
1.1.1	Converter configuration and rating.....	2
1.1.2	Ground electrodes.....	2
1.1.3	Reactive compensation & AC system requirement.....	2
1.1.4	Insulation co-ordination & Insulation levels.....	3
1.1.5	Interference levels.....	3
1.1.6	Control, Protection and Communication.....	3
1.1.7	Reliability and availability.....	3
1.1.8	Pollution and altitude aspects.....	4
1.1.9	Transmission line design.....	4
1.1.10	Station layout.....	4
1.1.11	Test requirements.....	4
2.0	Scope of the Working Group.....	5
3.0	Technology Status and Development.....	7
3.1	Converter transformers (including their bushings).....	8
3.2	Valves and valve halls.....	10
3.3	Wall bushings.....	12
3.4	High speed by-pass switches.....	13
3.5	High speed paralleling and de-paralleling switches.....	13
3.6	High speed DC neutral switches.....	14
3.7	DC isolators.....	14
3.8	Smoothing reactors.....	16
3.9	DC capacitors in DC harmonic filters.....	17
3.10	DC capacitors in DC PLC and RI filters.....	18
3.11	DC voltage dividers (DCVD).....	18
3.12	DC surge arresters.....	19
3.13	800 kVDC post insulators.....	19
3.14	800 kVDC Test circuit.....	20
3.15	AC switchyard.....	22
4.0	Converter Configuration and Rating.....	23
4.1	A bipole with one single converter per pole:.....	23
4.2	A bipole with two series converters per pole:.....	25
4.3	A bipole with two parallel converters per pole:.....	27
4.4	Transmission power larger than 6000 MW:.....	29
4.5	Neutral Bus configurations:.....	29
5.0	Ground Electrode.....	33
5.1	System considerations.....	33
5.2	Reliability considerations.....	34
5.3	Interference considerations.....	34
5.4	Design Criteria.....	35
5.5	Geophysical Methods.....	37
5.5.1	Survey Design.....	39
5.5.2	Electrode Line Design.....	39

6.0	Reactive Compensation and AC System Requirements .....	41
6.1	Reactive power absorbed by the converters.....	42
6.2	Reactive power compensation .....	42
6.3	Net reactive power interchange with the AC system.....	43
6.4	Limits on Reactive Power Interchange.....	43
6.5	Temporary Over-voltage Conditions .....	44
6.6	AC System Conditions.....	45
6.6.1	Sending End.....	45
6.6.2	Receiving End.....	45
6.7	Issues related to 800 kV .....	46
7.0	Insulation Co-ordination .....	47
7.1	Principles of HVDC insulation coordination.....	47
7.1.1	Insulation coordination for 800 kV HVDC systems.....	47
7.1.2	Converter Topology and Smoothing Reactor Arrangement.....	47
7.1.3	Smoothing reactor arrangement.....	48
7.1.4	Arrester arrangement .....	48
7.1.4.1	Converter transformer arresters type 'A2' .....	49
7.1.4.2	Converter group arrester type 'C1' .....	50
7.1.4.3	Converter group arrester type 'C2' .....	50
7.1.4.4	Mid-point arrester type 'M' .....	50
7.1.4.5	Smoothing reactor arrester type 'SR'.....	50
7.1.5	Arrester Arrangement for Parallel Valve Group Converter.....	51
7.1.5.1	Converter transformer arresters type 'A2' .....	51
7.1.5.2	Converter group arrester type 'C' .....	51
7.1.5.3	Mid-point arrester type 'M' .....	51
7.1.5.4	Smoothing reactor arrester type 'SR'.....	52
7.1.6	Insulation margins and withstand voltages .....	52
7.1.7	External Insulation .....	53
7.1.8	External Insulation of Outdoor DC Yard Equipment .....	54
7.1.8.1	Creepage distance .....	54
7.1.8.2	Shed form of housings .....	54
7.1.8.3	Corrections for altitudes.....	55
7.1.8.4	Minimum clearances / flashover distance.....	55
7.1.8.5	Height/length of the equipment .....	55
7.1.9	External Insulation of Indoor DC Yard Equipment.....	56
8.0	Insulation Levels .....	57
8.1	DC system parameters of two demonstration cases.....	57
8.2	Converter Main Data for Series Valve Groups.....	57
8.3	Converter Main Data for Parallel Valve Groups .....	58
8.4	Indicative protective levels and withstand voltages.....	58
8.4.1	Converter Station with Series Valve Groups .....	59
8.4.2	Converter Station with Parallel Valve Groups.....	60
8.5	Discussion of Insulation Levels.....	61
8.6	Withstand and testing levels of 800 kV main equipment.....	62
8.6.1	Converter Transformers .....	62
8.6.2	Thyristor Valves.....	62

8.6.3	Smoothing Reactors .....	63
8.6.4	Wall Bushings .....	63
8.6.5	800 kV DC Bus Equipment .....	63
9.0	Interference Levels.....	65
9.1	Purpose and Scope .....	65
9.2	Comparison of Electrical Environment of AC & DC Transmission Lines .....	65
9.3	Comparison of DC & AC Interference Effects.....	66
9.3.1	Electric and Magnetic Fields .....	66
9.3.2	Corona, Radio Interference (RI) & Audible Noise (AN) .....	66
9.4	Survey of Literature Published By Scientific and Health Organisations.....	66
9.4.1	WHO EHC (Ref. 2).....	66
9.4.2	Heath Council of Netherlands (Ref 5) .....	67
9.4.3	ICNIRP (Ref3, 6 &7).....	67
9.4.4	German Standards (DIN) .....	67
9.5	Survey of Technical Papers Related To HVDC Interference Effects.....	67
9.5.1	Paper on Environmental Characteristics.....	68
9.5.2	EPRI Report on HVDC Converter Stations for Voltages above 600 kV .....	69
9.5.3	Operating experience from HVDC test lines and transmission lines .....	69
9.6	Conclusion .....	71
9.7	Recommendations.....	71
10.0	Control and Protection .....	<b>Erreur ! Signet non défini.</b>
10.1	Control System.....	<b>Erreur ! Signet non défini.</b>
10.1.1	Operator Control Level.....	<b>Erreur ! Signet non défini.</b>
10.1.2	Converter Control and Protection Level .....	<b>Erreur ! Signet non défini.</b>
10.1.3	Field Level .....	<b>Erreur ! Signet non défini.</b>
10.2	Operation Modes.....	<b>Erreur ! Signet non défini.</b>
10.3	Provision for Master Control .....	<b>Erreur ! Signet non défini.</b>
10.4	Control Concept.....	<b>Erreur ! Signet non défini.</b>
10.4.1	Rectifier.....	<b>Erreur ! Signet non défini.</b>
10.4.2	Inverter.....	<b>Erreur ! Signet non défini.</b>
10.5	Control Functions.....	<b>Erreur ! Signet non défini.</b>
10.6	Protection Functions .....	<b>Erreur ! Signet non défini.</b>
10.7	Communication.....	<b>Erreur ! Signet non défini.</b>
10.7.1	Power Line Carrier (PLC).....	<b>Erreur ! Signet non défini.</b>
10.7.2	Optical Fibre Ground Wire (OPGW).....	<b>Erreur ! Signet non défini.</b>
10.7.3	Microwave .....	<b>Erreur ! Signet non défini.</b>
10.7.4	Satellite communication.....	<b>Erreur ! Signet non défini.</b>
10.7.5	Telephone systems .....	<b>Erreur ! Signet non défini.</b>
10.8	Control Issues related to 800 kV.....	<b>Erreur ! Signet non défini.</b>
11.0	Availability and Reliability.....	<b>Erreur ! Signet non défini.</b>
11.1	Review of some definitions .....	<b>Erreur ! Signet non défini.</b>
11.1.1	Energy Availability (EA):.....	<b>Erreur ! Signet non défini.</b>
11.1.2	Reliability.....	<b>Erreur ! Signet non défini.</b>
11.2	Major areas affecting Availability / Reliability .....	<b>Erreur ! Signet non défini.</b>
11.3	Overall Project Scheme.....	<b>Erreur ! Signet non défini.</b>
11.4	Requirements of Integrated AC / DC System.....	<b>Erreur ! Signet non défini.</b>

11.5	AC Switchyard Equipment .....	<b>Erreur ! Signet non défini.</b>
11.6	Equipment common to bipolar system .....	<b>Erreur ! Signet non défini.</b>
11.7	Electrode station design .....	<b>Erreur ! Signet non défini.</b>
11.8	Converter Transformer.....	<b>Erreur ! Signet non défini.</b>
11.9	Valve Hall .....	<b>Erreur ! Signet non défini.</b>
11.10	DC Switchyard Equipment .....	<b>Erreur ! Signet non défini.</b>
11.11	Control, Protection and communication requirement for both series and parallel converter groups.....	<b>Erreur ! Signet non défini.</b>
11.12	Auxiliary systems.....	<b>Erreur ! Signet non défini.</b>
11.13	Spares and maintenance .....	<b>Erreur ! Signet non défini.</b>
12.0.	External insulation: Pollution and altitude aspects for design.....	<b>Erreur ! Signet non défini.</b>
12.1.	Flashover process.....	<b>Erreur ! Signet non défini.</b>
12.2.	Operation experience .....	<b>Erreur ! Signet non défini.</b>
12.3.	Site conditions and test station.....	<b>Erreur ! Signet non défini.</b>
12.4.	Laboratory tests.....	<b>Erreur ! Signet non défini.</b>
12.5.	Means of improving pollution performance .....	<b>Erreur ! Signet non défini.</b>
12.6.	Recommendations.....	<b>Erreur ! Signet non défini.</b>
12.6.1	Surfaces.....	<b>Erreur ! Signet non défini.</b>
12.6.2	Profiles : .....	<b>Erreur ! Signet non défini.</b>
12.6.3	Creepage distances.....	<b>Erreur ! Signet non défini.</b>
12.7.	Altitude correction .....	<b>Erreur ! Signet non défini.</b>
12.7.1	Basic principles .....	<b>Erreur ! Signet non défini.</b>
12.7.2	Air parameters.....	<b>Erreur ! Signet non défini.</b>
12.7.3	Influence of air density .....	<b>Erreur ! Signet non défini.</b>
12.7.4	G-factor methods .....	<b>Erreur ! Signet non défini.</b>
12.7.5	Empirical proposal .....	<b>Erreur ! Signet non défini.</b>
12.7.6	Simplified approaches.....	<b>Erreur ! Signet non défini.</b>
12.7.7	Comparison of different correction methods and discussion	<b>Erreur ! Signet non défini.</b>
13.0	Transmission Line Design .....	<b>Erreur ! Signet non défini.</b>
13.1	Transmission Line basic configurations .....	<b>Erreur ! Signet non défini.</b>
13.2	Insulation Requirements .....	<b>Erreur ! Signet non défini.</b>
13.2.1	Internal overvoltages.....	<b>Erreur ! Signet non défini.</b>
13.2.2	Operating voltage.....	<b>Erreur ! Signet non défini.</b>
13.2.3	Specific leakage distance for various HVDC lines...	<b>Erreur ! Signet non défini.</b>
13.2.4	Tower head and Pole spacing .....	<b>Erreur ! Signet non défini.</b>
13.2.5	Lightning Performance .....	<b>Erreur ! Signet non défini.</b>
13.3	Corona related considerations.....	<b>Erreur ! Signet non défini.</b>
13.3.1	Conductor Surface Gradient .....	<b>Erreur ! Signet non défini.</b>
13.3.2	Corona Losses .....	<b>Erreur ! Signet non défini.</b>
13.3.3	Radio Interference and Audible Noise.....	<b>Erreur ! Signet non défini.</b>
13.5	Choice of Conductor .....	<b>Erreur ! Signet non défini.</b>
14.0	Layout of Converter Station.....	<b>Erreur ! Signet non défini.</b>
14.1	Function Blocks of Converter Stations.....	<b>Erreur ! Signet non défini.</b>
14.2	Layout of Converter Area .....	<b>Erreur ! Signet non défini.</b>

14.3	Layout of DC Yard .....	<b>Erreur ! Signet non défini.</b>
14.4	Layout of AC Yard .....	<b>Erreur ! Signet non défini.</b>
14.5	Layout of the Auxiliaries .....	<b>Erreur ! Signet non défini.</b>
14.6	General Layout of the Station .....	<b>Erreur ! Signet non défini.</b>
15.0	Test Requirement .....	<b>Erreur ! Signet non défini.</b>
15.1	Basis of test requirements .....	<b>Erreur ! Signet non défini.</b>
15.2	Test requirement of main 800 kV DC equipment.....	<b>Erreur ! Signet non défini.</b>
16.0	Summary .....	<b>Erreur ! Signet non défini.</b>
16.1	Transmitted power up to 6000 MW .....	<b>Erreur ! Signet non défini.</b>
16.1.1	One single converter per pole .....	<b>Erreur ! Signet non défini.</b>
16.1.2	Two converters in series .....	<b>Erreur ! Signet non défini.</b>
16.1.3	Two parallel converters.....	<b>Erreur ! Signet non défini.</b>
16.2	Transmitted power above 6000 MW .....	<b>Erreur ! Signet non défini.</b>
16.3	Current status of 800 kV DC technology.....	<b>Erreur ! Signet non défini.</b>
16.4	Conclusions.....	<b>Erreur ! Signet non défini.</b>

## 1.0 Introduction

In countries like India, Brazil, China, South Africa and Russia, large capacity hydro-electric projects are being developed with load centres at distances over 1500 kms. High capacity 800 kV HVDC systems ( $\pm 800$  kV or 800 kV) are being planned / under execution in China and India to evacuate power from large hydro electric generating stations. There are also indications that countries in the southern part of Africa are also exploring 800 kV HVDC systems. For such very long distance high capacity power transmission, HVDC power transmission at voltages of  $\pm 800$  kV would provide techno-economical advantages.

HVDC power transmission is an established technology for bulk power transmission over long distances from the generating stations to remote load centres. A number of long distance HVDC schemes are in operation at voltage levels of up to 500 kV such as Rihand-Delhi (1500 MW), Talcher - Kolar (2500 MW), Chandrapur – Padghe (1500 MW) Nelson River 2 (2000 MW), Three Gorges (3 x 3000 MW) and Pacific Intertie (2000 MW). However, Cahora - Bassa (1930 MW) HVDC transmission has been under operation at 533 kV since 1977, The highest DC voltage in the world is the Itiapu  $\pm 600$  kV, 3150 MW HVDC transmission system from Foz do Iguacu (at the border of Brazil and Paraguay) to Ibiuna, Brazil over a distance of about 800 km which is in operation for the last 25 years.

A study was carried out by CIGRE WG 14.32 in 2001 to determine the requirements for 800 kV HVDC systems. The CIGRE WG 14.32 report concluded that it is possible to build converter stations at 800 kV DC, provided the design is done specifically for 800 kV without extrapolation from the current DC voltage levels of 600 kV. The report indicated the following areas of concern for the 800 kV level:

- External insulation in polluted areas
- Converter transformers
- Smoothing reactors
- Availability of test labs

Work on development of 800 kV HVDC systems is being actively carried out by HVDC equipment manufacturers and converter transformers and 800 kV bushings have already been tested. With the experience of operating a number of HVDC power transmission systems up to  $\pm 600$  kV level and with the emerging technology developments, it can be considered that no major problem is expected for the design, construction of HVDC bipolar lines and converter stations of voltages up to  $\pm 800$  kV.

The report prepared by the earlier WG 14.32 at a time when none of the Utilities were planning HVDC transmission system beyond 600 kV. Although WG 14.32 did use 800 kV as the reference voltage, there were no actual projects at that time that were considering HVDC transmission voltage at 800 kV. Further WG 14.32 dealt only with converter stations for voltages above 600 kV and did not consider the HVDC line. However the situation today is different in view of the fact that there are several 800 kV HVDC projects that are being actively pursued and the equipment manufacturers have developed and tested equipment. In this context, CIGRE SC B4 has established WG B4-45 to assess the technology requirements for 800 kV HVDC systems.

This document makes a technological assessment of the 800 kV HVDC applications in evacuation of large amounts of power over long distances. It shall be of considerable value and benefit to the utilities and consultants who are responsible for power system planning and intend setting up HVDC schemes at 800 kV level.

Based on the past experience of the engineering and operation of HVDC stations up to 600 kV, the report has been prepared with various Chapters. A brief overview of each of the chapters which is given below:

## **1.1 Technology status and development**

This section deals with the development of various equipments for 800 kV HVDC stations. Due importance has been given to converter transformers as the failure of HVDC converter transformers has become an area of major concern and a subject of detailed introspection for many utilities for their system planning. The requirements of high speed DC switches which would play an important role in parallel converter configurations have also been discussed.

### **1.1.1 Converter configuration and rating**

The choice of converter configuration would be decided based on the philosophy of the utility on the staged construction of HVDC stations up to 800 kV and also techno-economic evaluation of various options of stage wise investments. This section considers both series and parallel configurations and their relative merits and demerits.

### **1.1.2 Ground electrodes**

The chapter discusses the electrode schemes and the requirements of site resistivity measurements.

### **1.1.3 Reactive compensation & AC system requirement**

Reactive compensation and harmonic performance of a HVDC system play an important role in a power system. HVDC converters consume substantial reactive power and necessary support / facilities should be provided within the converter

station. The chapter discusses the necessary steps to ensure proper integration of the reactive power requirements of the HVDC station with the connected AC system.

#### **1.1.4 Insulation co-ordination & Insulation levels**

Unlike AC equipment where required test values are well standardised, the required dielectric test values for DC equipment depends strongly on the station configuration design and insulation coordination study results for a specific project. Insulation Co-ordination for HVDC converter stations has followed the general principles established over the years and utilities have specified test levels based on the experience gained on several HVDC schemes operating at  $\pm 500$  kV. However, it has been observed that different utilities, have specified different test voltages for  $\pm 500$  kV HVDC systems. This report therefore makes an attempt to evolve a consensus among HVDC users and manufacturers for arriving at common insulation coordination rules for HVDC converter stations rated for voltages of  $\pm 800$  kV and above. In this regard issues such as effects of composite-voltage stresses, pollution effects, insulation margins and testing (levels and procedures) have been studied to arrive at common reference. Further efforts have been made to evolve converter configurations which lead to reduced equipment insulation levels for the purpose of economic design.

#### **1.1.5 Interference levels**

The chapter proposes guidelines for interference levels for 800 kV HVDC system based on information available from scientific organizations like ICNIRP & IRPA, WHO, etc.

#### **1.1.6 Control, Protection and Communication**

Large amounts of power would be handled by 800 kV HVDC system which calls for a robust and reliable control system. The chapter discusses the control requirements for various converter configurations.

#### **1.1.7 Reliability and availability**

The HVDC transmission forms a very important part of the power system. This chapter highlights the areas that are considered important to achieve high levels availability / reliability of the projects. The availability is also affected by the outages or disturbances in the system elements in which HVDC operates. Although, outages in the HVDC system that are on account of outages / disturbances in the rest of the system external to the plant being monitored are excluded while calculating the availability / reliability indices, however, these outages are important for the system as a whole. The factors which may results in outages of HVDC system due to external reasons can not be possibly eliminated but an attempt can be made to minimize these during the planning / specification preparation stage of the project.

### **1.1.8 Pollution and altitude aspects**

This chapter covers the aspects of pollution for the design of transmission line, selection of insulators for the converter station and transmission line. Another aspect of external insulation is the influence of altitude factor on design of transmission line and methods for altitude correction.

### **1.1.9 Transmission line design**

This chapter covers the different aspects to be studied in order to evaluate suitable characteristics for an 800 kV HVDC transmission line. To a very large extent the information given here has been developed by CIGRÉ JWG B2.17/B4/C1 and taken from as yet unpublished reports, listed in references.

### **1.1.10 Station layout**

This chapter covers the typical layout of converter station equipment and the area required. Further advantage of usage of different bus bar arrangement and space required under various schemes like GIS and AIS has been explained.

### **1.1.11 Test requirements**

This Chapter covers the dielectric test requirement for the 800 kV DC equipment, since other test requirement such as thermal and mechanical requirement as well as system test requirement are more specific project related. The required dielectric test values for DC equipment depends strongly on the station configuration design and insulation coordination study results for the specific project.

## **2.0 Scope of the Working Group**

The scope of work of the WG B4-45 approved by the Technical Committee is as under:

### Scope of Work

1. Examine the main circuit taking into account:
  - Converter configurations for 800 kV DC, i.e., series vis-à-vis parallel Configuration including staging of converters for future requirement
  - The rating of the converter station and its overload capability
  - Economic analysis for various options
2. Power transmission capacity of HVDC system with dynamic support for reactive power compensation. Consideration to be given to the use of conventional compensation vis-à-vis SVC/STATCOM or other electronic controllable schemes.
3. Assessment of technology with present status of development: that would include:
  - Thyristor valves
  - Converter transformers
  - Smoothing reactors
  - External insulation including bushings

This shall include testing requirement of various equipment including test voltage levels for lightning impulse, switching impulse and DC voltage test for all above equipment vis-à-vis present availability of testing facility

4. Insulation coordination, electric, magnetic field, interference levels for design of HVDC transmission system
5. Reliability and availability including redundancy considerations for;
  - Equipment common to bipolar system
  - Electrode station design and current rating
  - Transformer design consideration and review of design
6. Pollution design and insulator types for HVDC transmission system and remedial measures
  - Pollution design consideration
  - Insulator Types
7. 800 kV transmission lines design ;

- Line insulation and clearances
  - Conductor configuration
  - Tower configuration and design
8. Layout and clearances for indoor and outdoor switchyard
- Pollution consideration
  - Indoor and outdoor DC yard
  - Ventilation requirement for indoor yard
  - DC filter performance requirement in today's context

### **3.0 Technology Status and Development**

The development and status are described here for the components affected by going from 600 kV DC to the new voltage of 800 kV DC. The step affects, in essence, the equipment connected to the 800 kV DC bus, but some equipment on the ac side may be indirectly affected, without needing especially dedicated development efforts. The equipment covered is thus:

- Converter transformers (including their bushings)
- Valves and valve halls
- Wall bushings
- High speed by-pass switches
- High speed switches for paralleling / de-paralleling
- High speed DC neutral switches
- DC isolators
- Smoothing reactors
- DC capacitors in
  - DC harmonic filters
  - DC PLC and RI filters
- DC voltage dividers
- DC surge arresters
- DC post insulators
- AC switchyard

It may be noted that developing high speed DC neutral switches for 800 kV DC systems is not dictated by the pole voltage: the development is needed for the higher currents, 4 kA or more, that will appear in most 800 kV DC. Schemes with nominal currents in the order of 4 kA used to be limited to back-to-back schemes; however, for very large powers, even raising the voltage to 800 kV DC is not enough, and these high currents will affect several components.

It should also be noted that active DC filters are not included in the list. The interest in them has faded, since DC filtering requirements in most of the world have returned to levels commensurate with the needs of the surrounding telephone systems, and these performance levels can be achieved with passive filters.

Another item deliberately excluded from the list is gas insulated switchgear (GIS), including ducts for DC. GIS, even at lower DC voltages has proven to be very difficult, and thereby, also very expensive. Extrapolating from those experiences makes this type of switchgear even less attractive for 800 kV DC.

In general, it can be said that extending the technology from its present status at 500 and 600 kV DC to 800 kV DC is mainly a matter of being able to define the distribution of the higher voltage along larger dimensions. This is done by either having modules in which the voltage is graded with explicit resistors, or by compartments with resistive components in which the resistance is known. By doing

so, the unitary DC stresses on the materials can be kept within their respective design limits.

The same principles apply for the transient stresses, and these have to be graded by capacitive means. This is more widely regarded as usual, as the phenomena are present in ac equipment as well.

**3.1 Converter transformers (including their bushings)**

For converter transformers it is not really feasible to use explicit resistors for grading the voltage. The insulation is instead built up by a system with oil and paper. The DC grading is determined by the resistivities of these materials, while the transient and ac grading are determined by their permittivities. Refer to Figure 3.1

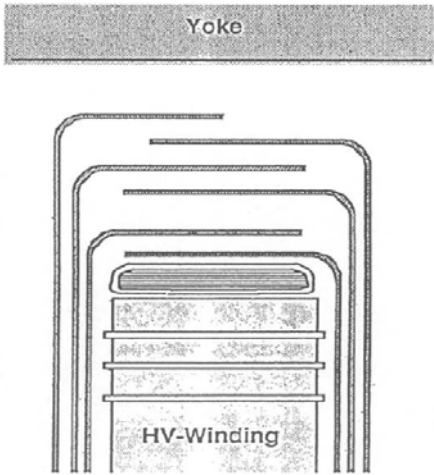


Figure 3.1. Transformer main insulation

Further developing the 500 and 600 kV DC transformer technology for coping with 800 kV DC meant revising the compartmentalizing of the volumes in the transformer insulation system.

The resistivity of the oil and paper in the insulation system changes with temperature and time. The latter has two aspects: on a longer perspective, aging; on a shorter perspective, one should remember that the current is not only carried by electrons but by ions as well, and the ion flow causes a depletion of free ions, which in turn affects the equivalent resistivity.

To begin with, a transformer prototype for the 800 kV DC group, with the characteristics highlighted, was tested in the laboratory at STRI, Ludvika. See Figure 3.2, and has been installed in an 855 kV DC long term test circuit, also at STRI, since November 2006 [6].



Figure 3.2: 800 kV Proto transformer under testing (Courtesy ABB)

Since then, actual 800 kV DC project transformers have been produced and successfully tested. An important part of the development process was to be able to

calculate the effect that many different conditions would have, at different temperatures, on the oil-paper system. This included the time variation of the stresses during eg, applied DC, polarity reversal, and applied ac. A tool for this kind of calculations is presented in [2].

Regarding the transformer bushings, the design is very similar to the ones being used for 500 kV DC. Since oil filled components are not desirable for the valve hall, new bushing have been designed without extrapolating from the existing 500 kV DC bushings. In the design for 800 kV DC, the main insulation on the external side; i.e., on valve hall side, is by gas, enclosed in a composite insulator body. On the inside of the transformer the interface is a capacitive core without housing.

The higher nominal current is also very important for this component, and was an important part of the total development work.



Figure 3.3-800 kV converter transformer bushing (Courtesy ABB)

The development design and the design for the projects under tendering as of this writing are for two winding transformers. This type is also expected to prevail in the future, as opposed to three-winding type. The latter would lead into serious transport difficulties, mainly because of the doubled MVA rating, but also because of the internal clearances necessary for the leads to the bushings.



Figure 3.4 – 800 kV Converter Transformer under testing (Courtesy Siemens)

### 3.2 Valves and valve halls

For the thyristor valves the situation is opposite to that of the converter transformers in the sense that it is possible to force the voltage distribution by the use of physical components in each part of the valves. For each thyristor position there is an auxiliary circuit comprising a snubber function, for distributing the transient voltages, and DC grading resistors for distributing the DC voltage as indicated in Figure 3.5. The components can be chosen so that the distribution of the voltages, transient or DC, will be as stiff as required to accommodate stray capacitances, leakage currents, etc..

This construction characteristic makes it possible to easily design valves for 800 kV DC with out major problems regarding the internal stresses. The matter is reduced to the choice of the number of thyristor positions. Each thyristor position is subjected to the same stresses, transient as well as DC, whether it is part of a 600 kV valve or of an 800 kV valve. The same applies to the stresses between the layers comprising the valve.

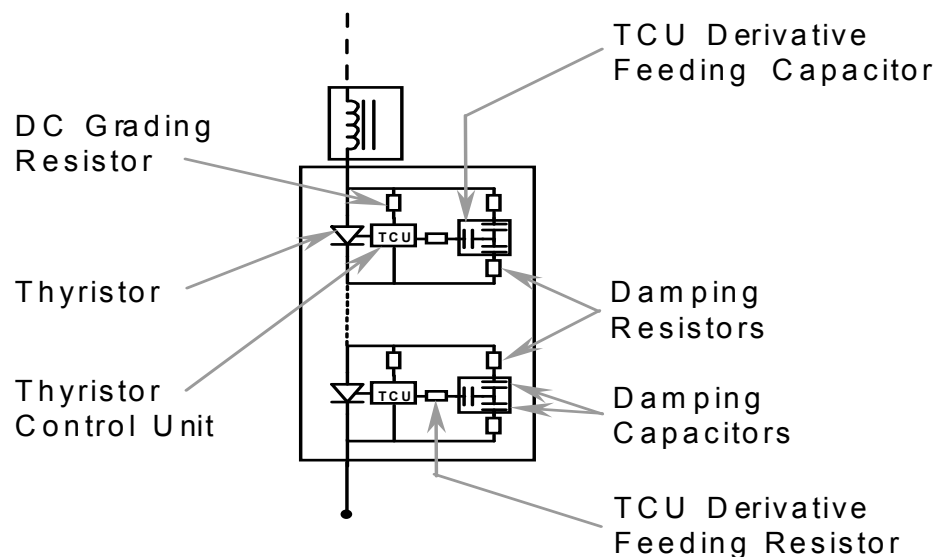


Figure. 3.5. The components of a thyristor valve.

The only consideration affected by the valve's higher voltage to ground regards the external stresses, namely, the air insulation to the walls, ceiling and floor. As is known, the necessary clearance for a given switching stress is not a linear function of it, and this aspect is more marked at higher voltages, making it imperative to:

- Select the forms of the valve external electrodes, usually called corona shields, very carefully, so as to obtain gap factors that are favourably large.
- Keep the insulation requirements as low as possible by judicious insulation coordination: careful choice of arrester locations, of arrester protective levels, and of insulation margins.

The external electrodes of the valves and bus work in the valve hall ensure that no corona will be present at normal operating conditions, but they have at least two other equally important functions, even if corona appears at transient overvoltages: they ensure that, for one, this will not affect the valve, and for the second, that the evenness of the fields inside the valve hall will be kept so that no breakdowns will occur.

At the very high switching type voltages expected, the shapes, locations and smoothness of the electrodes are extremely important, as found by extensive testing recently done expressly for 800 kV DC development [5]. The relative humidity in the valve hall shall be kept at or below 50%. During fast changes of temperature and humidity in the external ambient, a transient rise to not more than 60% can be accepted, as long as its duration is limited.

As the clearances are very sensitive to the voltage, it is interesting to consider the use of quadruple valves instead of double valves. The reason is that double valves require high insulation clearance for the 6-pulse bus, and this causes a low utilization factor of the space in the valve hall, especially for the configuration with series converters, in which the 6-pulse bus for the upper group has an equivalent 600 kV, and space has to be provided for 6 valves per converter group. Quadruple valves will only be three, and will only have equivalent 400 kV in one end.

For the parallel configuration the converters are connected directly between neutral and 800 kV, and the valves require even less clearance at the low voltage end, at 0 kV DC instead of 400 kV DC. This makes it even more attractive to use quadruple valves to avoid the clearances for the 6-pulse bus. For a real case, there may be additional considerations, other than just area and volume, especially the shape of the available land for the converter station.

An indirect difficulty caused by the necessary clearances in the valve hall is the mechanical precision and stability of the earthing switches inside it. If used, these have to receive special care to ensure that earthing will be properly accomplished without causing the valve hall dimension to increase inordinately to accommodate them. Else, the possibility to use earthing switches outside the valve hall can be examined on a case-by-case basis.

The thyristor valves are also affected by the large nominal and overload DC currents. Thyristors were developed for this application with the goal to keep the total number of thyristors down. The thyristors have to be able to cope with the high currents, and still keep a reasonable thyristor blocking capability voltage. The result of six-inch, electrically triggered thyristors (ETT), capable of handling 4.5 kA, and the corresponding overload and short-circuit currents, have been produced and tested.

### 3.3 Wall bushings

For the wall bushings at the 800 kV DC pole, the aspects given below have been found extremely important:

- Uneven wetting has to be avoided

This is very important, since it is not possible otherwise to control the voltage distribution on the outside of the external bushing.

A significant step in that direction is the use of surfaces that remain hydrophobic. It has been found that the most suitable solution is the use of a composite insulator body, with boron free fiberglass reinforcing, and silicone rubber sheds.

- The creepage distance and shed profile are critical.

It must be ensured that there will be enough creepage distance to cope with the expected pollution levels. In particular for the wall bushing, it is not possible to resort to a solution with indoor configuration: at some point in the circuit it is necessary to connect to the DC line pole. As for the shed profile, it must be chosen so that it will wash properly, and will not cause the gap between sheds to be bridged during heavy rain.

Horizontal bushings (at about 10~15° from horizontal) have the advantage that they get better washing with the rain, and have fewer problems with the water bridging the sheds, even in heavy rain. The first part may allow the use of somewhat reduced creepage distance, as long as the surface hydrophobicity is kept. The second part allows the use of shorter space between sheds, which in turn results in a shorter bushing for a given creepage distance.

For the internal design, it has been found that SF<sub>6</sub> insulation is the most appropriate material. It should be remembered that oil filled components in the valve hall are not desirable.

A wall bushing for 800 kV DC has been produced and has already passed type and routine tests at STRI in Ludvika, and it is now installed in the 855 kV DC test circuit already mentioned above.



Figure 3.6- 800 kV DC wall bushing during tests at STRI, Ludvika (Courtesy ABB)

### **3.4 High speed by-pass switches**

In the configuration with series connected converters it is necessary to use high speed by-pass switches. The reason is that it is not deemed acceptable to reduce the power of the pole to zero when connecting or disconnecting a group.

For these components, the function is the same as has been necessary since the old days, when mercury arc valve groups were connected in series to achieve the desired transmission voltage. The main difference is that at present, there have been developments in the materials and in the performance.

In normal operation, this component has to be able to withstand, on one side, the full pole voltage to ground, while on the other the voltage will only be half the pole voltage. This means that it will see half the pole voltage across its contacts.

When the switch is called upon to act under normal opening and closing manoeuvres, the valves will take care of the commutation stresses, and the component will only be a high speed switch, even if it will look very much like a breaker. Under emergency by-passing manoeuvres, there will be a make current which is higher than for a normal isolating switch, but limited to the current being regulated by the converters, which means it will be far below regular short circuit current duties. The necessary functions can be achieved today in a component without porcelain or oil. This allows its use inside the valve hall. The component may have two chambers, to be able to cope with the stresses.

### **3.5 High speed paralleling and de-paralleling switches**

In the configuration with parallel connected converters, it is necessary to use high speed switches to achieve the paralleling and de-paralleling functions. Again, the reason is that it is not deemed acceptable to reduce the pole power to zero to perform the manoeuvres.

Even though these devices resemble breakers, they are called switches, because they don't break any significant current: reducing the direct current to zero on a converter that will be disconnected is left to the valves. The switch will only have to break the leakage and ripple currents going through the converter's grading circuits and stray capacitances. These currents are negligible: the leakage current is very small by design, and the ripple current is small because the ripple voltage is quite small, and each converter has its own smoothing reactor.

The high speed requirement comes from two aspects that preclude the use of simple isolators:

- Sometimes, a faulty converter will have to be disconnected quickly because it is forcing down the whole pole; e.g. when it has an internal fault, rather than just a malfunction.
- When re-connecting a converter into a running pole the repeated arcs and extinctions that happen in an isolator when closing would put additional stresses on the converter valves. They would have to be designed for them. Rather than having a special valve design, or to bring the pole down for the manoeuvre, it is preferable to have high-speed switches.

### **3.6 High speed DC neutral switches**

These components will be located, as in transmissions of e.g. 500 kV DC, at the neutral, and are therefore not directly affected by the 800 kV DC at the pole. However, the higher currents expected for many of the coming 800 kV DC projects make it necessary to have switchgear that can manage the new requirements.

As a brief reminder, when the current in a path in a DC transmission is to be stopped, it has to be commutated to another path. To do this, the interrupter of the switch is opened to first commutate to an auxiliary LC circuit, which will in turn develop a counter voltage to force the current to commutate to the desired path.

For the interrupter to commutate to the LC circuit, its negative arc resistance is used to create a growing oscillation that will create a zero crossing in the interrupter.

For high currents, the most notable hurdle is that the arc characteristics of modern SF<sub>6</sub> interrupters are not very good for commutating direct current: At high currents, the arc voltage is in the hundreds, rather than thousands of volts, and its negative resistance almost or wholly disappears, depending on the temperature and pressure in the chamber.

A solution that is tested and robust is to pre-charge the capacitor in the LC circuit and to use an auxiliary switch to force the oscillation and the zero crossing(s). The added equipment (charger and auxiliary switch) is acceptable, but not very attractive. Development was therefore necessary to create the zero crossing and commutation without it.

### **3.7 DC isolators**

The real challenge in these components is similar to the one for the earthing switches in the valve hall, namely, the mechanical precision and stability needed for ensuring good contact. To begin with, the gap in the open isolator has to be large enough to manage the switching voltage requirements. The requirements on creepage distance to ground dictate, indirectly, very long support insulators for both sides of the isolators.

These two aspects combine to make it difficult to meet the stated challenge. At present, there are two approaches to solve it:

- Single break isolators

With multiple (three) support insulators on each side, and a movable arm with pantograph (semi- or full-) construction, either for horizontal or vertical operation. This approach is reliable and takes less space, as the gap is single, and the electrodes can easily control the fields to give a good gap factor. In addition, the triple support construction allows the use of Silicon Rubber Insulators



Figure 3.7 DC single break isolator (Courtesy Areva)

- Double break isolators

A rotating arm in the centre gives two gaps. All three support insulators (one at each end, and one for the rotating arm) are single. The approach gains mechanical precision and stability by having two smaller gaps instead of one, but the switching voltage distribution between them is rather uneven, and each gap is not significantly smaller than in the single break approach



Figure 3.8 DC Double break isolator (Courtesy Siemens)

If a converter station needs to be located in an area with much heavier pollution, at one point, it will be more convenient to opt for an indoor DC yard. Something similar can be said regarding the seismic level of the area in which the station has to be placed: at one point, it will be more convenient to opt for an indoor DC yard than to strengthen the insulators.

### **3.8 Smoothing reactors**

The solution arrived at present is with air core smoothing reactors. The reasons are discussed below:

Putting part of the smoothing reactor at the neutral and part at the pole reduces the ripple appearing at the upper converter, and allows the use of surge arresters with more stringent protective levels. This in turn reduces the necessary insulation levels at the upper converter. As explained above, the relationship between insulation and clearance is heavily non-linear, and reductions in insulation levels are strived for.

Splitting the smoothing reactor opens the question of how to handle the spares: If in oil, with one spare per station, the spare will have to be dimensioned for pole use, forcing an over-dimensioning. If in air, the spare reactor is only the coil and it can be used on either location.

There is an additional advantage of using air core reactors. Due to physical limitations in the production process, the necessary inductance for the expected currents will have to be produced in at least two coils per position. Having two coils per position improves the availability of the pole, since a failed coil can be by-passed, which can be done very quickly, without having to change the reactor to resume operation. The failed reactor can then be changed at a planned shutdown.



Figure 3.9- Air Core Smoothing Reactor under testing (Courtesy Siemens)

Another advantage is the possibility to test the reactors. With air core reactors, the LIWL voltage across each is not so large. With oil insulated reactors, testing for LIWL with an opposite DC voltage on the other terminal is not easy. It is not easy either to test with a LI consisting of the sum of  $LIWL + U_{DC}$ .

A not negligible argument in favour of air core reactors is the lower investment cost.

### 3.9 DC capacitors in DC harmonic filters

For these capacitors, the required levels of capacitance and the voltage rating, due to the DC stress and the harmonic voltage, the design will be with multiple capacitor units connected in series, also called strings, arranged in stacks, in a manner very similar to what is being done today for 600 or 500 kV DC. Care should be exercised, though, when defining the rated voltage of the capacitor, so that no undue margins are added. Present calculation methodologies permit rather precise prediction of the stresses in each capacitor unit and its internal capacitor elements, and for these large capacitors, the additional investment in engineering resources is easily justified by the savings it yields. The voltage grading along the strings is controlled by physical components. For the DC grading, each capacitor unit has resistors forcing the voltage, even accounting for the leakage currents in the unit bushings and in the stack's intermediate support or hang insulators.

Regarding transient grading, the string has the capacitances of the capacitor units, and these far exceed any stray capacitance. Extending the concept to 800 kV DC is thus easily achieved from the point of view of internal stresses. Regarding external stresses, two questions already mentioned before recur: clearances and electrode shapes. The clearances to the support structure and to adjacent structures have to be carefully designed, as are the electrodes and corona rings along the stack.



Figure 3.10-DC filter capacitor under installation (Courtesy Siemens)

### **3.10 DC capacitors in DC PLC and RI filters**

Depending on the filtering requirements, the PLC filter capacitors may be of stack construction type, with multiple capacitor units, similar to those of the DC harmonic filter capacitors, or, if lower capacitance is sufficient, it may be possible to use column type capacitors, similar to those in CVT's. For the capacitors in RI filters, column type construction is expected.

For the design of stack type, what was said above for DC harmonic filter capacitors is valid also for these capacitors, and extending the design for 800 kV DC is a relatively easy task. Column type capacitors will consist of more than one module, due to practical reasons. This is not new, and extending the design for 800 kV DC presents manageable challenges, which are discussed below.

Again, the question of voltage grading has to be addressed, but with one more dimension: the external insulation and the internal insulation have to be coordinated to avoid radial stresses beyond the material capabilities.

As for transient voltages, the capacitance of the modules themselves will control the internal grading. For controlling the external grading, and thereby the radial stresses too, appropriate corona rings will be used.

For grading the DC voltage, the modules will consist of capacitor elements, and there will be physical resistors to force a voltage grading, internally as well as among modules. To address the matter of a proper DC voltage grading along the external surface of the modules, composite insulator bodies will be used. Their use gives a hydrophobic surface, and the voltage unevenness in the surface can be kept low enough for the radial stresses to be within the material design criteria without going to a large number of modules.

The use of composite housing for the modules has the additional advantage of permitting a lower total length, with a direct benefit from the mechanical point of view.

### **3.11 DC voltage dividers (DCVD)**

The DC voltage measuring devices are expected to be of resistive type, just as the ones used at present, and with the same design current. The resistive characteristic gives them an inherent internal DC voltage grading. The capacitors used for giving appropriate response for transients give the device a good internal transient voltage grading. Both the resistive part and the capacitive part are made of modules with physical components, and an appropriate number of modules are connected in series. This construction makes it possible to extend the design to 800 kV DC and the challenge is to coordinate with proper voltage grading on the outside.

To control the transient voltage grading on the outside, appropriate corona rings are used. The control of DC voltage grading on the external surface of the housing is a little trickier. Because of the precision requirements on the DCVD's, it is not possible to build the device in modules as the RI filter capacitors described above: the external leakage currents would interfere with the internal currents and thereby with the precision. The housing is therefore built in one piece, and to ensure the radial stresses will be within design limits, the housing is composite, to keep the unevenness in the distribution to correct levels.

### 3.12 DC surge arresters

The arresters for DC pole application will be built up by modules in series, just as in present designs, with each module containing a certain number of ZnO blocks in series. Extending the design to 800 kV DC is rather straightforward from the point of view of internal stresses, since these devices have inherent voltage distribution among modules, for transient as well as for DC voltages. The use of composite material housing further minimizes the stresses in the blocks for controlling the evenness in the voltage distribution.

From the external point of view, it will be necessary to have appropriate corona rings for the new voltage, which is an almost obvious requirement. There is another aspect that is brought about by the voltage and that is the mechanical strength: Because of the expected creepage distance requirements, the total length of the arresters makes them weak against wind and seismic stresses. One present design is thus for hanging them.

The expected currents and energies that the arresters will be subjected to will result in more than one column in parallel: multicolumn design is anticipated, as shown in Figure 3.11

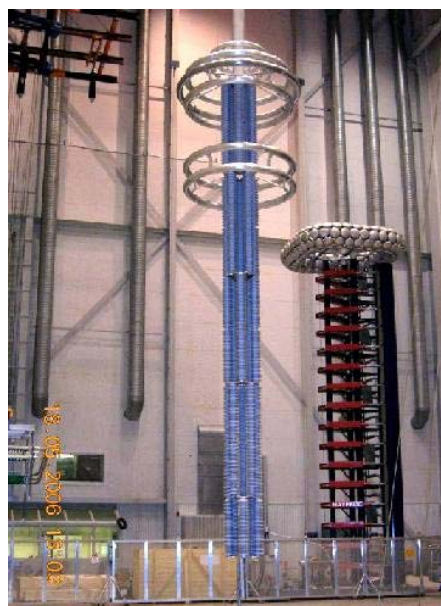


Figure 3.11- 800 kV Surge arrester under testing (Courtesy ABB)

### 3.13 800 kV DC post insulators

For supporting busses and some equipment in the DC yard, DC post insulators will be necessary which fulfill the following requirements:

- A. Their surface has to be hydrophobic and remain so even in heavily polluted environment.

- B. The shed profile has to have good characteristics against bridging during heavy rain.
- C. The mechanical withstand has to be as good as that of porcelain, or better.

Investigations show that support insulators made of composite material: fiberglass reinforced main body, with silicone rubber sheds, are the ones that best fulfill these requirements. Besides, the shed profile, in combination with the hydrophobicity gives them very good anti-bridging characteristics, which permits somewhat tighter spacing between sheds. These two characteristics permit reduction in the total length of the support insulator, which in turn makes the whole station design more robust against wind and seismic loads.

The mechanical withstand of composite support insulators also fulfils the requirement, but one must be aware that they are more flexible than porcelain; i.e. they will deflect more for the same applied lateral load.

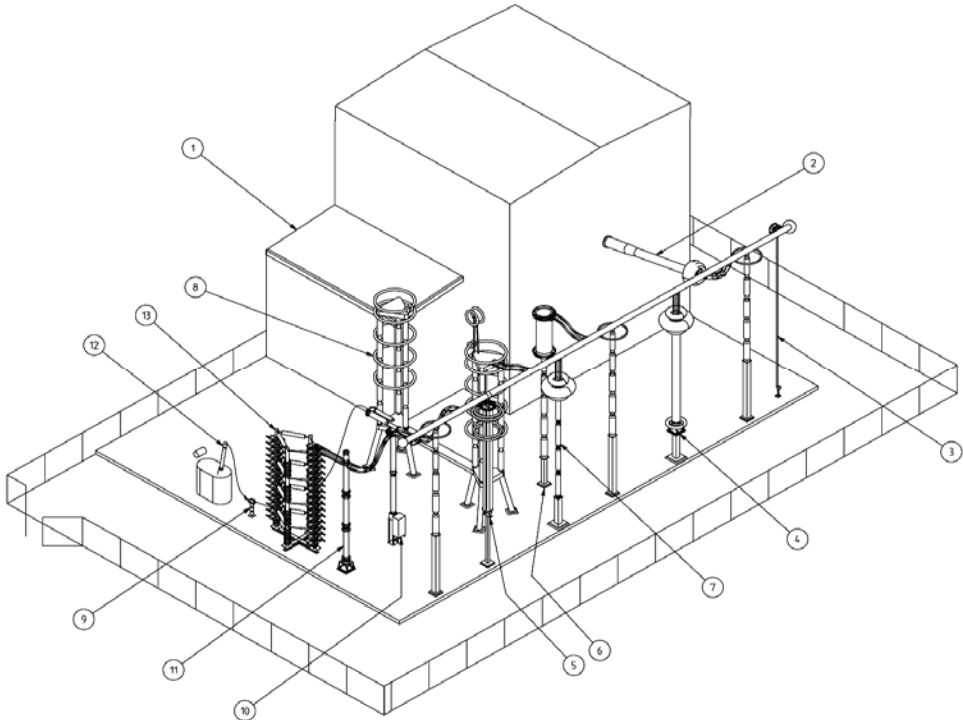
### **3.14 800 kV DC Test circuit**

For additional confirmation that the assumptions, calculations and laboratory tests are correct, ABB has installed a test circuit for long term voltage testing of 800 kV DC equipment at 855 kV DC. The circuit has been in service since mid-November 2006.

The following equipment has been installed and is being tested:

- A converter transformer prototype with complete insulation system design and geometry and a real bushing. The transformer prototype has its 800 kV DC bushing protruding into a simulated valve hall, heated up to a permanent 60°C. The prototype is housed in an adjacent smaller hall, also heated up.
- A complete wall bushing with its indoors side inside the simulated valve hall
- A DC voltage divider
- A pole surge arrester
- An RI capacitor of column type
- An isolator
- A high speed by-pass switch
- An optic DCCT
- An air core smoothing reactor prototype
- Support insulators
- Busses, slacks, clamps and connectors, and corona screens

An overview of the test circuit is shown in Figure 3.12, and a photograph of the actual test circuit is in Figure 3.13



Legends

- |   |                                   |
|---|-----------------------------------|
| 1. Transformer (in heated up enclosure) | 2. Wall bushing                   |
| 3. DC OCT                               | 4. DCVD                           |
| 5. Arrester                             | 6. Smoothing reactor              |
| 7. RI capacitor                         | 8. Disconnecting switch           |
| 9. Auxiliary arrester                   | 10. By-pass high speed switch     |
| 11. Calibrated DCVD                     | 12. Auxiliary step-up transformer |
| 13. Cascade dc voltage generator        |                                   |

Figure 3.12 Long term 800 kV DC test circuit. (Courtesy ABB)



Figure 3.13 Long term 800 kV DC test circuit. (Courtesy ABB)

### 3.15 AC switchyard

The use of 800 kV DC transmission is directly associated with the transmission of high powers for long distances. These two aspects combined make it necessary to ensure high availability and reliability, and the requirements will affect the bus configurations, and how the converters, ac lines, ac filters and ac shunt elements are connected to the buses and diameters/bays.

The high power will also mean tight minimum short circuit ratio conditions, and severe load rejection factors. The equipment in the ac switchyard will have to cope with those conditions.

#### **Acknowledgements**

Sincere acknowledgements are extended to Mr. Urban Åström for his valuable contributions and advice.

#### **References**

- [1] V. F. Lescale, U. Åström, J. Nunes, L. Weimers, D. Wu "Transmission with HVDC at 800 kV" Paper B4-106 presented at CIGRÉ 2006 Session 41
- [2] Uno Gäfvert, Albert Jakts, Christer Törnkvist and Lars Walfridsson, "Electrical Field Distribution in Transformer Oil", IEEE Transactions on Electrical Insulation, Vol27 No. 3, June 1992
- [3] HVDC Converter Stations for Voltages Above 600 kV, EPRI EL-3892, Project 2115-4, Final report February 1985
- [4] HVDC Converter Stations for Voltages Above  $\pm 600$  kV, Cigré Working Group 14.32, December 2002
- [5] Dong Wu, Urban Åström, "R & D on external insulation for  $\pm 800$  kV DC transmission", IEC/CIGRÉ Symposium on UHV in China in July 2007
- [6] Abhay Kumar, Dong Wu and Ralf Hartings, "Experience from First 800 kV HVDC Test Installation," ICPS 2007 - International Conference on Power Systems, CPRI, Bangalore, December 12 – 14, 2007.

#### 4.0 Converter Configuration and Rating

There are several configurations that can be applied for HVDC converter stations at 800 kV. The choice of a specific configuration will be dictated by:

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

The different possible configurations are presented and discussed in light of the above considerations. In addition, all the operational features of a specific configuration are also presented.

In all configurations, the discussion is limited to bipolar configurations, which means no monopolar system is envisaged.

#### 4.1 A bipole with one single converter per pole

The configuration in this case would be very similar to the currently used configuration for HVDC bipole rated for 500 kV and has been built for powers up to 3000 MW as shown in figure 4.1. The difference here is that even if the rated power is 3000 MW, the transmission distance can make it prohibitive to build the bipole at 500 kV. For example a transmission distances of 3000 km and a rated power of 3000 MW at  $\pm 500$  kV, the losses of the transmission line shall be about 16.2 % even using quad lapwing conductor ( $R=.036$  ohms/km).

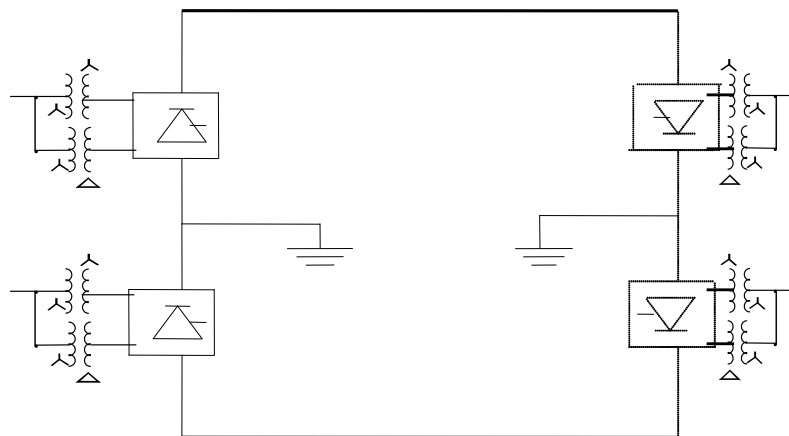


Figure: 4.1- Bipolar operation

If we consider the factors outlined above and apply them to this configuration, the following can be observed:

- The power to be transmitted certainly can be 6000 MW or higher. If we consider the starting point as 3000 MW, the DC current will be 1875 A and if the DC power is 6000 MW the DC current will be 3750 A. It is clear that the all these parameters are manageable.
- The transmission distance is not an issue.
- The staging here is limited to building one pole followed by the second pole. To limit any operation with ground return, the DC line will have to be built in bipolar from the start, to allow stage one to operate in metallic return mode. The losses during monopolar operation with metallic return are doubled.
- The maximum amount of power to be transmitted in stage 1, if the project is built in two stages, will be half the nominal bipolar power plus over load.
- From a reliability point of view, this is not any different from the current typical bipole of 3000 MW at 500 kV. The system has to withstand the loss of a pole rated at 1500 MW. However as we increase the rated power to levels above 3000 MW, obviously the loss of a pole will result in a larger loss of power so at 6000 MW the loss of a pole means the loss of 3000 MW. This is quite critical in most systems.
- The loss evaluation here is a non issue. The scheme is operating from the start at the full transmission voltage.
- The size and weight of the converter transformers is always a deciding factor. In this case for a bipole rated power of 3000 MW, the converter transformer rating based on single phase two winding units is 278 MVA. This is a manageable rating. However if the nominal bipolar power is 4000 MW, the transformer rating will be 370 MVA, now we are looking at large units. Certainly for a 6000 MW bipole, the rating of 555 MVA may be difficult for transport purpose.

To summarize, the following table highlights the features of this configuration

Transmitted Power	Transmission Distance	Staging	Power during staging	Reliability Consideration	Losses Evaluation	Size & Weight of Transformers
Can be as high as 7200 MW based on the thyristor current rating	No limitation	Can only be in two stages, one pole at a time	Half the power plus over load	Up to 3000 MW, it is not an issue because the pole rated power is similar to schemes that are already in service However for higher power the question will be the system impact of a loss of a pole	Not a concern, the operation is at full voltage from the start	Up to bipole power rating of 3000 MW the size and weight of a single phase two winding transformer is manageable. Beyond that it can be a problem

**4.2 A bipole with two series converters per pole**

In this configuration, two twelve pulse converters are connected in series per pole as shown in figure 4.2. The rating of the two converters can be the same, which means the voltage rating is 400 kV per converter, and each handles half the pole power. Another alternative is two dissimilar voltages rated valve groups, which also means the power rating of the two valve groups is different. For example the configuration of a 12 pulse bridge may be of one converter at 500 kV and the second one at 300 kV, or 600 kV and 200 kV. One reason for proceeding in the direction of the dissimilar rated series converters would be staging the project and the first stage power required is more than half of the total transmitted power. For example on a 6000 MW ultimate power 4500 MW is required for stage 1 and 1500 MW is required for stage 2. This approach can be used if the time interval between the two stages is long and the investment for the ultimate capacity can be deferred. However, one has to keep in mind that the cost of losses here will be a major factor in the evaluation because of operating the first stage at a lower DC voltage. It may be noted that the transmission line and some DC equipment would have to be rated for ultimate operating voltage. Obviously this alternative of dissimilarly rated converters in series has to be evaluated against other alternatives that allow the system to operate at full DC voltage during the staging. One has to also to keep in mind that dissimilar series converters calls for more spares.

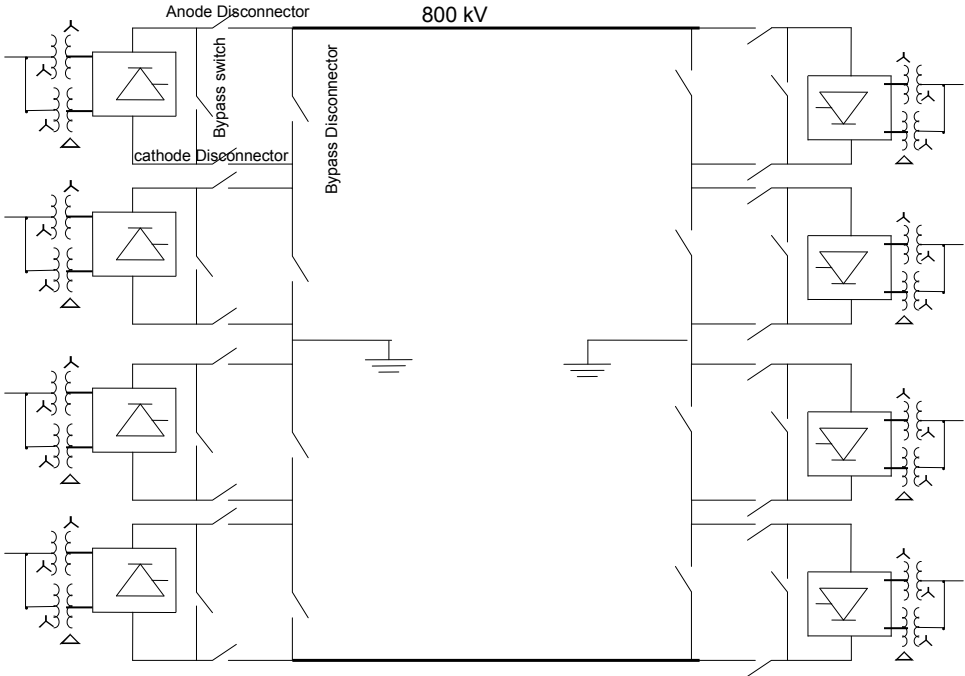


Figure: 4.2- Series connected converter

The discussion for the series converters per pole concentrates on similar rated converters. The dissimilar converters operate in the same manner and the reasons for using them have been discussed above. The power to be transmitted can be 6000 MW

or more. This means 1500 MW per converter and 3000 MW per pole. Again the economics will dictate how low the transmitted power can be per converter.

- The transmission distance here is not an issue as long as we are operating at full transmission voltage of 800 kV. The issue will only arise during outages of one converter in a pole and that pole has to operate at 400 kV.
- For staging of converters there are more choices and flexibility. If we take the example of a 6000 MW bipole, then stage one can be at  $\pm 400$  kV and a transmitted power of 3000 MW, depending on the distance. The second stage can be up to + 800 kV and – 400 kV, and a transmitted power of 4500 MW. The final stage can be the ultimate transmission of capacity of 6000 MW and  $\pm 800$  kV.
- The system will have higher energy availability than the single converter per pole just because the loss of one converter, which is the most common fault of considerable duration, only represents 25% of the total capacity.
- The loss evaluation is not an issue for operation at full voltage. However, it has to be considered very carefully if staging or monopolar operation is considered, or if dissimilar series groups are considered. For example in the case of dissimilar converters of 600 kV and 200 kV, for the loss of the 600 kV converter in one pole, the other converter would be operating at only at 200 kV and full load current which is meaningless for such long transmission systems.
- The size and the weight of the converter transformers, are quite manageable here, the typical single phase two winding will be in the order of 278 MVA. From spare transformers point of view four spare units are needed per station because of the different voltage classes of 800 kV, 600 kV, 400 kV and 200 kV. Although there are alternatives to this.
- There is more flexibility to operate at reduced voltages during any insulation type problems. For example, the poles can be operated at the typical 0.8 per unit (p.u.) DC voltages with two converters per pole or even down to one converter per pole at 400 kV.

Transmitted Power	Transmission Distance	Staging	Power during staging	Reliability Consideration	Losses Evaluation	Size & Weight of Transformers
Can be as high as 7200 MW Based on the thyristor current rating	No limitation	Practically can be in 3 stages	Can be 50%, or 75% depending on the staging strategy	For a loss of one converter only 25% of the power capability is lost, without considering any over load	Not a concern, for operation at full voltage	The size and weight of a single phase two winding transformer is manageable. 4 spare units are required per station

For series connected converters per pole, certain additional switchgear and measuring devices are required because of the series connection. As shown in figure 4.2, each converter will have a high speed by pass switch. The voltage across the switch is 400

kV DC plus the twelve pulse ripple and is the same for both converters as long as they are similar in rating. The difference is the insulation to ground. Also each converter will include, anode, cathode and by pass disconnects for connecting and isolating the converter.

The deblock and block of series converters are completely different from the single converter per pole. In addition even if the pole is shutdown there will be current in the by pass switches.

### 4.3 A bipole with two parallel converters per pole

Even though this is referred to as parallel converters per pole, in principle this can be looked upon as two bipoles with the same polarity poles connected in parallel. The configuration is shown in figure 4.3.

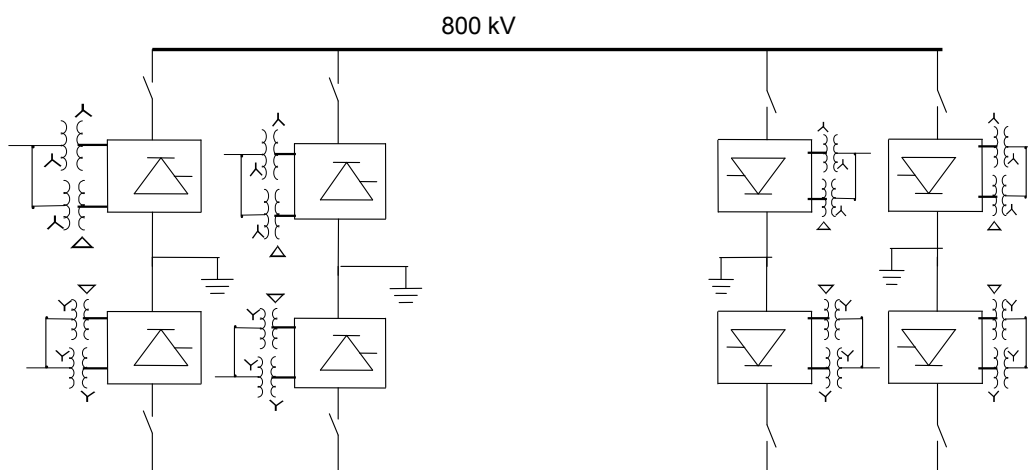


Figure 4.3- Parallel connected converter

Analysis:

In this configuration there are some unique features:

- Each pole is operating always at 800 kV which means lower losses during any converter outage. This is different from series connected converters per pole where the outage of a converter in a pole reduces the DC voltage in that pole to half, which means for the same power there will be higher losses.
- For the same power although the DC line current is the same for both series and parallel arrangements, the converter DC current is lower than the series connected converters. This means there is more room for overload capability on per converter basis based on the current state of the art for thyristor valves.
- From staging point of view and in particular if the time between stages is long, in the parallel configuration the pole is always operating at full voltage, which means lower losses. However the staging here can only be done on bipolar basis. For example for a 6000 MW, it can be in three stages only, stage one 1500 MW single

converter at 800 kV and metallic return, stage two 3000 MW from one bipole, and stage three the complete system at 6000 MW.

- In the parallel configuration, high voltage high speed switches (HVHS) are required one per pole. These switches are rated for carrying the full load DC current of the converter plus overload, insulated for 800 kV to ground and will have to withstand 800 kV DC across the switch contacts until associated isolators are opened. However, no DC current interruption capability is required.
- Unblock and block sequences are completely different from the series connected converters. The sequence has to be able to parallel and de-parallel the converters manually without any disturbance to the other operating converter. In the event of a converter protection trip, there will be a short interruption to the power from the parallel converter until the HVHS of the faulted pole is opened.
- The system will have similar energy availability as the series converters because the loss of one converter, which is the most common fault, only represents 25% of the total capacity. In addition because the current rating of the converter is lower than the series connected converters, there is more room for overload if required.
- The size and the weight of the converter transformers, are quite manageable here, the typical single phase two winding will be in the order of 278 MVA. From spare transformers point of view two spare units are needed per station
- For any insulation type problems the poles can be operated at the typical 0.8 p.u. DC voltage.
- In this configuration the converters can be built at different locations. In principle the two bipoles can be separated by any distance. This is similar to a multi-terminal DC system.
- For the loss of a converter, metallic return operation cannot be used for full load operation and therefore ground current has to be accepted.

The following table summarizes the features of this configuration

<i>Transmitted Power</i>	<i>Transmission Distance</i>	<i>Staging</i>	<i>Power during staging</i>	<i>Reliability Consideration</i>	<i>Losses Evaluation</i>	<i>Size &amp; Weight of Transformers</i>
Can be higher than 7200 MW based on the thyristor current rating	No limitation	Practically can be in 3 stages The stations can be built at different locations.	Can be 25%, or 50% and finally 100 %	For a loss of one converter only 25% of the power capability is lost. Without considering any over load. The overload capability here can be higher	Not a concern, the operation is always at 800 kV	The size and weight of a single phase two winding transformer is manageable. 2 spare units are required per station

Three sequences are envisaged in this configuration:

- Manual paralleling which means going into parallel operation on a per pole basis without any disturbance to the operating pole
- Soft de-paralleling, this means removing the converter manually from parallel without disturbing the operation of remaining parallel converters. This can apply for manual initiation as well as some soft type protection trips.
- Fault de-paralleling which is initiated by major protections.

#### **4.4 Transmission power larger than 6000 MW**

In the above analysis the transmitted DC power capability was limited to 6000 MW. And certainly it can be handled by both the series and parallel configurations with each having its advantages and disadvantages. However if we consider higher DC powers than 6000 MW for example 6500 MW and up, the DC line current will be 4063 Amps. In the parallel configuration the individual pole DC current will be 2032 Amps which can be easily handled by the present thyristor devices. However in the case of the series connected valve groups this high DC current of 4063 A means larger diameter thyristors (6 inch) could be preferred. This is important to allow for proper overload in case of the loss of a converter and also to simplify the design.

#### **4.5 Neutral Bus configurations**

One of the most critical areas in any bipolar configuration is the neutral bus area where in a single bipole the two poles come together. In fact if there is a common mode for failure in a bipolar system it is in this area. Obviously the neutral bus connection is critical in the present designs as much as for the future 800 kV DC systems. The main difference here is that the loss of the bipole due to a fault or failure of equipment in this area has a higher impact just because of the level of power transmitted.

In the series converter configuration the neutral bus configuration between the two poles can be:

1. The typical connection as shown in figure 4.4. In this case any fault past the Neutral bus switches (NBS) trips the bipole.

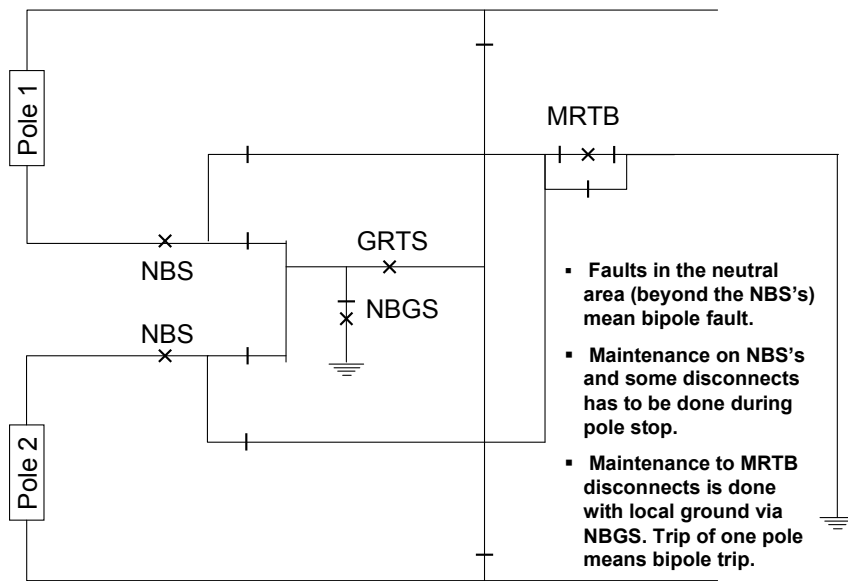


Figure: 4.4 Typical electrode line connection of a Bipole Terminal

2. The second alternative is to duplicate the MRTB (Metallic Return Transfer Breaker) and GRTS (Ground Return Transfer Switch) and configure them on per pole basis as shown in figure 4.5. In this case a fault in the neutral area even beyond the NBS does not shutdown the bipole.

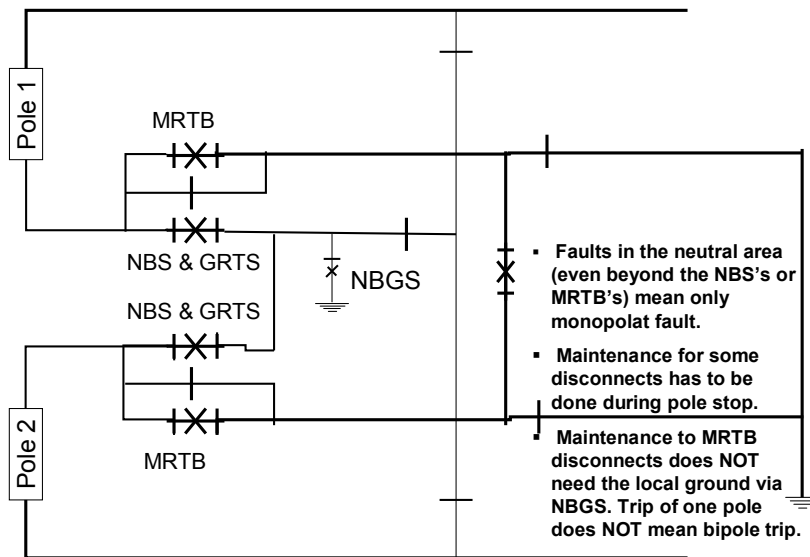


Figure.: 4.5- Duplication of MRTB

3. The third alternative as shown in figure 4.6 is a breaker and half arrangement which means more investment.

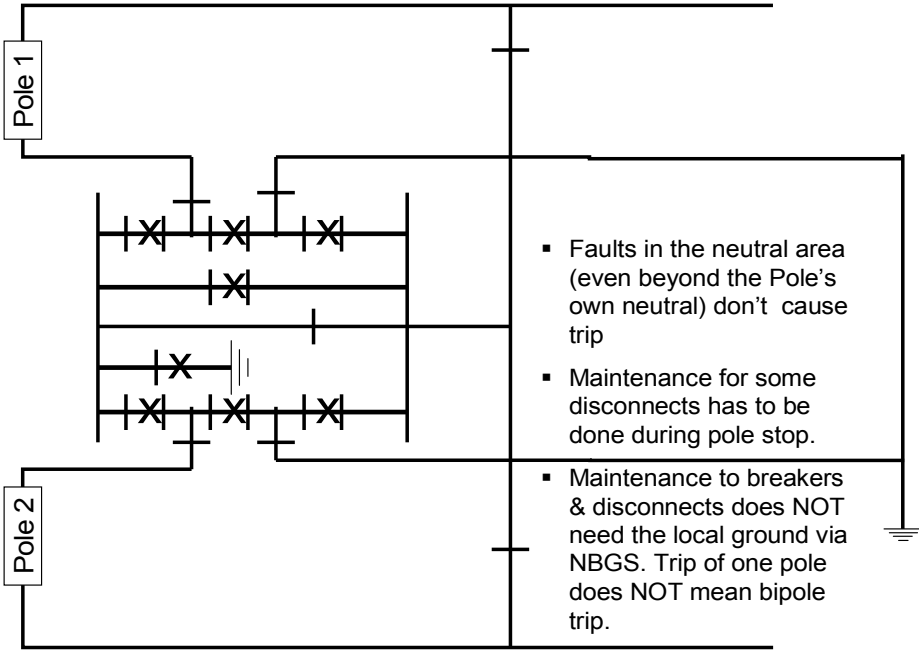


Figure.: 4.6 Electrode line connection with one and half breaker scheme

Although for the parallel configuration the same neutral bus arrangement can apply, the parallel configuration lends itself to a more reliable connection on the neutral busbar.

If the stations happen to be at two different locations then the neutral busbars are not connected together and two separate electrode lines will be used in any case.

If the two parallel converters are located at the same site still the neutral bus connection of the two parallel converters should be separated with a manual bypass connection that is typically left open under normal operating conditions. Two electrode lines could be used as shown in figure 4.7.

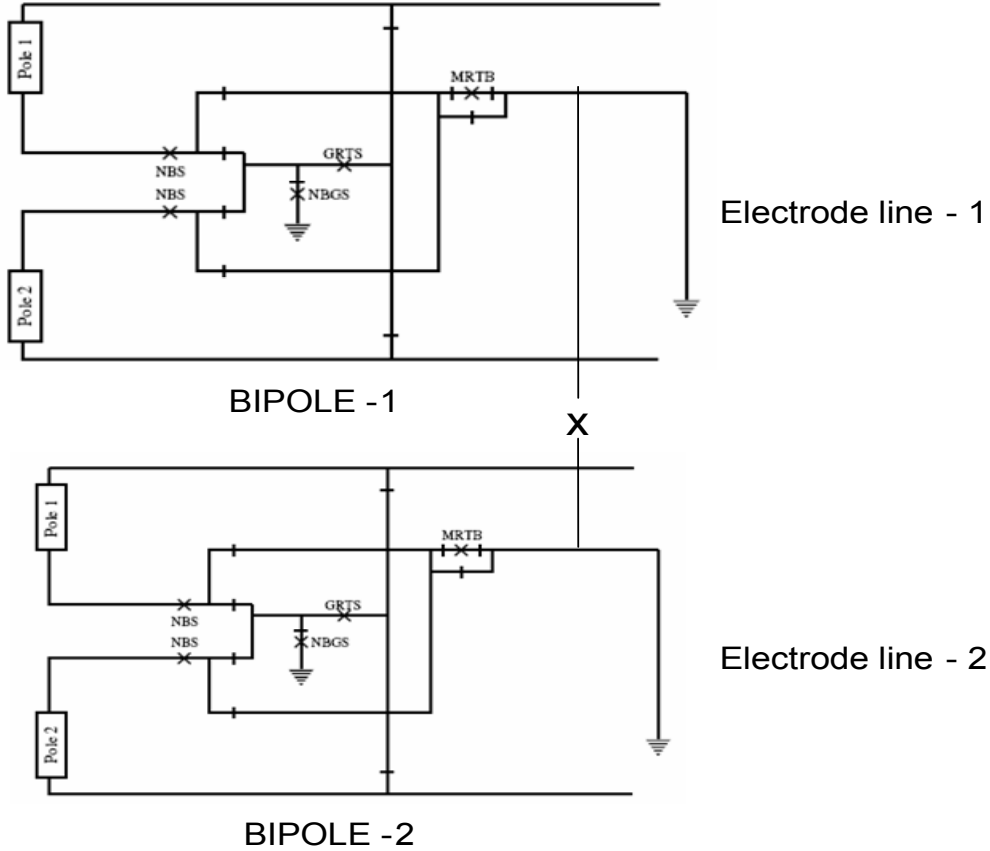


Figure: 4.7- Two Electrode Line Connection

## 5.0 Ground Electrode

This chapter discusses the system planning aspects to be taken into account while designing ground electrode schemes to be used in HVDC long distance transmission. Detailed design of ground electrodes is not given here as this is covered in WG 14.21 [1]. This is not strictly connected to the use of  $\pm 800$  kV, hence, the discussion relates to reliability factors for large overhead transmission projects and also to the design criteria to be used. As  $\pm 800$  kV HVDC overhead transmission systems are planned to be in bipolar configuration, even if using two monopolar lines, the ground electrodes are to be designed for equipment outages, forced or scheduled. This also means that they must be designed to act as both anode and cathode, the former being more demanding. Land electrodes are only considered here as sea or shore electrodes are generally associated with submarine cable systems. Given the large power ratings associated with  $\pm 800$  kV, electrode continuous current ratings up to 4000 A have been considered. A brief description of the design of land electrodes is also given.

### 5.1 System considerations

It must be remembered that the loss of ground electrode connection means loss of bipole. For short periods a bipolar system can be operated using the station ground mat if a fine current balancing system is utilised. The electrode itself is very robust, but careful consideration must be given to the electrode lines.

From a system point of view the most important criteria are rated current and period of operation at that current, as well as reliability and lifetime amp-hour design. The rated current is given by the pole design, however the period of operation on ground electrode is dependent upon availability of transmission line and how quickly the metallic return current path can be established. It is most important to define, in the event of prolonged station pole outages; the ground electrode is to be used for a few hours before switching to metallic return or for a longer period of the order of weeks. In this respect it is important to note the comments made in Chapter 4 “Converter Configuration and Rating” that the use of parallel converters, including multi-terminal operation, restricts operation in metallic return using the line pole and consequently large unbalance ground currents need to be considered. This is further discussed in Chapter 4.5. “Neutral Bus configurations”.

Among the advantages of using ground return, the lower losses than in metallic return can be of importance. Also using metallic return with the long transmission distances being considered at  $\pm 800$  kV, plus continuous current ratings of up to 4000 A, the insulation level of the neutral bus at the station remote from the electrode may be higher than previously used. In addition a larger converter transformer tap range may be required.

## 5.2 Reliability considerations

In practice land electrodes have proven to be very reliable and availability of the bipole has been mainly related to the problems in electrode line. This leads to the consideration of using two electrode lines, perhaps following different routes, for one bipolar station and electrode. An analogous solution was implemented for the Itaipu project, where the original design, following maximum separation of bipoles, had one electrode line for each bipole and electrode, however after vandalism problems on the lines a switching scheme using disconnectors was introduced to permit paralleling of both bipoles onto a single electrode during outages.

The proven high reliability of land electrodes has also led to the proposal to use a common electrode for two or more HVDC bipoles in the same region, especially if there is difficulty in obtaining a suitable site. In such a case it may be advisable to design an electrode with isolatable sections such that inspections and possible maintenance can be carried out without disconnecting the complete electrode.

When using one electrode for more than one bipolar transmission, or if two electrodes are rather close due to site restriction, then evaluation must be made of the infrequent case in which both projects are in ground return mode at the same time and with the same polarity. This rare occurrence of “double monopolar operation” (DMO) may impose restriction on the total ground current flow.

When evaluating the current duration (Ampere-hours) requirements of the electrode system, it should be remembered that HVDC transmission lines very rarely suffer permanent monopolar faults. Transmission line permanent faults usually involve tower failures such that both poles are affected. In this case metallic return or ground return is not feasible, and then there is no demand on electrode line either.

## 5.3 Interference considerations

There are various interference effects to be considered when locating and designing a land electrode. The most significant of these are:

- Potential gradient and step voltage at electrode site.
- Current density to avoid electro-osmosis in anode operation.
- Touch voltages to fences, metallic structures and buried pipes nearby.
- Corrosion of buried pipes or foundations.
- Stray current in power lines, especially via transformer neutrals.
- Stray current in telephone circuits

The main mitigation method for these possible interference issues, except step voltage, is to maintain a maximum possible distance from the electrode that is a very important parameter to be considered when selecting the electrode location. Step voltage is a function of current density at electrode. The most effective mitigation option is to

choose a site where the soil resistivity decreases with depth, thus limiting the area over which the current density at the surface is at a significant value. This decrease with depth is perhaps more important than absolute value as the electrode resistance to remote ground is normally rather low, even for modestly high soil resistivity. Details of interference mitigation procedures are not given here as these are considered outside the scope of this WG.

#### 5.4 Design Criteria

The design criteria fall into two categories, firstly those for design lifetime and electrical parameters and secondly safety and interference issues. Design lifetimes are typically 30-50 years, with the need to define currents in operation and period for which they are expected. This should take into account the operating modes and reliability criteria, as well as normal unbalance current, nowadays very small, of the order of 1% of rated current. As these are very much a function of each project, no values are given here, but a table of values from projects in operation is given in Table 5.1. Note that connected with rated current and the associated time, is the permitted temperature rise. This long term current may be particularly important for multi-terminal operation, including parallel converters, where due to the configuration it is not possible to use metallic return for station pole outages. The electrode resistance may appear to be an important parameter, however in practise the ohmic value is always very low in relation to line resistances, of the order of 0,4  $\Omega$ , and seldom a defining parameter.

Typical values of criteria associated with interference issues are given below, however it must be remembered that not only the conditions of the site and surrounding area are to be taken into consideration, but also local regulations regarding safety and interference.

- Potential gradient on surface: 2–20 V/m  
Mitigated by depth above electrode.
- Step voltage at electrode site boundary: 2–8 V/m  
Mitigated by depth or fencing area above electrode.
- Current density at soil/electrode interface: 1 A/m<sup>2</sup> typical
- Touch voltages: 2–5 V typical  
Mitigated by distance or section insulation of, say, fences, pipes.
- Corrosion of buried pipes or foundations:  
Requires local survey, 1–5 km distances typical, may consider cathodic protection or increase in existing protection.

- Stray current in power lines, especially via transformer neutrals:  
Requires local survey and study of mitigation methods
- Stray current in telephone circuits:  
Requires local survey and study of mitigation methods

The most significant parameters giving the major dimensions of the electrode are current density at coke-soil interface and temperature rise. This means that the design of land electrodes is very dependant on the available sites close to the converter station. Most land electrodes have been constructed by burying coke or derivative of coke, in a trench or well to form the electrode, with an iron or steel conductor within the coke to distribute the current. This has been arranged in a horizontal star or circular shape, while less commonly vertical electrodes have been used where space is restricted. Note that the feeder cables to the coke/iron electrode must be insulated and able to withstand corrosion. There are other designs and a brief overview is given in the table below. The high currents associated with recently proposed large transmission projects would favour the use of vertical electrode elements in order to reduce required land. These could perhaps be arranged in star or double circle configurations.

Project	Station	Type	Material	Dimensions	Continuous current	Continuous time	Resistance	Design Lifetime	Fence	Electrode line
CU Project	Coal Creek	vertical rod	coke / Si iron	14 x 60 m vertical	1680 A	90 days	0,03	40 yr	no	8 km
	Dickinson	vertical rod	coke / Si iron	16 x 60 m vertical	1680 A	90 days	0,04	40 yr	no	23 km
Cahora Bassa	Cahora Bassa	vertical rod	coke / graphite	5 x 30 m , 100 x 100 m	3300 A	72 h	0,06	5000 A.yr	yes	NA
	Apollo	vertical rod	coke / graphite	4 x 40 m , 40 x 40 m	3300 A	72 h	0,16	5000 A.yr	yes	NA
Gezhouba- Shanghai	Gezhouba	ring	coke / steel	500 m diam	1320 A	6 months	0,30	1347 A.yr	NA	NA
	Nan Qiao	linear	coke / steel	640 m	1320 A	6 months	0,05	1906 A.yr	NA	NA
Intermountain	Sevier	ring	coke / Si iron	914 m diam	2600 A	15 days	0,04	36 yr	NA	47 km
	Coyote	ring	coke / Si iron	914 m diam	2600 A	15 days	0,02	36 yr	NA	32 km
Inga Shaba	Inga	linear	coke / iron pipe	3 x 1460 m	1680 A	90 days	0,24	25 yr	NA	NA
	Kolwezi	star	coke / iron pipe	3 x 630 m	1680 A	90 days	0,14	25 yr	NA	NA
Itaipu Bipole 1	Foz do Iguaçu	ellipse	coke / Si iron	2700 m circumference	2750 A	30 days	0,27	50 yr	yes	15 km
	Cotia	ellipse	coke / Si iron	2500 m circumference	2750 A	30 days	0,24	50 yr	yes	67 km
Itaipu Bipole 2	Foz do Iguaçu	ellipse	coke / Si iron	2700 m circumference	2750 A	30 days	0,45	50 yr	yes	16 km
	Cotia	ellipse	coke / Si iron	2500 m circumference	2750 A	30 days	0,21	50 yr	yes	66 km
Nelson River 1	Dorsey	ring	coke / steel	767 m circumference	1800 A	30 days	0,4	50 yr	NA	22 km
	Radisson	ring	coke / steel	1260 m circumference	1800 A	30 days	0,4	50 yr	NA	12 km
Nelson River 2	Dorsey	double ring	coke / steel	767* m, 958 m circ.	4000 A	32 days	0,4	50 yr	NA	22 km
	Henday	ring	coke / steel	1720 m circumference	4000 A	32 days	0,4	50 yr	NA	11 km
New Zealand	Benmore	star	coke / steel	6 arms, 50-500 m	1200 A	100 days	0,1	45 yr	yes	8 km
	Haywards	shore	-	-	1200 A	-	-	-	yes	25 km
Pacific Intertie	Rice Flats	ring	coke / Si iron	3200 m circumference	1800 A	340 days	0,56	85 yr	no	11 km
	Santa Monica	sea	-	-	1800 A	-	0,02	-	-	50 km
Quebec- New England	Duncan	vertical rod	coke / Si iron	20 wells x 20 m deep	2900 A	100 h	0,57	50 yr	yes	NA
	Des Canton	ring	coke / steel	1885 m circumference	2200 A	15 min	0,11	50 yr	NA	9 km
	Commerford	vertical rod	coke / steel	6 x 70 m vertical	2200 A	15 min	0,12	50 yr	NA	18 km
Rihand- Delhi	Rihand	double ring	coke / steel	400 m, 300m,diam	1500 A	NA	NA	NA	yes	25 km
	Dadri	double ring	coke / steel	360 m, 180m,diam	1500 a	NA	NA	NA	no	25 km
Square Butte	Center	ring	coke / electr	NA	1100 A	7 days	0,04	NA	no	NA
	Arrowhead	ring	coke / electr	NA	1100 A	7 days	0,25	NA	no	NA
Volgograd- Donbass	Volzhaskaya	square	coke / steel	1200 m x 1200 m	900 A	NA	0,08	NA	NA	NA
	Mikhail	square	coke / steel	1200 m x 1200 m	900 A	NA	0,14	NA	NA	NA

NA: Data not available

Table 5.1: Characteristics of various Land Electrodes

When locating and designing the electrode consideration must be given to electro-osmosis, a phenomenon associated with anode operation in which there is a net water flow from the electrode. Thus the moisture content of the soil is most important. In some projects a wetting system is used in case of prolonged ground return.

The large area required by electrodes close to the surface led to the investigation into deep hole electrodes, where the objective is to reach a highly conductive layer 100 to 200 m below the ground surface. [3]. It was proposed to use a bored hole with an insulated conductor to an inert electrode in this highly conductive layer. This would reduce proximity effects due to currents close to the surface and also reduce required land area. Together this would lead to easier site acquisition and shorter electrode lines. Unfortunately first experiments proved difficult due to chemical and electrical effects at the electrode interface. Work continues investigating deep electrodes and the use of natural geological fault lines to reach the deep low resistivity layer appears promising.

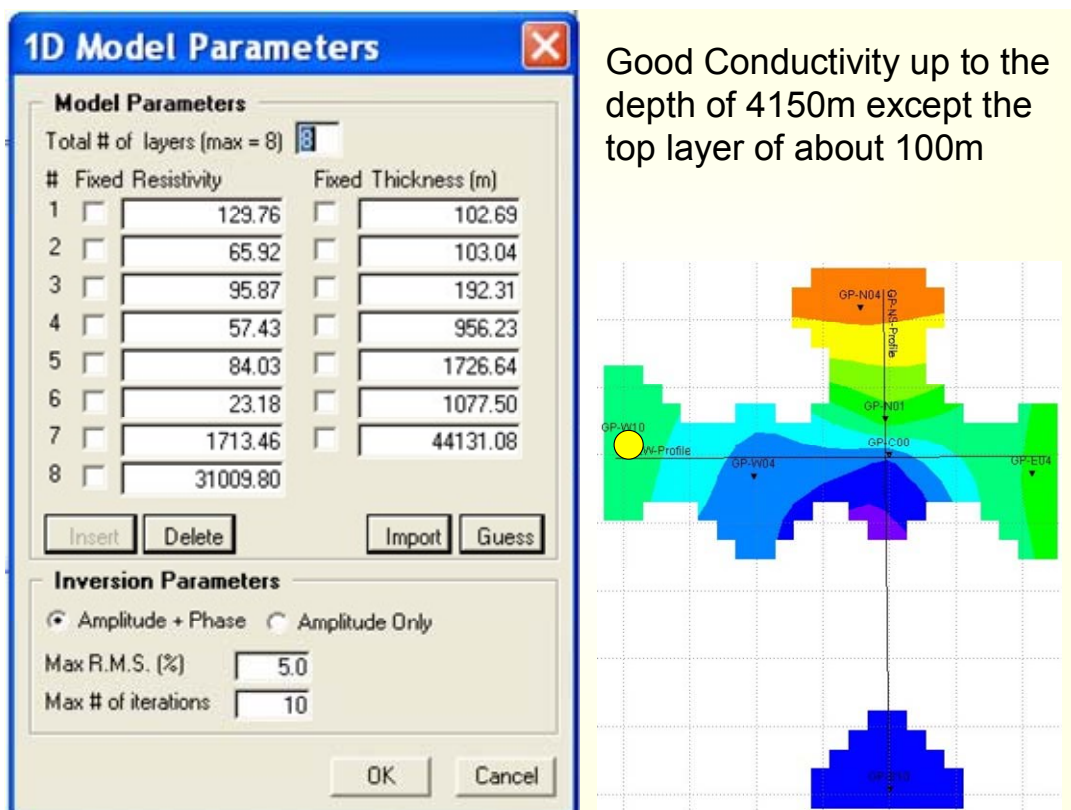
The high dependence on site conditions makes site testing most important. Soil resistivity at surface and depth has to be measured as well as thermal resistivity and moisture content. Note that these last two vary considerable and therefore require measurements over a period of time. Given this and that operation as an anode, at high currents, tends to dry the soil due to electro-osmosis. Many projects have performed a pilot test electrode program in order to confirm correct site selection. This involves a small electrode operated as an anode, but with the correct current density at soil/electrode interface, and a current source of some hundreds of amperes with a temporary line of some kilometres. The cathode electrode can be very simple grounding rods. In this way more reliable predictions of temperature rise and water loss can be obtained. Also, depending on length of temporary line, interference effects can be evaluated.

## **5.5 Geophysical Methods**

Multi-electrode Direct Current (DC) resistivity and MT (Magneto Telluric) techniques have been used by the Utilities to delineate the shallow and the deep resistivity structures, respectively, for the proposed HVDC Earth Electrode sites. DC resistivity method is an active source method and normally provides high-resolution images of the electrical resistivity structure up to a few hundred meters. It is also possible to use this method to delineate the structure up to a few kilometres provided a fairly large current is injected into the ground employing large electrode separations. Multi-electrode DC resistivity imaging is a fully automated technique that uses a linear array of multiple electrodes connected to a multi-core cable. A pre-defined electrode array, sequentially employing ordered combination of current and potential electrodes, provides a set of measurements of potential difference for these current-potential electrodes combinations which in turn can be converted to a pseudo-section of apparent resistivity as a function of depth using some pre-processing steps. The pseudo-section can then be inverted to get resistivity-depth section.

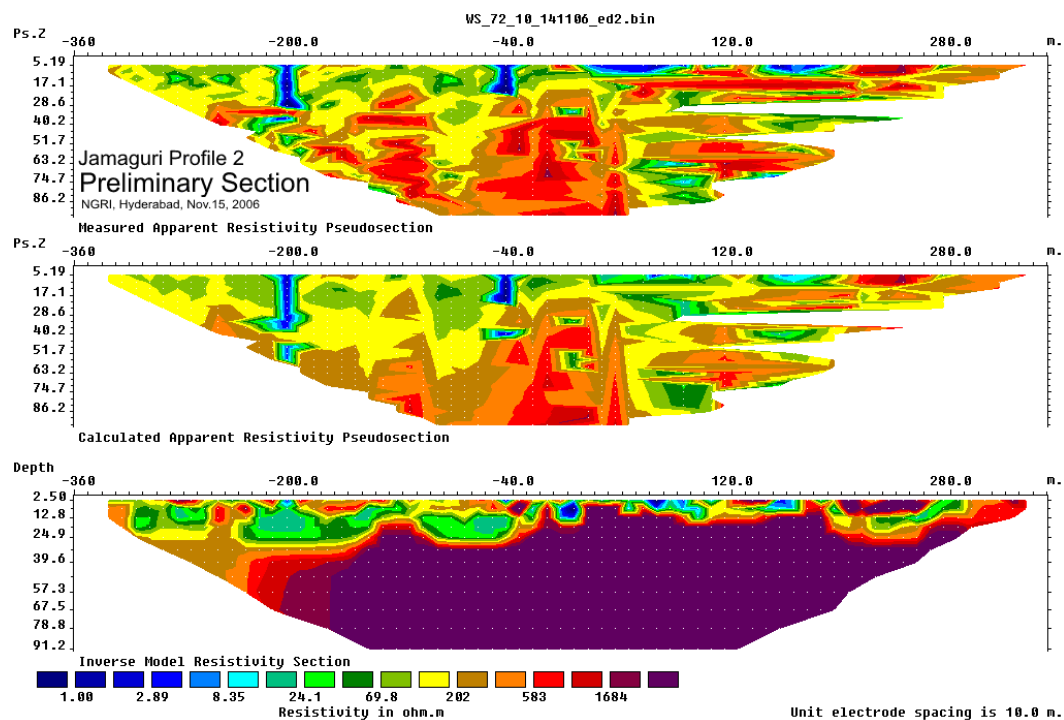
In contrast, MT method is based on natural electromagnetic (EM) fields to delineate the electrical structure of the earth. These natural sources are mainly located in the magnetosphere and ionosphere, separated from the earth's surface by the non conductive atmosphere. The earth being conducting, these natural sources induce secondary fields in the earth. Basis for the MT theory is provided by Maxwell's equations which relate electrical and magnetic fields. The vector nature of electromagnetic fields enables to estimate the tensor form of the resistivity structure by measuring five components time series data consisting of three magnetic ( $H_x$ ,  $H_y$ ,  $H_z$ ) and two electric ( $E_x$ ,  $E_y$ ) components.

Natural EM fields contain a wide spectrum of signals. Therefore, it is possible to get the deeper resistivity information by recording low frequency content of the signal which in turn means a longer duration of MT time series recording. For a sufficiently long time series record (a week or more) it is possible to reach the depth of more than 50 km in a moderate conductivity ground and because of this advantage MT method was used to investigate the deep resistivity structure of earth electrode sites. Additionally, there is also a logistic advantage, especially in the case of deeper (more than a couple of km) investigations where artificial source methods require a large energizing source making logistics extremely difficult. A typical result of such measurement of a particular location of ground electrode station is indicated below (Courtesy: POWERGRID, India):



### 5.5.1 Survey Design

Typically, the earth electrode sites, occupying an area of approximately 600m x 600m, can be covered with 7 multi-electrode DC profiles at 100m separation to image the shallow structure up to the depth of 150 m. Multi-electrodes resistivity imaging system having 80 electrodes at 10 m interval may also be used. This gave a total profile length of 790 m and a penetration depth of more than 120m. These systems allow automatic recording of data for different electrodes configurations. During this measurement, Wenner-Schlumberger configuration has been employed to acquire the data. A typical result of such measurement is indicated below (Courtesy: POWERGRID, India):



For deep resistivity investigations, an area within 10km radius from the earth electrode site is covered by about 13 MT soundings, each with time series recording of one day to achieve the desired depth of investigation, assuming moderately conducting ground conditions. This planning is to be done to ensure that apparent resistivity data of up to 5s period with good signal/noise (S/N) ratio is obtained. In some cases with very quiet and electric noise free sites it is possible to get good S/N data at much lower frequencies. The wide-band MT equipment used in field surveys consists of 6-channel data acquisition unit, three highly sensitive magnetic induction coils and GPS module. Commercially available software was used to analyse time series data and generate apparent resistivity curves. Resistivity inversion was also carried out by using commercial software.

### 5.5.2 Electrode Line Design

The electrode line must carry the pole current as specified for the current rating of electrode. Further it has been a practice to use two conductors in parallel in order to

provide protection based on comparison of current. As this protection may not be sufficiently sensitive to detect in normal bipolar operation, one single conductor should be able to carry full current for a short time. Note that due to the physical size of the conductors, normally ACSR, the breakage of a conductor is very rare. However there are many cases of vandalism where a conductor is stolen for the value of aluminium. This has led to the use, in some projects, of an impedance measuring system which generates an alarm to indicate changes in the electrode/electrode line properties.

As normal bipolar operation, and metallic return, have virtually no permanent current on the electrode line, the current rating of the two conductors can use higher temperatures than normally associated with transmission line conductors, taking into account the maximum continuous time for which rated current is expected to flow. Further, the possible requirement for short time emergency operation with only one conductor is probably the limiting criterion, but even then conductor total cross section is probably less than that of the line pole conductors. Even then, for expected lengths of say 50 km, the voltage drop on the electrode line is rather low, even at the high currents expected in some proposed schemes. This low voltage, say 1-5 kV, means that the insulation level of the line is determined by the need to have arc extinction following an insulator flashover. Such a flashover is probably due to direct or close lightning strike. Typically this results in an electrode line having insulation similar to an ac line of around 30 kV, with one or two standard suspension insulators. Installation of smoothing reactor on the neutral bus for the 800 kV HVDC systems generally do not have any effect on the electrode line insulation.

One possibility when there is difficulty in obtaining line right-of way close to the converter station is to carry the electrode line on the main HVDC towers until close to a suitable site. The electrode line can be used as an insulated shield wire and this has been done in at least one project.

### **References**

- [1] General Guidelines for the design of Ground Electrodes for HVDC links, WG 14.21, CIGRE Brochure, 1997.
- [2] Abhay Kumar, Liu ZeHong: "Three Gorges – Changzhou HVDC – A Transmission Project for Bulk Power and System Integration in China", CIGRÉ Regional Meeting, November 2001, New Delhi.
- [3] R N Nayak, R P Sasmal, S Sen "Selection of Ground Electrode sites using geophysical techniques for resistivity measurements for first  $\pm 800$  kV HVDC System in India "-CIGRE 2008 Paris session

## **6.0 Reactive Compensation and AC System Requirements**

This chapter considers the reactive power compensation requirements of the 800 kV converter stations and the requirements of the connected AC systems.

In principle these issues are not directly related to the choice of  $\pm 800$  kV for the DC transmission voltage. The compensation of reactive power at the converter stations follows the same principle as apply to any HVDC station. Similarly the AC system requirements are no different in principle to any scheme at lower DC transmission voltages.

However, the key difference introduced by the choice of 800 kV for the DC transmission voltage is that the level of power being transmitted is much higher and potentially much more critical to a country's infrastructure. At high power levels the key issues shall be as follows:

- The total reactive compensation required would be much higher compared to the presently operating HVDC schemes. Larger capacitor/Filter sub-banks may be required to be installed to meet the reactive power requirement of the converters. The largest size of filter/capacitor sub-bank would be dictated by the AC system short circuit level and the permissible Voltage change on switching of the sub-banks. This would in turn dictate how the reactive power compensation is arranged to ensure that the converter station matches with the AC system.
- The AC system able to support this high level of real and reactive power interchanges.
- Will the loss of a single bridge, or a pole, or in the extreme, but highly unlikely, case a bipole, result in unacceptable instability conditions on the connected AC system. There may be a need to install dynamic voltage support to be able to meet the required performance of not only for the DC scheme but also of the connected AC system.

In the following sections it is assumed that the HVDC scheme is transmitting a power of about 6000 MW, i.e. the DC current is 3750 A, which is within the capability of present thyristor converter technology. For two parallel converter configurations per pole, the DC current of 3750 A shall be shared equally by two parallel converters each having 1875 A nominal current. The reactive consumption of both of these configurations shall be of similar order. However, parallel converter configuration could deliver higher overload and thereby overall reactive consumption would be higher during overload operation of the remaining converters when one of the converter has tripped. The ac system should be able to support higher delivery of reactive power or else additional reactive compensation has to be provided for overload operation.

**6.1 Reactive power absorbed by the converters**

Due to the inherent inductance of the converter circuit, primarily in the inductance of the converter transformer, and the delays introduced in firing the thyristors, the rectifier and inverter station both consumed reactive power. For a real power of 6000 MW, the converter will absorb approximately 3600 MVAR which has to be locally available to minimize the exchange with the connected AC system. As the converter power increases from minimum power, here assumed as 10%, to maximum power (100%) the reactive power absorption increases. This increase is assumed to be linear and is shown as curve  $Q_{conv}$  in Figure 6.1.

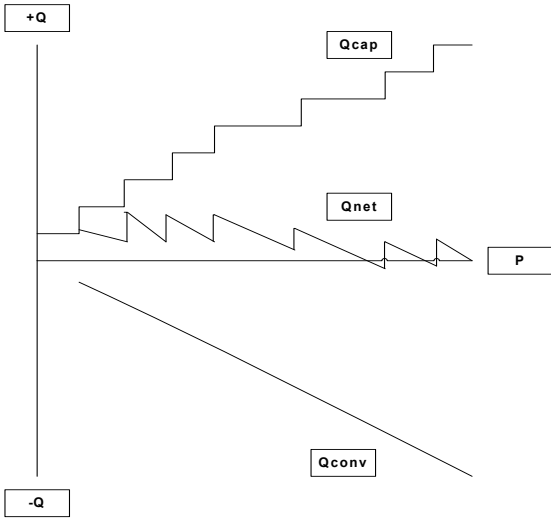


Figure 6.1 Reactive power interchange for 1 pole

**6.2 Reactive power compensation**

Clearly any AC power system will have difficulty in supplying this reactive power demand from the HVDC converter station, even if it is directly coupled to a large generation plant. Hence the normal practice is for an HVDC station to install reactive power compensation equipment, typically to achieve unity power factor at full load. Thus in the present example there would be approximately 3600 MVAR of shunt compensation installed at each converter station. Each pole of the complete bipole would therefore have 1800 MVAR of compensation. Each bridge (12 pulse converter) of the pole would have 900 MVAR of compensation. This requirement of 3600 MVAR could be met by switchable filter/capacitor sub-banks. Assuming the maximum sub-bank size of 200 MVAR, there could be a total of 18 switched capacitor sub-banks associated with the complete scheme, at each terminal station. Some, or all, of these banks would be configured as harmonic filters, which would influence their switching pattern, but not affect their role in reactive compensation. The subject of harmonics is not treated further in this document

As the power is ramped from minimum to maximum power the capacitor banks are progressively switched in to compensate for the absorption of reactive power by the converters. This is shown in curve  $Q_{cap}$  in Figure 6.1. The controls for reactive power

introduce hysteresis between switch-on and switch-off, to avoid hunting, but for simplicity this is not shown here.

### 6.3 Net reactive power interchange with the AC system

The net reactive power interchange ( $Q_{net}$ ) with the AC system, i.e. the absorption from or the generation into the system, is the summation of the two curves  $Q_{conv}$  and  $Q_{cap}$  as shown in Figure 6.1. In this example, considering only 1 pole to simplify the presentation, there is a 200MVAR generation of reactive power into the AC system before the converter is de-blocked at minimum power, here assumed to be 10%. Thereafter as the converter absorbs reactive power, with increasing power transfer, the capacitor banks ( $Q_{cap}$ ) are progressively switched in, initially to comply with harmonic performance requirements and latterly to match the reactive power. Ultimately at full load the switched capacitor banks match the converter reactive power absorption ( $Q_{conv}$ ) and the scheme is operating at unity power factor.

### 6.4 Limits on Reactive Power Interchange

The acceptable limits on the reactive power interchange need to be defined and the operation of the station is to be designed to comply with these limits. There are a number of reasons to limit the reactive power interchange with the AC system and these are briefly described below.

- a) In the steady state the flow of reactive power to/from the HVDC converter station will affect the load flow on the system and the voltage profile. Excessive VAR demand or generation may cause the voltage at the terminal station, or adjacent sub-stations to go outside normal operational limits. The sensitivity of a power system to such voltage variation will depend on the strength of the system. This has been further elaborated at temporary over voltage in the section 6.5 below.
- b) When a capacitor bank (or shunt reactor) switches in/out there will be a step change of voltage on the AC terminal bus. Using the simplifying assumption that the AC system is primarily inductive (high X/R), then the percentage change of voltage neglecting the effect of converter firing control is given by the following expression,

$$\Delta V/V = \Delta Q/(S - Q_{cap}) \quad (6.1)$$

where, S = system short circuit level (MVA)

$Q_{cap}$  = Total reactive power of capacitor bank connected at the time of switching (MVAR)

$\Delta Q$  = The size of the capacitor bank switched in-out.

It can be seen from the above expression that for a stronger AC system having higher system short circuit level (MVA), the voltage change on switching would be lower.

Normally the voltage step is assessed against the normal minimum short circuit level for the AC system at the converter station. Typically a voltage step of 2 – 3% is acceptable on a system for routine switching events, although higher figures, 5 – 6%, may be acceptable on an infrequent basis.

- c) The impact of the voltage step needs to be considered in terms of system stability. The steady state voltage change discussed above may be within normal allowable voltage variation on the system, for an EHV system typically  $\pm 5\%$ . However, if the step change in voltage initiates a transient instability in the system, this may lead to unacceptable consequences on the system. Hence the definition of the acceptable voltage step needs to consider both the steady state and the stability impacts of switching.

### **6.5 Temporary Over-voltage Conditions**

The presence of large amounts of reactive power compensation banks on the AC terminals of the station can have a severe impact on the AC system in the event of a sudden loss of power transmission capability. Under emergency condition the bridge, pole, or bipole can block instantaneously, releasing the reactive power from the switched capacitor banks onto the AC system. The resulting temporary over-voltage (TOV) will persist until the circuit breakers can clear the switched banks from the system. The potential over-voltage is normally limited by the presence of a surge arrester on the filter bus. The protective level and energy absorption capability of this arrester is designed to ensure that the TOV is limited to a level, which is compatible with the AC system. The protective level of this arrester needs to be co-ordinated with other arresters on the HV bus to ensure that energy from the TOV event is dissipated in this arrester and does not damage arresters on the converter transformer terminals, or other locations. As a consequence of the severe TOV duty, the filter bus arrester is normally of a special design, using multiple parallel columns to deal with the high energy requirements.

For an 800 kV transmission scheme, the critical issue is the higher real and reactive powers involved. The AC system needs to be sufficiently strong to withstand the worst-case TOV scenarios, without resulting in an unacceptable impact on the system. There are possible mitigation measures for potentially high TOV conditions,

- Use of dynamic reactive power compensation: This is normally considered for weak systems ( $SCR < 2$ ), but it is not anticipated that such measures would be required for a credible 800 kV transmission system.
- The provision of a short time overload capability, so that the loss of a block of power can be immediately picked-up by the remaining plant, thus avoiding some of the impact on the AC system.

## **6.6 AC System Conditions**

The ability of the AC system to support an HVDC transmission power of 5000 MW or higher was discussed in the report prepared by CIGRE WG14-32 “HVDC Converter Stations for Voltages above  $\pm 600$  kV”.

For a conventional DC system of 5000 MW rating, the minimum short circuit requirements for the power/voltage stability would be about 10000 MVA, unless very special measures are taken.

### **6.6.1 Sending End**

For the case of an HVDC system from a single large power plant, two situations are considered. The first one is that the power plant is connected radially to the HVDC system without any connection to a local AC network. Under such a situation an AC system with moderate strength can be envisaged, because both the rated power and transmitted power at any time will be matched by the capacity of the generators. The second case is that of an HVDC system connected to a power plant, which is part of an AC network. Under such a situation, the AC system conditions will usually be worse than the first situation because some of the power transmitted by the HVDC system can come from generators far away in the AC network. Under some extreme conditions, the AC system may be weak. However it seems that the application of HVDC systems at voltages above 600 kV are justified on the basis of transmitting bulk generated power from remote large generation sources, which means that the sending end AC system strength will be adequate.

### **6.6.2 Receiving End**

The receiving network AC voltage where an HVDC system at voltages above 600 kV is terminated has to be strong. AC networks with voltage levels of 765 kV, 500 kV, 400 kV, 330 kV and 230 kV have been built. However, whether such levels are suitable to receive high infeeds of DC power is a question that should be addressed.

For a 6000 MW HVDC system, the level of reactive compensation required is approximately 3600MVAR and assuming an Effective Short Circuit Ratio(ESCR) of 1.8 to 3, then the minimum AC system strength at the receiving bus would have to be in the range of 14,000 to 22,600 MVA.

230 kV AC networks are widely used as the main transmission voltage in many AC systems around the world. However, at 230 kV the system capacity is unlikely to be sufficient to support a DC power in-feed of 6000 MW.

The short circuit level of a bus in a 330 kV network connected to an HVDC bipole is usually between 5000 MVA to 15,000 MVA according to the location of the bus and type of generators in the network. For an HVDC bipole of 6000 MW capacity, it

becomes a weak or even very weak receiving AC system if connected to a 330 kV network. It may not be strong enough to support a 6000 MW HVDC system without special measures, if the SCL capacity of the network is less than 14,000 MVA.

The short circuit level of a bus in a 400 kV or 500 kV network connected to an HVDC bipole is usually between 10,000 MVA to 30,000 MVA according to the location of the bus and the generators in the network. An AC system at 400 or 500 kV is likely to be a strong or moderate in relation to a 6000 MW bipole.

It is evident that for such a level of DC power the ac system voltage would be 330 kV and above.

## **6.7 Issues related to 800 kV**

The key issues relating to reactive power compensation and AC system requirements are not substantially different for an 800 kV transmission scheme than for the present generation of HVDC schemes at voltages from 500 – 600 kV. The major impact will come from the much higher power rating of these new schemes, about 6000 MW necessitating higher levels of installed reactive power compensation with consequent higher impacts for steady state conditions and for temporary over-voltage conditions. System planners will need to consider the strength of the systems at the sending and receiving ends of these high power links, to determine whether they are suitable for credible (N – 1, or even N – 2) operating conditions. Scheme designers will need to consider the segregation of plant to minimize the risk of loss of more than one block of power, i.e. a bridge, and the short time overload capacity available to rapidly increase the output from the remaining plant.

## **7.0 Insulation Co-ordination**

This chapter describes major topics with regard to the insulation coordination in an 800 kV HVDC scheme. The discussion focuses on converter station main equipment without DC and ac filters. The principle ac filter arrangement does not differ basically from existing bipolar HVDC schemes (except the size of compensation equipment) and will be designed in a similar way. Same applies to the DC filter arrangement in a 800 kV scheme, where the most voltage stresses applies at high voltage capacitors, while the configuration and insulation levels within the filters remain the same as in the existing HVDC schemes. The insulation coordination of overhead lines and towers are described in Chapter 13.

### **7.1 Principles of HVDC insulation coordination**

Referring to the IEC TS 600071-5 “Insulation Coordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations” the primary objectives of insulation coordination are:

- Determination of maximum overvoltages to which various components of a system may be subjected to in practice
- Selection of insulation strength and characteristics of equipment including those for protective devices, used in order to ensure a safe, economic and reliable installation in the event of the above overvoltages.

As an essential difference to ac applications no standardized withstand voltages are used in HVDC systems.

#### **7.1.1 Insulation coordination for 800 kV HVDC systems**

While the basic principle described above is valid for all HVDC systems worldwide, in practice different arrester protection scheme can be found depending on the specific converter arrangement, environmental condition and manufacturer’s philosophy. Examples for such arrester arrangements can be found in IEC TS 600071-5. Installation of additional arresters is useful, if overvoltages can be reduced or limited in such a way that the resulting withstand voltages of the corresponding equipment reduces overall costs or provides other advantages such as easier manufacturing processes or better transportation features.

The insulation coordination for an 800 kV HVDC system is conceptually based on the same procedures as used for existing HVDC schemes. However, special attention is drawn to the specific converter topology and the arrester arrangement is adapted accordingly as described in the following sections.

#### **7.1.2 Converter Topology and Smoothing Reactor Arrangement**

##### **Converter arrangement**

As described in Chapter 4, 800 kV converter station may have a configuration with either single 12 pulse valve group per pole, or two 12 pulse valve groups in series per pole or two 12 pulse valve groups in parallel for each pole. The selection of the converter configuration depends much on various factors such as transportation

limitations, stage-wise development of the scheme and aspects of availability and reliability. With regard to the insulation coordination of the converter station with single 12 pulse valve group per pole it is rather a straightforward procedure as described in IEC 60071-5. Therefore the following sections focus more on the converter configuration with series valve groups in each pole, as there is no difference between the various configurations as long as the insulation requirements of 800 kV DC equipment are concerned.

**7.1.3 Smoothing reactor arrangement**

It is assumed that the smoothing reactor is of air insulated dry-type design and the total inductance consisting of several units/coils is split between HV and neutral bus. This provides significant advantages by reducing the harmonic ripple of the operating voltage to ground at several locations within the converter station. Especially at the HV transformer secondary side this lowers the stresses during steady state operation and hence lowers the continuous operating voltage of additional arresters to be installed here. These arresters and their protective levels are essential for determination of adequate withstand voltages of these transformers.

Besides the reason described above, this arrangement of coils also provides economical advantages since the insulation to ground at the neutral bus is much simpler compared to 800 kV. The following two figures 7.1 and 7.2 demonstrate the effect of installation 50 % of the inductance at the neutral bus:

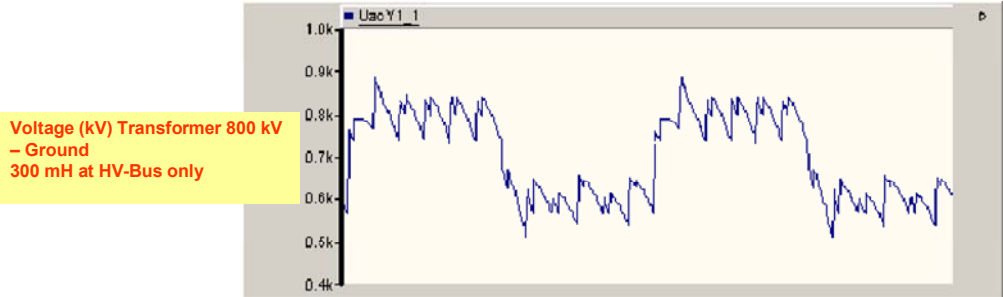


Figure: 7.1



Figure: 7.2

**7.1.4 Arrester arrangement**

The following figure shows a proposed arrester arrangement. It should be noted that modifications or additional arresters may be possible in the final design.

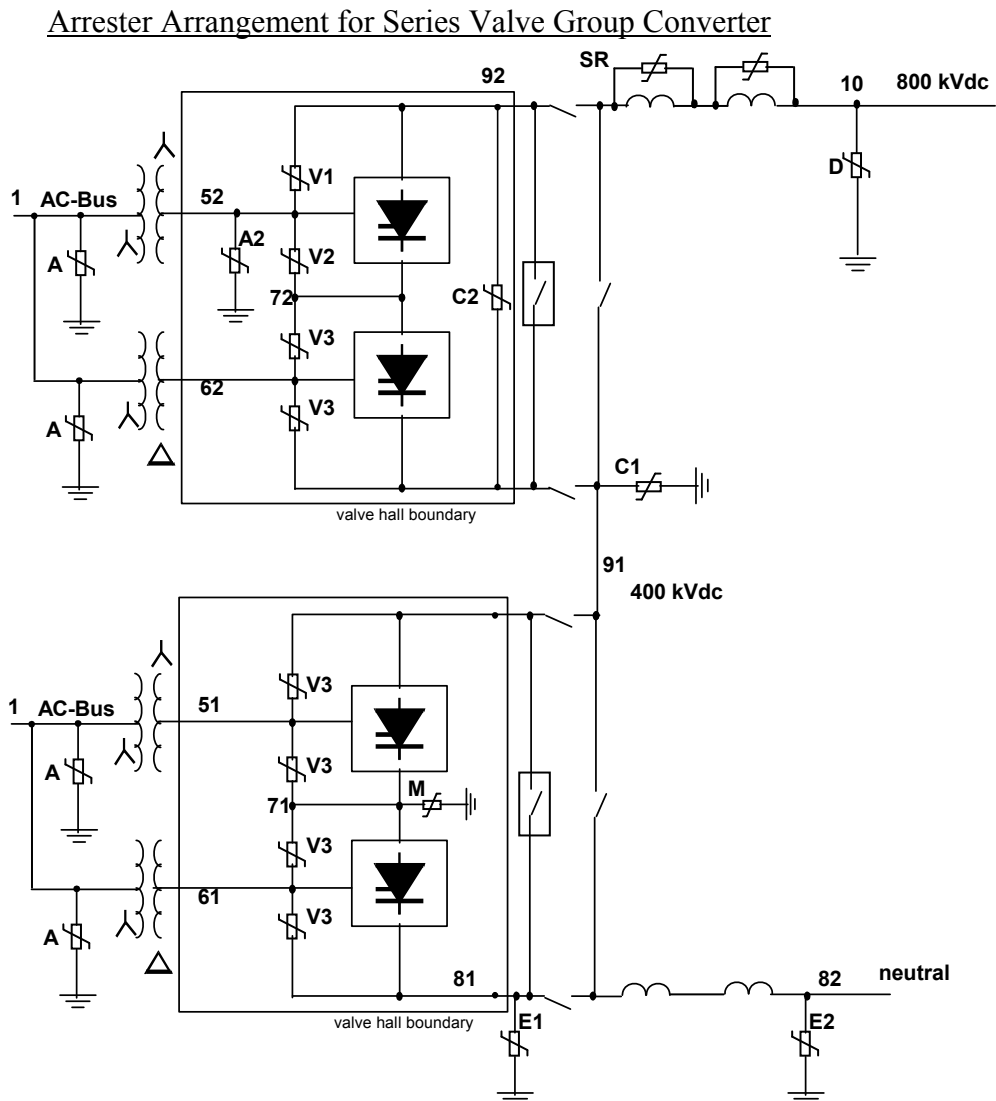


Figure: 7.3

Besides the arresters which are well-known from 500 kV single 12-pulse group designs, the following arresters are introduced:

#### 7.1.4.1 Converter transformer arresters type 'A2'

The ZnO-arresters type 'A2' may be installed on the secondary side of the star group converter transformer 800 kV winding to ground. This arrester is useful to limit overvoltages to ground. Without this type of arrester, a series connection of multiple arresters (e.g. V2+V3+C1, refer to Figure 7.3 above) would define the protective level at location '52' which would lead to higher protective levels. Major event to produce overvoltages at this location is a transferred switching surge from ac side which adds between the phases of the individual six-pulse groups. Lightning surge stresses are typically not decisive since direct lightning strokes can be excluded in the valve hall and attenuation of lightning surges from ac and DC sides is provided by transformer and smoothing reactor.

The operating voltage for this arrester is determined by the conducting status of the valves, i.e. DC voltage “jumps” between 600 kV and 800 kV. Furthermore, a 12-pulse ripple is super-imposed. The smoothing reactor connected at the neutral bus significantly reduces this 12-pulse ripple. Depending on the overall design the A2 arrester can also be omitted. However, in case the converter transformers are completely outside of valve hall, then additional A2 arresters may also be necessary also at LV transformers.

#### **7.1.4.2 Converter group arrester type 'C1'**

The LV 12-pulse converter group (400 kV bus) is protected by the arrester type 'C1' against overvoltages from the AC- and DC-side. During operation with the HV 12-pulse bridge bypassed this arrester limits overvoltages to adequate values for the 400 kV bus equipment. During operation at 800 kV in the event of an inadvertent closing of bypass switch of the HV 12-pulse group this arrester protects the LV 12-pulse bridge. In this case the pre-charged DC line and DC filters will discharge into this arrester.

#### **7.1.4.3 Converter group arrester type 'C2'**

The HV 12-pulse converter group (800 kV bus) is protected by the arrester type 'C2' against overvoltages from the AC- and DC-side. High duties for this arrester are produced during ground faults at location 62 (refer to Figure 7.3 above). C2 arrester may also be connected directly to ground.

#### **7.1.4.4 Mid-point arrester type 'M'**

The ZnO-arresters type 'M' will be installed between the two six-pulse groups of the LV 12-pulse group and ground. It protects the transformer secondary side of the star connection. This is necessary since due to installation of part of the smoothing reactor inductance at the neutral bus, the overvoltages to ground could increase.

#### **7.1.4.5 Smoothing reactor arrester type 'SR'**

Depending on the overvoltage withstand capability, a ZnO-arresters type 'SR' may be necessary to be connected across each smoothing reactor coil of the 800 kV bus. These arresters will not operate during normal operation since their protective level is rather high. Also during disturbances like commutation failures these arresters should not operate. However, in case of severe overvoltages from AC- and DC-side high overvoltages across the inductance may occur. These are limited by the arrester type 'SR'. For lightning or steep front surge overvoltages an arrester across each coil allows to inhibit unequal voltage distribution across the arrangement.

### 7.1.5 Arrester Arrangement for Parallel Valve Group Converter

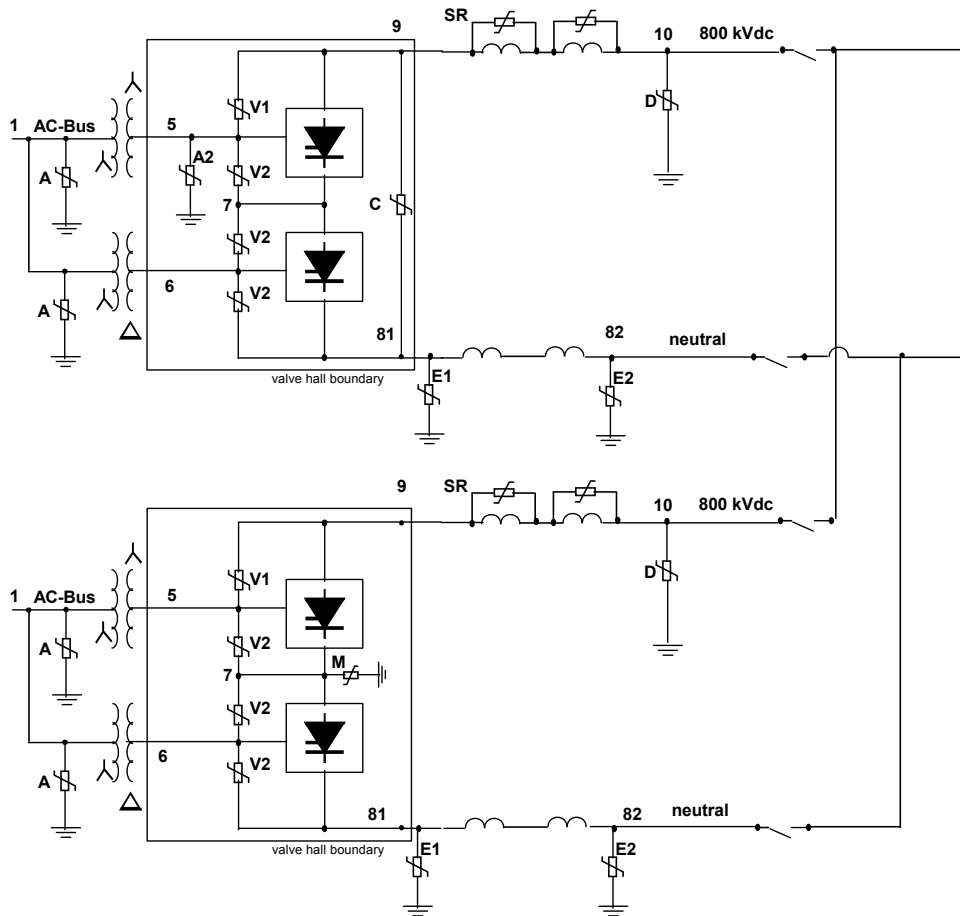


Figure: 7.4

The arrester arrangement for parallel valve groups is very similar to the 500 kV single 12-pulse group designs. Two possible arrangements are shown in the two parallel valve groups:

#### 7.1.5.1 Converter transformer arresters type 'A2'

The ZnO-arresters type 'A2' has same function as at the series valve group converter to limit the overvoltage stresses at 800 kV transformer terminals. This function can also be taken by "M" and "V" arresters.

#### 7.1.5.2 Converter group arrester type 'C'

The 12-pulse converter valve group is protected by the arrester type 'C' against overvoltages from the AC- and DC-side.

#### 7.1.5.3 Mid-point arrester type 'M'

The ZnO-arresters type 'M' will be installed between the two six-pulse groups and ground. It protects the transformer secondary side of the star connection in conjunction with valve arresters.

#### 7.1.5.4 Smoothing reactor arrester type 'SR'

Same function as in the series valve group converters.

#### 7.1.6 Insulation margins and withstand voltages

Insulation margins as factors between required withstand voltages and corresponding protective levels of arresters shall consider:

- allowance for limitation in modelling and in data for calculating the overvoltages
- allowance for ageing of insulation
- allowance for changes in arrester characteristics
- allowance for dispersion in the product quality

The following insulation margins are recommended as minimum values for an 800 kV scheme:

<u>Equipment</u>	<u>Switching / Lightning / Steep Front Impulse</u>
Valves	15 / 15 / 20 (10/10/15)*
Others: oil insulation	15 / 20 / 25
Others: air insulation	15 / 20 / 25

\* As per IEC 60700-1, "Thyristor valves for high voltage direct current (HVDC) power transmission – Part1: Electrical testing", lower safety margins can be used for valve impulse testing.

The above given safety margins as recommended by IEC standards have been used for various HVDC schemes worldwide. Furthermore, state-of-the-art simulation tools meanwhile allow to calculate the maximum voltage stresses with high accuracy removing the need to include additional margins. The proposed lower values for valves are in line with IEC 60700-1 "Thyristor valves for high voltage direct current (HVDC) power transmission - Part1: Electrical testing", which is very much related to thyristor valves. This standard explains in Annex A why lower safety factors can be justified for valve impulse tests (switching, lightning, steep front). As the thyristor valves, based on this, are tested with safety factors of 1.1/1.1/1.15 for switching/lightning/steep front, it is logical to design the valves also using insulation margins of 10%/10%/15% for switching/lightning/steep front impulse voltages.

Due to the project specific arrester arrangements and equipment designs standardized withstand voltages as known from ac applications are not practicable for HVDC systems. Therefore, multiplying the insulation margin with the protective levels is the most suitable way to determine the equipment's withstand voltage requirements.

The margins given above are as per IEC 60071-5 and CIGRE WG 33.05, Electra No. 96 as well as IEC 60700 for testing of thyristor valves.

Another aspect with regard to the safety margins shall be addressed is the additional safety margins of valve side transformer bushings, which has been practiced in many previous DC projects. Bushings, prior to being installed and tested as part of the transformers, are pre-tested separately. Withstand levels of transformer bushings for these tests compared to the levels of transformers are specified in the relevant documents as follows.

IEC 62199 "Bushings for DC application" requires 15% increased withstand levels for DC applied voltage, DC voltage polarity reversal and AC voltage compared to the corresponding values of the converter transformers.

Regarding lightning and switching impulse withstand levels IEC 62199 does not specify such increased test levels for transformer bushings, whereas some HVDC projects define 10% higher values. It is to be noted that IEC 60137 "Insulated bushings for alternating voltages above 1000 V" does not specify increased withstand levels for AC transformer bushings for lightning and switching type voltages, neither.

The only background and reason for increased withstand levels of converter transformer bushings is to achieve additional margin for the bushing part with respect to transformer testing. On the other hand, during operation dielectric stresses are identically the same for bushings and transformers which does not justify to increase the insulation levels of the bushings. The possible side effect by applying an extra safety margin for bushings in a transformer is even more apparent for the 800 kV DC systems, in which extra insulation in the bushings would make them larger than they anyway need to be for the actual voltage stresses. However, as per existing IEC 62199, the bushings in converter transformers shall be designed and tested for the 15% higher margin voltage requirements than the converter transformers.

It should be noted that the margins discussed above and the resulting withstand voltages are valid for internal insulation. Furthermore, air clearances of equipment installed up to 1000 m above sea level are covered by these values. Aspects with regard to the external insulation such as air clearance, creepage distance are discussed section below.

### **7.1.7 External Insulation**

External insulation aspects for 800 kV DC equipment refer mainly to the creepage distance and air clearance requirements as well as aspects of insulation material and shed profiles.

An indoor DC yard solution seems to solve many problems related to DC voltage operation in polluted areas. However, excellent experience using insulators with

composite material was gained in various 500 kV HVDC schemes with outdoor DC yard worldwide. Hence, this solution – adapted for 800 kV requirements – offers significant advantages compared to porcelain insulators and allows an outdoor DC yard solution depending on the pollution levels at site of installation.

### 7.1.8 External Insulation of Outdoor DC Yard Equipment

This subject will be dealt with more details in Chapter 12.

#### 7.1.8.1 Creepage distance

The specific creepage distance (mm/kV) for HVDC equipment depends mainly on the pollution levels at site of installation. Thus there is no need to adapt different specific creepage distances on the 800 kV DC equipment with respect to existing (500 kV DC) equipment. Furthermore, it is known that ideally, the creepage distance should be the same for both porcelain and composite insulators as the hydrophobic properties of the insulators temporarily is lost under pollution condition and the time of recovery may be several hours depending upon the type of composite material and pollutant. It has been reported that some of the projects are under operation with reduced creepage up to 25%, however, it is difficult to conclude that the creepage distance could be reduced for composite insulators in all cases due to insufficient data, testing and field trial and also variance in hydrophobic characteristic of various composite material.

Depending on the average diameter  $d_m$  of equipment housing, different specific creepage distances have been used for the DC equipment in the HVDC schemes. Typically for a heavy polluted area (ESDD up to  $0.075 \text{ mg/cm}^2$ ) the following specific creepage distances have been applied by some utilities:

	Porcelain	Composite Housing
$d_m < 400 \text{ mm}$	57 mm/kV	42.75 mm/kV
$d_m < 500 \text{ mm}$	59 mm/kV	44.25 mm/kV
$d_m < 600 \text{ mm}$	61 mm/kV	45.75 mm/kV
wall bushing (horizontal)	60 mm/kV	45 mm/kV

The total creepage distance needed for the corresponding equipment shall be calculated taking the adequate reference voltage into account. According to IEC 60071-5, Clause 8 and Clause 3.1 the highest mean or average operating voltage, excluding possible harmonic and commutation overshoots, shall be used as voltage level to determine the required leakage distance for the insulation of DC equipment.

#### 7.1.8.2 Shed form of housings

Shed profile is important for the pollution flashover performance of equipment housings. From experience, two types of shed forms are advisable for DC application:

alternate and the deep under-rib sheds. (The latter applies for porcelain housings only.) A further characteristic feature of the shed profile to be kept in mind is the ratio between shed spacing and shed overhang which should not be less than 0.7 to 0.8 depending on the pollution level.

While the performance of different shed forms is well described for porcelain insulators in the literature [7], there is no preferred shed form of composite housing with silicon rubber for HVDC application. Indeed there are various shed forms with shed distance starting from 38 mm up to 60 mm successfully in operation for many years, many of them are exposed to the severe environmental conditions including heavy rain fall. Therefore shed form is a matter of design optimization by the manufacturers taking various aspects into account including operating experience.

#### 7.1.8.3 Corrections for altitudes

Air clearances of the DC switchyard should be corrected for altitudes higher than 1000 m above sea level. Correction of air clearances of DC yard apparatus and the applicable test voltages will be done for altitudes higher than 1000 m above sea level according to the stipulations in the related equipment standards.

With regard to the need of correction of creepage distance at high altitude, there is no generally accepted rule in the current international standards. Although the physics of decreased air density at higher altitude may have impacts on the insulation capability along equipment surface, it is, however, rather a usual industrial practice that no altitude correction will be done for creepage distances as a function of altitude, neither in AC nor in DC substation. As long as the specific creepage distance is conservatively selected and the composite material is applied for the equipment housing, it is acceptable to apply the same design method for 800 kV DC equipment, that is, no altitude correction for creepage distances.

#### 7.1.8.4 Minimum clearances / flashover distance

For 800 kV DC equipment the minimum flashover distance can be well calculated based on the required insulation levels. The switching impulse level will become the dimensioning quantity. Lightning impulse and DC voltages are not decisive with respect to the flashover distance. The correct design of the flashover distances will be verified by corresponding type testing of the equipment.

#### 7.1.8.5 Height/length of the equipment

As a consequence of creepage distance requirements and appropriate shed forms, the height of a small diameter porcelain solid core insulators (consisting of e. g. six units)

cannot be less than approximately 12 m. Hence, the required flashover distance is more than met. The required and feasible height/length of equipment with composite housings, however, can range from the calculated flashover distance of about 8 m up to approximately 10 m. Composite housings may consist of one or more units, depending on the type of equipment. Further decisive aspects for the height/length of such housings are the mechanical design (seismic, wind loads etc.) and the handling of the equipment during manufacturing and transportation. (Special measures may also be needed for the higher insulator columns to ensure the required mechanical strength in the field.) Taking all aspects into account the height/length of the equipment shall be rather at the lower end.

### **7.1.9 External Insulation of Indoor DC Yard Equipment**

According to experience with indoor DC yard, the required minimum creepage distance can be reduced to the range of 20 ... 25 mm/kV which is valid for both types of insulating material, porcelain and silicone rubber. For the internal design of valves the creepage distance can be kept in the proven range of 12 ... 14 mm/kV due to controlled climate conditions and positive pressure inside the valve hall.

However, it should be noted that the requirements on air clearances resulting from switching impulse level will most likely become the dimensioning factor for insulator length of the equipment.

#### **Acknowledgements**

Sincere acknowledgements are extended to Mr. Marcus Haeusler and Dr. Hermann Koelsch for their valuable contributions and advices.

#### **References**

1. IEC TS 600071-5 “Insulation Coordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations
2. CIGRE, Application Guide for Metal Oxide Arresters without Gaps for HVDC Converter Stations, Prepared by WG 33/14-05
3. CIGRE, Application Guide for Insulation Coordination and Arrester Protection of HVDC Converter Stations, Prepared by WG 33-05
4. HVDC Converter Stations for Voltages Above 600 kV, EPRI EL-3892, Project 2115-4, Final report February 1985
5. HVDC Converter Stations for Voltages Above  $\pm 600$  kV, Cigré Working Group 14.32, December 2002
6. IEC TS 60815-1, Selection and dimensioning of high-voltage insulators for polluted conditions – Part 1: Definitions, information and general principles
7. CIGRE, Polluted Insulators: A review of current knowledge, prepared by WG 33.13, TF 33.13.01

## 8.0 Insulation Levels

This chapter describes insulation levels and testing levels of main equipment in 800 kV HVDC converter station.

### 8.1 DC system parameters of two demonstration cases

In order to provide an overview of the protective levels and insulation requirements at all major location in a 800 kV station, two typical examples of 800 kV station, one with two series valve groups per pole and other one with parallel valve groups per pole, are selected for demonstration purpose. The insulation values provided apply basically to other converter configuration as well.

The main circuit parameters on which the insulation coordination is based are given below and shall be understood as representative example. Depending on the final system parameters, arrester data and arrester arrangement the insulation coordination has to be adapted. However, this example gives typical values and the final results may not differ significantly.

Since the inverter station operating voltages are lower than the rectifier, the insulation coordination in this chapter focuses on the rectifier station.

### 8.2 Converter Main Data for Series Valve Groups

The main circuit arrangement consists of two 12-pulse groups (400 kV each) connected in series resulting in a nominal operating voltage of 800 kV per pole. Each group can be by-passed allowing operation at 400 kV.

AC voltage, nominal	500 kV	
AC voltage, maximum	550 kV	
DC voltage, rectifier, nominal	± 800 kV	(per pole)
DC voltage, rectifier, design value	± 816 kV	(per pole)
DC voltage rectifier, nominal	± 400 kV	(per 12-pulse group)
DC voltage rectifier, design value	± 408kV	(per 12-pulse group)
DC current, nominal	4000 A	
transformer impedance, uk	18 %	
rel. inductive. voltage drop, dxn	0.09 p.u.	
rel. resistive voltage drop, drn	0.004 p.u.	
total. Rel. voltage drop, dxtot	0.094 p.u.	
no-load voltage, Udion	229.4 kV	
transformer rating (6-pulse), Sn	960.8 MVA	
transformer secondary. Voltage, Usec	169.8 kV	
transformer tap size	approx. 1.25 %	
transformer tap, step number	+18 / -4	
smoothing reactor size	300 mH	per station and pole
	(50%, i.e. 2x75 mH on neutral bus,	
	50%, i.e. 2x75 mH on HV bus)	

### 8.3 Converter Main Data for Parallel Valve Groups

The main circuit arrangement consists of two 12-pulse groups (800 kV each) connected in parallel connecting to the same pole conductor. Each valve group can be operated alone at rated voltage of 800 kV.

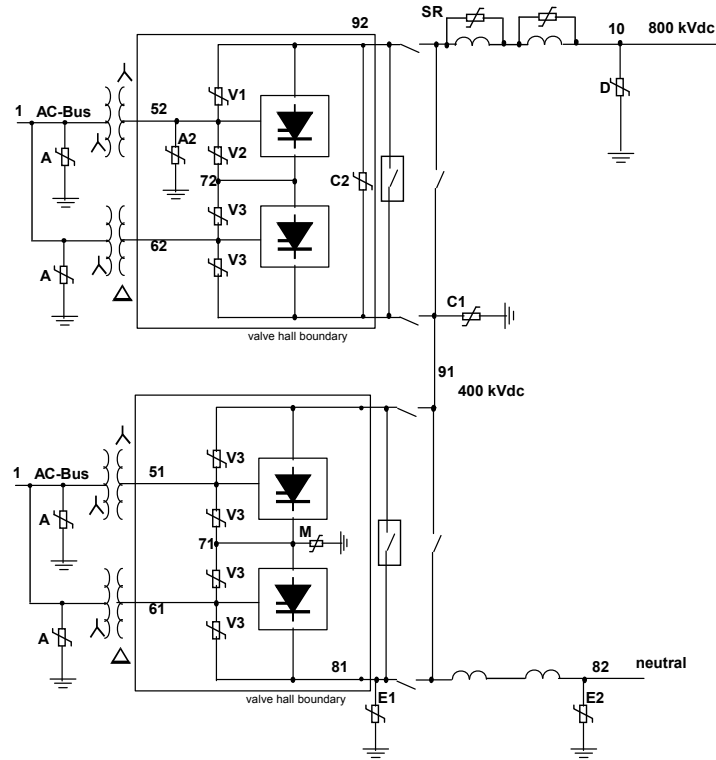
AC voltage, nominal	400 kV
AC voltage, maximum	420 kV
DC voltage, rectifier, nominal	± 800 kV (per pole)
DC voltage, rectifier, design value	± 816 kV (per pole)
DC current, nominal	3750 A (per pole)
DC current, nominal	1875 A (per 12 pulse valve group)
transformer impedance, uk	18 %
rel. inductive. voltage drop, dxn	0.09 p.u.
rel. resistive voltage drop, drn	0.004 p.u.
total. rel. voltage drop, dxtot	0.094 p.u.
no-load voltage, Udion	459 kV
transformer rating (6-pulse), Sn	900 MVA
transformer secondary. voltage, Usec	340 kV
transformer tap size	approx. 1.25 %
transformer tap, step number	+18 / -4
smoothing reactor size	200 mH per station and valve group (50%, i.e. 100 mH on neutral bus, 50%, i.e. 100 mH on HV bus)

### 8.4 Indicative protective levels and withstand voltages

Determination of protective and withstand levels of main equipment follows generally procedure given in IEC 60071-5 and is based on the characteristics of arresters used.

The following tables give an overview on the proposed arrester values for the two proposed typical valve group arrangements. As the arrester values may depend on the manufacturers and the detailed design, the withstand voltages are rounded up moderately in order to give ‘worst-case’ values. Hence, the final insulation levels of the equipment are likely to be below the values presented herein. The margins (withstand level / protective level) used for determination of withstand levels are in accordance with values given in Chapter 7.

### 8.4.1 Converter Station with Series Valve Groups

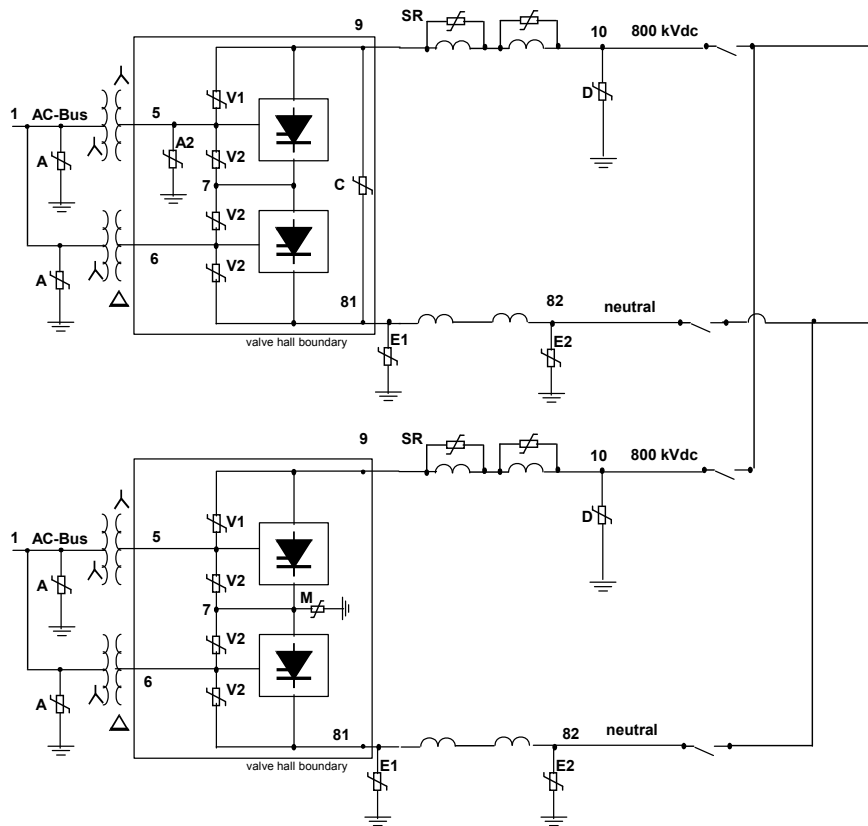


Arrester Type		A	A2	V1	V2	V3	M	C	D	E1	E2	SR
MCOV/CCOV	kV	318	946	245	245	245	245	473	816	<120	<80	<100
	rms		crest	crest	crest	crest	crest	crest	DC	rms	DC	ac
Lightning												
- Protective Level	kV	907	1344	395	395	395	435	791	1579	288	288	730
- at Current	kA	20	0.6	2.4	1.2	0.6	0.6	5	10	20	20	10
Switching												
- Protective Level	kV	780	1344	395	395	395	435	721	1330	245	245	600
- at Current	kA	2	1.0	4.0	2.0	1.0	1.0	1.0	1.0	2	2	1

Location	1	51	61	71	52	62	72	81	82	91	92	10
MCOV(kV)	318	473	245	245	946	710	710	120	80	473	946	816
	rms	crest	crest	crest	crest	crest	crest	rms	DC	crest	crest	DC
LIPL (kV)	907	---	---	---	---	---	---	288	288	791	---	1579
SIPL (kV)	780	830	640	435	1344	1116	1116	245	245	721	1344	1330
BIL (kV)	1550	1300	950	750	1800	1550	1550	450	450	1175	1800	1900
SIL (kV)	1175	1050	750	550	1600	1300	1300	325	325	950	1600	1600

Location	51 & 61 ph-ph	51 - 61	81 - 91	52 & 62 ph-ph	52 - 62	91 - 92	92 - 10	81 - 82	Valves V
LIPL (kV)	---	---	---	---	---	---	---	---	---
SIPL (kV)	465	790	721	465	790	721	2100	300	395
BIL (kV)	750	1175	1175	750	1175	1175	<2450	450	435
SIL (kV)	650	950	950	650	950	950	2450	375	435

### 8.4.2 Converter Station with Parallel Valve Groups



Arrester Type		A	A2	V1	V2	M	C	D	E1	E2	SR
MCOV/CCOV	kV	254	946	490	490	490	946	816	<120	<80	<100
	rms		crest	crest	crest	crest	crest	DC	rms	DC	ac
Lightning											
- Protective Level	kV	724	1344	790	790	870	1582	1579	288	288	730
- at Current	kA	20	0.6	2.4	1.2	0.6	5	10	20	20	10
Switching											
- Protective Level	kV	623	1344	790	790	870	1442	1330	245	245	600
- at Current	kA	2	1.0	4.0	2.0	1.0	1.0	1.0	2	2	1

Location	1	5	6	7	81	82	9	10
MCOV(kV)	254	946	473	710	120	80	946	816
	rms	crest	crest	crest	Rms	DC	crest	DC
LIPL (kV)	724	---	---	---	288	288	---	1579
SIPL (kV)	623	1344	830	1116	245	245	1344	1330
BIL (kV)	1425	1800	1300	1550	450	450	1800	1900
SIL (kV)	1050	1600	1050	1300	325	325	1600	1600

Location	5 & 6 ph-ph	5 - 6	81 - 9	9 - 10	81 - 82	Valves V
LIPL (kV)	---	---	---	---	---	---
SIPL (kV)	930	1580	1442	2100	300	790
BIL (kV)	1300	2100	1800	<2450	450	869
SIL (kV)	1175	1950	1675	2450	375	869

### 8.5 Discussion of Insulation Levels

Comparing to the values proposed in former study reports [2, 3] the insulation levels given here are lower, particularly for 800 kV transformers. The reasons are:

- Introduction of A2 arrester directly protecting the 800 kV transformer
- Split arrangement of smoothing reactors (HV and LV side) to reduce the operating voltage of A2 arrester enabling a more optimized protective levels
- Application of modern ZnO-arrester with low protective levels and high energy absorption capability
- Consequent application of proven design practice and relevant IEC standards

Following table shows an overview of some representative values with respect to the insulation coordination out of the two former study reports. The reason of discrepancy can be traced to the protective levels of arresters and the safety margins used in each individual study report. EPRI report [2] used higher safety margins in accordance to the practice in that time. The CIGRE WG report [3] selected the insulation levels without providing the base of calculation. These values seem to be selected conservatively.

It can be concluded from discussion above that the insulation levels proposed for the  $\pm 800$  kV scheme in this report is adequate. They are consistent with the arrester arrangement, arrester protective levels, safety margins and procedures given in the IEC standards.

		EPRI Report [2]	CIGRE WG 14-32 [3]	CIGRE WG B4-45
Valves	protected by	parallel arresters	parallel arrester	parallel arresters
	Arrester protective ratio	1.65	1.65	1.62
	MCOV	239 kV	248 kV	245 kV
	SIPL	395 kV	408 kV	395 kV
	Min. margin	15%	15%	10%
	SIWL	454 kV	469 kV	435 kV
800 kV Transformer, sec. side	protected by	3x bridge arrester + 1 valve arrester	Indirectly by arresters in series	directly by A2-arrester
	Arrester protective ratio		1.65	1.62
	MCOV	956	-	946
	SIPL / LIPL	1496 / 1813	1644 / - kV	1344 / 1344 kV
	Min. margin	20 / 25 %	15 / 20 %	15 / 20 %
	SIWL / LIWL	1800 / 2250 kV 1800 / 1950 kV*	1891/ 1990 kV	1600 / 1800 kV

DC Bus Equipment	protected by	4 x bridge arresters	directly by D-arrester	directly by D-arrester
	Arrester protective ratio		1.65	1.63
	MCOV	956	-	816
	SIPL / LIPL	1468 / 1779 kV	- / - kV	1330 / 1579 kV
	Min. margin	20 / 25 %	15 / 20 %	15 / 20 %
	SIWL / LIWL	1800 / 2250 kV 1800 / 1950*	1675/ 2100 kV	1600 / 1900 kV

\* withstand levels by introducing TA –arrester (DC bus to ground arrester)

### 8.6 Withstand and testing levels of 800 kV main equipment

Based on the results of insulation coordination study the withstand levels of converter station equipment can be determined in accordance with procedure as given in IEC 60071-5. Particularly the high voltage main equipment (800 kV converter transformer and DC bus equipment) are in the focus of further discussion, while other equipment can be generally design and tested as in the existing HVDC schemes.

#### 8.6.1 Converter Transformers

Insulation and testing levels for converter transformer shall be selected as per IEC 61378-2 “Converter transformers, part 2: Transformers for HVDC applications”.

		Wye-Winding/Bushing	Delta-Winding/Bushing
SIWL	kV <sub>pk</sub>	1600	1300
LIWL	kV <sub>pk</sub>	1800	1550
Applied AC 60 Min.	kV	907	691
DC withstand test voltage	kV	1253	947
Polarity reversal test voltage	kV	968	713

#### 8.6.2 Thyristor Valves

Insulation and testing levels of thyristor valves shall follow IEC 60700-1 „Thyristor valves for high voltage direct current power transmission, part 1: electrical testing”. The insulation levels of single valves are determined directly by the protective levels of parallel connected valve arresters, while the valve tower may be protected by series arresters.

#### Double and Quadruple Valve Tower

SIWL	kV <sub>pk</sub>	1600
LIWL	kV <sub>pk</sub>	1800
Applied AC 60 Min.	kV	300 (15 s)
DC withstand test voltage	kV	240 (30 min)
		1350 (60 s)
		1050 (3 h)

### 8.6.3 Smoothing Reactors

Only high voltage side smoothing reactor connecting to the 800 kV DC bus is considered here. The insulation levels of smoothing reactor on the low voltage side shall adapt to the voltage levels of the neutral bus, which depends on the DC current and line resistance in the scheme.

SIWL	kV <sub>pk</sub>	1600
LIWL	kV <sub>pk</sub>	1800
Applied AC 60 Min.	kV	907
DC withstand test voltage	kV	1253
Polarity reversal test voltage (for Oil insulated Reactor)	kV	968

### 8.6.4 Wall Bushings

Insulation and testing levels of 800 kV wall bushing shall follow IEC 62199 „Bushings for d.c. application”.

SIWL	kV <sub>pk</sub>	1600
LIWL	kV <sub>pk</sub>	1800
Applied AC 60 Min.	kV	865
DC withstand test voltage	kV	1000
Polarity reversal test voltage	kV	1020

### 8.6.5 800 kV DC Bus Equipment

800 kV DC bus equipment includes DC bus arresters, disconnectors, bypass switches, voltage dividers, current transducers, DC filter and PLC filter capacitors, and supporting insulators.

SIWL	kV <sub>pk</sub>	1600
LIWL	kV <sub>pk</sub>	1900
DC withstand test voltage	kV	1200
Polarity reversal test voltage	kV	1020

**8.7** The above insulation levels have been worked out, are typical minimum values for a particular layout, arrester arrangement, arrester data and system parameters etc. It is suggested that for each specific project, detail insulation co-ordination studies are to be carried out taking into account of station layout, system parameters, arrester data, arrester arrangement etc. and the insulation level need to be decided on that basis.

### **Acknowledgements**

Sincere acknowledgements are extended to Mr. Marcus Haeusler and Dr. Hermann Koelsch for their valuable contributions and advice.

### **References**

1. IEC TS 600071-5 “Insulation Coordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations
2. HVDC Converter Stations for Voltages Above 600 kV, EPRI EL-3892, Project 2115-4, Final report February 1985
3. HVDC Converter Stations for Voltages Above  $\pm 600$  kV, CIGRE Working Group 14.32, December 2002

## 9.0 Interference Levels

The interference effects due to HVDC transmission lines consist mainly of the following:

- (i) Electric field effects
- (ii) Magnetic field effects
- (iii) Corona
- (iv) Audible noise
- (v) Radio Interference

Though the same limits can be applied to corona, audible noise and RIV for both AC and DC systems, the limits for electric and magnetic fields for AC and DC transmission lines are different due to their different perception thresholds. As on date literature and guidelines exist for AC electric and magnetic fields at 50/60 Hz because of the widespread use of power at this frequency in most of the countries. At present, the maximum DC transmission voltage of  $\pm 600$  kV exists (Itaipu, Brazil) and HVDC transmission systems of  $\pm 800$  kV are being considered in countries like India, China, and South Africa. Considering the need of high capacity HVDC transmission line in near future guidelines for limiting exposure to electric and magnetic fields from HVDC transmission lines are required.

### 9.1 Purpose and Scope

The main objective of this Chapter is to propose reference level guidelines for exposure limits to interference effects from  $\pm 800$  kV HVDC transmission lines. Literature of various scientific organizations viz. ICNIRP and IRPA, health organizations such as WHO and Health Council of Netherlands were studied for this purpose. Further, technical papers on operating HVDC transmission lines and HVDC test lines have also been considered for preparation of guidelines. Since DC lines produce lesser audible noise and radio interference in comparison to AC lines (see section 9.3.2 hereunder), exposure limits for these effects could be taken from AC lines which have been studied exhaustively in the past. This guideline therefore pertains mainly to electric field effects and its limits for HVDC lines.

### 9.2 Comparison of Electrical Environment of AC and DC Transmission Lines

DC is a unidirectional steady current unlike AC which is sinusoidal in nature. Due to the steady flow of current, the field produced by DC transmission lines are static unlike the fields produced by AC which are time varying. During corona phenomenon in AC transmission lines, air ions formed in the process are alternately repelled and attracted, as voltage polarity changes on the conductor at 50/60Hz as the case may be. Therefore movement of the charge is restricted just around the conductor. In DC

however in the event of corona, the air ions get attracted towards the opposite polarity pole and some get carried towards the ground by wind, thus increasing the field at ground level and near to the line. The electric environment of a DC transmission line is more complex and variable than an AC transmission line because of the effects of the air ions and varying atmospheric conditions (*Ref 1*).

### **9.3 Comparison of DC and AC Interference Effects**

#### **9.3.1 Electric and Magnetic Fields**

Since static electric field cannot enter conductive objects like human body, the mechanism of its interaction is only surface electric charge unlike time varying AC electric field which induces both electric current and electric field (*Ref 2, WHO EHC; Ref 3, ICNIRP Statement*). The adverse effects due to static electric field are therefore less pronounced than time varying AC electric field. The static magnetic field can enter conductive objects and produce an electric field in moving objects like tissues. In addition, the effects of space charge due to ions and the associated ion current density should be taken into account in DC.

#### **9.3.2 Corona, Radio Interference (RI) & Audible Noise (AN)**

There is no basic difference in the AC and DC corona mechanism. The DC line RI noise has a lower nuisance value than an AC line resulting in lower requirements of signal to noise ratios. Further the DC radio interference levels and audible noise levels are decreased by rain, wet snow and other atmospheric conditions that thoroughly wet the conductor unlike AC levels which increase with such atmospheric conditions (*Ref. 4, EPRI Report*). Hence, the audible noise and RI limits applied to AC lines can also be applied for DC lines.

### **9.4 Survey of Literature Published By Scientific and Health Organisations**

Technical papers published by various scientific and health organisations in respect of biological and health effects due to static fields were studied and salient findings have been summarized below:

#### **9.4.1 WHO EHC (Ref. 2)**

The typical values of static electric field encountered under exposures to various conditions are 30 kV/m under a 500 kV HVDC transmission line, 20 kV/m in front of TV & VDU and up to 500 kV/m while walking on non conducting carpets. The direct effects due to this static electric field comprises of (i) charge induced on the human body resulting in perception in case of strong fields or (ii) shock received by touching a metal object insulated from ground. The laboratory studies on humans have indicated perception range for static electric fields between 10 to 45 kV/m. Further the experiments carried out failed to demonstrate any adverse health effects from DC electric field except for perception of stress resulting from prolonged exposure to micro shocks.

For static DC magnetic fields, laboratory experiments carried out on cells, cellular components etc. suggested no detrimental effects on major development, behavioral, physiological parameters for short term exposures up to 2.0 Tesla. Indications like vertigo and nausea were found above this level. Further EHC based on IARC report, categorises carcinogenicity to humans from static magnetic fields as ‘non classifiable’ due to inadequate evidence in humans.

#### **9.4.2 Heath Council of Netherlands (Ref 5)**

The threshold for charge generated by a static electric field which may result in movement of hair lies at approximately 20 kV/m and that field up to and beyond 1200 kV/m may be generated under conditions like walking on synthetic carpet in a dry environment. These fields however do not result in negative health effects even though discomfort due to startle response from associated spark discharge may be caused. Further animal studies with exposures up to 340 kV/m have not identified any effect on blood count, reproduction and prenatal mortality.

In respect of static magnetic field, since no biological effects have been demonstrated below static magnetic field of 2T, a continuous exposure limit of 200mT (safety factor of 10) has been proposed for working population and a continuous exposure limit of 40 mT (further safety factor of 5) has been proposed for the general public.

#### **9.4.3 ICNIRP (Ref 3, 6 and 7)**

The guidelines state that perception of electric field charges due to static field shall not occur below 25kV/m. It also states that spark discharges causing stress or annoyance should be avoided.

The exposure limit for static magnetic field provided by the ICNIRP guidelines is 200mT for occupational exposure and 40 mT for general public exposure which is also in agreement with Reference 5.

The comments included in the ICNIRP are applicable to time varying electric field and due to that they should not be considered here.

#### **9.4.4 German Standards (DIN)**

According to DIN standard, occupational exposures should not exceed a static electric field of 40 kV/m and a higher limit of 60 kV/m is permitted for exposures up to 2hrs (Ref 8).

### **9.5 Survey of Technical Papers Related To HVDC Interference Effects**

Technical papers and reports related to DC interference effects have been studied with regards to HVDC and salient findings have been summarized below.

### 9.5.1 Paper on Environmental Characteristics

#### **HVDC overhead lines by Prof. Koshcheev (Ref 9) & Russian Regulations (Ref 10)** *Electric & Magnetic fields*

Discomfort to humans typically felt under AC transmission lines is not observed for HVDC transmission lines. The average threshold of detection to DC field being 45kV/m. The sparks discharges due to HVDC are also quite infrequent compared to HVAC. The ionic currents through human body under HVDC transmission lines (2-3  $\mu$ A) are typically 100 times lower than UHVAC transmission lines, implying that the sensation perceived shall not go beyond stimulation of hair. Hence significant safety measures are not required for HVDC transmission lines.

The electric environment of HVDC transmission lines is not steady and is influenced by environmental factors like wind, rain etc. Hence various approaches are followed to limit its effects. One of the approaches is to prescribe limits to time of exposure to the associated fields. These limits in DC transmission lines may be imposed on (i) total electric field by a certain level of space charge and (ii) limits imposed separately on electrostatic field and ion current density. The limits on total static electric field followed by the Russian Federation are given in Table-1 and the same are incorporated in guidelines for Russian DC transmission lines. The guidelines w.r.t limits imposed separately on electrostatic field and ion current density are given in Table-2. No guidelines exist for magnetic fields associated with DC transmission lines since the fields encountered are very low compared to prescribed limits for magnetic field exposure.

<b>REFERENCE LEVELS FOR STATIC ELECTRIC AND MAGNETIC FIELDS</b>						
<b>Exposure category</b>	<b>E-field strength (kV/m)</b>	<b>E-field, ceiling (kV/m)</b>	<b>B-field (mT)</b>	<b>B-field, ceiling (mT)</b>	<b>B-field, pacemakers (mT)</b>	<b>Geomagnetic field attenuation (<math>\mu</math>T/<math>\mu</math>T)</b>
<u>Occupational</u>	$60 \cdot t^{(-)1/2}$	60	10* (15**)	30 (50**)		2
<u>General public</u>	15	15				
t is time in hours						
* The work day limit (8 hours). The time limitation for static magnetic field between 10 (15**) and 30 (50**) mT is the following: from 61 up to 480 min for 10 (15**) mT, from 11 up to 60 min for 20 (30**) mT and from 0 up to 10 min for 30 (50**) mT						
** The limit for localized exposure (arms, hands)						

Table-1: The limits on total static electric & magnetic field followed by the Russian Federation.

Field conditions	Time of exposure (hours)
E=15kV/m & J= 20nA/m <sup>2</sup>	8
E=20 kV/m & J= 25nA/m <sup>2</sup>	5

Table-2: The limits on electric field and ion current density for DC transmission lines

### 9.5.2 EPRI Report on HVDC Converter Stations for Voltages above 600 kV

The minimum ground clearance for HVDC transmission line has been worked out based on a maximum electric field (without space charge effect) limit at ground level of 15 kV/m.

### 9.5.3 Operating experience from HVDC test lines and transmission lines

A number of countries are having DC transmission lines at  $\pm 450$  kV /  $\pm 500$  kV voltage level. The design for the  $\pm 450$  kV bipole transmission line from Hydro Quebec to New England adopted a criteria of limiting the current density to  $100 \text{ nA/m}^2$  for fixing the minimum height of conductors based on purely subjective observations. Based on this (minimum conductor height 13 metres, pole spacing 11 metres & 4 x 35.6 mm conductor) the maximum measured values of total electric field on the test line were found to be 27 kV/m (L5 level) and 11 kV/m (L50 level) at  $\pm 450$  kV. The measured electric field without space charge was found to be 8.8kV/m. The current density was found to be  $70 \text{ nA/m}^2$  (L5 level) and  $7 \text{ nA/m}^2$  (L50 levels). For test lines at voltage of  $\pm 750$  kV the measured values of space charge free and total electric field was of the order of 14 kV/m and 25 kV/m (L50 levels) respectively. The current density was found to be  $60 \text{ nA/m}^2$  (L50 levels). The results are summarized and tabulated in Table-3. (Ref 12)

There are three 500 kV HVDC bipole transmission lines in India (4 x 35.05 mm conductor with pole to pole clearance of approximately 12 to 13 m and minimum ground clearance of 12.5m) traversing varied geographical and climatic conditions. One of these lines has been in operation since 1989. The field levels and ion current density levels calculated as per Reference 14 for the above lines are as per Table-4 below. No adverse public response has been reported with respect to these transmission lines.

The calculated electric field limits with space charge effect taken for design of  $\pm 600$  kV HVDC Itaipu transmission line in Brazil is 40 kV/m under no wind conditions.

Experiments on test lines at IREQ Canada at  $\pm 950$  kV level (6 x 40.6 mm bundle configuration, pole spacing of 17 metres and minimum conductor height of 13 m) have yielded maximum total electric field of approximately 40 kV/m. (Ref 13).

Further, the electric field and current density under DC transmission lines have been observed to be statistical in nature and influenced by atmospheric conditions like humidity, wind velocity, wind direction etc. and should be selected based on technical evaluation and on feedback from operating experience of existing systems.

Voltage level	Electric fields (kV/m)		Current density (nA/m <sup>2</sup> ) (L50)
	Without space charge	Total electric field with space charge (L50)	
+450 kV	8.8	11	7
$\pm 750$ kV	14	25	60

Table-3: Measured values of electric fields and current density for test line at IREQ

Conditions	Electric fields (kV/m)		Current density (nA/m <sup>2</sup> )
	Without space charge	Total electric field with space charge	
Saturated Conditions	10	40	100
Normal operation under fair weather	10	20	28
Normal operation under rainy weather	10	27	60

Table-4: Limits and estimated values for electric field and current density for 500 kV Indian bipole transmission lines (Ref 14)

### 9.5.3.1 Results for $\pm 800$ kV HVDC Bipole transmission line

Maximum electric field with space charge and ion current density under fair weather conditions estimated (based on Ref. 15) at different ground clearances for design of the proposed  $\pm 800$  kV HVDC Bipole transmission line in India are shown in Table-5 below.

Minimum conductor height (m)	Total Electric Field with space charge (kV/m)	Ion Current Density (nA/sqm)	Note:
16	34	56	<u>Salient Line Parameters</u> Conductor bundle: Hexagonal Lapwing Diameter of sub-conductor: 38.2mm Sub-conductor spacing: 457mm Pole to Pole Spacing: 22 m Conductor Surface gradient: 21kV/cm
18	29	36	
20	25	25	
22	22	17	

Table-5: Calculated electric field & ion current density values for values for  $\pm 800$  kV HVDC Bipole transmission line

Information on the location (under the line or at the edge of the r.o.w), probability of being exceeded, method of calculation, positive or negative pole, etc of the values indicated in this Table.

## 9.6 Conclusion

Various exposure limits for static electric fields have been prescribed by various scientific and health organizations. The perception level of electric fields has been observed to be 20 to 25 kV/m (reference 5). Further it has also been observed that the limits of up to 40 kV/m have been permitted. In all cases there has not been any demonstrable evidence for adverse health effects from DC electric fields.

The above limits, however, take into account only static fields and not the space charge effects and associated ion current density observed during corona specifically for DC transmission lines.

Regarding magnetic field exposure limits of 200 mT has been prescribed by various scientific and health organizations.

The operating experience from existing HVDC transmission lines indicate that the transmission lines designed for computed exposure limits up to 27 kV/m and 60 nA/sqm are in operation without any adverse public response. Ion current density up to 100 nA / sq.m has also been adopted. Further, the Russian approach has been observed to be rather conservative. The estimated values of electric field and ion current density for  $\pm 800$  kV HVDC Bipole transmission line with pole spacing of 22 metres, 4 x 38.2 mm conductor are 25 kV/m & 25 nA/sqm for minimum conductor height of 20 metres and 29 kV/m & 36 nA/sqm for minimum conductor height of 18 metres.

## 9.7 Recommendations

Since there is no operating HVDC bipole at 800 kV level, operating experience of 500 kV to 600kV HVDC bipoles and results of experiments on test lines at higher voltage levels have to be considered at present for fixing the exposure limits with respect to electric fields and ion current density at  $\pm 800$  kV level. Considering no known adverse public response from existing operating Bipole lines for (i) calculated total maximum electric field of 27 kV/m and ion current density of 60 nA/sqm for 500 kV and (ii) maximum calculated ion current density of 100 nA/sqm for  $\pm 450$  kV, it is proposed that levels of 25 kV/m total electric field and 100 nA/sqm ion current density under fair weather conditions may be considered for the initial 800 kV bipole HVDC transmission line and electrical clearances calculated on this basis. The above levels can be considered to be safe since total electric field level up to 40 kV/m has been considered for the design of the only operating 600 kV bipole. Further, electric field generated shall be limited only to a small section of the right of way. The

maximum conductor temperature shall also occur only for short durations resulting in lowering probability of exposure to the above limits.

Based on the above limits, minimum conductor height of 20m is found to be generally acceptable for design of the initial 800 kV HVDC bipole transmission line having parameters as detailed in Table-5. Possibility of adopting higher levels in generally inaccessible/remote areas along the line route may also be considered. The limits however may be reviewed on obtaining adequate field experience at 800 kV level.

Magnetic field limits of 200 mT for occupational exposure and 40 mT for public exposure may be maintained which in any case is not likely to be generated by the 800 kV HVDC Bipole.

Considering that access in HVDC terminals & yards would be limited to operating personnel and only for limited time, exposure limit of 30 kV/m electric field & 100 nA/sqm ion current density could be considered acceptable.

### **Abbreviations**

WHO: World Health Organisation

EHC: Environmental Health Criteria

ICNIRP: International Commission on Non Ionising Radiation Protection

IARC: International Agency for Research on Cancer

EPRI: Electric Power Research Institute

L5 level: 5% Probability of value exceeding this level

L50 level: 50% Probability of value exceeding this level

### **References**

- 1) Electrical and biological effects of transmission lines: A Review; US Dept. of Energy, BPA, Oregon; 1989.
- 2) Static fields: Environmental health criteria; WHO; 2006.
- 3) ICNIRP Statement on General Approach to Protection against Non ionizing Radiation; 2002.
- 4) Transmission Line reference book HVDC to  $\pm$  600 kV, EPRI.
- 5) Exposure to electromagnetic fields (0 Hz to 10MHz); Health Council of Netherlands 2000.
- 6) ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz). Health Physics 74 (4): 494-522; 1998.
- 7) ICNIRP Guidelines on Limits of Exposure to Static Magnetic Fields. Health Physics 66 (1): 100-106; 1994.
- 8) ILO: Website:www.ilo.org; Encyclopedia

- 9) Environmental characteristics of HVDC overhead transmission lines; Prof. L. A. Koshcheev; St.Petersburg, High Voltage Direct Current Power Transmission Research Institute, Russia; 2003.
- 10) WHO, EMF World wide standards database, Website: [www.who.int](http://www.who.int)
- 11) EPRI Report, HVDC Converter Stations for voltages above 600 kV
- 12) Corona performance of a  $\pm$  450 kV Bipolar DC transmission line configuration; Dallaire & Maruvada; IREQ, Canada;1987
- 13) Corona generated space charge environment in the vicinity of HVDC transmission lines; P.S. Maruvada; IREQ, Canada;1982
- 14) Conductor Bundle optimization- A report on Chandrapur-Pagdhe transmission project, NTPC.
- 15) Degree of Corona Saturation for HVDC transmission lines; Gary B. Johnson; IEEE Transactions on Power Delivery, Vol. 5, No. 2; April 1990

## **10.0 Control and Protection**

This chapter considers the control, protection and communication requirements for an HVDC scheme. In general the requirements for an 800 kV scheme are similar to a conventional scheme, but where new issues are involved these are addressed. However, there are two key issues, which are to be addressed while controlling 800 kV schemes.

The 800 kV HVDC scheme would be handling much higher power as compared to the presently operating schemes. The power transmission capacity of 800 kV HVDC schemes could be of the order of 6000 MW or higher. To achieve such high ratings, several converter configurations as discussed in Chapter 4 are possible for 800 kV schemes. Depending on the converter configuration i.e. single, two series or parallel valve groups, the converter switching sequences and control philosophy would differ. In case of two series connected bridges per pole, a complete functional strategy will need to be developed for the control, protection, supervision and co-ordination of single bridges in an operating pole. This will include inter-blocking strategies and procedures to cover the different initial/final stages of the bipole. Similarly, for two parallel connected converters per pole, a functional strategy for paralleling/de-paralleling, fault isolation, co-ordination and communication requirements need to be developed. Depending upon the staging philosophy adopted for each HVDC schemes, provisions need to be built in the controls, protections and their interfacing with communication systems for proper integration of the overall scheme.

Due to the very high power transfers on such links, there may be a need for structural re-organisation of the complete control and protection system and its ancillary services to meet higher reliability requirements than has been required in the past. This may introduce the need for redundant/duplicate measurement and control signals, segregation of auxiliary power systems and the segregation both physically and electrically of control functionality, e.g. bridge, pole and bipole etc..

### **10.1 Control System**

The Control system shall essentially have following requirements:

- Hierarchical Controls
- Redundancy
- Self Diagnostic features
- Stability of controls
- Immunity against interference
- Expandability
- Reliability, safety and maintainability

In case of staging of the HVDC scheme, the control system for first stage shall have provisions and expandability so that it is easily possible to integrate future controls to achieve common master control for two stages of the project.

Figure 10.1 shows an overview of a typical HVDC control and protection scheme. The scheme can be considered in three main levels,

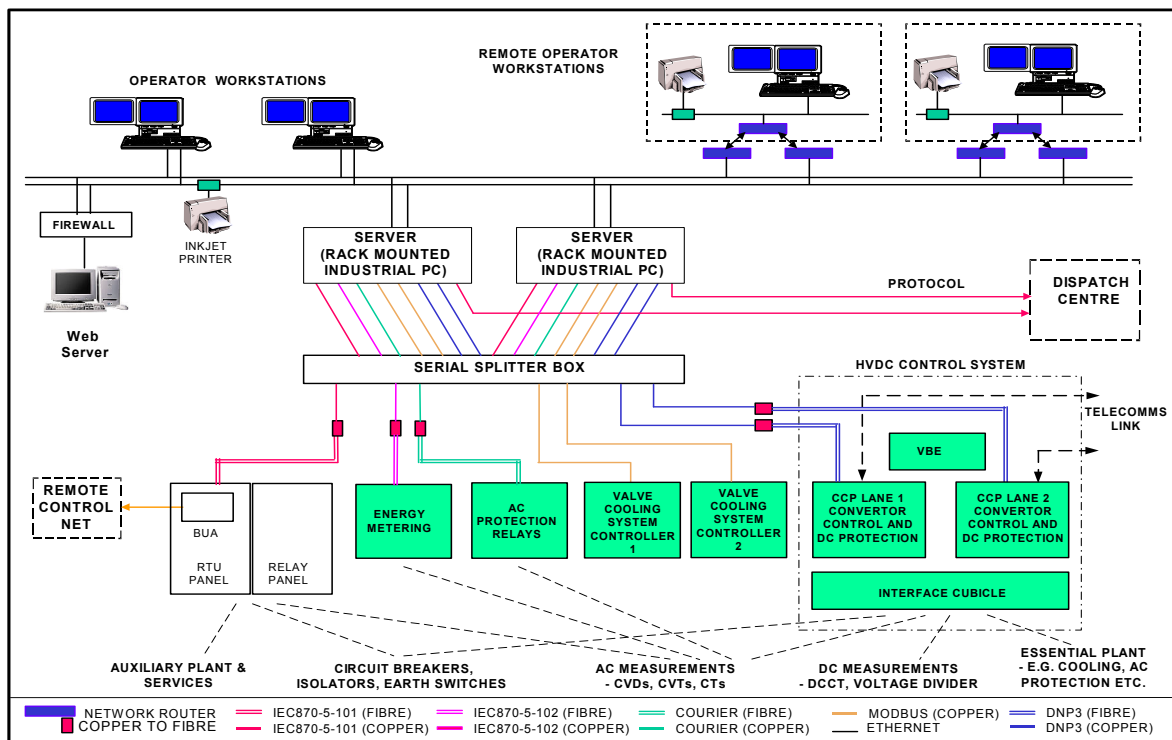


Figure 10.1 Overview of HVDC control and protection Scheme (Typical)

### 10.1.1 Operator Control Level

This contains the Human Machine Interface (HMI) through which the operators control the operation of the HVDC station. Local workstations are available on the control room and, if required remote control stations can also be provided. It is also possible to link the control system to other locations through communication link, with suitable firewalls, to ensure security of the system. This could allow the manufacturer to access information from the control system for remote diagnostics.

### 10.1.2 Converter Control and Protection Level

This contains the main control functions for the HVDC converters, including the individual bridge/converter, pole and bipole controls. These functions are described further in Chapter 10.5. This level also includes the electronic protection functions for the thyristor valves and the DC circuit, which are described in Chapter 10.6.

Telecommunications between converter stations comes into the control channels directly.

### 10.1.3 Field Level

This contains the signals from the entire station, which are required by the main converter control and protection system. These field signals come from the auxiliary power supply system, the circuit breakers, AC measurement devices, DC measurements device, the cooling plant, and the conventional protection systems.

Figure 10.2 gives the typical Control system hierarchy for a HVDC scheme built in two stages.

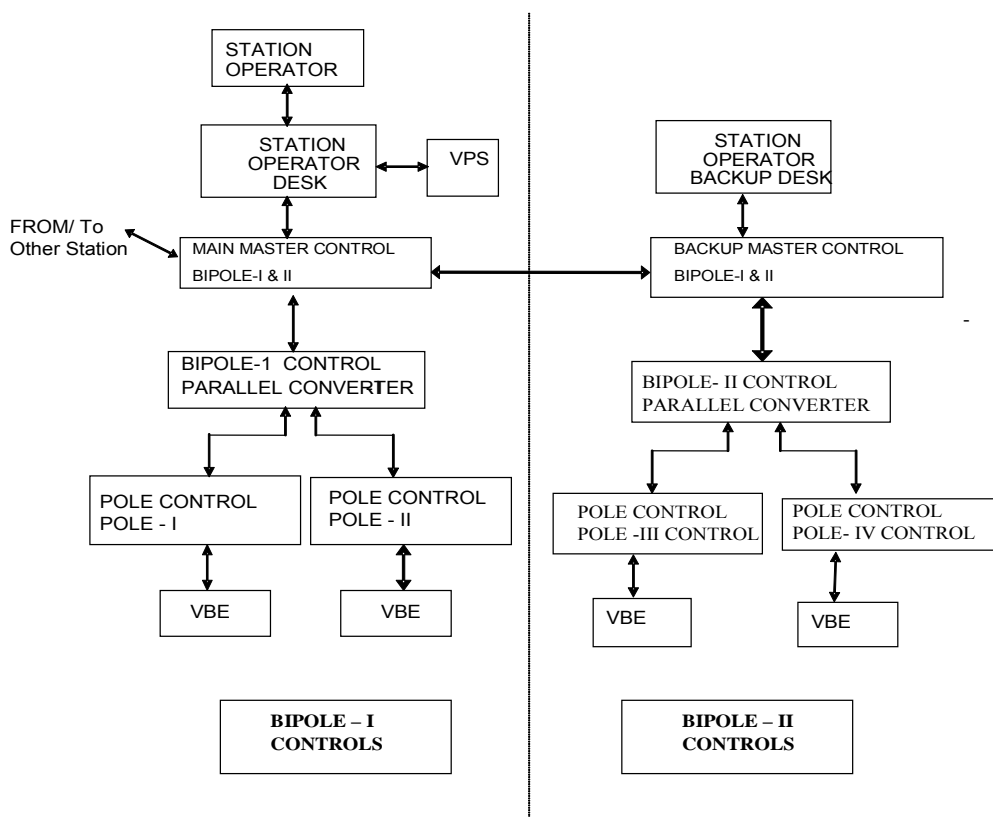


Figure 10.2: Typical Control system hierarchy for a HVDC scheme built in two stages

## 10.2 Operation Modes

The HVDC transmission scheme is designed to transmit power in the following modes of operation. One valve symbol in the following diagrams corresponding to the different modes of operation represents one 12-pulse bridge. The converter transformers and other AC and DC equipment, are omitted for simplicity

- a) Bipolar operation (Figure 10.3) at nominal DC voltage (100%), or at reduced DC voltage (70 - 80%), if system conditions demand this. Both 12-pulse bridges per pole are available on each pole.

The Bipole Controller will act to minimise the difference between the measured DC current of each pole such that the mean electrode current is minimised.

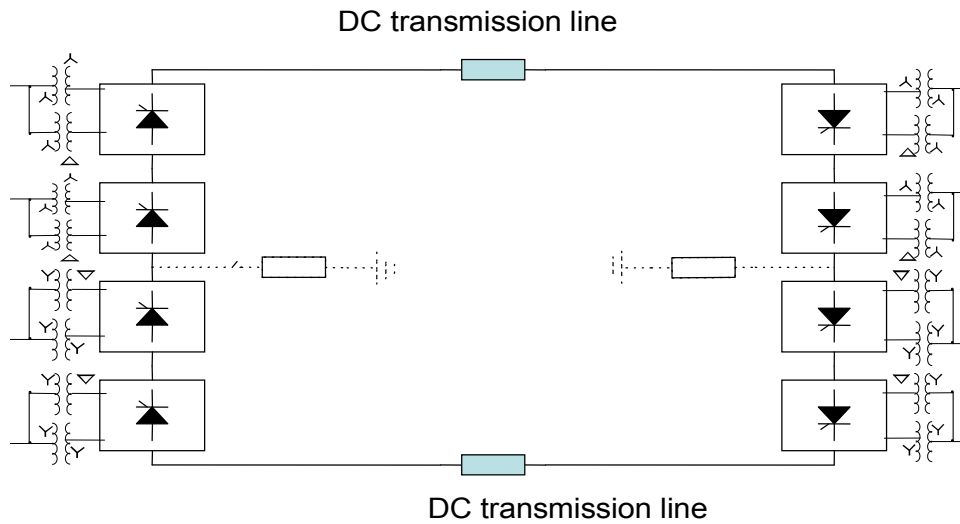


Figure 10.3: Bipolar Configuration

- b) Bipole operation (Figure 10.4) with one 12-pulse bridge shorted out by the bypass circuit breaker. Only one 12-pulse bridge is available in the upper pole.

c)

This situation could occur due to a fault on the equipment of one of the bridges, or due to scheduled maintenance on one of the bridges.

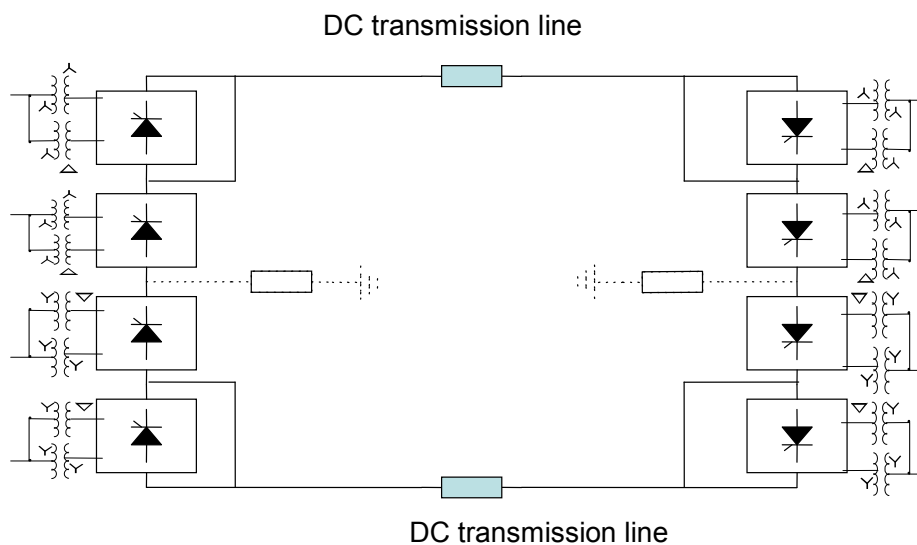


Figure 10.4: Bipole operations with one bridge out of service

- c) Monopole operation (Figure 10.5) at nominal DC voltage (100%) or at reduced DC voltage (70 - 80%) with the current return path via the ground electrode connection.

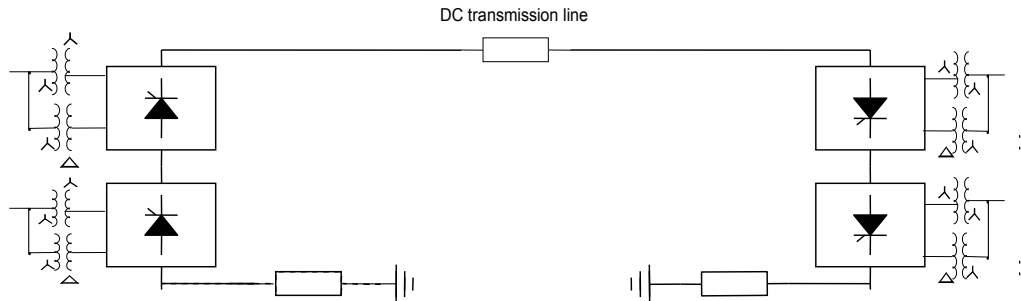


Figure 10.5: Monopole Configuration with Ground Return

In this case a complete pole is out of service, possibly due to a major fault on the overhead line.

- d) Monopole operation (Figure 10.6) at nominal DC voltage (100%) or at reduced DC voltage (70 - 80%) with the current return path via the HV conductor corresponding to the pole, which is not in operation.

In case both the bridges of one pole were unavailable for service, perhaps due to scheduled bridge maintenance and concurrent equipment fault, resulting in only monopolar operation. In this case the HVDC operation switched to metallic return mode to avoid ground return operation.

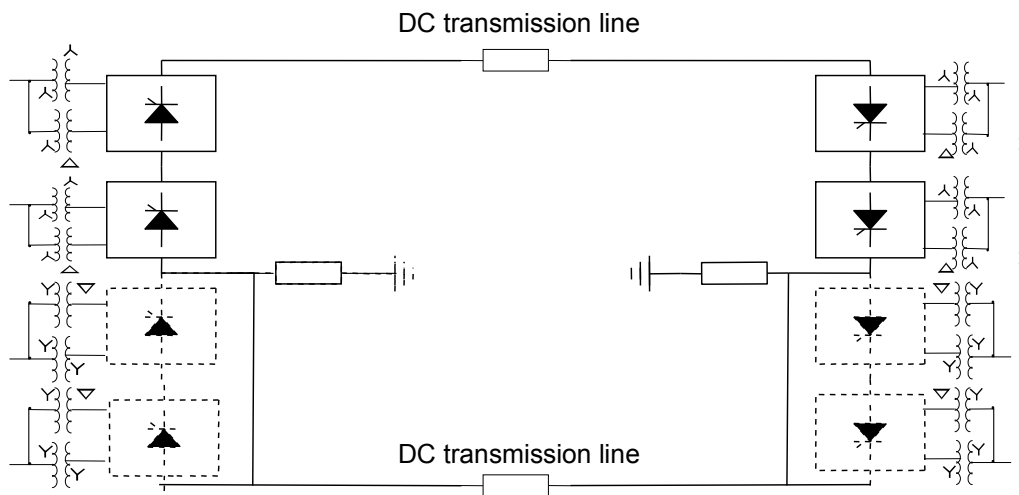


Figure 10.6: Monopolar Configuration with Metallic Return

### 10.3 Provision for Master Control

A Master control facility is required to control and co-ordinate the power flow among the terminals. One of the terminals is the master controller and the other terminals act

as slave station. Changes in power order, current order, control mode selection and various other sequences, at both pole and bipole levels at a Master control station, are automatically executed at the slave station through the telecommunication link without operator's assistance.

Control equipment shall at least consider the following functional requirements:

- a) The master controller through the bipole/pole/converter controller shall provide for:
  - i. Sequences to connect/ isolate converters or DC line sections.
  - ii. Manual and Automatic initiated paralleling and de-paralleling sequence for parallel converters
  - iii. Manual and automatic switching for bypass switches for series converters
  - iv. Fault initiated de-paralleling or bypassing sequence.
  - v. Set power/ Current orders, Ramp rates, and Limits.
  - vi. Start/ Stop Converters.
  - vii. Set power and allocate Losses.
  - viii. Coordination of power modulation and frequency control
- b) Overload capability of the converters may be utilised to compensate loss of power due to outage of any of the valve groups.
- c) Pole current limits include the parallel configuration of both ends of the transmission line.
- d) The master control designs coordinates operation of paralleling and de-paralleling high speed switches of the valve groups and also coordinate high speed force retard command between the parallel converters to limit the contribution to a converter fault current from the parallel converters.
- e) The converters may use a voltage pre-charge prior to paralleling with an operating converter in order to reduce the inrush current and impact on the operating system when paralleling.
- f) Necessary controls shall be installed at the inverter to modify the firing characteristics of a parallel converter during commutation failure of the other converter in order to share the system current and enhance recovery.
- g) Necessary protection coordination and operation as required while restarting after DC line faults shall be implemented at the rectifier and inverter. Coordination for operating high-speed switches at parallel valve groups shall be provided for de-paralleling the faulted valve group. Line protection operation and restarting shall be coordinated between the parallel converters at the rectifier and inverter ends and also isolating the faulted line section. High-speed switches at the terminals and line sections shall be kept for isolating faulted valve groups or line section.

In addition to the above, control and protection systems supplied shall have necessary controlling, coordinating and isolating features in line protections, VDCOL (Voltage Dependent Current Order Limit) settings, Voltage/ Current controller reference settings, provision for signal exchange via telecom with parallel valve groups and multi-terminal operation, if envisaged in future.

### 10.4 Control Concept

A typical static characteristic for a HVDC transmission scheme is shown in Figure 10.7. This shows the rectifier characteristic (ABCDE) and the inverter characteristic (WXYZ). The operating point of the DC system is defined by the intersection of the two characteristics, i.e. the point O. The rectifier current order ( $I_o$ ), determined by the power control, determines the constant current part of the characteristic (CD). The inverter voltage order ( $V_o$ ) maintains the constant DC voltage part of the characteristic (XY).

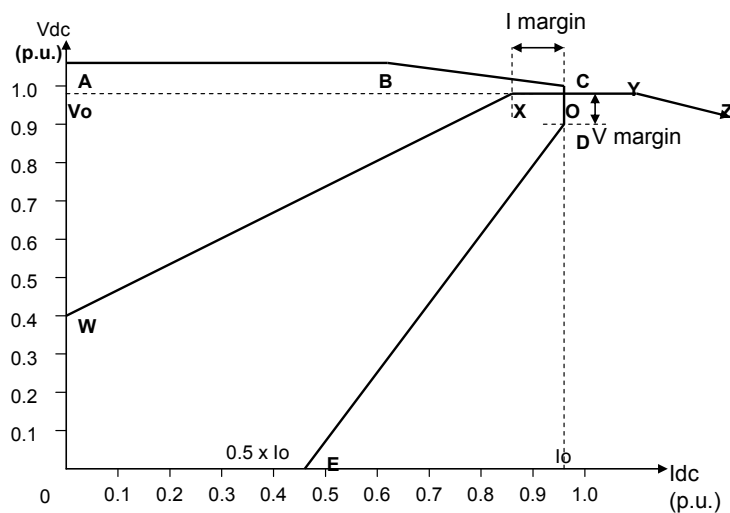


Figure: 10.7: Static Control Characteristic

Other static characteristics can be developed to determine the steady state operation of the converter controls and the specific operation of the controls in response to system perturbations.

#### 10.4.1 Rectifier

- a) DC current control by firing angle regulation.
- b) Tap-changer control to maintain the firing angle within a limited steady-state range.

Under steady-state conditions the rectifier will control the DC current to maintain constant DC power at the rectifier terminals. This control is achieved by continuous

variation of the rectifier firing angle with changing system conditions. Should the rectifier firing angle go outside of the band, defined as the steady-state range, then rectifier converter transformer tap-changer action will be invoked, increasing or decreasing the converter transformer valve winding voltage as appropriate and hence returning the rectifier firing angle to within the steady-state range.

#### **10.4.2 Inverter**

- a) Cascade DC voltage/Constant Extinction Angle (CEA) control.
- b) Tap-changer control to maintain the rectifier DC voltage within a limited steady-state range.

The basic control function of the inverter under steady-state conditions is to maintain the DC voltage of the rectifier DC terminals at a target value. Additionally, it is of economic advantage to maintain the steady-state inverter extinction angle at a minimum value in order to minimise inverter losses and reactive power absorption.

#### **10.5 Control Functions**

The control functionality provided for 800 kV scheme is basically the same as any long distance HVDC transmission scheme. To ensure the reliability of the scheme the controls (bipole / pole / converter) should be based on a dual redundant system, i.e. if a fault is detected in one processor, the other processor will automatically take over control.

#### **10.6 Protection Functions**

The overall protection of a complete HVDC scheme can be categorized in two parts, AC protection of conventional station plant and DC protection of the thyristor converters and the DC circuit. Normally the DC protection is as independent as possible from the control system in which it operates. For added security, the protection functions are often duplicated.

The protective scheme is designed to meet the following general requirements:

- i. The aim of the protection scheme is to detect abnormal condition that might expose the equipment to hazards and to isolate the faulty equipment / zone as early as possible to have minimum disturbance.
- ii. Protection setup should be arranged in overlapping zones or protections shall be duplicated.
- iii. Fault discrimination should be such that fault in one converter does not cause tripping of other converters.

- iv. The protection shall be arranged so that testing and maintenance can be arranged in one converter/pole without affecting the operation of the other converter(s)/pole(s).
- v. For bipole, the protection philosophy shall be to avoid undue bipole outage during any circumstances by having separate measuring devices for each pole or a bipole related protective function should not initiate protective actions on a single criterion.

## **10.7 Communication**

It is normal practice to operate transmission systems, whether AC or DC, with telecommunication links to share knowledge of system conditions across the network and to improve the performance of the systems during steady state and fault conditions. Such communication is of particular importance for long distance HVDC transmission systems, where good communication between the rectifier and inverter station can be essential for good operation of the link. It has always been the case in the past that reliable and safe operation of a HVDC transmission scheme shall be possible without a functioning telecommunications link. Although there are examples of HVDC schemes, which have been designed to operate without telecommunication links, it is assumed that for a bulk power transmission scheme at 800 kV a telecommunication system will be required. Given the potential rating of such schemes, from 3000 MW up to 6000 MW, and the criticality to the operation of a national network of an 800 kV scheme, it is also assumed that any telecommunication scheme may require a backup system also.

There are a number of available technologies for communication between converter stations. The following section considers the merits and de-merits of four systems.

### **10.7.1 Power Line Carrier (PLC)**

PLC systems are well known and widely used by transmission utilities and there is considerable experience in their use on both AC and DC systems. The system requires a low capital investment, primarily in the terminal station communication equipment and in repeater stations along the transmission line. The PLC system is suitable for long distances using intermediate repeater stations, however these stations will require a local source of auxiliary power, which may be a logistical problem if the DC line passes through un-populated areas. The number of repeater stations shall be more than one (1) for line distance above 1400 kms and the 800 kV DC yard equipment are prone to flashover for repeater location at polluted areas and the cost of repeater station is also substantial.

PLC systems have a relatively low bandwidth, hence limited information transmission capacity, but normally sufficient for the purpose. Signal propagation delay is not a significant issue.

Because they use the DC wires or shield wires to carry the signals the system is prone to interference due to line faults, which impacts on the reliability of the system. Depending on the bandwidth used for communication, PLC filtering may be required at the converter stations to limit injection of electromagnetic noise from the thyristor valves.

### **10.7.2 Optical Fibre Ground Wire (OPGW)**

The OPGW system embeds a fibre-optic in the overhead ground wire. Thus a special cable needs to be run for the entire length of the transmission system. This adds to the capital cost of the scheme. Repeater stations are required to boost the signal, which require a local source of auxiliary power. OPGW systems will require more repeater stations than a PLC system however the cost of repeater station would be less compare to total cost of the project.

OPGW provides a high transmission rate and a large band-with, allowing a larger amount of information to be transmitted than PLC systems. Signal propagation delay is not a significant issue. Thus voice and video information can be transmitted.

The fibre-optic being optical signal, is immune from electromagnetic interference arising from corona on the DC wires or faults on the transmission system.

OPGW are widely available and are becoming more widely used in transmission systems. However for reliability back up to fibre optical communication shall enhance the security and reliability of 800 kV transmission systems.

### **10.7.3 Microwave**

Microwave systems can provide the required bandwidth and for HVDC transmission systems, however there may be limitation in regard to video requirement and time duration of communication for control & protection signal. However as microwave commonly operates on a line of sight basis there is a need for frequent repeater stations, which adds to the capital cost of the system. Alternative systems exist, such as tropospheric scatter systems that do not require line – of – sight and can have repeater stations at up to 800 km separation.

Microwave systems are immune to electromagnetic interference effects from line faults or corona. However, they can be susceptible to environmental effect, which interferes with the “visibility” between transmitter and receiver and further there may be difficulty in getting frequency clearance from Govt. agencies.

### **10.7.4 Satellite communication**

Capacity could be acquired on a commercial satellite to provide the necessary telecommunications between converter stations. The capital cost of such a system

would be low, in comparison with the above systems. The band-width available should be sufficient for the purposes of the DC link. The major technical issue would be the transmission delay involved in receiving a signal from the remote station and shall have an impact on the control logic.

A satellite system would be shared with other users, unlike the dedicated systems described above. There would also be an on-going connection charge for the service.

#### **10.7.5 Telephone systems**

Capacity could be acquired on a commercial telephone system, requiring only a limited capital expenditure. However, unless it was a digital system this would have a low band-width and a low transmission rate, but may be sufficient for the duty.

This would also be a shared system, with an on-going connection charge. The key issue on such a system would be the reliability of the communication link, which would probably not be commensurate with the required importance of the DC link.

### **10.8 Control Issues related to 800 kV**

This section has raised a number of issues where the requirements for 800 kV transmission schemes, may require some additional measures compared with more conventional schemes. The measuring systems should also be provided with redundancy such that no single outage or malfunction or outage of a measuring transducer should result in reduction of power level.

The control system must perform smooth switching in of converter groups following commands from operator or as part of a sequence as well as switching out of converter groups following protective actions.

Modern control systems have become more compact and lower cost, as increasing processor power has allowed the former bridge, pole and bipole controls to become effectively one unified control system. Due to the operation with cascaded 12-pulse converters, i.e. 2 bridges per pole and the need for higher reliability, due to the increasing power rating of a bridge (up to 1500 MW) and a pole (up to 3000 MW), there may be a case for re-instating separate bridge, pole and bipole control cubicles. This may be required to minimise the risk of loss of major blocks of power and the consequent impact on the AC systems.

Greater segregation of auxiliary power supplies to the control and protection systems may be required, to ensure that any such failure can only affect one bridge, not a complete pole /bipole.

There may be a case for the duplication of certain key input signals from the field to the controls, to ensure the integrity of the control functions against simple wiring faults, or fuse failures, etc. The control and protection system may be designed such that no single contingency or fault in the high voltage section, with the exception of

permanent DC line fault, should result in a reduction of power level greater than the capacity of a single twelve pulse group.

Telecommunications between converter stations may require main and back up systems, especially where the transmission line passes through harsh environmental areas, or where the availability of auxiliary power for repeater stations is at risk.

In general the design of the converter stations may be required to minimise or eliminate all shared functions that can simultaneously affect more than one unit of controllable power.

## **11.0 Availability and Reliability**

The terms Availability and Reliability are intended to a measure the performance of the HVDC system in terms of energy availability and outage frequency. The availability and reliability parameters provide a target for the design of the project as well as monitoring the performance of the project. These parameters, therefore, are very important and paying attention to these in all stages of the project from planning to implementation and operation is essential to get a system that performs in a predictable and acceptable manner.

The availability / reliability of HVDC projects throughout the world is monitored in accordance with the CIGRE Brochure 346 (14-97, WG-4 publication) "PROTOCOL FOR REPORTING THE OPERATIONAL PERFORMANCE OF HVDC TRANSMISSION SYSTEMS". This document also provides the definitions used for monitoring and reporting availability and reliability for HVDC system. The details of availability and reliability monitoring procedures and target limits to be met are usually spelt out in the technical specifications for a particular project. It is, however, noted that considerable proliferation exists in the technical specifications of various HVDC projects. To obtain a reliable data that provides sound comparative figures for future projects it is highly recommended that the project specifications follow the some standard terminology used in the above mentioned CIGRE protocol.

The HVDC projects operate as a part of the power system. Therefore, their availability is also affected by the outages or disturbances in the system elements in which HVDC operates. Although, outages in the HVDC system that are on account of outages / disturbances in the rest of the system external to the plant being monitored are excluded while calculating the availability / reliability indices these outages are important for the system as a whole. The factors which may results in outages of HVDC system due to external reasons can not be possibly eliminated but an attempt can be made to minimize these during the planning / specification preparation stage of the project.

This document is not intended to provide details on how to specify or calculate availability / reliability for HVDC projects. The discussion in this document is in a broader sense to highlight areas that are considered important to achieve high levels of availability / reliability of the projects separately while operating as a part of larger power systems. In this perspective the characteristics which make an HVDC project reliable may be stated as follows:

- long continuous operations without fault
- being fault tolerant, that is, being able to recover from faults quickly
- only partial and acceptable loss on major faults, and
- well integration in the AC system.

Due to their large size the 800 kV HVDC projects may have to be built in stages and therefore availability / reliability and continuity of service during various stages of construction will be of utmost importance. As this aspect is highly dependent upon a particular planning of a project it is not addressed here.

The project design and its monitoring with regard to availability and reliability considerations may be done with the established practices.

## **11.1 Review of some definitions**

The two main indices that measure the availability and reliability of an HVDC project are:

### **11.1.1 Energy Availability (EA)**

Energy availability is a measure of the energy that could have been transmitted taking into consideration all outages both forced and scheduled.

Usually, the EA is determined over "Period Hours" (PH) based on "Equivalent Outage Duration" (EOD). Generally PH covers one year and the EOD is determined from the cumulative effective time during which outages of equipment have impact on the transmission capability of the system. A system has to meet the EA limits averaged over a longer period, say three years.

The EA is a system level parameter that is determined from the outages of components or subsystems that can reduce the energy availability. If a component outage does not reduce the availability of the system to transmit the defined amount of power under the resulted condition, it will not have effect on the EA of the project. By providing parallel redundancy in the system component and doing scheduled maintenance one can obtain a system with very high EA. Since parallel redundancy does not cause any reduction in the operation of the project, this aspect is utilized to carry out schedule maintenance such as control and protection, ac harmonic filters etc... However, in case of high voltage equipment it is also often necessary to take shut down of part of the power transmission system to carry out scheduled maintenance.

While designing the system the manufacturer would develop a system model of the plant to predict the energy availability. The basic data required to carry out the analysis is related to the Mean Time Before Failure of each component used to build the system. Once the whole model is built the designer can analyze the effect of each failure on the connected equipment and how the failure is percolated and finally the designer can determine effect on the plant availability.

The most critical value with respect to the energy availability of a HVDC system is the annual Forced Energy Unavailability. Usually the design target of forced energy unavailability for converter station is at about 0.5%.

### **11.1.2 Reliability**

Reliability is usually measured in terms of Equivalent Outage Frequency (EOF) which is derived from the number of forced outages of curtailment occurrences of poles and Bipole in a PH (Period Hours), usually one year.

Typical forced outage rate used as design base in the recent HVDC projects (2 converter stations excluding line):

- pole outage: 5 – 6 per year per pole
- bipole outage: 0.1 per year

With more than one twelve pulse group per pole the above number may be modified and valve group outage shall be included. Comparing to a scheme with single valve group pole the pole outage becomes in this case considerably lower, as only common pole equipment failure will lead to a pole outage, while other failures in valve group result only in valve group outage. Possible target values can be for example for a system with two series valve group converters per pole:

- 12 pulse bridge (Converter) outage: 2 - 2.5 per year per converter
- pole outage: 2 – 3 per year per pole
- Bipole outage: 0.1 per year or less

For HVDC system with parallel valve groups arrangements (e.g. 4 parallel valve groups per pole forming 2 typical bipoles), as line is excluded in these statistics, each bipole should be considered independently for outage consideration. Possible target values for the outage rates can be for example as follows:

- pole outage: 5 – 6 per year per pole
- bipole outage: 0.1 per year

Due to the high power rating of 800 kV system it is utmost important to reduce the bipole outage rate. An effective measure is to separate the both poles as much as possible. The common part, which is usually the neutral bus, electrode line and ground electrode, can also be designed in a way that single failure will not affect the bipolar operation of the whole system. Separate neutral bus and separate ground electrode are feasible options.

## **11.2 Major areas affecting Availability / Reliability**

The reliability figures of the existing HVDC scheme are compiled by CIGRE working group B4 AG 04-TF 1. These figures are published once in two years by CIGRE. The latest publication by this committee entitled "A Survey Of The Reliability Of HVDC Systems Throughout The World During 2005-2006, CIGRE Session 2008" shows that, in general, the present day HVDC projects are reliable with forced energy unavailability figures better than the guaranteed values. The area of concern generally fall for converter transformer in the AC switchyard, DC yard equipment and transmission line. These problems are also not generic in nature and are confined to a very few specific projects.

However, to achieve high level of availability / reliability for an HVDC system following points are considered important:

- Overall project scheme
- Integration of the project into ac system
- AC switchyard equipment
- Equipment common to bipolar system
- Electrode station design
- Converter Transformer
- Valve Hall
- DC Switchyard Equipment
- Control, Protection and communication requirement for both series and parallel converter groups
- Auxiliary systems
- Spares and maintenance

### **11.3 Overall Project Scheme**

The configuration of a HVDC project, arrangement of its main circuit equipment including such as number of poles, number of valve groups and their arrangement in series / parallel, types of converter transformers, DC switchyard equipment etc., would be strongly affected by the maximum continuous power transmission requirements together with the limitations of transportation of converter transformers, current carrying capability of thyristors, DC line length (resistance) etc.

It is seen from the table below which shows the main characteristics of HVDC projects assumed with rating from 3000 to 6000 MW.

**Table-1: Comparison of various HVDC Schemes**

		1	2	3	4	5	6	7
POWER LEVEL	MW	3000	4000	4000	5000	5000	6000	6000
Configuration*		I	I	I	II	III	II	III
No. of Poles		2	2	2	2	2	2	2
No. of 12 pulse groups per pole		1	1	1	2	2	2	2
Rated DC voltage	kV	500	500	600	800	800	800	800
Voltage level per twelve pulse group	kV	500	500	600	400	800	400	800
Rated DC line current	kA	3.00	4.00	3.33	3.13	3.13	3.75	3.75
Rated current for valves	kA	3.00	4.00	3.33	3.13	1.56	3.75	1.88
DC line resistance (assumed)	ohm	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Line losses / pole	MW	135.00	240.00	166.67	146.48	146.48	210.94	210.94
Line losses	%	9.00	12.00	8.33	5.86	5.86	7.03	7.03
Conv. Trans. - Type		1P2W	1P2W	1P2W	1P2W	1P2W	1P2W	1P2W
Conv. Trans. - No. / Station		12	12	12	24	24	24	24
Approx. Conv. Trans. Rating, rectifier	MVA	296	394	394	247	247	296	296
Nominal dx, total (Typical)	%	8	8	8	8	8	8	8
Nominal Firing Angle (Typ.)	deg	15	15	15	15	15	15	15
Nominal Extinction Angle (Gamma) (Typ.)	deg	18	18	18	18	18	18	18
Reactive power for rectifier	MVA <sub>r</sub>	1530	2040	2040	2551	2551	3061	3061
Loss of power on loss of a valve group / conv. Trans.	MW	1500	2000	2000	1250	1250	1500	1500
Line losses on loss of a valve group / conv. Trans. (for affected pole)	MW	-	-	-	146.48	73.24	210.94	105.47
Ground current on loss of valve group / conv. Trans.	kA	0.00	0.00	0.00	0.00	1.56	0.00	1.88
Loss of power on loss of a pole line.	MW	1500	2000	2000	2500	2500	3000	3000
Ground current on loss of pole line.	kA	3	4	3.33	3.125	3.125	3.75	3.75

\*Configurations: I: One twelve pulse group per pole  
 II: Two twelve pulse groups per pole in series assuming equal voltage  
 III: Two twelve pulse groups per pole in parallel

Choosing a suitable scheme for a given power level would be vital to achieve high availability / reliability for the project. In this regard following points can be noted from the above table:

1. For all of above power rating the chosen converter transformer is single phase two winding type. Choosing a single phase three winding transformer would be double the MVA value shown which would result in prohibitive requirements for transportation. Only for case of 5000 MW power transmission the converter transformer MVA even for single phase three winding type is close to 500 MVA. But here also the size of the converter transformer would be dictated by the system voltage level and again single phase two winding type may be the only practical option available.
2. At 4000 MW /500 kV the rated current value for the transmission approaches 4 kA which may not leave the required margins for the transient overload capability of the thyristor. Further, keeping in view the high line losses and ground currents in case of pole outages with its DC line, it seems appropriate to increase the voltage level of the system. The column 3 shows the same 4000 MW power transmission with DC voltage raised to 600 kV. In this case the DC current level is well within the capability of the existing 5 inch thyristor devices.
3. At power levels of about 5000 MW and beyond it would be necessary to have more than two valve groups because with only one valve group the system would be close to or exceeding the practical limits of both the converter transformers and thyristor valves. As a result only systems with two twelve pulse groups are indicated in the above table when power transmission is equal to or above 5000 MW.
4. One of the major decisions concerning HVDC project of power level around 5000 MW and above is regarding the arrangement of twelve pulse valve groups. Both series and parallel groups have their relative advantages and disadvantages. The major areas of difference are with respect to ground currents and transmission line losses during a valve group outage. Whereas a series group will have no ground current when operating with a valve group out, the parallel arrangement will have ground currents flowing. However, due to reduction in voltage on outage of a valve group the line losses in case of series group shall be much higher compared to those in the parallel group.
5. One major advantage of parallel group is that it is highly suitable for stage wise development of a system. By virtue of the fact that the parallel valve groups can be physically placed at a distance from each other and including at different points in the ac network. This arrangement may provide considerable advantages in the overall

availability of the system due to easier integration into the network. This aspect is further discussed below in the next section.

The above, by no means, is a complete or definite list of possible options. The project configuration may also be influenced by criteria guided by the requirements of integrating the project into the ac network. For example, due to availability / reliability considerations a decision may be taken to go for an additional pole / bipole even when, theoretically, lower number of pole(s) / bipole may suffice.

In general a configuration that results in the least complex alternative should be chosen. Therefore, if it suffices the power transmission and equipment transportation requirements, choosing only one twelve pulse group per pole may be advantageous from availability / reliability point of view.

#### **11.4 Requirements of Integrated AC / DC System**

Important consideration in this regards are:

- Definition of design criteria laid out in technical specifications. The most important aspects are from the point of view of outage criteria of the converter group, pole or bipole vis-à-vis the stability requirements of the ac system.
- The ac system strength vis-à-vis DC power in various stages.
- Reactive Power Considerations – static and dynamic support requirements.
- Coordination of various converter groups – taking out / bringing in the series groups and paralleling / de-paralleling the parallel groups.
- Any possibilities of interactions among HVDC projects nearby
- The ac system in the vicinity of terminal stations - requirements following outages of local and remote ac system elements.
- The transient and short term overload capability of the project is critical to maintain system stability following faults and to take care of outages in the DC as well as AC system. Thus these projects should have adequate overload capability.

#### **11.5 AC Switchyard Equipment**

The important points to be considered are:

- Requirement of any dynamic support and its redundancy
- The ac switchyard switching scheme and requirements of sectionalizing the buses. Connection point of valve groups in the ac switching scheme.
- The reactive power support – requirements at low power, redundancy, sub-bank sizing, ac filters, pre / post conditioning of firing angle while switching.
- Measuring equipment redundancy.
- Protection of ac filters high voltage bus.

### **11.6 Equipment common to bipolar system**

The equipment common to bipolar schemes include the neutral bus scheme, especially the area where the neutral buses of the two poles combine. The equipment in this area such as HSGS (High Speed Grounding Switch) for neutral bus, MRTB (Metallic Return Transfer Breaker), Arresters, Measuring and protection systems are important.

### **11.7 Electrode station design**

The maximum electrode current would depend upon the power rating and chosen voltage level of the DC scheme. For 800 kV HVDC projects the electrode current may approach 4 kA. At such high currents the performance of ground electrode may become very critical and it is considered that solutions that ensure low ground electrode currents would be desirable.

The most important consideration with respect to the performance of ground electrodes are concerning local indices regarding touch and step potential and remote effects like the induced currents in the transformer neutral and other metallic structures in the vicinity.

Meeting local requirements in terms of step potential, effective resistance etc. at the electrode station can be tackled by the design of ground electrode but for remote effects the ground electrode has virtually no influence and effects due to ground current at locations remote from the ground electrode are governed by the earth geology, injected current and the electrical power system in the area. Therefore, deciding the best location of ground electrode is of paramount importance for the functioning of the project in a mode where considerable ground currents flow.

A study that takes into consideration the combined effect of the earth geology, surrounding infrastructure and power system is generally required to decide the best location of an electrode station. This aspect was covered in details in Chapter 5.

Sometimes two conflicting situations may arise: at one hand there is a need to reduce the current in the ground electrode and on the other hand there is shortage of space for accommodating ground electrodes if several HVDC projects are coming in the same area resulting in a need for high capacity common ground electrodes i.e. ground electrodes to accommodate more than one HVDC project. In such situations there would be a requirement to extensively examine all operating conditions and to evaluate strategies to ensure high availability of the operating transmission systems.

### **11.8 Converter Transformer**

The failure of converter transformers in some of the HVDC projects has caused major concern to the utilities and manufacturers throughout the industry in spite of the fact that these failures have been mostly confined to some specific projects and are not a

general phenomenon. (CIGRE JTF B4.04/A2-1 on Analysis of HVDC Thyristor Converter Transformer Performance). Please refer to this document for details.

The majority of failures are mainly related to:

- insulation failure between the inter-turn on the valve side winding
- thermal design due to blocking of oil flow or reduced flow
- faults due to tap changer and between the tap changer leads
- mechanical / electrical failures of bushings
- stability of converter transformer oil
- core and magnetic shield

The converter transformer undergoes additional stresses as compared to conventional ac transformer due to several reasons such as:

- the commutation process during which the valve side windings are short circuited
- high amount of asymmetric current and for longer durations following a short across valve or valve side phase to ground faults
- small DC component on the secondary side currents
- exposure to complex voltage wave shape and presence of such effects as commutation overshoots
- DC voltage stresses
- harmonic currents and overvoltages due to harmonic currents
- very large number of tap changer operations
- relatively large number of faults on DC line causing stresses on the valve side windings

Therefore, the design of HVDC converter transformers must take into considerations all of above factors. It is very important that the design of converter transformers be done in close association with the complete design of the HVDC system taking into considerations all its steady state, overload and transient operating conditions. Before manufacture the converter transformer, design shall be examined as per the “Guidelines for Conducting Design Review for HVDC Converter Transformers” prepared by the CIGRE JWG A2/B4-28

The response of transformers internal inductances and capacitances to the imposed overvoltages should be analyzed in detail.

The possibility of core saturation due to DC component either due to commutation process, ground return operation or geo-magnetically induced currents should be examined.

It should be ensured that the breather arrangement of the transformer does not allow any moisture ingress.

The CIGRE JTF B4.04/A2-1 also points out that one of the main reasons for Forced Energy Unavailability in the HVDC projects has been the unavailability of a spare converter transformer. Therefore, in spite of stringent design and quality control during manufacturing it is important to have adequate spare capacity at each station. To improve availability the possibility to have electrically and mechanically identical or interchangeable transformers should be explored. Further, placement of spare transformers, arrangements of installed units should be such as to allow easy replacement.

High quality oil with low sulphur contents is to be used.

In addition to above a thorough factory testing in line with the latest standards and recommendations should be done. While in operation, a thorough condition monitoring of converter transformers including on line monitoring, periodic testing of oil including DGA (Dissolved Gas Analysis), partial discharge measurement may be considered.

Care should be taken while doing oil filtration to ensure that oil is not contaminated by use of improper materials in the oil filtration process or by way of handling.

### **11.9 Valve Hall**

Experience has shown that the valve halls of HVDC systems are one of the most reliable subsystems of an HVDC project. The areas of problems, however, have been there mainly relating to the fire inside the valve hall, degradation of optical fibers, valve cooling leakage, moisture ingress and dust leaking in through the valve hall ventilation system. For HVDC projects proper attention must be paid to the above areas in addition to ensuring that each valve group must be able to be maintained separately without shutdown of the other valve groups.

### **11.10 DC Switchyard Equipment**

In case air core smoothing reactor is opted and two coils are used, possibilities to bypassing one coil upon a failure of coil if acceptable for operation.

The major challenge for DC switchyard equipment will be a) the mechanical design due to large dimensions and b) proper voltage distribution, inside and outside, in series connected (parts of) equipment. Predominately, the use of DC voltage distribution by a pre-defined resistive current may have to be adopted. Such technology can be found in the design of DC voltage divider, DC filter capacitor, DC PLC-coupling capacitor and ZnO-arresters.

Another aspect, which is to be considered for HVDC equipment, is the external insulation of outdoor equipment. The creepage and clearance requirements may result in long length, which may require utmost care during design and manufacturing of equipment like disconnectors and wall bushings etc.

### **11.11 Control, Protection and Communication requirement for both series and parallel converter groups**

The control and protection systems have to be provided with redundancy and hot standby arrangement such that no single contingency results in any reduction of power carrying capacity of the system.

The measuring systems should also be provided with redundancy such that no single outage or malfunction or outage of a measuring transducer should result in reduction of power level.

The design of the switching arrangement and control and protection system should be such that no single contingency or fault in the high voltage section, with the exception of permanent pole to ground DC line fault, should result in a reduction of power level greater than the capacity of a single twelve pulse group. In case of a permanent pole to ground fault on the DC line the capacity reduction should not be more than the capacity of a single pole.

The control system must perform smooth switching in of converter groups following commands from operator or as part of a sequence as well as switching out of converter groups following protective actions.

A reliable and redundant telecommunication would be required although it may be possible to carry safe operations and protective actions without telecommunication link.

Another aspect that needs attention is the immunity of protective circuits due to electromagnetic induction especially when high currents may be flowing in the parallel control and protection or power circuits.

The special design aspects of control and protection system in 800 kV HVDC system is dealt in Chapter 10.

### **11.12 Auxiliary systems**

The auxiliary power changeover schemes must have adequate redundancy in equipment and capacity and sound changeover logics to ensure no tripping of converter group / pole / bipole during single auxiliary system outages or changeovers.

The faults in the auxiliary systems including battery backup systems must be able to be isolated immediately to avoid any possible bipolar outage.

### **11.13 Spares and maintenance**

Following aspects shall be considered in the design to ensure high availability and reliability of the whole HVDC system:

- Adequate number of spares and tools and tackles
- Equipment failure diagnostic tools
- Trained manpower
- Modular construction / system configuration
- Easy maintainability without undue need for taking shutdown of unaffected equipment e.g. possibility of isolation for maintenance of subsystems like ac filter sub-banks, DC filters, converter transformers for each group, control and protection equipment, part of auxiliary systems etc.
- Reduction in time for replacing converter transformer, smoothing reactor, bypass switches etc.

Special attention should be paid to the specific HVDC equipment, which are crucial for the DC system operation and have usually a long lead time for delivery of spares. Among such equipment the converter transformer is regarded as most critical equipment, which has some negative operational record in the past in few HVDC schemes. Besides careful design and proper maintenance it is worth to consider the possibility to increase the number of spare units on site to increase the system availability in case of some unforeseen events.

### **Acknowledgements**

Sincere acknowledgements are extended to Mr. Devinder Kumar for his extensive contributions and advice.

## **12.0. External insulation: Pollution and altitude aspects for design**

The study of external insulation is considered a key topic for the research program related to 800 kV HVDC [1], for the transmission lines as well as for the DC equipment. A research project on the external insulation for 800 kV HVDC system was undertaken by STRI in 1992. A large number of experiments were performed in STRI's laboratory with pollution test ability up to 1200 kV DC [2]-[5]. As a result, design rules for HVDC insulators were established up to 800 kV.

It is important to differentiate between insulators used for transmission lines and those used at the station. In a line, there will be a very large number of insulators, and they will be exposed to varying site conditions, due to the long line length of 800 kV DC transmissions. At the converter or switching or repeater stations, the insulators will be installed in smaller amounts. Their maintenance will thus be easier. The aspects discussed below are mainly aimed at station insulators, but the principles are applicable to line insulators as well.

Another important aspect of external insulation is the necessary air clearance under different conditions, especially as affected by altitude. The success of 800 kV DC projects will be heavily dependent on appropriate design criteria. At 800 kV DC, the air clearances will be quite large, and their impact on the total cost will be significant: too small clearance is just as bad as too large clearance. A section of this Chapter is also devoted to discussing altitude correction methods.

### **12.1. Flashover process**

In order to discern proper design criteria it is important to understand the phenomena of the flashover process.

A pollution flashover is actually caused by wet pollution.

In inland areas, the pollutants that accumulate on insulator surfaces are mostly in the form of dry dust. This dry pollution may then be wetted by rain, fog, or condensation. This situation is referred to as Type A pollution in the revised IEC 60815 - 2008. Near sea coastlines, or at sea, pollution comes to the insulator in wet form, such as salt fog. This type of pollution is referred to as Type B pollution in the same document.

A typical flashover in an insulator with hydrophilic surface follows the process described below:

- *Pollution accumulation:* The existing pollution from the air is accumulated on the surface of the insulator, as governed by the existing amounts, the electric fields (through electrostatic forces), the insulator shed profile, etc. It is important to note here that the pollutants accumulated may contain different types of salts.

- *Wetting and pollution dissolution:* Water comes to the accumulated pollution on the surface and dissolves at least part of the pollution, thus becoming conductive. The water can come from rain, from fog, from condensation, or from adsorption. The different types of pollutants will have different rates of solution in water, and different rates of water adsorption.
- *Leakage current:* The wetted pollution starts conducting, and a leakage current is established on the surface
- *Dry band formation:* The heat generated by the leakage current will dry some of the conductive paths faster than others, since neither the pollution nor the amounts of water are evenly distributed. Non-conductive dry bands are formed.
- *Partial arc activity:* The voltage accumulates across the non conductive dry bands. This creates partial arcs over them.
- *Total flashover:* During the dynamic processes of dry-band arcing activities, a total flashover may occur across the whole insulator.

From the description above, there are two very important aspects that should be emphasized:

- There are two key ingredients to a flash-over: Pollution accumulation, and wetting. A flashover will not be produced if there's no pollution, or if the pollution does not become wet.
- The pollution accumulation and the flashover phenomena have different patterns under AC and DC conditions.

## **12.2. Operation experience**

Several reviews and studies have been carried out on the operational experience of the existing HVDC stations worldwide. Some of the results of these studies have been published, e.g. [6], [7].

The operational experience from existing HVDC stations, from 250 to 600 kV has shown that the flashover rate of these stations has no direct correlation to the voltage levels of the stations. It has also been seen that there is neither tendency nor need to choose a higher value for the specific creepage distance because of higher voltage levels; i.e. for a given pollution level, a linear relationship exists between the DC voltage and the necessary total creepage distance. This is also seen by laboratory tests, such as those shown further on in section 12.4.

With suitable design, a very low flashover rate of 0.05 flash-overs per pole per year has been achieved in a total of 80 poles (47 stations) around the world, as shown in the figure 12.1 below.

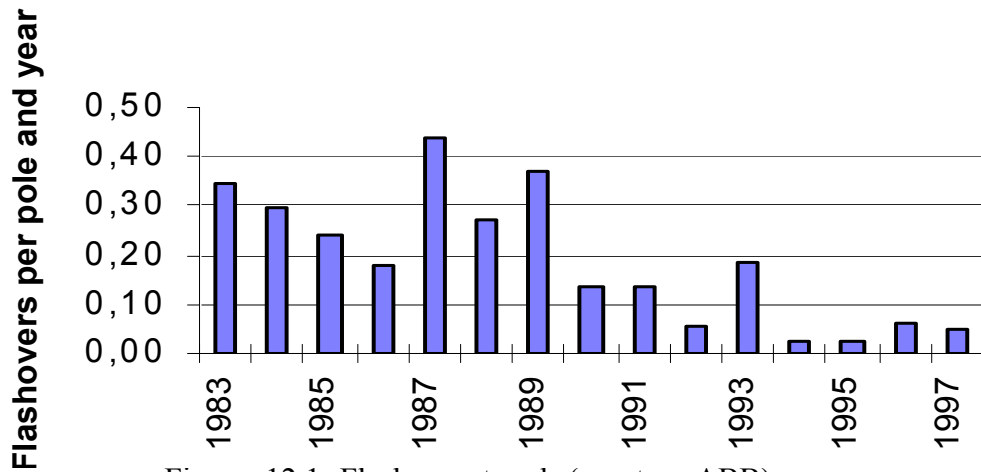


Figure: 12.1- Flash over trends (courtesy ABB)

Good operational experience with silicon rubber insulators, even with shorter creepage distance than that of porcelain, has been observed. This has also been reported for line insulators [8]. The effects of hydrophobic coatings and of booster sheds have proved to be very effective. The well known uneven wetting flashovers on, mostly, wall bushings have been prevented with insulators with hydrophobic surface. The effect of the counter measures can be seen in the figure 12.2 below.

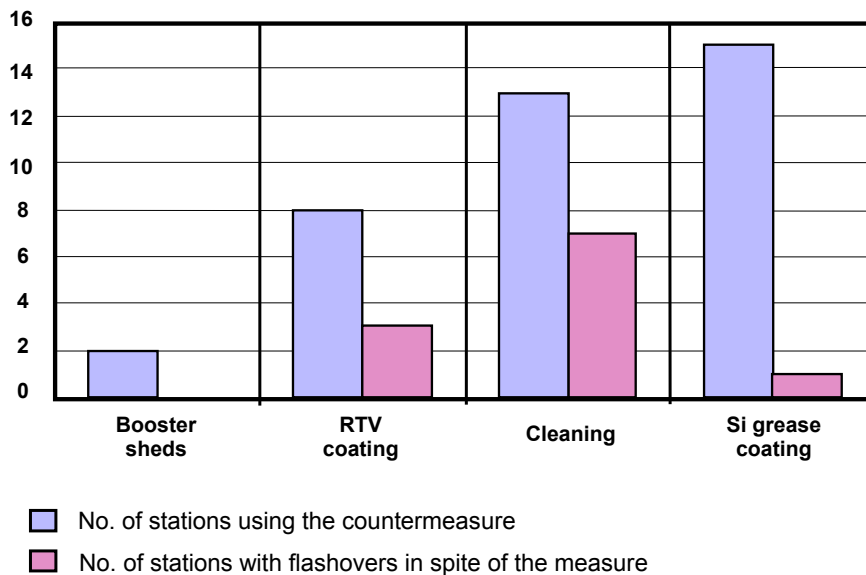


Figure: 12.2 Effect of counter measures (courtesy ABB)

The experience with silicon rubber insulators in HVDC has been so far very good, as the examples below show:

A) USA. Pacific Intertie

- Porcelain line insulators with 35.3 mm/kV:  
Needed washing every 60 days
- Silicone line insulators with 27.1 mm/kV: no flashover in 18 years
- Porcelain wall bushing: 23.2mm/kV, with hydrophobic coating:  
Satisfactory performance.
- Porcelain wall bushing at 500 kV, 40mm/kV, with RTV coating:  
Satisfactory performance.
- Silicone rubber wall bushing:23.2 mm/kV: no flashover for 10 years

B) China. Several 500 kV DC projects

- Porcelain insulators:  $\geq 40$  mm/kV: cleaning every year
- Silicon rubber insulators: at 75% creepage: Decreased pollution flashover

C) Nelson River 500 kV DC experience

The first HVDC composite wall bushing went in service in Nelson River bipole 2 at 500 kV DC in 1989. This bushing has been in service since then until now with no flashovers and without cleaning.

The bushing is an outdoor/indoor type bushing with a resin impregnated condenser core in a fiberglass tube coated on the outside with silicone rubber. The outdoor part of the bushing is supplied with silicone rubber sheds while the indoor part does not have sheds. The whole bushing is filled with SF6 and Nitrogen mixture (80%/20%) to allow for operating temperature down to -50 degree C.

The main technical data of the bushing:

- DC voltage 545 kV
- DC current 2000 Amps.
- Creepage distance outdoor 13.7 meters, Indoor 3.6 meters
- Outdoor specific creepage distance 27.3 mm/kV

There have been a few early-aging cases, which are attributable to quality and design problems rather than to the use of silicone rubber itself. They have, though, shown that the choice of material is important, including its aging withstand.

### **12.3. Site conditions and test station**

Apart from the voltage, the most important factor for insulator selection is the site conditions. One should be aware that insulators under DC voltage may collect more pollution than insulators under AC voltage at the same site [9]. In order to make long-term measurement on site, a “portable” test station has been used in some instances. The “portable” test station can, with relative ease, be dismantled and installed at a new site with limited efforts.

In the test station a DC voltage (100 kV) is generated to energize insulators. The monitoring equipment includes continuous measurement of the leakage current on the tested insulators, and it also measures pollution, and collects weather data like wind, rain, humidity and temperature.

Results of tests at two sites with such test station, as well as a description of the portable test station itself can be found in [10].

**12.4. Laboratory tests**

Laboratory tests with uneven rain and pollution have been performed on different types of insulators [2]-[6]. It is clear from laboratory studies that for an SDD level equal to or higher than 0.02mg/cm<sup>2</sup>, a linear relationship holds between the required creepage distance and the applied voltage for the same type of insulator, as shown in Figure 12.3 below.

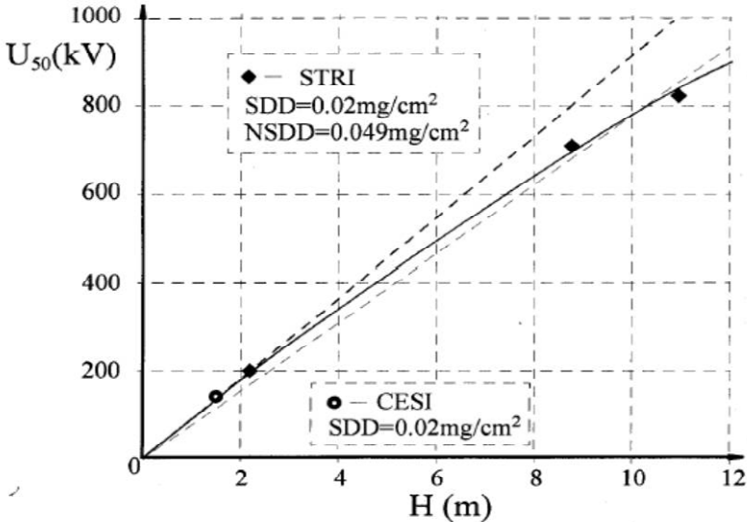


Figure 12.3: Pollution Test Results

Insulators of different shed profiles have been compared in laboratory tests. The results show that a relative large shed spacing is of importance for good pollution performance. This conclusion is applicable for insulators of hydrophilic surface. For insulators with hydrophobic surface, limited results exist. However, a relative large shed spacing, even for this type of insulator, is considered to be advantageous in pollution and heavy rain conditions.

**12.5. Means of improving pollution performance**

There are several means to tackle the flashover challenge. They are based on means to reduce the probability of the two key steps named under the phenomenon description. The most important ones are:

A) *Reduce conductive paths by reducing the pollution*

○ *Site selection:*

When possible, locations with or close to heavy pollution sources should be avoided.

○ *Cleaning:*

The insulator cleaning periodicity will also aim at reducing the accumulated pollution on the insulators surface. The cleaning is normally done off-line; there's very limited experience on live line washing under high DC voltage

○ *Indoor DC yard:*

In extreme cases, an indoor DC yard or hall can be adopted. The aim will be to avoid water on the pollution. Obviously, no rain should come indoor, but condensation and adsorption should be also avoided. Pollution should be low, depending on the tightness of the hall, but this is not the main line of defence, as is the case in valve halls.

○ *Shed profile and installation angle:*

A proper choice of profile will have the right aerodynamics so that industrial or desert pollution will not accumulate in pockets, and will be properly washed away. Insulators installed at an angle, such as is the case with modern wall bushings, exhibit better natural washing. Some examples of “short-long” and “under-rib” profiles are shown in the figure 12.4 below

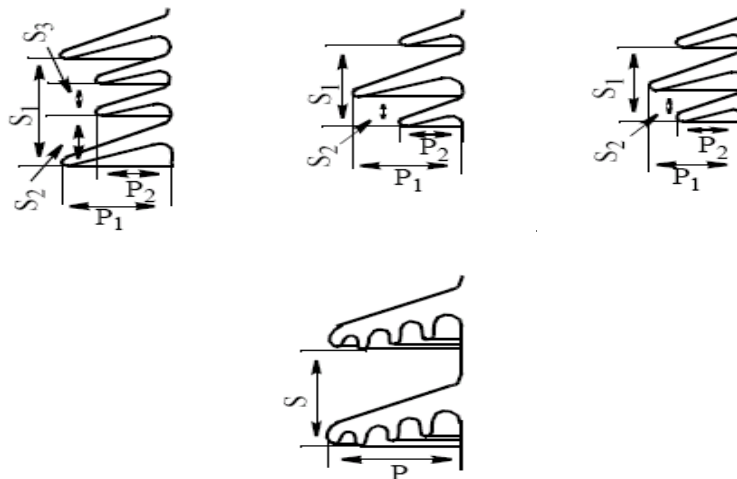


Figure 12.4

B) *Prevent wetting with pollution dissolution*

○ *Hydrophobic insulator surface:*

Having a hydrophobic surface will prevent the formation of conductive paths on it, since the water will not form continuous bodies. This can be achieved by several means, but the most extended ones are to either make the insulator

from a material that is intrinsically hydrophobic, such as silicone rubber, or to treat the surface to achieve this property, with silicone grease, or with RTV (room temperature vulcanised rubber). Depending on the material properties, the design principles will be somewhat different. Close up photographs of different materials below show their different behaviour when wetted.

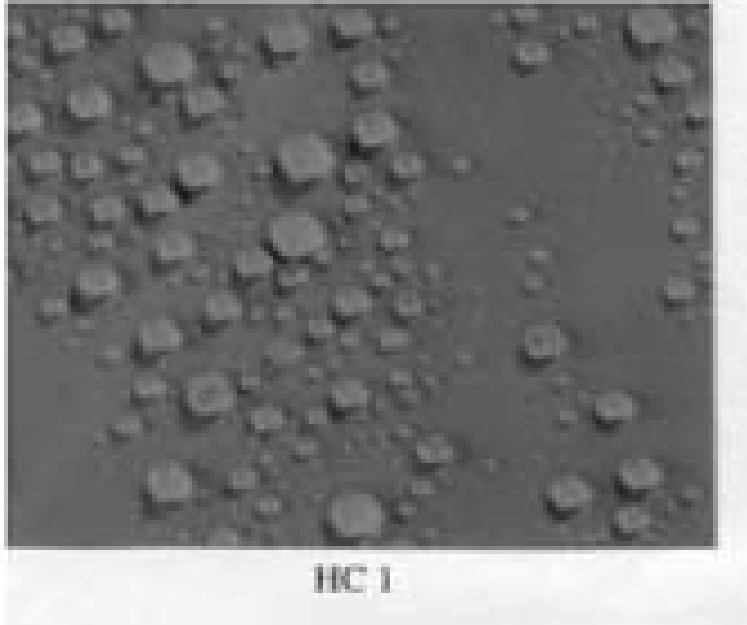


Figure 12.5 Example of water behaviour on hydrophobic material

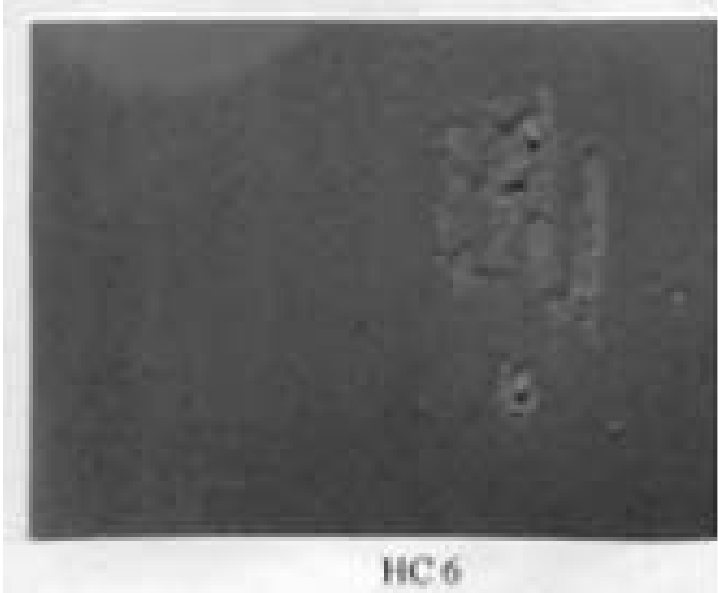


Figure 12.6 Example of water behaviour on hydrophilic material

It is important that the material in or on the surface has the ability to transfer its hydrophobicity to the pollution is deposited on it. The purpose is to achieve enough hydrophobicity at least just before water comes (rain, condensation or adsorption).

C) *Reduce conductive paths by preventing wetting*

○ *Booster sheds:*

Booster sheds seem to contradict the principles named above, since they will create dry bands. This is true, but the dry bands will occur in a controlled fashion, since they will occur below the sheds. An even more important effect is that the booster sheds will prevent water bridging during heavy rain, and this is especially important at the beginning of the rainy season.

An additional effect of the booster sheds is that they provide some barrier effect against partial arcs.

○ *Shed profile with “protected” creepage:*

A profile may protect some parts of the surface from getting wetted. The question arises about how difficult it may become to clean the insulator’s “protected” parts

○ *Indoor DC yard:*

Putting the DC yard indoors, in a hall, will prevent the direct ingress of rain water. For the protection to be complete, though, the humidity in the air will have to be controlled, to avoid condensation and adsorption. It has been found that keeping a relative humidity level of 50% or lower will accomplish the desired tasks for industrial pollution, such as in the Zhengping converter station of the Three Gorges – Changzhou 500 kV DC transmission. The Zhengping station has indoor DC switchyards, one for each pole. They were decided because of high levels of industrial pollution.

Unfortunately there are no reports on needed relative humidity in converter stations with indoor DC switchyard chosen because of sea/salt pollution, such as is the case with the Cross Channel transmission.

Controlling the relative humidity should not be too difficult, but it can be of considerable magnitude for 800 kV DC, since the halls will be rather large. Pollution thus will no longer be a dimensioning factor, and the insulator profile will no longer be critical.

D) *Reduce leakage currents by increasing resistance*

The idea behind reducing leakage currents is to reduce their heating effect, and the amount of ionization the partial arcs will generate. In that way, the probability for flashover will be reduced.

The leakage currents on the surface cannot be reduced by reducing the voltage: they have to be reduced by increasing the resistance. The leakage resistance grows with the resistivity and with the length, and decreases with the cross section; even if the relationships are not as simple as in the traditional formula

$$R = \rho \cdot \frac{L}{A}$$

Where

- R is resistance
- $\rho$  is resistivity
- L is length
- A is area of cross section

The resistance can thus be made larger by either increasing the creepage distance, or the surface resistance, or by reducing the insulator perimeter by reducing its diameter.

○ *Long creepage distance*

Increasing the creepage distance can be pursued through the profile selection, while keeping in mind that it is necessary to respect a minimum shed spacing to avoid shed-to-shed bridging and water bridging. The total length of the insulator will grow with the creepage distance.

○ *Lower cross section*

As mentioned above, this is achieved by reducing the insulator diameter. This is obviously possible only for support or suspended insulators, but not for component insulators such as bushings, DCCT's etc... OCT's are an exception, since the insulator can be made very thin, as it does not need to withstand radial stresses.

○ *Hydrophobic surface*

To achieve a high resistivity on the surface, hydrophobicity is a key factor. An adequate material on the surface, such as silicone rubber, or RTV, or silicone grease will provide this property. The durability of the property is important. Silicone rubber of good quality will keep this property for the life time of the installation. Even when the property seems to be exhausted after intensive pollution, the material will transfer its hydrophobicity to the new pollution after some time. Silicone grease may need to be removed and reapplied. A similar situation may occur with RTV.

It is thus important to have a material whose hydrophobicity reduction when polluted is low; it should besides have a good capacity for transferring the internal material to the surface, so as to make the pollution hydrophobic too, and it should have good recovering ability on its own surface.

Comparing silicon rubber insulators with porcelain ones, several remarks can be made:

- A shorter creepage distance can be used in polluted areas, especially for Type A pollution. In coastal areas, with Type B pollution, the hydrophobicity can be lost quickly, and condensation or adsorption can come before recovery. A similar statement can be made of areas in which wet pollution could come quickly.
- Silicon rubber insulators have better pollution performance, as reported by certain utilities
- In clean areas, where the advantages of silicon rubber insulators over porcelain are not so marked, the necessary creepage distances for either solution will be short, and the total length will not be so critical.

With very heavy industrial pollution, the use of Silicone Rubber Insulators (silicone rubber) with good ability to retain a hydrophobic surface is a good solution. Today, Silicone Rubber Insulators are used on almost all the apparatus insulators, e.g. bushings in DC yard, DCVD's, etc.. Only station post insulators are still of porcelain material. Hydrophobic coating of different types has often been applied afterwards, after some operation experience. Station post insulators of composite material are now under intensive development. It may be mentioned that it is not desirable to design a new system with RTV and silicone greasing coating as these are to be removed and reapplied again and again depending upon pollution level. However, this is a good solution for existing projects where the pollution level has been increased from its design level during their service life and there is occurrence of flashovers during adverse weather condition

## 12.6. Recommendations

### 12.6.1 Surfaces

The insulator surfaces should be hydrophobic.

### 12.6.2 Profiles

A typical 800 kV DC vertical insulators of silicone rubber or other hydrophobic material in converter stations. It is shown in the figure 12.7

- 1, Shed spacing:  $S \geq 65 \text{ mm}$
- 2, Shed overhang:  $P \leq 1.2 \times S$
- 3, Difference in shed overhang:  $P - P1 \geq 20 \text{ mm}$
- 4, Inclination of upper surface:  $\alpha > 10^\circ$
- 5, inclination of lower surface:  $\beta > 3^\circ$

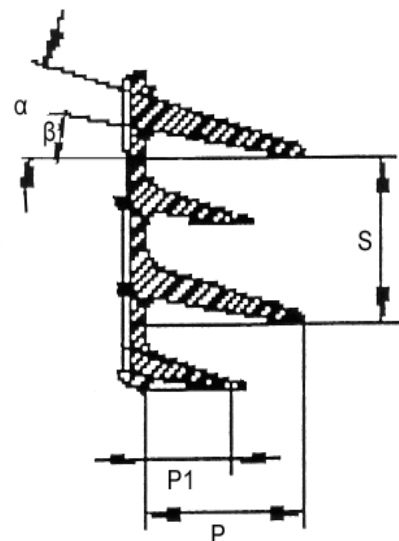


Figure : 12.7

Note 1: Too large value of  $\beta$  will result in areas with high pollution accumulation and therefore is not recommended.

Note 2: If the profile is helicoidal, the relation of pitch to diameter shall result in an inclination that is at least  $2^\circ$  smaller than  $\alpha$  at the root to ensure that water will run to the lip rather than along the helix.

For horizontal insulators, such as wall bushings, there's better natural washing, and the elimination of rain water happens at every shed, with practically no risk for bridging between the insulator's sheds. For these reasons, the recommended shed spacing and the relationship between shed spacing and overhang can be somewhat relaxed.

In addition, for so called horizontal insulators, a small inclination in the order of  $15^\circ$ , with the external terminal higher than the base flange, is to be preferred.

### **12.6.3 Creepage distances**

The specific creepage distance (mm/kV) for HVDC equipment depends mainly on the pollution levels at site of installation. Thus there is no need to adapt different specific creepage distances on the 800 kV DC equipment with respect to existing (500 kV DC) equipment. Furthermore, it is known that different surface material of equipment housing (porcelain or silicon rubber) has different behaviour under the same pollution conditions. Theoretically, the creepage distance should be same for both porcelain and composite insulators as the hydrophobic properties of the insulators temporarily is lost under pollution condition and the time of recovery may be several hours depending upon the type of composite material and pollutant. It has been reported that some of the projects are under satisfactorily operation with reduced creepage up to 25% or even more than 25%, however, it is difficult to conclude that the creepage distance could be reduced for composite insulators in all cases due to insufficient data, testing and field trial and also variance in hydrophobic characteristic of various composite material. However, this aspect of creepage distance reduction in DC insulators is being dealt by a separate CIGRE WG.

The total creepage distance needed for the corresponding equipment shall be calculated taking the adequate reference voltage into account. According to IEC 60071-5, Clause 8 and Clause 3.1 the highest mean or average operating voltage, excluding possible harmonic and commutation overshoots, shall be used as voltage level to determine the required leakage distance for the insulation of DC equipment.

For pollution levels higher than  $0.100 \text{ mg/cm}^2$ , the creepage distance will result in very long insulators. This makes the mechanical design difficult and expensive. Careful consideration should thus be given to the option of having an indoor DC switchyard.

## 12.7. Altitude correction

Some of the transmission schemes at 800 kV DC foreseen for the 10 coming years have station(s) in the neighbourhood of 2000 m above sea level. By contrast, most HVDC equipment manufacturing and testing facilities are located at very moderate altitudes. The considerable clearances that 800 kV DC dictates makes it very important to be able to predict with reasonable accuracy the behavior of the insulating air at such altitudes.

CIGRÉ as well as IEC have published methods for altitude correction [11], [12]. In addition to these, there are various national standards. It would be beneficial to everybody, utilities, consultants, and manufacturers, to reach consensus on which methods to apply. An overview is given below.

### 12.7.1 Basic principles

The correction factor is defined here as:

$$k_a = U/U_0$$

Where  $U$  is the breakdown voltage at site conditions and  $U_0$  is the breakdown voltage at standard reference conditions.

### 12.7.2 Air parameters

The dielectric strength of air is influenced by the air temperature, pressure, and humidity. The influence of temperature and pressure can be taken into account simultaneously, at least as a first approximation, by the relative air density,  $\delta$ .

$$\delta = \frac{p_1}{p_0} \times \frac{273 + 20}{273 + T}$$

Where

- $p_1$  is the atmospheric pressure at other than standard conditions
- $p_0$  is the atmospheric pressure at standard reference conditions
- $T$  is the temperature (in °C) at other than standard conditions

The pressure ratio can be calculated using the equation below (even if there are other equations)

$$\frac{p_1}{p_0} = \left(1 - \frac{6.5 \times H}{288}\right)^{5.256}$$

Here:

- $H$  is the altitude above the sea level in km.

With the help of the given equations the relative air density,  $\delta$ , can be calculated. The other important parameter to calculate is the absolute humidity,  $h$ . These two parameters have also certain co-effects; i.e. they are interdependent for a given individual mass of air, but the air is always changing, especially for outdoor conditions. As for the high altitude correction, it is mainly a correction for air density. It should be noted that for outdoor conditions, it might be assumed that the effects of ambient temperature and humidity tend to cancel each other, as pointed out in IEC60071-2. However, inside the valve halls and HVDC halls, if used, the temperature is elevated by the losses; the total cancellation of the temperature effect by humidity may not be assumed.

### **12.7.3 Influence of air density**

The breakdown of a long air gap goes often through the processes of: corona inception, streamer propagation, leader formation and propagation, and final jump. The streamer and leader processes are the decisive processes.

It has been concluded in literature that the influence of  $\delta$  is most significant on the streamer formation and propagation. Therefore, if a positive streamer dominates the breakdown processes in this gap, the dielectric strength of an air gap is reduced proportionally to  $\delta$ , i.e.  $k_a = \delta$ . This is in principle the case for a shorter gap, shorter than 2 meters, under positive voltage.

For a longer gap, typically longer than 2 meter, the breakdown will be caused by the streamer and the leader process subsequently. The air density has little influence on the leader process. Therefore, the dielectric strength of a longer air gap is reduced less than proportionally to  $\delta$ . The reduction is approximated by the value of  $k_a = \delta^n$ , where the exponent,  $n$ , is smaller than one,  $n < 1$ , in most cases.

Therefore, the main task for arriving at the altitude correction for a long air gap is to evaluate the exponent  $n$ . However, the value of  $n$  is not just a simple function of the gap length, but also a function of gap structure, as well as the relative air density,  $\delta$ , in a complex way. The function can be expressed as  $n = f(U/L, k_{\text{gap}}, \delta)$ . Here  $k_{\text{gap}}$  is the gap factor.

### **12.7.4 G-factor methods**

The correction methods using the “G-factor” were summarised and presented in the CIGRÉ guidelines [11]. These are based on studies.

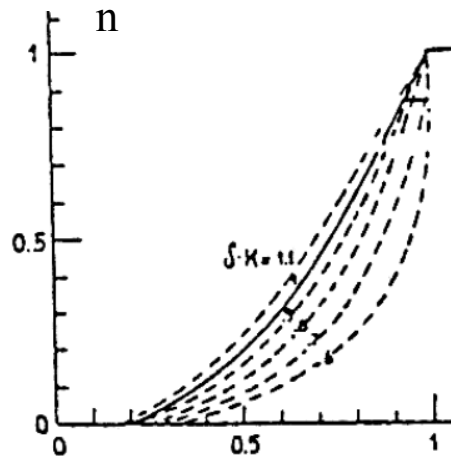
To take into account both effects: from the gap length,  $L$ , and the gap structure, the factor,  $G$ , is introduced. The value of  $G$  is the ratio of the mean electric field,  $E$ , at the breakdown voltage of a given gap and the average electric field of the positive streamer,  $E_s$ , at the same atmospheric conditions.

$$G = \frac{E}{E_s} \quad \text{With } E=U_{50}/L \text{ and } E_s= E_{s0} \times \delta \times k.$$

Here:

- $k$  is the correction for humidity
- $E_{s0}$  is the average electric field of the positive streamer at standard reference atmosphere

$$E_{s0}=500 \text{ kV/m}$$



**Figure 12.8**

The exponent  $n$  of  $\delta^n$  is given in Figure 12.8 as function of  $G$ , with the value  $\delta \times k$  as index. The curves are given for cases where  $\delta \times k= 0.6$  to  $1.1$ . For high altitude correction, one can assume  $k=1$ . In most cases for long air gaps under positive voltage, we have  $E < E_s$ ; therefore,  $G < 1$ ; and then the correction will be  $k_a = \delta^n > \delta$ .

It is important to note that the curve with solid line in the figure, for  $\delta \times k = 1$ , gives the same relationship as is given in IEC 60060-1 (1981) for  $n=f(G)$ . This curve can be applied with an acceptable accuracy for cases where  $0.9 \leq \delta \times k \leq 1.1$ . However, it is not recommended for high altitude correction, as pointed out by the Cigré guidelines.

In most of the cases, the value of  $U_{50}$  for a given gap is only known at the standard reference atmosphere, so it is necessary to use  $G_0$  instead of  $G$  in the calculation.

$$G_0 = \frac{E}{E_{s0}} = \frac{U_{50}}{500 \times L}$$

### 12.7.5 Empirical proposal

An empirical formula is presented in the Cigré guidelines [11] for high altitude correction as the three steps that follow:

$$G_0 = \frac{U_0}{500 \times L \times \left[ 1 + \frac{(k_{gap} - 1)}{3} \right]}$$

$$T_0 = 1.4 \times k_{gap}^{1.6} \times \frac{1 - 0.8 \times G_0}{1 - 0.2 \times G_0}$$

$$k_a = \frac{0.8 \times [1 + T_0 \times (1 - \delta)] \times (\delta - 0.2 \times G_0)}{1 - 0.2 \times G_0} + 0.2$$

In the formula,  $U_0$  is the  $U_{50}$  at standard reference atmosphere. This formula is said to be applicable to altitudes up to 3000 meters.

### 12.7.6 Simplified approaches

To obtain the exponent  $n$  of  $\delta^n$  without using the complicated  $G$  factor, simplified approaches were used in IEC and other standards or literature. The exponent  $n$  in these approaches was presented as only a function of the gap length or a function of the withstand voltage, e.g.  $n=f(L)$  or  $n=f(U_w)$ . This is done with the condition that the types of gaps to be calculated are of similar structures. As a common character, all the simplified approaches give more conservative correction values than the  $G$  factor correction, i.e. give lower breakdown voltage at the high altitude.

In EPRI's "Transmission line reference book: HVDC to  $\pm 600$  kV", known as the green-book, the values of  $n$  of  $\delta^n$  are given as function of gap lengths. The test results are given for only up to 4 meters. The value of  $n$  goes down as the gap length increases.

Gap length L (m)	Exponent n
1.5	1
2.3	0.9
3.05	0.8
3.8	0.7

#### Chinese Power Industry Standard

In the Chinese Power Industry Standard DL/T 620-1997, the exponent  $n$  of  $\delta^n$  is given also as function of the gap length, with  $n=1.12-0.12L$ , with  $L$  in meters. The relation is said to be suitable for gaps 1 to 6 meters long.

#### IEC60071-2

In the standard IEC60071-2, the relative air density is given in a formula as:

$$\delta = e^{-\frac{H}{8150}} \quad \text{Where H is in meters.}$$

The exponent  $n$  of  $\delta^n$ , denoted as  $m$  in this standard, is given as a function of the withstand voltage of the gap with:  $m=f(U_w)$ .

IEC60071-2 and 60071-5[13]

In the earlier days, no altitude correction was required for altitudes up to 1000 meters above the sea level. The “new” rule of correction, in 60071-2, requires correction from the sea level. The correction required at 1000 meters for, e.g. 1700 kV is about 6%. One observation is made on the contents in 60071-5. In this document, it is suggested that the margin between switching impulse withstand level (SIWL) and switching impulse protection level (SIPL), 15%, covers the effect of 1000 meters above the sea. Although this judgment can be discussed, the fact that no correction was used for stations located up to 1000 meters and no breakdown has been reported would support the existence of a certain margin which covers the few percent correction corresponding to this altitude. According to this consideration, the correction made for an altitude that is higher than 1000 meters can be made in such a way that the effect of the first 1000 meters is removed.

As an example, for  $U_w=1700$  kV, for an altitude of 1000 meters,  $k_a$  could be defined as  $k_a = 0.945$ , and at an altitude of 1850 meters, it could be defined as  $k_a = 0.901$ . The resulting correction would be:  $0.901 / 0.945 = 0.953$ .

IEC 60694 (2002)

In this standard, the correction is also applied only for altitudes above 1000 meters. Further simplification and approximation are made from the curves given in IEC 60071-2 for the relationship of  $m = f(U_w)$ . A constant value is taken with, e.g.  $m=0.75$ . The formula for correction therefore becomes:

$$k_a = e^{-0.75 \frac{H-1000}{8150}}$$

**12.7.7 Comparison of different correction methods and discussion**

Figure 12.9 below give some examples for a comparison between different correction methods. The conditions used for comparison are given at the top of each figure. The different correction factors are plotted against the gap length. The correction methods included in this comparison are:

- Correction with G factor by the curves in Figure 12.8;
- Correction with G factor by the empirical proposal;
- Correction according only to IEC60071-2;
- Correction according to IEC60071-2 and 60071-5, i.e. considering only the altitude beyond 1000 m from sea level.
- Correction according to DL/T 620-1997.
- Correction according to the green book.

The trends of all the correction curves reflect the principle that air density has less effect on longer gaps.

H=1850 m, T=20°C, k<sub>gap</sub>=1.3

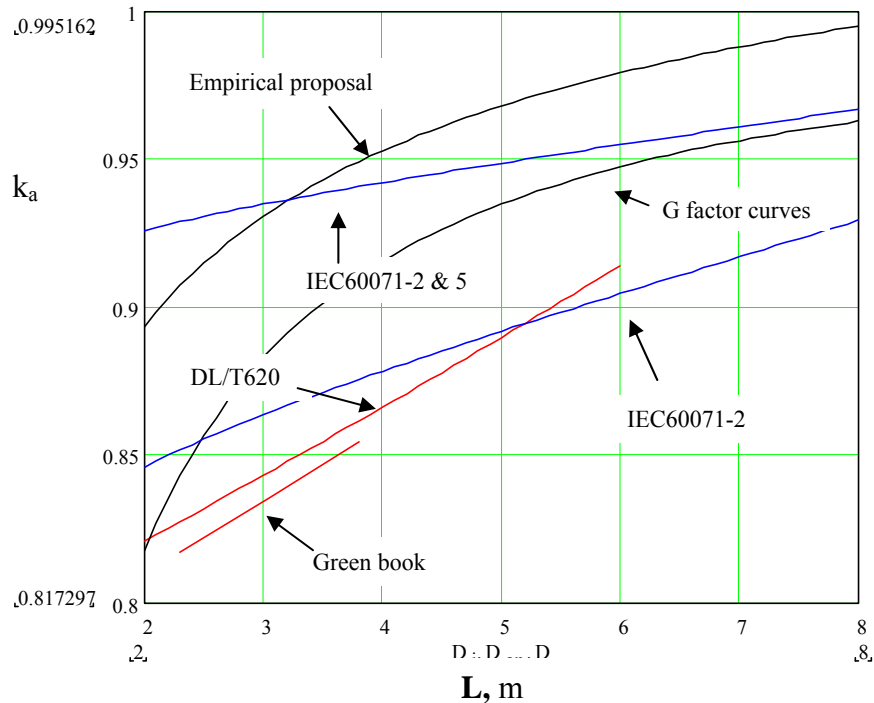


Figure 12.9

### Acknowledgements

Sincere acknowledgements are extended to Mr. Dong Wu for his extensive and valuable contributions and advice.

### References

- [1] P.C.S. Krishnayya, P.J. Lambeth, P.S. Maruvada, N.G. Trinh, G. Desilets, S.L. Nilsson, "An evaluation of the R & D requirements for developing HVDC converter stations for voltages above  $\pm 600$  kV", CIGRÉ 1988 Session, 14-01.
- [2] W. Lampe, D. Wu, "Dimensioning outdoor insulation for  $\pm 800$  kV transmission", CIGRÉ SC 33 Colloquium, 2.9, New Delhi, Sept. 1 to 2, 1993
- [3] Wu, R. Hartings, U. Åström, "Investigations on the outdoor insulation of  $\pm 800$  kV DC transmission systems", Proceedings of the international Conference on Power System Technology, Beijing, China, Vol. 2, pp771-774, Oct. 18-21, 1994
- [4] Wu, R. Hartings, U. Åström, "The performance of station post insulators in uneven rain under DC voltage", 9th ISH, paper 3237, Graz, Austria, August 28- September 1, 1995

- [5] D. Wu, R. Hartings, U. Åström, B. Almgren, S Nord, “The performance of station post insulators for UHVDC applications” 10th ISH, August 25-29, 1997, Montreal, Canada.
- [6] W. Lampe, B. Almgren “External flashover in HVDC stations” CIGRÉ SC 33.91 (Coll.) IWD, 1991
- [7] B. Almgren, U. Åström, D. Wu, “Operational experiences of insulators in HVDC converter stations” Proceedings of the eleventh national power systems conference, NPSC-2000, Bangalore, India
- [8] X.D. Liang, S.W. Wang, Z.Y. Su, ”Experience with composite HVDC and HVAC insulators in China: from design to operation” Proceeding of 2003 World Conference on Insulators, arresters and Bushings, pp15-22
- [9] D. Wu, Z.Y. Su, “The correction factor between DC and AC pollution levels: review and proposal” 10<sup>th</sup> ISH, Montreal, Quebec, Canada, Aug. 25-29, 1997
- [10] Zhiyi Su, Weimin Ma, Dong Wu, Urban Åström, and Greger Karlsson “Measurement of Site Pollution Severity under DC Voltage by Means of A Portable Test Station.” Paper published on the 14 International symposium on High Voltage Engineering, Tsinghua University, Beijing, China, August 25-29, 2005
- [11] WG 33-07, “Guidelines for the evaluation of the dielectric strength of external insulation” Cigré Brochure 72
- [12] IEC International Standard 60071-2 (1996) “Insulation coordination. Part 2. Application guide”
- [13] IEC International Standard 60071-5 (2002) “Insulation coordination- Part 5. Procedures for high voltage direct current (HVDC) converter stations”

### 13.0 Transmission Line Design

The design of HVDC transmission lines, including 800 kV, follows the same principles as that of EHVAC lines. The difference is that the ruling criteria for design are likely to be different. For HVDC, the operating voltage is normally the decisive factor for insulator string length and this tends to dominate the tower design. Other considerations of lightning and switching overvoltages need to be considered, but normally are not critical. The conductor size and configuration may be limited by corona related issues, but for large powers and transmission distances, conductor size is probably given by economical considerations.

In the following sections the different aspects are discussed in order to evaluate suitable characteristics for an 800 kV HVDC transmission line. To a very large extent the information given here has been developed by CIGRÉ JWG B2.17/B4/C1 and taken from as yet unpublished reports, listed in references. These are available via the JWG and to be formally issued in 2008/2009.

#### 13.1 Transmission Line basic configurations

Although not strictly connected to the use of  $\pm 800$  kV, consideration must be given to the basic configuration of the transmission line and the cost verses reliability factors for the project, in addition to the design criteria to be used. As  $\pm 800$  kV overhead transmission systems naturally have large power ratings and are planned to be in bipolar configuration, then in most cases it is logical that a bipolar transmission line be used. However, the use of two monopolar lines should also be considered as reliability issues may make their use attractive. Converter configurations are discussed in Chapter 4, where it can be seen that all are bipolar and can be used with one bipolar or two monopolar transmission lines.


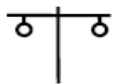
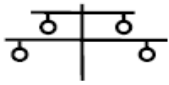
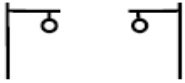
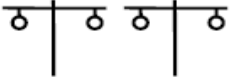
Variant	Tower Configuration	Remaining Transmission Capacity		Tower breakage	Relative cost %
		Ground return			
		permitted	not permitted		
Single monopolar line		0	0	0	85
single bipolar line		50 (100)	0	0	100
double bipolar line		100	100	0	114
Two monopolar lines		50 (100)	0	50 (100)	126
two lines (bipolar or homopolar)		100	100	100	136

Table : 13.1

The relative costs and reliability of various transmission line configurations are given in the table 13.1 above, taken from CIGRÉ report 186 from WG 14.20 [1].

Unless otherwise mentioned, this chapter assumes a single bipolar line. Double bipolar lines are not considered here at 800 kV.

The mechanical construction of most bipolar HVDC lines has the structure between the two poles, this putting a limit on minimum pole spacing. Some lines use a cross rope structure as shown in Figure 13.1, consider by some to be more economical.

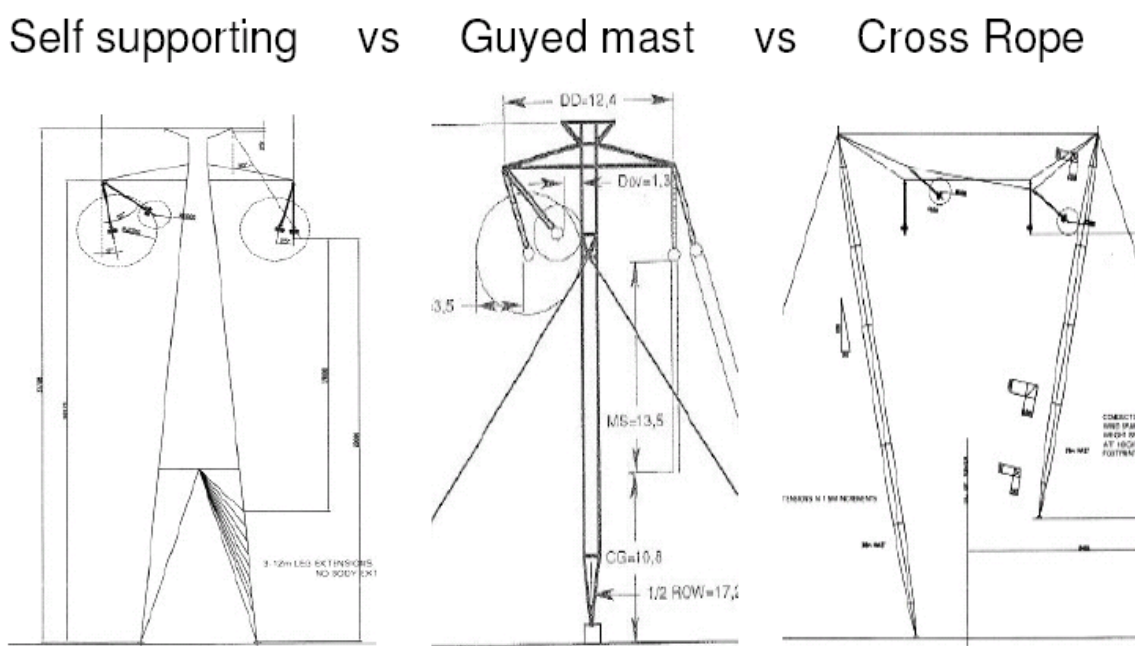


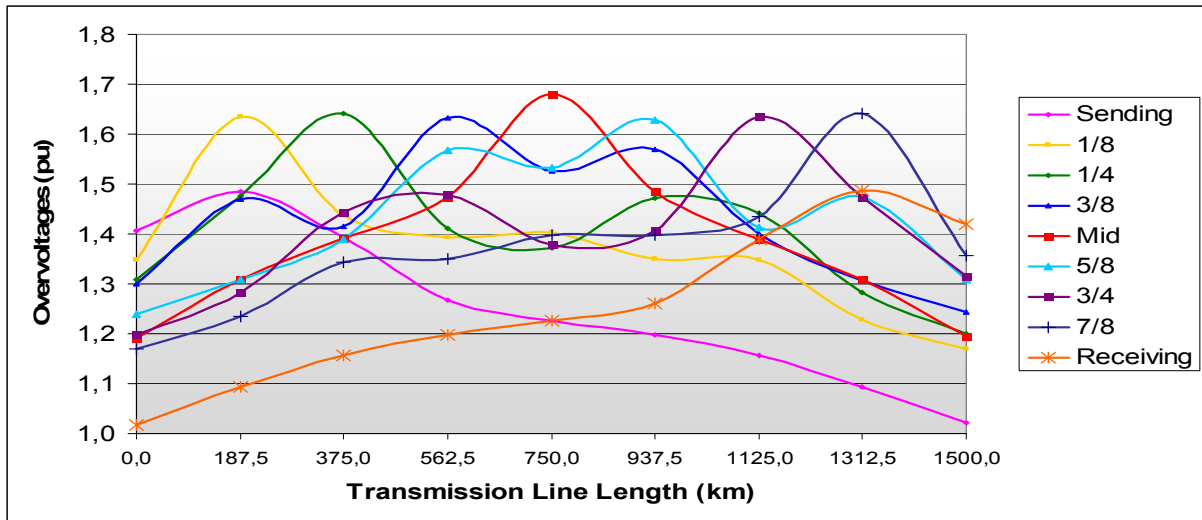
Figure 13.1

## 13.2 Insulation Requirements

The insulation of an HVDC line is stressed by atmospheric overvoltages, internal overvoltages and normal operating voltage. The first two impose requirements on the insulator string length, while operating voltage influences the choice of leakage distance. Together they define the minimum tower head distances and hence pole spacing. This is discussed in more detail in JWG B2.17 report 23 [2].

### 13.2.1 Internal overvoltages

Internal overvoltages are generated during faults as there are no switching operations as in AC lines. The figure below shows per unit overvoltages for fault at various locations along a 1500 km line. The results are for a typical HVDC line and using frequency dependent modelling. The results also vary significantly according to line length and termination, but the maximum value of 1,7 pu has been widely accepted for many years.



Line length	Frequency dependent model
750 km	1.50 pu
1500 km	1.68 pu
2250 km	1.78 pu
3000 km	1.85 pu

Table 13.2 Internal overvoltage as function of line length

If we also consider that a longer line has more exposure to faults and that we should permit one consequential flashover per 100 years from internal overvoltages, then the required clearance is increased for longer lines. Using an estimated rate of single pole to ground flashovers of 1 per 100 km per year (probably due to lightning) then we obtain the following clearances to meet the value of consequential flashover per 100 years, see table 13.3.

Gap	Distance (m)			
	750 km	1500 km	2250 km	3000 km
Conductor-to-tower	4.50 m	5.62 m	6.25 m	6.81 m
Conductor-to-cross arm	3.77 m	4.69 m	5.23 m	5.64 m
Conductor-to-guy wires	4.23 m	5.29 m	5.88 m	6.37 m
Conductor-to-ground	5.92 m	7.52 m	8.49 m	9.38 m
Conductor-to-ground (with a 4.5m object under the line)	4.79 m	6.00 m	6.70 m	7.31 m

Table 13.3 - Clearance distances as a function of line length

**13.2.2 Operating voltage**

The operating voltage defines the minimum necessary conductor-structure clearance for extreme wind conditions and also the number insulators to be used in the string. For the first, the following premises are considered:

- withstand voltage regarding the most unfavourable condition: positive polarity, conductor-to-structure;
- maximum operating voltage and correction due to the atmospheric conditions: 1,15 pu

The distances conductor-to-structure were obtained according [3] (Green Book) and are shown on Table 13.4.

Operating Voltage (kV)	Clearance (m)
300	0.70
500	1.20
600	1.50
800	1.90

Table 13.4 - Clearances for operating voltages (m)

Regarding the insulator string, the relatively low values of internal overvoltage mean that the length is dictated by leakage distance considerations, even at low levels of pollution. This has meant that in most projects where glass or porcelain insulators are used, that the insulator profile has a relatively high ratio of leakage distance to unit spacing when compared to conventional ac insulators. The figure 13.2 below shows an under-rib, fog type insulator unit, typically used on HVDC transmission lines, although other types, such as outer-rib have been proposed. For this type of insulator the ratio unit spacing to leakage distance is over 3,0.

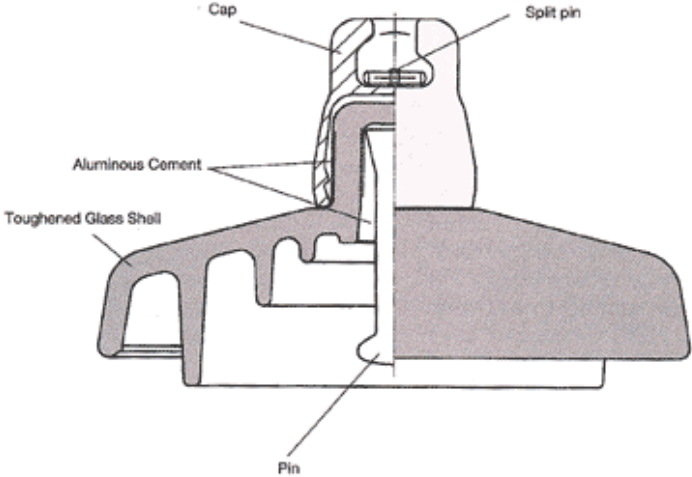


Figure: 13.2

Table 13.5 below shows the leakage distances for some operating HVDC lines.

<b>pollution level</b>	<b>IEC 815</b>	<b>Light</b>	<b>Moderate</b>	<b>Heavy</b>	<b>Very Heavy</b>
ESDD	Na mg/cm <sup>2</sup>	< 0,06	0,06 - 0,2	0,2 - 0,60	> 0,60
Specific creepage	mm/kV	20 - 25	25 - 32	32 - 40	40 - 70
<b>Projects</b>					
Skaggerak	± 250 kV			36,7	46,9
New Zealand	± 250 kV	22,0			50,0
Konti Skan Denmark	± 250 kV		27,0	32,0	38,0
Konti Skan Sweden	± 250 kV	22,0	27,0		
C.U.	± 400 kV		25,4		
HQ - New England	± 400 kV		30,0		
Nelson River I	± 450 kV	23,7			
Nelson River II	± 500 kV	21,3			
Pacific Intertie	± 500 kV	18,3	28,5	38,7	
Rihand - Delhi	± 500 kV		32,0	41,0	
Chandrapur - Padghe	± 500 kV			41,0	45,3
Inga - Shaba	± 500 kV		25,5		
Gezhouba - Shanghai	± 500 kV		36,0	44,5	
Gezhouba - Shanghai *	± 500 kV			35,0	44,0
3 Gorges - Changzhou	± 500 kV			37,0	
Cahorra Bassa	± 533 kV	22,9	26,8**	34,4***	
Itaipu	± 600 kV		27,2		
* Composite, all others glass or porcelain      ** altitude >1000m, *** New, after 1997 IEC 815 for ac insulators, used to define pollution level					

Note: \* As per IEC recommendation

Table 13.5

### 13.2.3 Specific leakage distance for various HVDC lines

The specific leakage distance varies considerably and is very much a function of pollution levels along the line route. For this reason no firm recommendation can be given here, but for the purposes of this chapter the specific leakage distance is taken to be 30 mm/kV, corresponding to light pollution in the table 13.5 below. 30 mm/kV at 800 kV, with spacing ratio of 3,0 gives a string length of 8 m and this is used for other calculations below, plus a hardware length of 0,25 m. In the case of V-strings an angle of 45° is taken for calculations, although this can be questioned.

The use of silicone rubber insulators has been a practice in HVDC in test cases on existing lines for many years [4]. HVDC is particularly suitable for silicone rubber insulators due to the fact that there is no high power arc following a flashover. However silicone rubber insulators have been used on transmission lines only as a remedial measure in locations where pollution flashovers have been a problem for glass or porcelain insulators. Now, with the application of 800 kV, the use of silicone

rubber insulators may be advantageous for highly polluted area which needs to be studied at the design stage.

#### **13.2.4 Tower head and Pole spacing**

Given the information above, we can calculate the minimum dimensions of the tower head and pole spacing. For I-strings, the string angle to be considered is a function of wind, temperature and conductor size. In general for consideration of clearance for operating voltage a very conservative set is used, probably with wind return period of 50 years. This gives high swing angles, maybe higher than  $45^\circ$ , and is likely to be the limiting criterion. For internal overvoltages, a swing angle based on CIGRÉ Brochure 48 [5] with a wind intensity corresponding to 1% probability of being exceeded in a year when considering switching surge overvoltages is used. This gives swing angle of the order of  $15^\circ$  and also conservative results. Based on operating voltage clearance given in table 13.3, we obtain a minimum pole spacing of about 20 m for 800 kV, given operating clearance and an assumed tower width of about 3 m. This value is relatively variable, as in practice conductor sag, especially with guyed towers, has to be taken into account.

For V-strings there is no swing angle and the insulator string, plus hardware, most probably defines the tower clearances. This gives a somewhat lower minimum pole spacing than for I-strings, about 17 m for long lines, as this now is a function of clearance for internal overvoltages and so depends on line length.

For the cross rope tower lower minimum pole spacing could be used, but this has not been investigated in detail so far.

#### **13.2.5 Lightning Performance**

In order to ensure good performance, given the insulation characteristics defined above, most 800 kV lines would use two shield wires for effective protection against direct strokes. In regions with low ceramic levels it may be possible to use one shield wire and still obtain acceptable performance.

For the strokes that hit the shield wire, there will be an overvoltage that is coupled to the pole conductors and may lead to insulation failure (back flashover). In bipolar HVDC lines, the different polarity means that only one pole is likely to flashover and this has been proven in practice over many years. With 800 kV lines, this effect should be even greater.

#### **13.3 Corona related considerations**

This section includes discussion of corona losses (CL), radio interference (RI) and audible noise (AN). Factors influencing the choice of conductor bundles are discussed below and provide the basis for selection of the conductor bundle.

The results given below are taken from work by JWG B2.17 [6].

### 13.3.1 Conductor Surface Gradient

The parameter that has the most important influence on corona performance is the conductor surface electric field or what is commonly known as conductor surface gradient. When bundled conductors are used, the electric field around the sub-conductors of the bundle is distributed non-uniformly, with maximum and minimum gradients occurring at diametrically opposite points and the average gradient at a point in between. The degree of non-uniformity increases with the number of sub-conductors in the bundle as well as with the ratio of the sub-conductor radius to the bundle radius.

When the electric field at the surface of a transmission line conductor exceeds a certain value, partial electrical breakdown of the surrounding air takes place, giving rise to corona discharges.

The occurrence of corona discharges leads to a number of effects that have important influence on transmission line design. Corona effects that are generally taken into account in the design of both AC and DC transmission lines are CL, RI, AN and visual effects. In the case of HVDC transmission lines, the combined effect of DC electric fields and corona-generated ion currents at ground level have also to be taken into account as design considerations.

The conductor surface electric field at which the onset of corona discharges occurs is defined as the corona onset gradient of the conductor,  $E_c$ . The corona onset gradient of a given conductor depends on many factors, the most important being the conductor radius, surface conditions and ambient air density. It depends also on the type of voltage applied to the conductor, AC or DC, and in the case of direct voltages, also on the polarity.

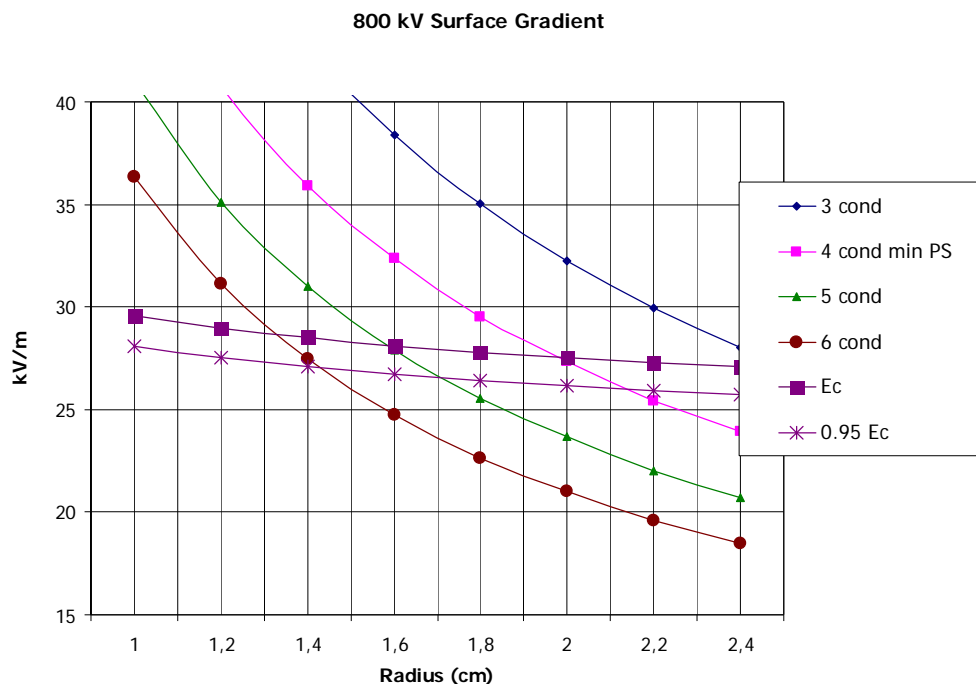


Figure: 13.3: conductor surface gradients at  $\pm 800$  kV for various bundle configurations

The figure 13.3 above shows conductor surface gradients at  $\pm 800$  kV for various bundle configurations, as well as corona onset gradient,  $E_c$ .

From the figure above, the following table gives an estimate for the limits of conductor size for various bundle numbers.

kV	Number Subcond.	I Strings radius (cm)	I Strings # MCM	V Strings radius (cm)	V Strings # MCM
$\pm 800$	3	None		None	
	4	2.18	2,167	2.388	2,515
	5	1.71	1,272	1.92	1,590
	6	1.4	954	1.58	1,113

Table 13.6

Shield wire shall be studied for various modes of operation and selected suitably.

### 13.3.2 Corona Losses

Corona losses on both AC and DC transmission lines occur due to the movement of both positive and negative ions created by corona. However, on AC lines, the positive and negative ions created by corona are subject to an oscillatory movement in the alternating electric field near the conductors and therefore confined to a very narrow region. On DC lines, however, ions having the same polarity as the conductor move away from it, while ions of opposite polarity are attracted towards the conductor and are neutralized on contact with it. In the case of bipolar HVDC transmission lines, unipolar space charges fill the space between each pole and ground while ions of both polarities mix in the bipolar region between the two poles and are subject to some amount of recombination. Theoretical calculation of corona losses from HVDC transmission lines requires analysis of the complex electric field and space charge environment in the unipolar and bipolar regions [8]. Ambient weather conditions have a large influence on corona losses from the line. The losses are lower under fair weather conditions than under foul weather conditions such as rain, snow etc. However, the ratio of foul weather to fair weather CL on a DC line is much lower than in the case of an AC line.

Because of the complexity of theoretical calculations and the large number of factors influencing corona on HVDC transmission lines, it is necessary to obtain empirical formulas from data of long-term corona loss measurements made on experimental lines. However, the amount of data from DC lines is much more limited than in the case of AC lines and, consequently, the accuracy and applicability of empirical formulas may be limited. In the case of 800 kV lines no long term data exists and empirical formulae have to be extrapolated, mainly on basis of comparable surface gradients.

### 13.3.3 Radio Interference and Audible Noise

While corona losses occur due to the creation and movement of ions by corona on conductors, radio interference and audible noise are generated by the pulse modes of corona discharges. The characteristics of corona-generated RI and AN on DC transmission lines differ significantly from those on AC lines. Firstly, while all three phases of an AC line contribute to the overall RI and AN of the line, only the positive pole of a DC line contributes to the RI and AN level. Secondly, the RI and AN levels of DC transmission lines under foul weather conditions such as rain etc., which produce rain drops on conductors, are lower than those under fair weather conditions. This is contrary to the case of AC lines on which foul weather conditions produce the highest levels of RI and AN, much higher than in fair weather. Again in the case of 800 kV HVDC lines no long term data exists and empirical formulae have to be extrapolated.

### 13.4 Field Effects and related considerations

Induction effects under ac transmission lines are defined mainly in terms of the magnitude and frequency of the alternating electric fields at the ground level. In the case of DC transmission lines, however, the magnitudes of both the electric field and the corona-generated ion currents at ground level are required to characterize any induction effects.

Corona-generated ion space charge fills the entire space between the conductors and the ground plane. In the cases of both unipolar and bipolar DC transmission lines, only positive or negative unipolar space charge exists at ground level. The combined presence of DC electric field and ion space charge is generally known as space charge field [8].

Taking the proposal from Chapter 9, Recommendations, that levels of 25kV/m electric field & 100 nA/sqm ion current density under fair weather conditions may be considered for the 800 kV transmission lines, we arrive at the following table. This table 13.7 is taken from the Technical Brochure of JWG B2.17.

Voltage kV	Conductor per pole	I string MCM	I string Height (m)	V string MCM	V string Height (m)
800	4	2167/2515	17.5	2515	17.5
	5	1272/2515	18.0	1590/2515	17.5
	6	954/2515	18.7	1113/2515	17.5

Table 13.7- Minimum ground clearance for various configurations

The differences in ground clearance are mainly due to pole spacing, a rather low value of 17 m being used for V-strings. This reduces the electric field at ground level.

It is therefore recommended that HVDC transmission lines be designed to limit the calculated fair weather ground-level values of electric field to 25 kV/m and ion current density to 100 nA/m<sup>2</sup>. In the absence of information or data on ion current density, a tentative guideline to limit the electric field to 25 kV/m under the line may be used. Note that these are fair weather values with a 50% probability of being exceeded (L50). This means that under other weather conditions the probability of being exceeded may be higher than 50%.

### **13.5 Choice of Conductor**

The choice of conductor for HVDC lines takes into consideration resistive losses, voltage drop and corona effects. The first two are a function of line resistance, while the last is a function of the conductor diameter and bundle configuration. There is no influence on bundle and pole spacing similar to reactance considerations for ac lines.

The maximum current carrying capacity of the conductors is generally not a limiting factor as other factors, especially the economic evaluation of losses, give an overall cross-section well above this limit. Often an emergency overload capacity has to be taken into account, well above the nominal current used for loss considerations. This may approach the maximum current carrying capacity, but most important is that the temperature rise does not violate ground clearances with extra sag.

For  $\pm 800$  kV lines with transmitted powers above 3000 MW the economic evaluation of resistive losses will most probably be the determining factor for overall conductor cross section and this in turn will lead to bundle numbers of four or more due to limitations on size of individual sub-conductors. The economical criteria for such studies is not discussed here as this generally varies according to project data such as peak and average energy transmission, generation costs and expected future energy prices. However it is important to note that both capacity loss at full load and energy loss need to be taken into account.

For very long lines, some attention has to be paid to the voltage drop along the line. To a certain extent this is mitigated by the tap-changers of the converter transformers, but can be limiting for use of high emergency overload currents and metallic return.

For lines with transmitted powers below 3000 MW the corona effects discussed above may be the determining factor for overall conductor configuration. Loss evaluation should define total cross section while corona effects define the bundle configuration and pole spacing.

**References**

1. CIGRÉ report 186 “Economic Assessment of HVDC Links, June 2001” from WG 14.20.
2. CIGRÉ JWG B2.17/B4/C1, Overvoltages and insulation Coordination, B2-06 (JWG17) 23 M Masuda/ J A Jardini.
3. EPRI “Transmission Line Reference Book HVDC to 600 kV”, EPRI Report 1977
4. CIGRÉ report WD 40 “Service Performance of Composite Insulators used on HVDC Lines, March 1996” from WG 22.03.
5. CIGRÉ Brochure 48 “Tower Top Geometry” WG 22-06, June 1995
6. CIGRÉ JWG B2.17/B4/C1, Corona Effects and Fields, B2-06 (JWG17) 24, J. A. Jardini
7. CIGRÉ JWG B2.17/B4/C1, Corona Considerations. Calculations and Results, B2-06 (JWG17) 33, P. Sarma Maruvada; J. A. Jardini
8. Maruvada, P.S., Corona Performance of High-Voltage Transmission Lines, Research Studies Press Ltd., Baldock, Hertfordshire, U.K., 2000.

## 14.0 Layout of Converter Station

### General

- a. The main direction of the station should be selected in such a way that all the AC and DC transmission lines to the station can be connected naturally.
- b. Land usage should be minimized.
- c. All function blocks should be defined rational and clear. Spaces required during operation, construction, maintenance and fire fighting should be considered.
- d. The converter area should preferably not be on the back-filled part of the site.
- e. The main noise sources, such as converter transformers, smoothing reactors, AC filters should at best located as far as possible from the residential areas.
- f. The road to the station should be connected to the main road system and naturally to the gate of the station which should be close to the building used as office and reception.
- g. There should be possibility for extension.

### 14.1 Function Blocks of Converter Stations

There are many function blocks in a converter station as in the following:

**Converter Area:** The area consists of valve halls, converter transformers, including space for converter transformer installation and movement, the service building(s), and smoothing reactors including possible space for reactor installation and movement if oil insulated reactors are used.

**DC Yard:** DC yard is composed of 5 main areas. Two symmetric areas are used for pole equipment including DC filters, DCCT, DC voltage divider, PLC filters of the DC side, DC pole arresters, disconnectors and ground switches. Another two symmetric areas are used for by-pass switches and disconnectors for series connected converters. An area is used for the neutral apparatus.

**AC Filter Yard:** For stations of such an important HVDC project as  $\pm 800$  kV HVDC project, it may be considered to use filter banks which are connected to the AC bus as a normal unit, like an AC line or a 12 pulse converter. A filter bank in layout point of view is usually composed of a few sub-banks and a single bus with switch gears for switching in and out of the sub-banks.

**AC Yard:** AC yard is the place where AC buses and switch gears for all the units, including all the AC lines to the station, all converters, all filter banks and possible autotransformers or individual transformer(s) as auxiliary power supply, to be connected together. An 800 kV HVDC project is usually connected to the 345 kV and above AC network. The single line diagram of the AC yard will be of  $1\frac{1}{2}$  or double bus scheme.

**Auxiliaries:** Main auxiliaries in a converter station consist of auxiliary power and power supply system, water supply system, valve cooling system, HVAC system for valve hall and the service building.

**14.2 Layout of Converter Area**

The type of converter transformers and the scheme of transformer-valve connection are the most important issues for converter area layout. For ±800 kV projects, single phase two winding transformers will usually be used. In such a case, the multi-valve type and the scheme of transformer-valve connection are as in the following.

The first scheme is double valve with 3 Y/Δ transformer on one side, connected to the 3 double valves to form the lower voltage 6-pulse converter, and 3 Y/Y transformers on the other, together with the other 3 double valves, forming the higher voltage 6-pulse converter. This scheme is shown in Figure 14.1. It is very natural on the valve side but needs an extension of AC feeder from the AC yard. This type of valve and transformer-valve connection is used in three ±500 kV, 3000 MW HVDC projects in China.

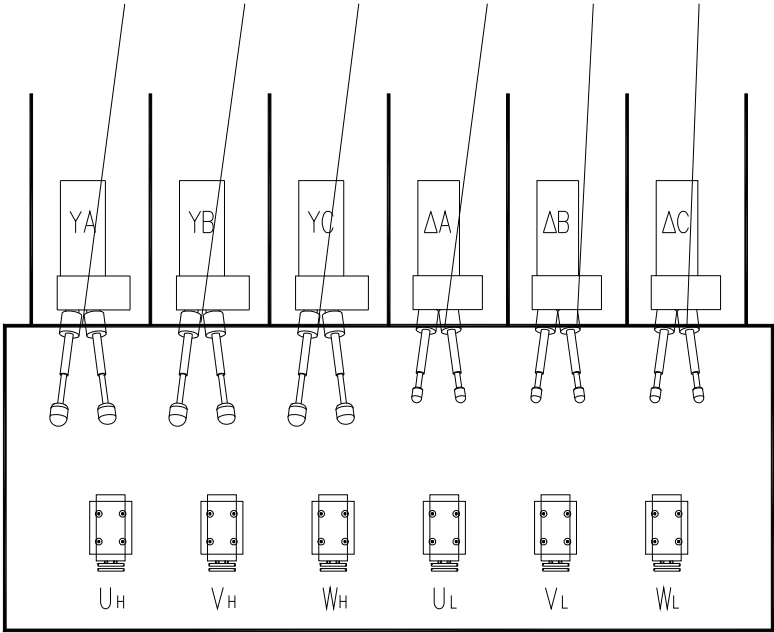


Figure. 14.1 12 pulse converter scheme 1

Scheme 2 is shown in Figure 14.2. It is a scheme for quadruple valve design. It is similar to normal 12 pulse converter. The only difference is that one of the three quadruples is fed by a Y/Y and a Y/ Δ transformer.

If the valve hall is located vertical to the line facing the AC yard, the AC feeder(s) can come from both sides of the valve hall. Consequently, another economic scheme, scheme 3, can be built as in Figure 14.3. Quadruple valves are used and feed by Y/Y and Y/ Δ transformers from both sides of the valve hall.

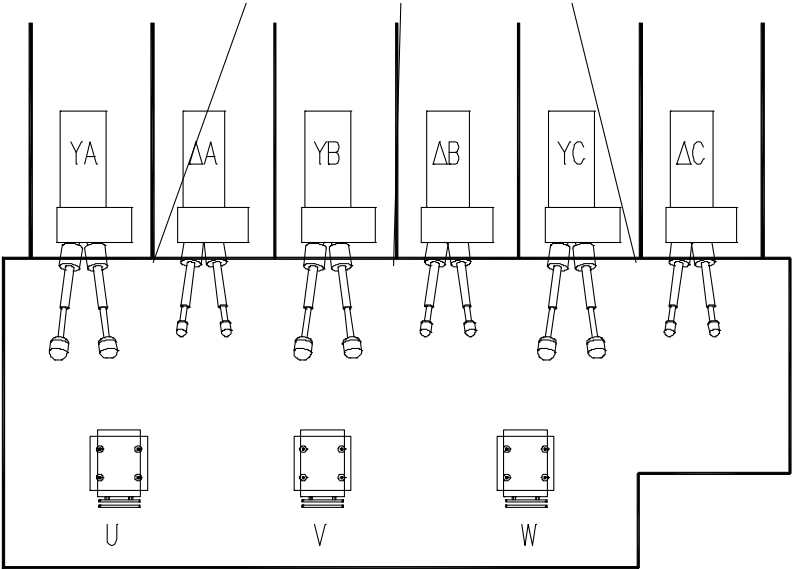


Figure. 14.2 12 pulse converter scheme 2

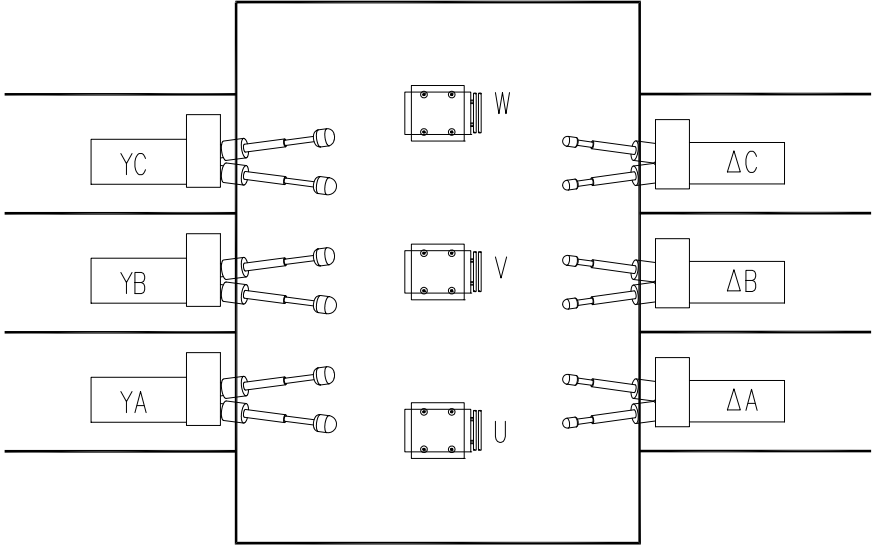


Figure. 14.3- 12 pulse converter scheme 3

There are two main categories of layout design of the converter area for ±800 kV HVDC converter stations, horizontal and vertical layout of the 4 valve halls.

For horizontal layout, only scheme 1 and scheme 2 can be used. The simplest horizontal layout is shown in Figure 14.4. It will take a very long and narrow place and may make the layout of other parts in the station difficult.

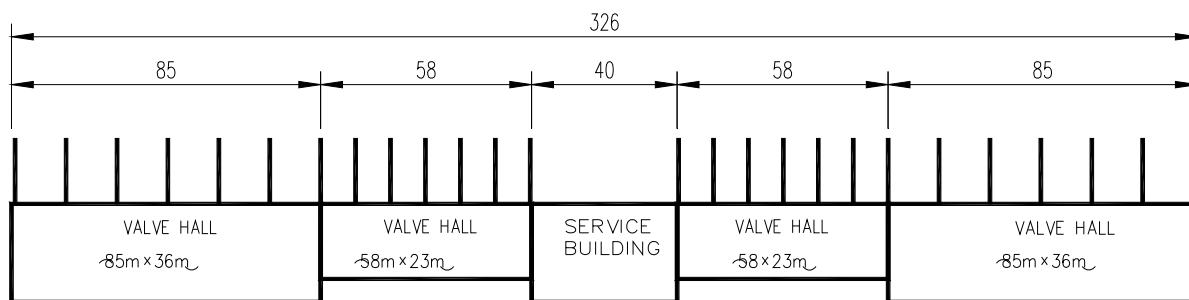


Figure 14.4 The simplest and most direct horizontal layout of converters

Some modification can be done to shorten the distance between valve hall and the place where the converter control and protection is located as shown in Figure 14.5. This modification would make the area longer.

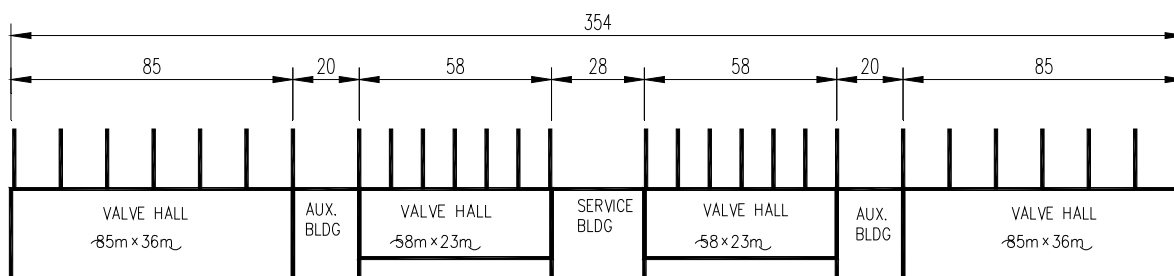


Figure.14.5 modified horizontal layout

Further optimized horizontal layout is shown in Figure 14.6. It can both reduce cable length and land requirements.

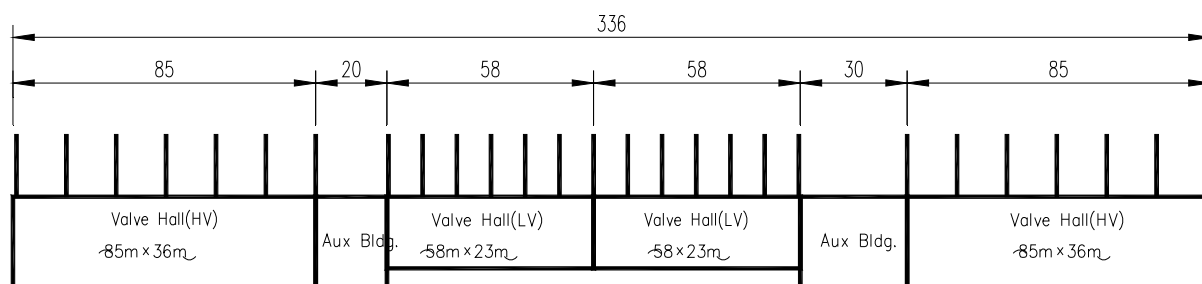


Figure. 14.6 optimized horizontal layout of converter area

If scheme 1 or scheme 2 of 12 pulse converter is used, a vertical valve hall layout can be designed as shown in Figure 14.7. The converter area can be shorter by some 50 m.

As the result, it is easier to match the other parts of the converter station. it is very suitable for audible noise control.

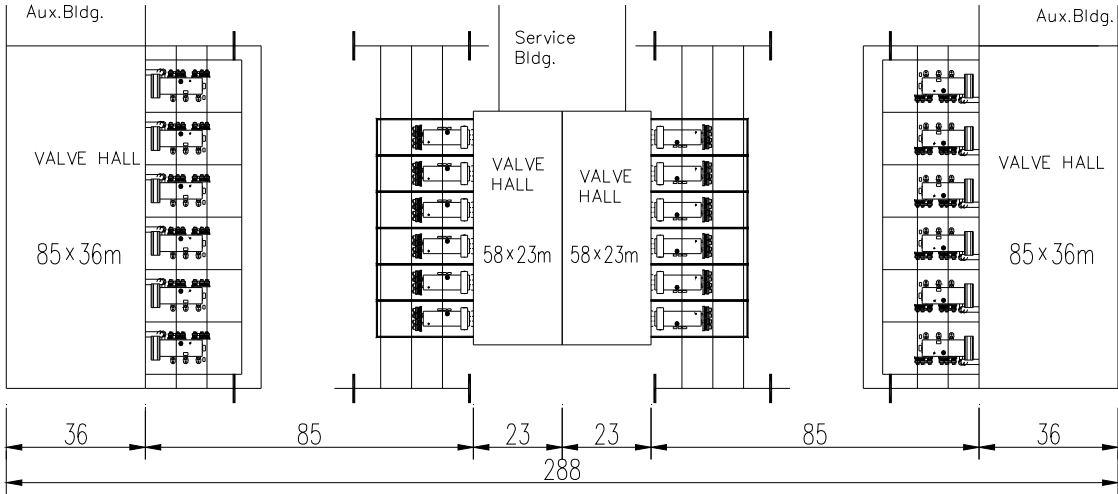


Figure. 14.7 vertical valve hall layout of converter area

If the converter area can be located on one side of the AC yard instead on one terminal, a long and narrow area is not a problem. Then the economic converter scheme 3 can be used. The layout of converter area is shown in Figure. 14.8.

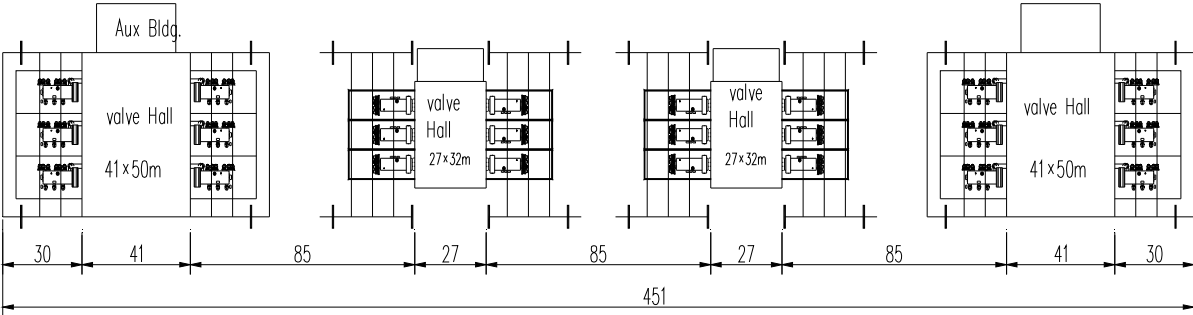


Figure. 14.8 vertical valve hall layout of converter area with quadruple valve design

**14.3 Layout of DC Yard**

DC yard of a converter station is usually of the same width with the converter area. It is always located on the side of the converter opposite to the AC yard. The length of the DC yard is determined by space for pole apparatus including upper converter isolating disconnector, two DCCT's, two or even more than two of pole arresters,

disconnectors for DC filters, DC voltage divider, line isolating disconnector. 150-160 meters is typical length. A typical layout of DC yard is shown in Figure 14.9

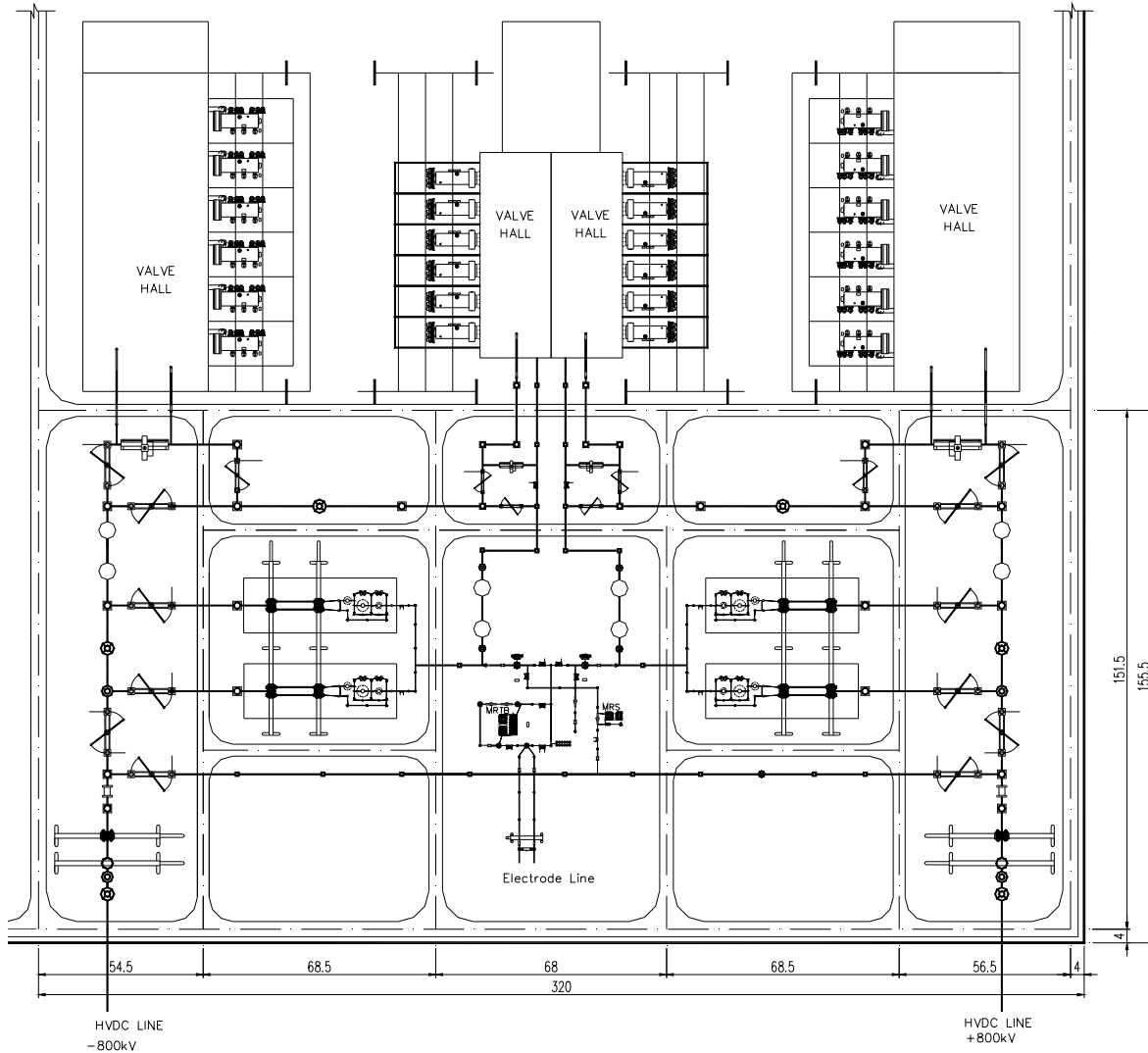


Figure. 14.9 Typical layout of DC yard for series connected converter configuration

#### 14.4 Layout of AC Yard

AC yards in 800 kV HVDC converter stations are of exactly the same design of normal substations. The layout of AC yard depends mainly on single line diagram and type of switchgear. Double bus or one and a half configuration is the standard design. AIS circuit breaker with live tank, dead-tank breaker, HGIS and GIS are main type of switchgears for AC voltage from 345kV and above.

For converter stations, the outlet AC lines usually come from the same side of the AC yard. It is not convenient to connect the AC lines to the bays. A typical SLD with one and a half circuit breaker layout is shown in Figure 14.10.

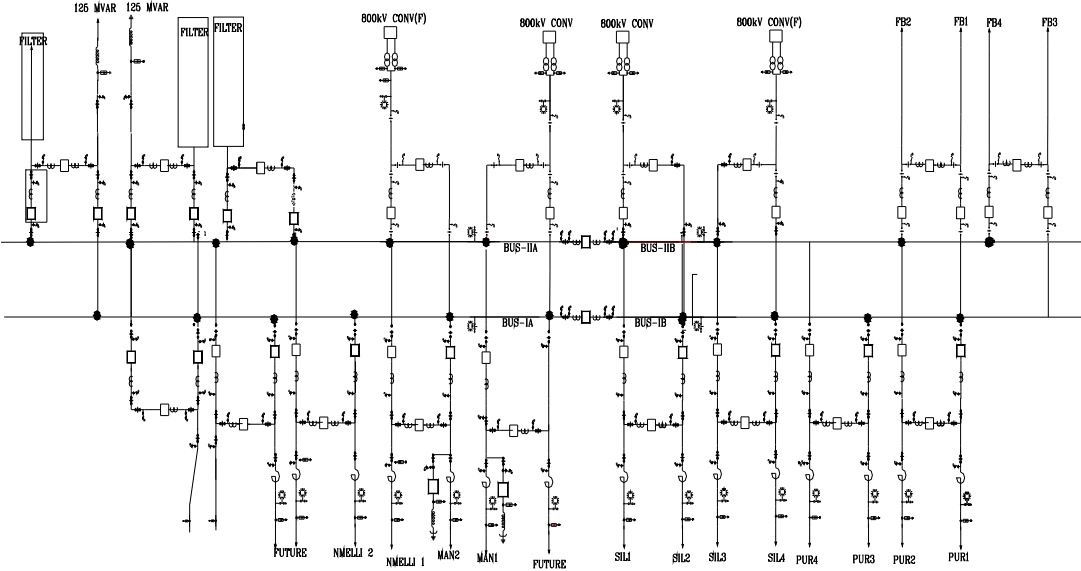


Figure. 14.10 – Typical SLD of one and a half circuit breaker configuration

**14.5 Layout of the Auxiliaries**

The auxiliaries, which are involved in the normal operation of the converters, should be located near the valve halls and the service building. Due to the difference of dimensions of low-voltage valve halls and high-voltage valve halls, as well as the service building, there are enough places for the cooling towers and out-door part of HVAC systems for service building and the valve halls.

Adequate care should be exercised while routing cables, pipes etc. to ensure proper segregation between poles and converters.

**14.6 General Layout of the Station**

Three main factors are dominant to the general layout of HVDC converter stations. They are the type of AC switchgears and SLD, the layout of converter area, the relative location of the converter area to the AC yard. Two examples of general layout are shown in Figure14.11 and Figure 14.12.

What shown in Figure 14.11, is a typical layout of receiving end HVDC converter stations. AC voltage is 500 kV with 4 outlet transmission lines and the type of

switchgears is GIS. 5 AC filter banks are used. Horizontal layout of converters is designed. The converter is located at one side of the 500 kV AC GIS yard.

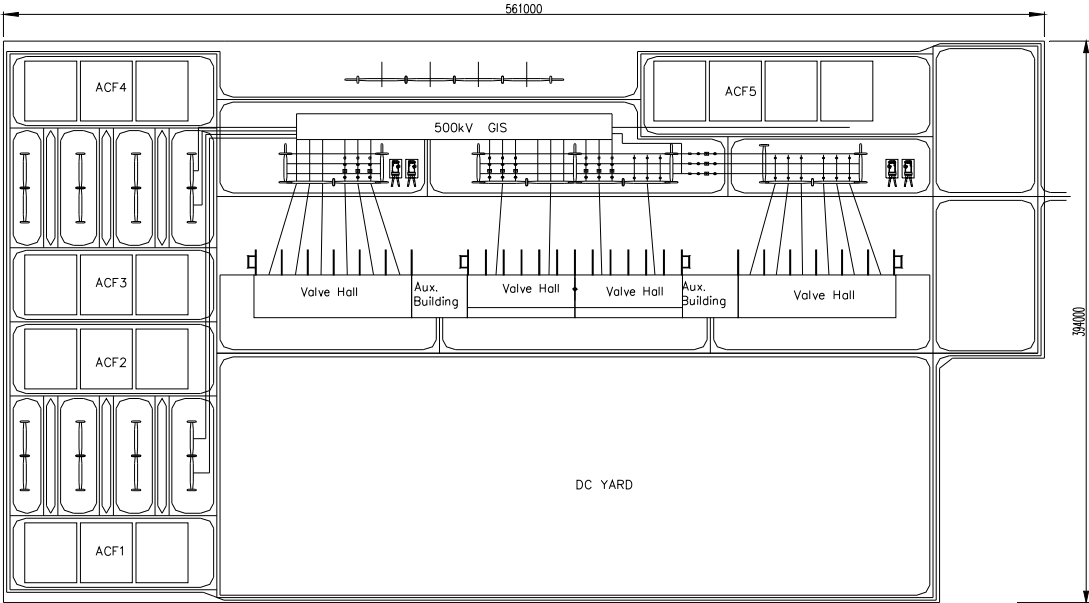


Figure 14.11 General layout of a typical HVDC converter station with GIS AC yard

The layout shown in Figure 14.12 is for a typical sending end HVDC converter station. AC voltage is 500 kV with 6 outlet transmission lines. The type of switchgears is live tank AIS. Vertical layout of converters is design. The converter area is located on one terminal of the AC yard.



Figure 14.12 General Layout of a typical HVDC converter station with AIS AC yard

## **15.0 Test Requirement**

For equipment usually three categories of tests are required:

i) Type tests:

The purpose of type tests is to verify the design. In general the first built unit of a particular design will be designated for undergoing type tests.

ii) Routine tests:

The purpose of routine tests is to control the manufacturing quality of equipment. Therefore every individual unit has to undergo all prescribed routine tests.

iii) Special tests:

Special tests are those which are agreed between manufacturer and customer. The tests have the character of a type test but they do not always have to be designated on the first built unit.

For system usually two categories of tests are required:

i) Factory acceptance tests:

The purpose of factory acceptance tests is to verify the designed functionality. The system functionality will be evaluated for all kinds of predefined conditions. Adjustment and improvement will be made when necessary.

ii) Site acceptance tests:

The purpose of site acceptance tests is to verify the system performance in connection with other station equipment under predefined operational conditions.

## **15.1 Basis of test requirements**

Once the converter station design and the equipment ratings are determined, test requirements for equipment can be determined based on:

- System design study results of specific project;
- Applicable IEC/IEEE standards;
- Specific project related national standards and/or utility own requirements;

The test requirements can vary from project to project. It is difficult to make a general test requirement without knowing the specific project related information.

The basic guiding principles should be to make sure the test requirement is well balanced and should not overstress the equipment during tests. Besides making sure the operation stresses are well represented, by laboratory tests are also very important. Drawing up a suitable test requirement requires therefore knowledge and experiences.

### **15.2 Test requirement of main 800 kV DC equipment**

For the reasons explained above, the only general test requirement is probably the dielectric test requirement for the 800 kV DC equipment, since other test requirement such as thermal and mechanical requirement as well as system test requirement are more specific to a project.

Unlike AC equipment where required test values are well standardised, the required dielectric test values for DC equipment depends strongly on the station configuration design and insulation coordination study results for the specific project. Therefore no standard values can be stated.

## 16.0 Summary

Currently long distance HVDC systems with overhead lines operate at  $\pm 600$  kV, 3150 MW, and a transmission distance in some cases of 1700 km on a single bipolar line. Although, all these parameters are not simultaneous, there is only one system operating at  $\pm 600$  kV and the majority of systems are operating at  $\pm 500$  kV. Until now the transmission voltage of 500 kV has been certainly adequate for transmitting up to 3000 MW for a typical distance of 1000 km. However, as the transmitted power levels increase beyond the 3000 MW and the transmission distance increases above 2000 km range this level of voltage is not adequate unless more than one bipolar circuit is considered, even though the economics will probably be against the choice of such low DC voltage.

If one divides the transmitted power levels to some distinct categories, it may be easier to examine the alternatives realistically.

- Transmitted power up to 6000 MW
- Transmitted power greater than 6000 MW

### 16.1 Transmitted power up to 6000 MW

At power level of 6000 MW the DC line current will be 3750 A which is manageable with 5-inch thyristors. However, from a DC circuit perspective there are several alternatives. The choice of a particular alternative will depend on both the technical and economic evaluation.

#### 16.1.1 One single converter per pole

From rating point of view one single 12 pulse converter per pole is possible at this power rating. The DC current per pole is the same as the DC line current of 3750 A. However, even though it is possible, it has certain limitations and drawbacks.

- The size and weight of the converter transformers, although by using single phase two winding units this issue may not be limiting.
- Each pole power is 3000 MW and the loss of the pole/valve group results in the loss of 3000 MW. This may be critical for the ac system and especially in view of the fact that because of the limitation of the current carrying capability of 5" thyristors there is no big margin for over load of the remaining pole.

It is clear that even at this power level a single converter per pole is not a favourable solution unless it is part of a bigger picture of transmission alternatives such as multiple bipoles or the presence of parallel ac lines.

### **16.1.2 Two converters in series**

The pole DC current is again 3750 A. However, in this case the bipole has 4 valve groups, two groups connected in series in each pole. The two valve groups in series may be identical in DC voltage rating or unequal DC voltage rating. The configuration of identical in DC voltage rating certainly has definite advantages over the single group per pole scenario.

- The weight and size of the converter transformers are more manageable.
- The loss of a valve group only represents 25% of the transmitted power.
- The overload capability is still limited by the present size of the thyristors.
- The series valve groups are attractive if the staged developments of the DC system are over a very short period of time; otherwise the losses are high if the system is developed over a long period of time due to the operation at low voltage.
- Balanced DC current is always available as long as there is one valve group in each pole.

The alternative of using two series groups per pole with unequal rating can be considered if there are long staging times. For example at the first stage the power to be transmitted is 4000 MW and few years later the balance of power of 2000 MW is to be added. Obviously one approach is to use two different voltage rating valve groups in series per pole.

### **16.1.3 Two parallel converters**

In this case the DC current per pole will be 1675 A, and each pole is always operating at the full voltage of 800 kV, in this configuration,

- The size and weight of the converter transformers are manageable.
- The losses are the lowest for the loss of a converter due to the operation always at 800 kV.
- If the staging is over a long period of time then the accumulated losses are the lowest.
- There are more possibilities and margins for overload because of the low DC current in the pole.
- Upon the loss of a converter, there will be a ground return current if it is desired to operate at the full rating of the remaining converters.
- The parallel converters are certainly advantageous if the generations or the loads are two different locations, then the stations can be at different locations. In principle this is multi-terminal operation.

## **16.2 Transmitted power above 6000 MW**

If the transmitted power is higher than 6000 MW and let us consider even 6500 MW, then for a bipolar system the DC line current is 4062 A. Now for the series connected converters the pole current is also 4062 A. This current rating is marginally manageable by the 5 inch thyristors, and more over there is hardly any room for overload. We have to keep in mind that an overload feature in this situation of the high level of power will be important. State of the art 6" thyristor would be beneficial for such schemes. However in the case of the parallel converters the pole current will be 2031 A. This is certainly manageable even with the 5 inch thyristors and it also allows for overload.

## **16.3 Current status of 800 kV DC technology**

For transmission power above 3000 MW and distance longer than 1000 km, 800 kV HVDC system is considered as a technically and economically feasible and suitable choice.

Each 800 kV pole can be configured either by two 12 pulse bridges in series or in parallel depends on the power rating and other requirements of specific projects.

The technology status and development described in this report shows that the industry is in the process of establishing the new voltage level of 800 kV HVDC systems.

The 800 kV HVDC technology will be further matured during realisation of the first generation of 800 kV HVDC system. The most challenging 800 kV HVDC equipment will be:

- Converter transformers: Due to the relative high failure rate in the existing HVDC projects effort are needed to improve the performance of this key equipment in design as well as testing. Reference can be made to the work of CIGRE JWG A2/B4-28 "HVDC Converter Transformer".
- Smoothing reactors: Comparison of oil immersed and dry type smoothing reactors can be further evaluated in first generation of 800 kV HVDC systems.
- 6 inch thyristors: For power ratings of above 5000 MW, 6" thyristor valves have more advantages than 5 inch thyristor valves for series converters.
- DC wall bushings: Special attentions have to be paid on insulation design in areas of high pollutions.
- DC supporting insulators: Composite type insulators are most likely the suitable choice. Mechanical design and long term dielectric performance are the points of attention.
- Insulators for OHL: For the order of 2000 km overhead lines of 800 kV HVDC application, the dielectric performance of line insulators influences directly the number of line flashovers. Frequent DC line flashovers are very harmful for the

converter station equipment. Attention should be paid on design and testing of line insulators.

- Other DC side equipment such as arrestors, disconnectors, voltage dividers, etc. Attentions should be paid on these equipments because their reliability influences directly the reliability of the complete pole.

After the first generation of 800 kV HVDC systems being realized, following questions can be raised regarding future development

- Is there need for bulk point-to-point transmission for voltage level above 800 kV, power rating above 7200 MW for series connected converters at 800 kV, and distance beyond 2000 km, for utilisation of large remote hydro power?
- Is there need for 800 kV HVDC multi-terminal systems as super backbone grid as well as for power transmission purpose?
- Is it techno-economical feasible and also there is a need to go for 1000 kV DC system?

## 16.4 Conclusions

800 kV HVDC systems are considered where large amounts of power is required to be transmitted over distances in the range of 1000 km to 3000 km. Based on the studies carried out by the working group and the work being carried out in the area of 800 kV systems, no major problem is anticipated with the application of 800 kV HVDC technology. The test levels specified in this Technical Brochure should be beneficial both to the utilities and manufacturers and should be streamlined the requirement of testing and test values for type test and special tests to be done for 800 kV HVDC equipment. Decisions taken in China and India do indicate that these countries have already carried out detailed studies envisaging these applications and have gone ahead with implementation. The voltages above 600 kV has not been used so far and prototypes/type testing of equipment for voltages up to 800 kV DC for China and India projects shall provide ample confidence to power utilities all over the World.

Two (2) HVDC transmission links namely “Yunnan - Guangdong 800 kV HVDC Interconnection”, & “Xiangjiaba - Shanghai  $\pm 800$  kV UHVDC transmission project” are under construction stage in China. Several major equipments have already been manufactured and successfully type tested. Indian 800 kV multi-terminal HVDC project “Biswanath Chariali- Agra; North-North / East / North Inter-connector” and “Jingping - Sunan  $\pm 800$  kV HVDC Transmission Project” in China are under implementation.

The salient features of the 800 kV HVDC projects under implementation are indicated below:

**SALIENT FEATURES OF YUN-GUANG 800 KV  
HVDC INTERCONNECTION - CHINA**

• Rectifier	YUN
• Inverter terminal	GUANG
• Converter Configuration	Series Connected
• Total distance:	About 1428 Km
• Rated Power:	: 5000 MW
• Operating DC Voltage	: ± 800 kV DC
• Reduced Voltage operation	: 70 % of nominal operating voltage
• Operating AC Voltage for Rectifiers and Inverter Terminals	: 525 kV AC
• Operating Modes	<ul style="list-style-type: none"> <li>•Normal bipole operation</li> <li>•Monopolar with metallic return</li> <li>•Monopolar with ground return</li> <li>•Reduced voltage operation</li> </ul>

**SALIENT FEATURES OF XIANGJIABA-SHANGHAI  
±800KV HVDC PROJECT - CHINA**

• Rectifier	Xiangjiaba
• Inverter terminal	Shanghai
• Converter Configuration	Series Connected
• Total Distance:	About 1715 Kms
• Rated Power:	: 6400 MW
• Operating DC Voltage	: ± 800 kV DC
• Reduced Voltage operation	: 70 % of Nominal operating Voltage
• Operating AC Voltage for Rectifiers and Inverter terminals	: 525 kV AC
• Operating Modes	<ul style="list-style-type: none"> <li>•Normal Bipole operation</li> <li>•Monopolar with metallic return</li> <li>•Monopolar with ground return</li> <li>•Reduced voltage operation</li> </ul>

**SALIENT FEATURES OF JINPING – SUNAN  
±800KV HVDC PROJECT - CHINA**

• Rectifier	JINPING
• Inverter terminal	SUNAN
• Converter Configuration	Series Connected
• Total distance:	About 1935 Km
• Rated Power:	: 7200 MW
• Operating DC Voltage	: ± 800 kV DC
• Reduced voltage operation	: 70 % of nominal operating voltage
• Operating AC Voltage for Rectifiers and Inverter terminals	: 525 kV AC
• Operating Modes	<ul style="list-style-type: none"> <li>•Normal bipole operation</li> <li>•Monopolar with metallic return</li> <li>•Monopolar with ground return</li> <li>•Reduced voltage operation</li> </ul>

**SALIENT FEATURES OF MULTI-TERMINAL SCHEME - INDIA**

<ul style="list-style-type: none"> <li>• Proposed locations:</li> <li style="padding-left: 20px;">Rectifiers- 1 terminal</li> <li style="padding-left: 20px;">Rectifiers- 2 terminal</li> </ul>	<ul style="list-style-type: none"> <li>: Biswanath Chariali, Assam</li> <li>: Kishanganj, West Bengal</li> </ul>
<ul style="list-style-type: none"> <li>• Proposed location: Inverter terminal</li> </ul>	<ul style="list-style-type: none"> <li>: Agra, Uttar Pradesh</li> </ul>
<ul style="list-style-type: none"> <li>• Total Distance:</li> <li style="padding-left: 20px;">Rectifier 1 to Inverter Station</li> <li style="padding-left: 20px;">Rectifier 2 to Inverter Station</li> </ul>	<ul style="list-style-type: none"> <li>: About 1728 Kms</li> <li>: About 1108 Kms</li> </ul>
<ul style="list-style-type: none"> <li>• Rated Power:</li> <li style="padding-left: 20px;">Rectifiers- 1 terminal</li> <li style="padding-left: 20px;">Rectifiers- 2 terminal</li> <li style="padding-left: 20px;">Inverter Terminal</li> </ul>	<ul style="list-style-type: none"> <li>: 3000 MW</li> <li>: 3000 MW</li> <li>: 6000 MW (parallel configuration)</li> </ul>
<ul style="list-style-type: none"> <li>• Operating DC Voltage</li> </ul>	<ul style="list-style-type: none"> <li>: ± 800 kV DC</li> </ul>
<ul style="list-style-type: none"> <li>• Reduced Voltage operation</li> </ul>	<ul style="list-style-type: none"> <li>: 80 % of Nominal operating Voltage</li> </ul>
<ul style="list-style-type: none"> <li>• Operating AC Voltage for Rectifiers and Inverter Terminals</li> </ul>	<ul style="list-style-type: none"> <li>: 400 kV AC</li> </ul>

<ul style="list-style-type: none"> <li>• Reactive Power Exchange Limits with 400kV AC for all terminal with min 150 MW DC Power</li> </ul>	: 30 MVAR Maximum Export at 420 kV
<ul style="list-style-type: none"> <li>• Reactive Power Exchange Limits with 400kV AC for all terminals with max. 3000 MW DC Power</li> </ul>	: 0 MVAR import at 380 kV
<ul style="list-style-type: none"> <li>• Ground Electrode Current</li> </ul>	: 3750 Amps
<ul style="list-style-type: none"> <li>• Future Expansion, if any</li> </ul>	: Yes
<ul style="list-style-type: none"> <li>• Operating Modes</li> </ul>	<ul style="list-style-type: none"> <li>• Normal bipole operation</li> <li>• Monopolar with metallic return</li> <li>• Monopolar with ground return</li> <li>• Reduced voltage operation</li> </ul>