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Advanced HVDC Systems at ±800 kV and Above

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PRODUCT DESCRIPTION

High-voltage direct current (HVDC) has been applied to transmit bulk power over long distances for the past 40 years. Several HVDC systems have been constructed for this purpose and have operated successfully. A few of the earlier HVDC systems included Pacific Inter-Tie, Nelson River Bipoles 1 and 2, Cahora Bassa, Inga shaba, and Itaipu. In these HVDC systems, the DC voltage is 500 kV with the exception of Cahora Bassa (533 kV) and Itaipu (600 kV) and the DC power is up to 3000 MW. In recent years, several HVDC systems in India and China have been constructed at a DC voltage of ±500 kV and DC power up to 3000 MW. The single converter per pole at 500 kV and up to 1500 MW became a standard block.

However, in the last 10 years there has been a need to generate power from large hydro plants at very remote locations and transmit this power to the load center in a narrow transmission corridor. The level of power being considered is 6000 MW, and the distances are over 2000 km. In this regard, the current transmission voltage of 500 kV is not economical. A transmission voltage of 800 kV per pole has been selected in many earlier studies as well as by system planners.

This report addresses the technical requirements necessary to achieve a transmission voltage of 800 kV per pole.

Results & Findings

The report concluded that developing HVDC systems for 800 kV is economically realizable. However, specific attention should be given to the following:

- HVDC system configuration
- Reliability and availability in view of the large amount of power transmitted
- AC system requirements and the interaction with the HVDC system
- Equipment testing levels

Challenges & Objective(s)

This report is intended for system planners and HVDC system designers. The report addresses the needs and the design aspects that are required immediately for projects that are going to be implemented soon. Therefore, the document provides system planners with the actual experience of developing HVDC projects at ±800 kV.

Applications, Values & Use

Although the work concentrated on a DC voltage level of 800 kV, the obvious next step would be going to higher levels of DC voltage. This increase would reduce system losses and allow further levels of transmission power. However, more research will be required as well as development of test facilities.

EPRI Perspective

This report presents the collective experience of a utility that is embarking on an 800-kV transmission project plus the experience of several leading consultants in the field of HVDC transmission. The document covers a very broad spectrum of what has to be considered in this area. Other projects are underway to produce documents on this same topic, and this is the first of those reports to be published.

Approach

The project goal was to develop a guide for system planners on how to approach the requirements of transmitting a large amount of power with HVDC at an ultra high voltage level.

The experts contributing to this work are familiar with and are involved in developing this type of project on the world scene.

Keywords

High-voltage direct current (HVDC) transmission
Transmission planning
Ultra high-voltage direct current (UHVDC)
Bulk power transmission
HVDC converters
Transmission voltage of 800 kV

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1
SYSTEM PLANNING PERSPECTIVE FOR 800 KV DC SCHEMES

Introduction

In this Chapter, key planning issues, including system interaction, selection of location of inverter terminal, maximum DC power that may be injected, strength of the system, reactive power management, fault impacts upon system performance, etc., for ±800 kV HVDC system planning are presented. This Chapter also describes possible ±800 kV HVDC configurations with focus on planning aspects, and analyze main operational performance statistics for HVDC based on available information from publications as well as from CIGRÉ, providing a basic planning guidance on reliability indices.

The issues are directly related to ±800 kV HVDC applications, and it is assumed that many basic concepts of HVDC are known to the reader.

Operational Characteristics of HVDC

The principal operational characteristics of high capacity ±800 kV HVDC system are discussed and also, since the scope here is ±800 kV HVDC systems, only thyristor - based converter technology is considered, i.e. the so called line commutation converters technology.

Reactive Power and Stability

±800 kV HVDC transmission is an appropriate application for bulk power transfer over a long distance, because HVDC, unlike AC transmission, is not constrained by stability limits and does not require intermediate substations for voltage and reactive power control.

However, reactive power is required at both terminal stations to support converter requirements, and maintain appropriate AC voltage range at the terminals. The reactive power consumed at each terminal is directly proportional to the transmitted DC power. The reactive power requirement is mostly achieved with AC harmonic filters which also reduce the AC harmonic currents to acceptable levels and shunt capacitors. If simulation studies show that dynamic over voltages during disturbances are too high, then dynamic reactive power compensator, such as SVC or STATCOM may be required. Also filters and capacitor banks are divided into reasonable size banks, for redundancy and switching in acceptable steps.

Control of Power Level

Unlike ac, the power transmitted via DC is not dependent on the voltage angle displacement between the terminals. However, the level of acceptable power injected by the inverter has a direct relation with the receiving AC system strength. Stronger (higher short circuit power) the AC system is, more power may be injected into that grid. This relation is usually referred to as SCR – Short Circuit Ratio (MVA level/Pd).

Voltage Dependent Characteristics

Thyristor based HVDC converter is, so called, current sourced converter, which means that DC current in the line is unidirectional and the DC voltage would have to be reversed for power reversal. It requires AC voltage to perform the commutation process (transfer of current from valve to valve) and to generate DC voltage. If the AC voltage falls below 90% on the inverter side, due to symmetrical or asymmetrical fault, there is probability of a commutation failure. Under such situation, the DC system may aggravate the AC system stability. After the fault is cleared, the rate of increase in DC power needs to be coordinated with AC system capability to provide the reactive power.

Overload of HVDC Transmission Line

Required overload capability of the HVDC transmission is a very important planning issue. NERC transmission planning criteria states that one pole outage of a bipolar HVDC line corresponds to one three phase AC circuit outage. Planning of high power HVDC transmission requires studies of AC network where HVDC converters are located. If the HVDC is within a synchronous AC system, the capability of AC network along with temporary overload capacity of parallel AC lines and the remaining DC pole needs to be considered. In case of HVDC connecting two asynchronous grids, the in-built overload capacity of remaining healthy pole(s) becomes important.

Normally, design of HVDC lines has been to accommodate double the normal current for temporary periods. This capability can be accomplished through a combination of some extra-capacity in the conductors plus some safety margins available in the mechanical design criteria of the line, assuming that this overload will be of short duration, i.e., an emergency situation. In summary, the issue of overload criteria for HVDC lines requires that:

- HVDC lines are designed on corona performance basis, as seen in Chapter 4. This results in the conductor size being larger than required for thermal capacity criteria. Therefore, HVDC lines may be able to carry double the normal current for temporary periods;
- For contingencies of required temporary over-current capability, temperature rise criteria could be relaxed if necessary;
- For overload, care must be taken with conductor ground clearance due to increased sag

Overload of Converter Stations

Any inherent overload capability of the DC line can only be utilized if matched by overload capability of converters. Thus it is important to consider temporary overload requirements of converters stations and corresponding additional cost, at planning stages of an HVDC scheme.

The industry experience in general could be summarized as follows:

- Transformers: 10 to 15%, continuous overload is available without additional cost, and with little or no loss of life assuming redundant coolers are available.
- Valves: short term (say, 2 hrs), overload of up to 10% is available at no additional cost, assuming redundant coolers are available or during low ambient temperature, < 30ºC.
- Continuous overload of 33% can be obtained with relatively small additional cost, provided the valve current rating has sufficient margin over the nominal current rating and low ambient temperature conditions.
- Transient overload, of order of 33% for 5 seconds, can be available at no additional cost, and can be utilized for HVDC power modulation to enhance AC system stability.
- Filters: if overload capability is to cover a converter pole outage, then filters associated with that converter pole are usually used to supply the reactive power on overloaded converter pole.

Obviously any additional overload capability can be obtained for additional cost. Table 1-1 summarizes some overload design data utilized in HVDC commercial schemes of large power ratings.

Table 1-1
Summary of Overload Design Data Utilized in Commercial Schemes

Overload Ratings of Some HVDC Schemes

Project	Rating, MW	Short time Overload		Long time Overload	
		Duration	Per unit	Duration	Per unit
Rihand - Dadri	1500	5 s	1.33	2 hr	1.1
Vindhyachal	500	5 s	1.2	2 hr	1.1
Intermountain	1600	1 s	2.0	Cont.	1.5
Gesha	1200	10 s	1.25	2 hr	1.1
Itaipu	3150	5 s	1.25	20 s	1.15
Tian Guang	1800	3 s	1.5	Cont.	1.1
3 Gorges Changzhou	3000	5 s	1.5	2 hr	1.13
3 Gorges - Guangdong	3000	5 s	1.5	2 hr	1.13
Thailand – Malaysia	300	10 min.	1.5	None	
Cobara Bassa	1920	None		None	

Source: Teshmont

AC/DC Analysis

One very central concept when analyzing the behavior of ac/dc systems, in steady state, is the Maximum Power Curve, which is related to the maximum DC power that can be injected in the receiving network with a stable operation. This concept described in this section, is based on CIGRÉ [1] reports.

Effect of the AC System Strength

The amount of power that can be injected into an AC system from a DC link is mainly dependent on the capability of AC system to provide reactive power to the inverters while maintaining the AC voltage at the inverter commutating bus. In case of weak AC system where the Short Circuit Ratio (SCR) is low (less than 2), there is a possibility of voltage instability in the HVDC system. This can be avoided by providing dynamic reactive support devices i.e., SVC, STATCOM, series capacitor compensation, etc.

Maximum DC Power Injection

From a planning perspective, one important subject to be addressed is the calculation of the level of DC power injection into an existing or planned AC grid, without running into undesirable operational effects. The concept developed is the Maximum Power Curve (MPC).

Figure 1-1(a) and (b) describe the MPC obtained for two relations of SCR. The MPC curve of an ac/dc system is derived basically through the applications of load-flow calculations; Figure 1-1the values of the AC voltage, tap positions and extinction angle are kept constant, while the DC current Id is varied (slowly).

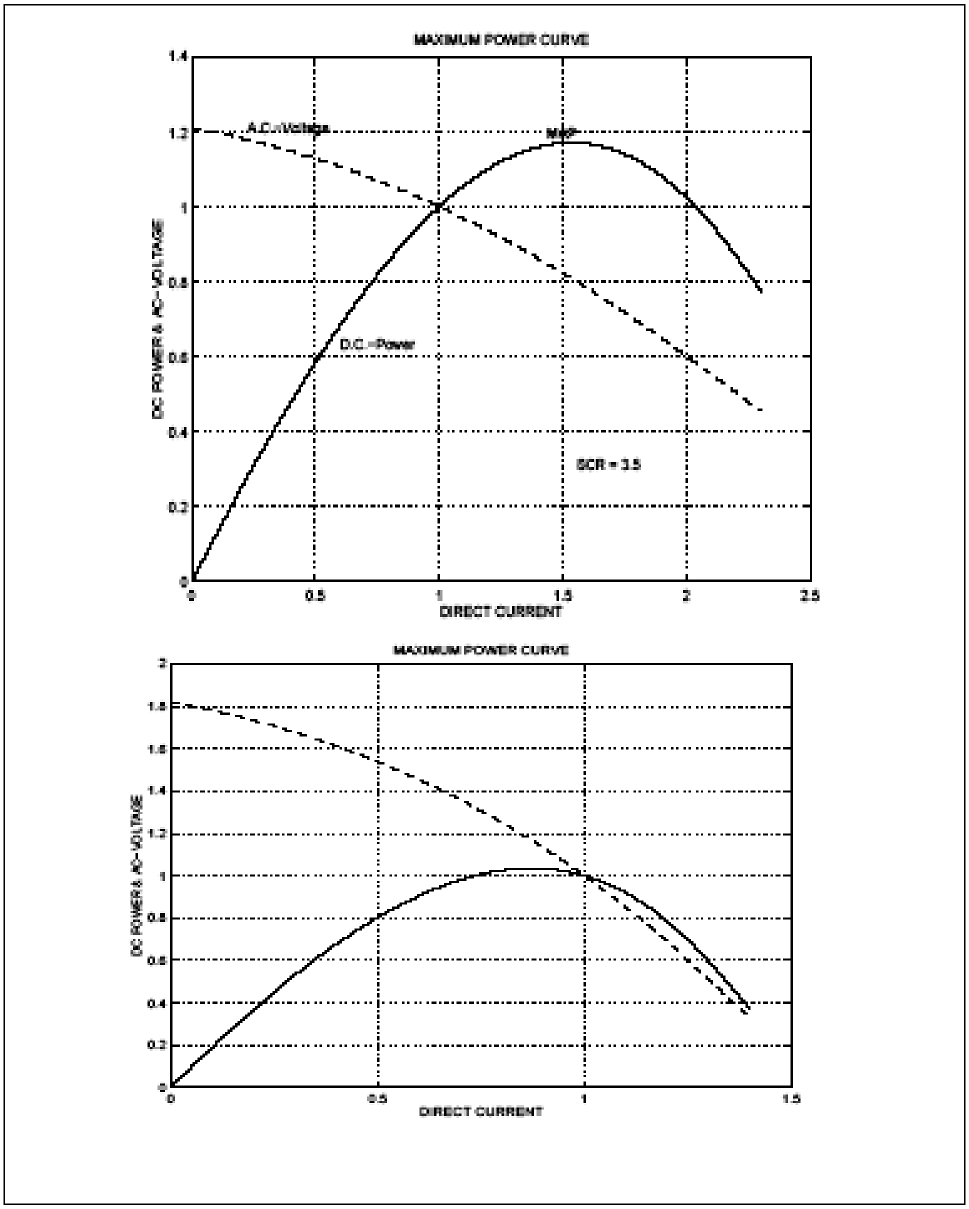

Figure 1-1
(a) Maximum Power Curve SCR = 3.5 and (b) Maximum Power Curve SCR = 1.5

Figure 1-1(a) for SCR = 3.5 corresponds to safe system operation. The operation point is obtained with AC voltage and DC current at nominal values. The MPC reaches its maximum at DC current of 1.5 p.u., meaning that there is a control margin from the DC system to assist the AC system if needed. The operating point is at left of the peak of the power curve. Thus, more than the rated DC power could be injected into the system, or, the AC system has an inherent capability of absorbing more power from the DC link.

On the other hand, Figure 1-1(b) for SCR = 1.5 corresponds to a situation in which more DC power is injected than is possible for the AC system to absorb. The operating point of AC voltage and DC current at rated values is at the right side of the peak point, operation either non-practical or unstable, depending whether the DC system is in constant current or constant power control mode. In this case, the SCR of the system could be improved with addition of reactive power support equipment with dynamic capability or through the reduction of the AC system impedance through series capacitor compensation.

When dealing with ±800 kV HVDC systems, it is an important to consider how much power can be absorbed by the AC grid at the inverter terminal. The dimensioning of the HVDC system in terms of rated power should take into consideration the MPC at the interconnection point.

Commutation Failures

One key aspect to be analyzed in an HVDC system is related to causes and consequences of commutation failures (c. f.).

A commutation failure will occur from a sudden reduction of the AC voltage at the inverter terminal, which will reduce the voltage-time area necessary for commutation between valves and for the outgoing valve to block (recovery charge period). The effect of commutation failures, as seen by the AC system is shown in Figure 1-2. Effectively, the inverter is “short-circuited” (stops feeding power, i. e., the DC voltage and valve AC voltage go to zero) and will only restart operation after the cause is cleared, which is, after the AC system voltage is restored.

In the 1990’s CIGRÉ [2] presented some interesting studies with the aim at analyzing the development mechanisms of commutation failures. These will be highlighted here.

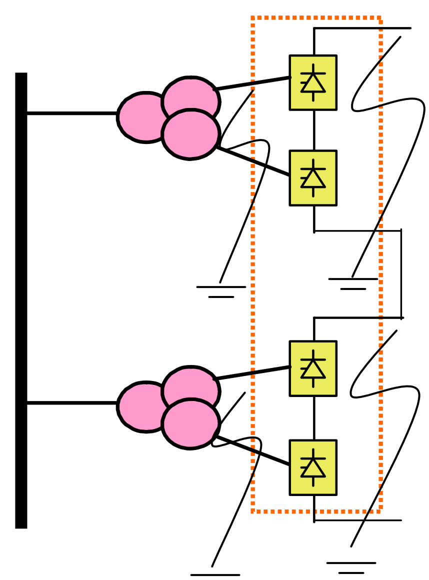

Figure 1-2
Short – Circuit Effect of Commutation Failure upon DC and AC Voltages

Main causes of c.f. are:

- Sudden AC voltage drop
- Sudden AC voltage angle shift

The voltage variation (magnitude and angle) which will lead to c. f., under ideal steady –state conditions, can be expressed by the simple formulae:

$$\Delta V=1-((I'd / Id) * (Xcpu / (Xcpu +\cos(\gamma 0+\varphi)- \cos\gamma))$$ **Eq. 1-1**

Where:

- Id and I'd are the pre-fault and post-fault DC current
- Xc is the commutation reactance (assuming an ideal voltage source behind the transformer)
- $\gamma 0$ is the critical commutation angle and γ is the pos fault extinction angle
- φ is the shift voltage angle (for unsymmetrical fault; zero for symmetrical)

Equation 1-1 can be considered as the generalized equation where the phase shift φ would be zero for symmetrical three-phase voltage reduction. In theory, the main difference, in the commutation failure probability between three-phase and single-phase faults is mainly attributed to asymmetric zero-crossing phase shifts for single-phase faults, ignoring non-power frequency distortions and assuming infinite AC systems.

It is interesting to see that three parameters influence the probability of c. f.:

- Xc, or the system impedance seen by the converter
- Δ Id or the DC current rise due to the voltage dip: this can be to some extend controlled by the smoothing reactor Ld
- the operating extinction angle γ

For $\pm$800 kV systems, as the level of power would be high, commutation failure is an event of extreme importance for reliability and security of supply. If the probability of c.f. can be reduced, by means of designing the key parameters accordingly, the overall effect upon the AC system will be very significant. Obviously, these key parameters, as Xc and Ld can not be solely designed to offer lower probability of c. f., since important economic aspects are involved in selection of their rating. Therefore larger γ and consequently somewhat higher valve rating may be necessary.

Selection of Inverter Terminal Location

The AC system connected at Inverter terminal should be strong enough to maintain the AC voltage under different conditions. For this, following studies need to be carried out:

i. AC voltage drop at inverter terminal during fault in the vicinity for different scenarios and system configurations

ii. Development of Q-V (reactive power-voltage) curve at the AC side of the terminal under different network configurations.

iii. The techno-economics of reactive power management by way of providing filters/capacitors or by exchange with the system needs to be examined. The Q-V curve shall helps in analyzing and quantifying the reactive power requirement at the terminals.

iv. Requirement of dynamic reactive compensation device/series capacitor compensation also needs to be examined.

Studies for Rectifier Terminal

In the event of DC power blocking, it is likely that large value of filter/capacitor may remain in the circuit for certain duration leading to high AC voltage condition. This may also result into self-excitation of nearby generators. This needs to be examined specifically when there is no parallel electrical path.

Reactive Power Management Studies for Parallel AC System

In the event of outage of one pole/bipole or blocking of DC power, the power will be transferred to parallel AC system. To maintain the system security, reactive compensation requirements both static and dynamic type in the AC system need to be studied and identified.

Typical 800 kV DC Configurations

When we look at the potential ±800 kV HVDC projects in the world, mostly in China, India, Brazil and possibly in the southern part of Africa, and since the project's economics is intrinsically related to large blocks of power over long distances, the concept of a DC transmission line to connect a remote generation project is the most probable configuration.

To facilitate the analysis from the reliability standpoint, a configuration of 2,000 km and 6,000 MW, bipolar transmission, is chosen as a typical case. To transmit 3,000 MW through a pole, its arrangement would include two 12-pulse converters either in series or in parallel.

Series Converters

For the series arrangement, 12-pulse 400 kV valve groups, is shown in Figure 1-3.

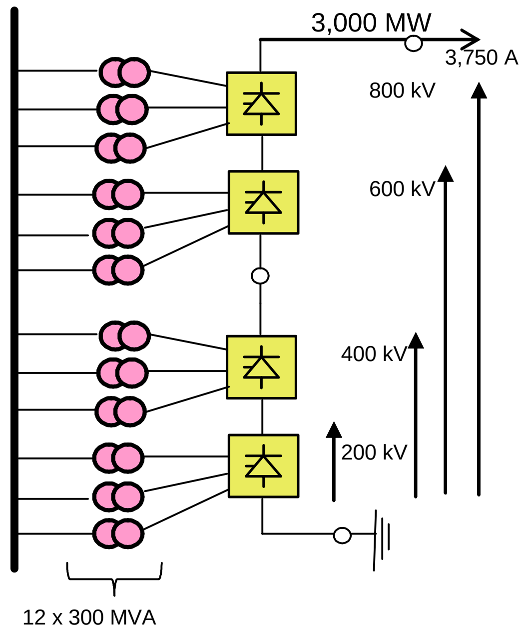

Figure 1-3
12-pulse 400 kV Valve Groups

It is assumed a total transformer rating of 3,600 MVA is needed to handle the 3,000 MW of DC power.

The advantages/disadvantages of this scheme are:

- no difficulty in transportation/ handling of converter transformers;
- one of the valve groups will be insulated for only 400 kV;
- only one among four transformer groups will have full insulation at 800 kV;
- if one 12-pulse bridge fails, half of the pole power can still be transmitted with balanced currents between poles (no ground return), however the voltage level will be half of nominal, and losses would be higher;
- for long distance staging at 400 kV first is not practical due to high losses; so the installation at full power is done at once;
- 4 spare units are needed per station unless some provision is made to build the 600 kV and 800 kV units to fit in the space of the 200 kV and 400 kV units
- the overload margin is limited due to the present commercially available thyristors in the World

Parallel Converters

The parallel arrangement will have all 12-pulse converter valves insulated for 800 kV level, as shown in Figure 1-4.

The advantages / disadvantages of this scheme are:

- 2 spare transformer units only are required, as minimum, per station;
- the loss of a converter still means operation at 800 kV with half power in the pole with the loss of converter; however it also means ground current return, since currents will be unbalanced. Metallic return can not be used unless the same polarity parallel converter is removed from service;
- if ground current is acceptable during loss of one 12-pulse converter, with 33% overload capable converters, the remaining three 12-pulse converters can handle full load.

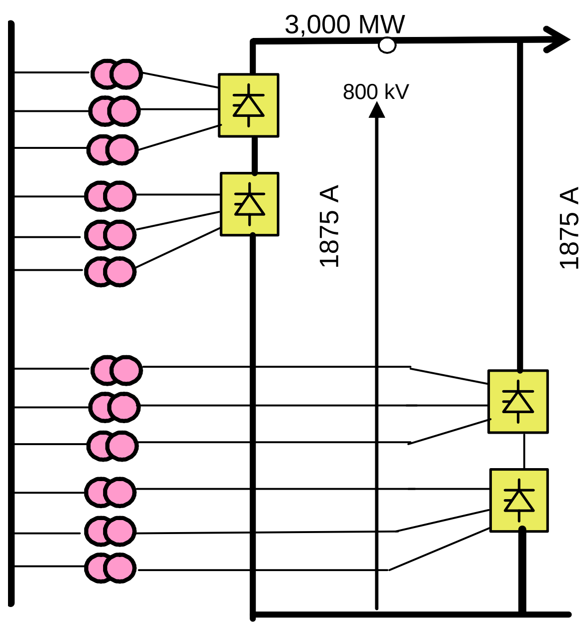

Figure 1-4
800 kV Parallel Valve Group Arrangement

HVDC Statistics and Operational Performance and Reliability Aspects

HVDC is one technological area for which systematic account has been maintained for operational performance statistics of the majority of schemes under commercial operation. CIGRÉ Advisory Group AG 04 [3], within Study Committee B4 (HVDC and Power Electronic Equipment) has taken care of annual operational reports from most schemes, since the 1970's.

In this section, only the most important aspects of these statistics will be described, in order to provide guidelines for system planners.

Statistics from Commercial Schemes

The following statistics are addressed here:

- transmission lines
- converters and valves

This section presents typical operational performance statistics made available in HVDC projects of high importance to 800 kV applications: the FURNAS - Itaipu 600 kV system in Brazil [4]; and Three Gorges-Changzhou (3GC) and Three Gorges-Guangdong (3GG), both in China [5].

The overall CIGRÉ Energy Unavailability statistics of HVDC schemes worldwide, in terms of energy average availability with and without considering converter transformer is given in Table 1-2.

Table 1-2
Overall HVDC Statistics with and without Transformer Outages

Overall Energy Availability of HVDC schemes (10 year records), considering: a) overall performance; b) excluding transformer failures	a) 98.5 % b) 99.5 %
Forced Energy Unavailability – Specification Targets	0.5 % (or 99.5% of availability)
Scheduled Energy Unavailability – Specification Targets	1 % (or 98.5 % of availability considering forced and scheduled)

Also, these CIGRÉ statistics lead to the following remarks:

i) Failures do not occur at every scheme; however, in the schemes where they happen, one can see a high concentration of failures;

ii) Four out of more than fifty HVDC schemes concentrate 65% of failures rates;

iii) Observed failures have different origins, that is, there is no one dominant cause (mechanical, bushing, static shields, tap-changer);

iv) Most failures are observed in higher voltage and large power ratings schemes; however, the failures do not occur at the highest insulation units only;

v) Apparently, failures tend to be more co-related to high MW units.

Taking information from the FURNAS - Itaipu statistics [4], it has been reported that the transmission line average repair time is around 0.6 hours/event.

There is another important FURNAS - Itaipu statistical data [6] presented in Table 1-3 which makes reference to the number of transmission lines outage events.

Table 1-3
FURNAS Itaipu DC Transmission Line Statistics 1993 – 2005

Itaipu HVDC ± 600 kV	Bipole 1						Bipole 2					
	P1 -			P2 +			P3 -			P4 +		
	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm
1993	0	1	0	8	1	2	2	0	3	2	0	0
1994	3	0	3	3	0	1	1	2	3	3	0	1
1995	4	0	0	3	0	1	0	0	0	3	1	0
1996	3	0	0	5	0	0	0	0	0	5	0	0
1997	5	2	5	0	0	1	0	0	1*	2	0	1*
1998	2	1	0	4	2	2	0	0	1*	1	0	1*
1999	2	0	0	3	0	0	2	0	1	2	0	1
2000	5	0	1	7	0	1	2	0	0	3	0	0
2001	1	0	1	1	0	1	0	0	1	0	0	1
2002	0	0	1	1	1	3	1	0	0	0	0	2
2003	5	0	0	2	0	0	0	0	0	2	0	0
2004	7	2	3	0	0	0	0	0	0	0	0	0
2005	1	0	2*	3	1	1*	4	0	0	1	1	1
Total	38	6	14	40	5	12	12	2	8	24	2	6
13y ave	**2,92**	**0,46**	**1,08**	**3,08**	**0,38**	**0,92**	**0,92**	**0,15**	**0,62**	**1,85**	**0,15**	**0,46**

The number of transmission line permanent outages (average per year), according to Table 1-3 is less than 1. These are the important events for reliability and planning studies. From the above information, one can reach the conclusion that an average forced outage time of DC transmission lines is less than 1 hour/year. It is worth mentioning that these statistics refer to either monopolar or bipolar line outages. Bipolar outages are very much fewer than the monopolar outages; bipolar outages (which are highlighted as *) occurs only when tower breaks downs. Most faults at DC transmission lines are monopolar and the lightning is not known to hit both poles. Also for lighting outage, the converters rapidly extinguish the fault and restart in 100-200ms. Usually three restart attempts are made with the third one at reduced voltage. It is also worth mentioning that unlike AC transmission, in case of damaged line insulation, either or both poles of DC transmission can be operated continuously at reduced voltage, with appropriate delay angle and tap-changer position.

The figure of one event per year with a repair time of 1 hour could be a suitable reference for ±800 kV systems HVDC transmission lines reliability criteria.

Another available statistic can be obtained in recent HVDC projects in China. Reference [5] describes, as shown in Table 1-4, the reliability and availability targets specified in the recently implemented HVDC projects that interconnect Three Gorges plant to east China.

Table 1-4
Reliability and Availability Targets for HVDC Projects in China

Index/Parameter	Target Value
Overall Forced Energy Unavailability (FEU)	0.5% or less
Overall Schedule Energy Unavailability (SEU)	1.0% or less
Single Pole Forced Outage Rate	6 per year or less
Bipole Forced Outage Rate	0.1 per year or less

For converter station outages, Table 1-5 provides practical indices that have been adopted in many recently issued specifications, which could be applied for new ±800 kV HVDC systems.

Table 1-5
Average DC Stations Outages Criteria Adopted in Specifications

	Outages Per year	Ave. Duration hours
Pole (per pole per station)	6	7.50
Bipole (per station)	0.100	8.00

Following are some practical indicators, criteria and guidance, for Utilities involved in planning and designing new HVDC schemes, with emphasis on ±800 kV HVDC applications.

The main issues that the system planners should continuously address:

- What the HVDC system can do for the AC system and whether the link would have the role of power supply (MW based) or energy interconnector (MWh based). Reliability criteria will be different for each application, which may change the design of the HVDC system.
- How the HVDC link may adversely affect the AC system and the means of mitigation.
- HVDC brings different characteristics to the network as compared to HVAC.

Favorable and unfavorable HVDC characteristics will be:

- Favorable technical characteristics: Precise, quick, large-signal power changes are available, as is modulation ability.
- Unfavorable technical characteristics: full HVDC link power can be interrupted upon sudden large reduction of AC voltage for longer duration and failure of transmission tower during cyclone or tornado etc.

From a Regulatory standpoint, ±800 kV HVDC projects may require:

- Demonstrate the necessity for a new line, especially at ±800 kV, both technically and economically
- Show that the introduction of a new line does not degrade the operational performance of the existing AC system.
- Address environmental concerns.

The Loss of Large Blocks of Power

As in this study, a configuration of ±800 kV DC and 6,000 MW (in one bipole) with no parallel AC interconnection was selected to serve as a reference for Reliability and Planning issues, the amount of power that can be dropped for HVDC outage should be studied in great detail.

The HVDC outage will affect both terminals in a different manner. At the rectifier, this will be seen as a load rejection, and most likely will accelerate the generators speed and system frequency will be elevated, and possibly with high temporary overvoltage. At the inverter, this will be perceived as a generation drop, and most likely, giving rise to stability, low voltage and power swings issues.

Preliminary studies need to be carried out where various faults are simulated and necessary remedial measures planned to reduce the downtime of the converters such as keeping margins in overload criteria of each 12-pulse converter, special protection schemes such as controlling of load / generation as the case may be.

Reliability Planning Criteria

There are three categories of MW loss:

- Critical: the ones that lead to a disconnection of full DC power;
- Severe: the ones that lead to loss of half of the power; these could be partially counteracted by overloading the remaining equipment;
- Less severe: the ones that lead to loss of 25% of full power.

Last but not least, the function of the HVDC in the AC system, either being a MW power supply or an MWh energy interconnector may affect the level of security employed in the Reliability and Design studies. An interconnector can be designed with some relaxation in its Reliability design as compared to a vital MW supplier link.

Conclusions

Based on the information and discussion topics raised up in this Chapter, a summary conclusion is now presented.

- The number of forced bipolar line outages is very small; usually these faults are associated with tower breakdown (due to extreme winds for instance), and therefore most line faults happen at one pole (due to insulation failure or switching misoperation, for instance); this is why the issue of operation with one pole with metallic return or ground return (via electrodes) becomes so important in HVDC schemes;
- While planning the overload capacity of HVDC line, studies need to be carried out for combined ac/dc network. Decision of DC overload capacity depends upon the capacity of ac/dc network connected with the proposed link,
- The voltage on the AC side of the inverter terminal is to be maintained under different operating conditions. For this, studies need to be carried out to determine voltage drop at the inverter terminal during fault in the vicinity for different scenarios and system configurations, development of Q-V (reactive power-voltage) curve at the AC side of the terminal, techno-economics of reactive power management by way of providing filters/capacitors or by exchange with the system needs to be examined. Requirement of dynamic reactive compensation device/series capacitor compensation also needs to be examined.
- At the rectifier terminal, in the event of HVDC power blocking, it is likely that large value of filter/capacitor may remain in the circuit for certain duration leading to high voltage condition. Hence, possibility of self -excitation needs to be studied.
- In the event of outage of one pole/bipole or blocking of DC power, the power will be transferred to parallel AC system. To maintain the system security, reactive compensation requirements in the AC system, both static and dynamic, and series and shunt type in the AC system need to be studied and identified.
- For transmission of say, 6,000MW at ±800 kV HVDC level, feasibility of two 12-pulse converters in series or in parallel configuration need to be studied and optimum configuration depending upon the requirements is to be selected. Suitable margin in the overload capacity will also be required for either short or long duration, to take care of 12- pulse converter outages;
- Full loss of the whole station is a much rarer event than losing one pole (in the case of one converter per pole) or a portion of a pole (in the case of two series or parallel converters per pole);
- The statistics available would have to be used with different criteria, depending upon if the link will have the role of either power supply (MW based) or energy interconnector (MWh based)

- However, even knowing that the number of expected average hours of unavailability is reduced, the possibility of losing a power block of 3,000 – 6,000 MW, even being a rare event or typically of short duration, is a subject of major concern to a grid; perhaps, rather than doubling equipment as a safeguard, system measures to alleviate the impact upon the grid, such as load transfer, special switching in the network as well as in the DC station, generation re-dispatching etc., could be analyzed;
- Also, to allow monopolar operation, the HVDC system designer should carefully dimension and plan the ground electrodes, as this element plays an important role when only one pole conductors is available.
- Provision should be made for metallic operation, so that operation with ground return would not be for long duration.

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2
CONVERTER CONFIGURATIONS

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
- 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

In the following sections the different possible configurations will be presented and discussed in light of the above considerations. In addition all the operational features of a specific configuration will also be presented.

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

A Bipole with One Single 12-Pulse Converter per Pole

The configuration in this case would 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 2-1. The difference here is that even if the rated power is 3000 MW, the transmission distance may be prohibitive to build the bipole at 500 kV. For 3000 MW power transfer over a distance of 3000 Km, DC voltage of ± 500 kV may not be feasible.

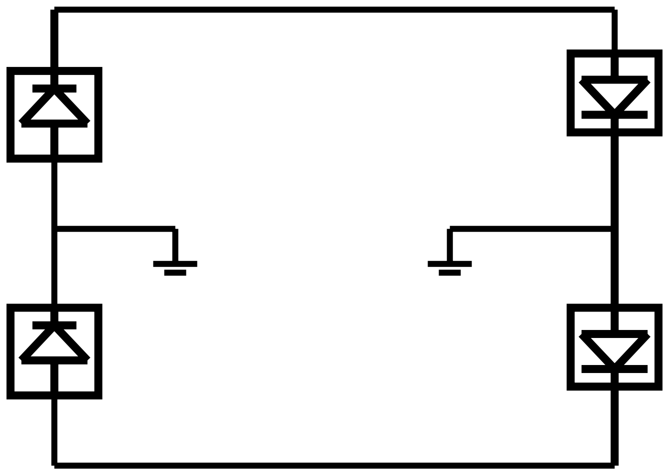

Figure 2-1
A Bipolar System with One 12-Pulse Group per Pole at 800 kV

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

The power to be transmitted can be as high as 6000 MW. 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 in building one pole followed by the second pole. In order to limit operation with ground return mode, bipole DC line will have to be built from the beginning to allow stage one to operate in metallic return mode. The losses during mono-polar metallic return are doubled compared to monopolar ground return mode of operation.
- The maximum amount of power to be transmitted 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 in no way 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 not an 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 for manufacturing and transportation. However if the nominal bipolar power is 4000 MW, the transformer rating will be 370 MVA, leading to very large units. Certainly for a 6000 MW bipole, the rating of 555 MVA is not feasible.

A Bipole with Two 12-Pulse Series Converters per Pole

In this configuration, two twelve pulse converters are connected in series per pole as shown in figure 2-2. The voltage 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 12 pulse converter valve groups, which also means the power rating of the two 12 pulse converter bridges is different. For example one converter can be 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 and 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. Obviously this alternative of dissimilar 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 affect the spares required.

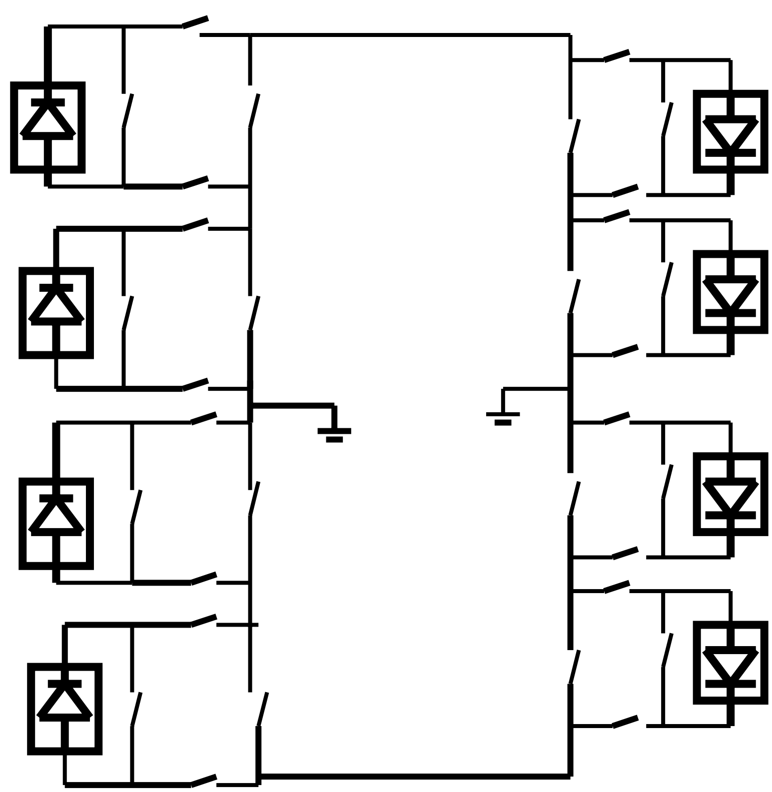

Figure 2-2
A Bipole with Two Series Connected Valve Groups per Pole

The discussion for the series converters per pole will concentrate 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 as high as 6000 MW. This means 1500 MW per 12 pulse converters and 3000 MW per pole. Again the economics will dictate how low the transmitted power can be.
- 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 ±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 ±800 kV.
- From a reliability perspective, 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, 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 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 , this pole will be operating at only at 200 kV and full load current.
- 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 PU DC voltages with two converters per pole or even down to one converter per pole at 400 kV.

For series connected converters per pole, certain additional switchgear and measuring devices are required because of the series connection. As shown in figure 2-2, 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 function of the by pass switch is to allow the deblocking of the converter before it is put in service and to do fast by pass during blocking. The deblock and block of series converters are completely different from that of the single converter per pole. In addition even if the pole is under shutdown there will be current in the by pass switches.

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 2-3.

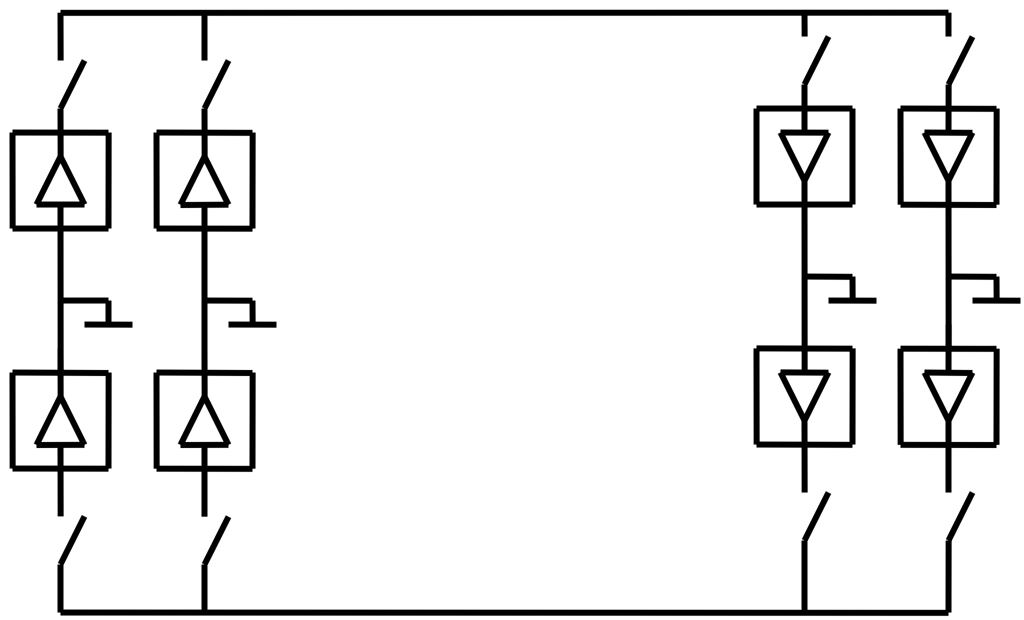

Figure 2-3
A Bipole with Two Parallel Converters per Pole

In the parallel configuration of the two 12 pulse converters, 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 (for similar converter bridges), 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 in the parallel arrangement 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. However, no DC current interruption capability is required.

The deblock 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 pole. 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.

From a reliability perspective, 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 parallel converter is lower than the series connected converters, and if 5 inch thyristors are used, there is more room for overload if required . However with the availability of 6 inch thyristors which are capable of handling 4000 Amps, the overload is not an issue anymore. Therefore this is not a problem.

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 because of star and delta winding wise connectivity.

For any insulation type problems the poles can be operated at the typical 0.8 pu DC voltage.

In this configuration the converters can be built at different locations. In principle the two bipoles can be separated by any distance but a reliable communication system between parallel converters is a must for smooth recovery from faults and proper current sharing between converters. 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. However, in case of lower transmitted power level, the ground current can be minimized with proper control philosophy by making different power order between the remaining operating poles.

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 which means removing the converter manually from parallel without disturbing the 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.

3

THE RESEARCH AND DEVELOPMENT REQUIREMENTS- IDENTIFICATION OF ASPECTS THAT DESERVE ATTENTION

Introduction

During 1980's, anticipating the next stage of high power HVDC transmission, there was a considerable R&D work underway on various aspects of HVDC transmission beyond ±600 kV, notably ±800 kV and ±1000 kV. However, increased opposition to transmission lines, followed by privatization/competition, lack of long term planning, and environmental campaign for renewable generation, and distributed generation etc., put a stop or slowed down much of this R&D on UHV transmission technology. Now high interest in UHVDC transmission in countries such as China, India, Brazil and parts of Africa has materialized with strong growth in electric load and potential for harnessing remote hydro-sources. Such opportunities for transmission of large hydro power from remote sources will arise in many developing countries.

There is already a considerable experience on ±500 to ±600 kV, but not without some problems. However, given that experience, it would not seem to be a big problem to go to the next higher level of ±800 kV. Furthermore, the R&D work carried out during the 1980's did not reveal major road blocks. Also, given inputs from manufacturers of Converter Stations, who have indicated that they are ready to take orders for 800 kV DC, it is clear that China and India will proceed with ±800 kV DC installations on the assumption that no major problems are expected for the design and construction of HVDC transmission lines and converter stations for ±800 kV. The fact still remains that no one has yet built an ±800 kV system, and therefore one can not categorically say that there will not be surprises, as often is the case with first of a kind complex systems. With care, thought and international R&D collaboration, it is safe to say that ±800 kV does not represent an unreasonable risk.

Performance Issues for HVDC

Negatives:

- DC Insulation is affected by pollution (Overhead Line and Bushings)
- Transformers Reliability has been below expectation
- AC System Faults create Commutation Failures
- Uncertainty of Harmonic Levels during design

Positives:

- Fast recovery from DC line faults
- Can operate at reduced voltage when insulation is weakened by pollution or physical damage
- Monopolar operation during pole outage
- Power modulation to stabilize AC System
- Does not respond to cascade outage crisis of AC System

R&D should focus on reducing the effect of negatives and enhancing the positive.

There are two categories of R&D aspects:

1. R&D aspects to reduce risk and improve reliability:
   - Bushings
   - Transformers
   - Overhead line and bus support insulators
   - Earth Electrodes
   - Dynamic over-voltages
2. R&D aspects to reduce cost and improve performance
   - Converter technology
   - Reduced voltage operation
   - Active filters
   - Simulation tools

Following paragraphs convey the state of the art and where R&D would help reduce risk, improve reliability, reduced cost and improve performance.

Transmission Lines

Based on R&D carried out by EPRI, IREQ, CRIEPI, CESI, CEPEL and NIIPT, there is enough electrical data available to suggest that several transmission line design companies have and can design ±800 kV lines. Never-the-less, there is a need for further research related to design data on air clearances, corona, RI, and audible noise.

Regarding air gap clearances for steady state and switching surge withstand, the relationship appears to be almost linear (withstand strength decreases somewhat as the gap length increases) up to ±800 kV and even ±1000 kV.

Although four conductor bundle configuration seems adequate for ±800 kV from the point of view of corona etc., for very long lines, conductor and bundle size may have to be larger, determined not only by the value of losses, but also the impact of total voltage drop in the line on the recovery of the system following AC system faults.

Research on various insulators reveals a big problem with regard to the effects of pollution, particularly urban, automobiles and industrial, and to a lesser extent agriculture, on the insulator surface and its effect on the steady state and switching surge withstand levels. Salt in the air is also a big problem. Under DC voltage, insulators electro-statically collect airborne particles so much so that often the flashover level of outdoor insulation under DC is lower than AC rms levels. A large number of tests have been carried out on insulators, porcelain, glass, and non-ceramic and a wide variety of shapes. These tests include laboratory and field tests. Methods of artificial pollution for laboratory testing, and sophisticated instrumentation and data gathering have been developed. Anti fog shaped porcelain insulators seem to have better performance, and so do the non-ceramic insulators. V insulator strings seem to have better performance than I strings. For a given route of a proposed transmission, it is possible to rely on gathered field data from test sites along the route to determine the required insulation.

Never the less, insulation length required may vary by 2:1 depending on the severity of the combination of atmospheric conditions and particles in the air. Much of the data is experimental with inadequate understanding of basic physics behind certain pollutants sticking to the insulator surface. What we need is basic research on finding materials and designs suitable for high DC stress in the presence of air pollution.

There is a need for research on corrosion and long term life in the presence of combined electrical, pollution, and UV radiation stresses.

Bushings

Bushings represent another problem, not only in terms of pollution, but also for internal stresses and long life. Bushings perhaps are the highest risk equipment. It is clear that non-ceramic bushings will be used. Basic research is needed on internal stresses, and relationship between internal and external stresses. For pollution issue periodic online blowing of air or clean water spraying could be considered and investigated for vertical and inclined bushings.

Transformers

Transformers including their bushings for ±800 kV are also the highest-risk equipment. Concern largely relates to presence of DC stress and combined ac/dc stress on oil/paper spaces and chemical interactions. Basic work would help understand short term and long term effects of DC stress, combined dc/ac stress and use of appropriate insulation grading, barriers, oil flow, chemical composition of oil, paper conductor etc.

DC Switchyard

In areas with moderate to high pollution, there is a serious problem in terms of pollution of DC insulators and periodic maintenance requirements for cleaning the DC insulators. For such conditions indoor DC switchyard has been proposed, but there is no data on what indoor means in terms of clean indoor atmoaphere and level of pollution. Does the indoor DC switchyard needs to be as clean as the valve hall or is there less stringent and hence less costly requiremet? Alternate is SF6 insulated DC bus, however extensive research is needed to establish designs and long term reliability of SF6 bus insulators under DC stress.

Converter Technology

At present high power HVDC schemes are based on 12-pulse converters using conventional thyristors (with gate turn on but without gate turn off capability).

Significant advances continue to be made in the conventional Thyristor based technology. Today one can expect thyristors with 8-10 kV 3000-4000A ratings, with direct light triggering and self protection. As before, the valves may continue to be assembled on site from pre-assembled pre-tested modules (panels). Efforts are needed to increase power per module, as limited by thyristor ratings, thermal efficiency, electrical/mechanical and transportation considerations.

Whereas cost of devices is not significant in relation to the total cost of HVDC Converters, the characteristics of devices, i.e. ratings, di/dt, dv/dt, losses, packaging etc. have much to do with the cost of what surrounds devices, i.e., transformers, filters, magnetics, auxiliary equipment etc.

Much can be done to improve conventional thyristor technology itself. R&D can help reduce forward voltage drop, conduction losses, switching losses and gate power requirements. Particularly important is to improve thermal performance of thyristor packaging. This can be done by reducing and even eliminating dry press-pack junctions. These junctions have high thermal resistance, which in turn reduces the current carrying capability. Thyristor happen to be the component that limits short-term overload capability of HVDC systems. Solder bonded joints can increase converter overload capability to match the rest of the system equipment.

For industrial applications (at relatively low power and low voltage level), the technology has moved on to gate turn-off devices, i.e. IGBT and GCT/IGCT based PWM Voltage Sourced Converters. These turn-off device based converter technology has been used for HVDC and frequency conversion, of ratings up to several hundred MW and kVs. There is no reason to believe that with research and development on converter technology, PWM or stepped-voltage Voltage-Sourced Converter technology could not be projected to UHV and thousands of MW levels. Such converters require much smaller AC filters, provide reactive power and do not require AC voltage support on the AC side; significant advantages over thyristor-based technology. Also with present current sourced converters, power reversal is achieved with DC voltage reversal; not very suitable for multi-terminal schemes with power reversal capabilities. With Voltage Sourced Converters, it is easy to accommodate power reversals in multi-terminal schemes. Much work is needed in development of turn-off devices. It would be a great advantage to have GTO like devices with low conduction losses, but with low switching losses and low gate power requirements. Further work is also needed on bonded junction IGBTs instead of press-pack IGBTs. On a long term basis R&D is needed on wide band-gap materials (SiC and Diamond) based devices.

Harmonics

Passive filters, particularly on the AC side, represent an uncertainty with regards to harmonic performance in a real system as against simulation based design calculations. Advantages of active filters are that an active AC filter will cover a wide range of harmonics, will be insensitive to temperature variations, will not be a sink for harmonics other than its own, accommodate wide variations in the AC system impedances, damp sub-synchronous oscillations and will generally be smaller size that the passive filters. Different ideas for active AC filters and hybrid active/passive AC filters need to be investigated for best designs.

Active DC filters, should also be seriously considered and investigated.

Ground Electrodes and Metallic Return

Still today, design and location of ground electrodes represents a level of uncertainty with regards to the risk of saturation of transformers and pipe corrosion. While this is not specific problem for UHVDC schemes, higher current levels involve greater difficulty in finding suitable electrode locations. This uncertainty results from unknown formation of deep layer of earth with a few tens of miles of the electrode sites. It is necessary to investigate techniques used by oil/gas and mining exploration companies.

For some schemes ground return, even for emergency purposes may be prohibited. For such schemes, design and use of earth/shielding wire as return conductor should be investigated. The issues include: size and type of conductor, insulation requirement, clearance of arc flashover etc.

Control and Protection

Controls and protection will of course be digital based. Hardware will generally follow the technology developed for information systems and industrial controls and not specially built for HVDC projects. Much can be done with intelligent control and protections system to collect data and predict events? What role can GPS play in control and protection?

Dynamic Over-Voltages

For such long distance, high-voltage high-current schemes, it would be extremely important to minimize AC system over-voltages and over-currents during disturbances and ensure stable recovery from disturbances. Role of STATCOMs and SVCs for AC side voltage control need to be defined. Apart from reduced DC voltage operation during DC line insulation damage, it may also be important to reduce the level of polarity reversal during forced-retard for forcing the line current to zero during line faults and commutation failures etc.. Simulation based R&D are needed to refine control and protection strategies.

Synchronized switching of transformer and capacitor bank breakers should be looked into with the objective of reducing over-voltages and resonances and prolong equipment life.

For control of dynamic over-voltages, it is necessary to evaluate use of STATCOMS, SVCs and high power gapless arresters.

Reduced Voltage Operation

Possibility of operation at reduced voltage, say 80% by tap change and firing angle control during bad weather conditions is very important for operation with polluted insulators during foul weather conditions or partly damaged insulation. There is a need for R&D to understand the level of required voltage reduction and condition of insulators, bushings and climate.

Simulation Tools

Simulation technology continues to advance. Days of new physical/analog simulators seem to have gone. Many non real-time digital simulation tools have been developed and continue to be refined. However, for designing digital control and protection it is essential to have real time simulation with hardware/software in the loop capability. Software for such a digital simulation should also be used in a non-real time manner on any modern PC.

Real time simulation could also support operation and maintenance of the installed system and support operator training. Such an onsite simulator could receive available on line data form various monitoring devices and provide information on the missing data as well as, by running contingency calculations predict potential problems.

Although physical/analog simulators have a degree of credibility because they feel like a real system and operate in a continuous time domain like a real system, they are expensive, take a long set up time and are not very flexible. Digital simulator on the other hand is based on mathematical representation of equipment and the system and solves all the equations in discrete steps. This creates a credibility issue for digital simulation particularly where power electronics, with very frequent switching operations, is involved. Is the math correct? Has the software for each equipment been checked and verified against real equipment? Is the integration time step small enough for accuracy and credibility? Smaller integration time step for converters is needed for good accuracy.

4 STATE OF THE ART OF HVDC TRANSMISSION LINES

Introduction

The use of increasingly higher voltages makes HVDC systems economically feasible for transmitting larger blocks of power over longer distances. Considerable research and development work has, therefore, been carried out over the past fifty years to study the electrical performance and obtain the data necessary for the design of HVDC transmission lines. Early research focused on studies required to design transmission lines in the range of ± 400 kV to ± 600 kV. Some exploratory studies have also been carried out to establish the technical feasibility of transmission lines at voltages above ± 600 kV.

Electrical design of HVDC transmission lines, particularly at voltages above ± 200 kV, requires consideration of:

- Corona Performance
- Air Insulation Performance
- Insulator Performance

Corona is produced by the presence of electric field on the conductor. Corona performance of a HVDC transmission line is defined in terms of:

- corona losses (CL),
- radio interference (RI) in the vicinity of the line
- audible noise (AN) in the vicinity of the line
- electric field in the vicinity of the line
- ion current in the vicinity of the line

Corona performance design criteria have a direct impact on the selection of the conductor bundle configuration, its height above ground, pole spacing, etc.

One of the major inputs for selection of the minimum air gap clearances required between the conductors and the tower structure, conductors and ground plane as well as between the positive and negative conductors of a bipolar HVDC transmission line are based on the dielectric withstand characteristics of these gaps when they are subject to the normal operating voltage as well as the switching and lightning overvoltages that might occur on the line. Knowledge of the magnitudes of the overvoltages and the withstand characteristics of the air gaps is, therefore, essential for determining the main dimensions of the transmission towers. Considerations of safety and live-line maintenance as well as mechanical characteristics of the conductor bundles etc also play a role in determining tower dimensions.

Choice of the type of insulators and the length of the insulator string required to support the conductors is based on the withstand characteristics of the surface insulation. The critical design consideration in this case is the ability of contaminated insulators to withstand the normal operating voltage under the severity and type of contamination experienced by the transmission lines.

The current state of knowledge available for the electrical design of HVDC transmission lines is reviewed in this section.

Corona

Of all the corona effects produced by HVDC transmission lines, CL has essentially an economic impact on line design, while RI, AN and electric induction effects have an environmental impact. In general, CL along with the I^2R losses in the conductors influences economic choice of the optimum conductor bundle. Since RI, AN and electric induction effects may have different types of impact on the people in the vicinity of HVDC transmission lines, it is necessary to develop appropriate design criteria limiting them to acceptable levels..

Early research on DC corona was carried out mainly to understand the discharge physics and the criteria for the onset of corona on conductors [1-3]. Since the technical and economic feasibility of HVDC transmission was established more than fifty years ago, considerable research and development work has subsequently been carried out on the corona performance characteristics of line configurations with different conductor bundles. In addition to laboratory investigations on basic corona physics, studies on outdoor test lines were conducted [4-6], mainly to determine corona losses for practical line configurations.

One of the first comprehensive investigations of DC corona was carried out at the Anneberg test station of Chalmers University of Technology and ASEA in Sweden [7-10]. Corona studies were conducted on a test line about 240 m long and at voltages up to ± 600 kV. The measurements included CL and RI for different monopolar and bipolar conductor configurations, mainly under fair weather conditions, since it was observed that, unlike in the case of AC corona, RI levels for DC corona were *lower* under conditions of rain than in fair weather. It should be mentioned, however, that DC corona losses in rain are higher, as in the AC case, compared to those in fair weather. Some consideration was also given in these studies to voltages and currents induced on objects located under DC lines in corona.

An extensive program of DC corona research, comprising laboratory studies as well as investigations on outdoor test lines, was carried out by the National Research Council (NRC), Canada. Laboratory studies included determining the basic characteristics of corona current pulses generated by positive and negative corona on line conductors [11] and the influence of wind on DC corona [12]. Two outdoor test lines, perpendicular to each other and each about 113 m long, were used to study the CL and RI performance characteristics of a number of single as well as bundled conductor configurations in monopolar and bipolar modes of operation. The studies were done at voltages up to ± 600 kV.

The NRC test facility was used initially to determine the corona performance characteristics of a number of conductor bundles [13, 14] and subsequently to evaluate the CL and RI performance of conductor bundles selected for use on the Nelson River ± 400 kV transmission lines of Manitoba Hydro [15]. Later on, measurements were made to determine the CL and RI performance of the operating Nelson River transmission line and were compared with those made earlier on the NRC test line [16].

Corona studies in Germany were carried out on an experimental line about 1 km long and energized at ± 450 kV. Long-term measurements were made to obtain statistical data on RI and CL at the nominal voltage, while short-term measurements were made to determine the variation of RI and CL with conductor surface gradient as well as the lateral profiles and frequency spectra of RI [17]. Some of the significant results of this study were observations of the influence of relative humidity, the absolute water content of air and of the wind velocity perpendicular to the line on RI and CL.

The Bonneville Power Administration (BPA) established the HVDC test center at The Dalles, Oregon, in 1963 for the purpose of carrying out research and development necessary for the design and operation of the ± 400 kV DC transmission line from The Dalles, Oregon to the northern suburbs of Los Angeles. The test center comprised essentially of a multi-span test line about 6.8 km long, DC power supplies to energize the line at ± 400 kV and the necessary instrumentation for studies on the corona performance of different conductor configurations [18,19].

Following completion of the ± 400 kV transmission line, the test center was modified and designated as the "EPRI-HVDC The Dalles Project" for corona and insulation studies of transmission lines in the range ± 400 kV to ± 600 kV. The results of a four-year research and development project, specifically directed at investigation of the phenomena, characteristics and requirements of DC transmission lines in the ± 400 kV to ± 600 kV range, were summarized in a reference book [20], popularly known as the Green Book.

Corona studies were carried out on different conductor configurations installed on different sections of the test line. Corona losses, RI and television interference (TVI) as well as audible noise (AN) were measured and a large amount of statistical data was obtained during different weather conditions. For the first time in a large-scale project, the corona-generated space charge and electric field environment in the vicinity of DC transmission lines was characterized experimentally. Extensive measurements were made of ground-level electric fields and ion currents and the possible induction effects on people and objects located in this environment were investigated.

Following publication of Transmission Line Reference Book HVDC to ± 600 kV (Green Book), EPRI sponsored a large project at the Institut de Recherche d'Hydro-Québec (IREQ) with the objective of investigating and obtaining technical information on the performance aspects of corona, air insulation and insulators for HVDC transmission in the range of ± 600 kV to ± 1200 kV. The project, which was carried out in two phases between 1975 and 1982, explored a wide range of problems of research and development in this voltage range, and provided useful information for the design of future HVDC systems.

In the first phase of corona studies [21], three conductor bundles consisting of 4, 6 and 8 sub-conductors were selected for operation at nominal voltages of ± 750 kV, ±900 kV and ± 1050 kV respectively. Long-term tests were carried out under different weather conditions on each of the three conductor bundles and statistical information was obtained on CL, RI, TVI and AN. Special instrumentation was developed for the measurement of ground-level electric field and ion currents, while commercially available ion counters were used to measure the space charge density. In addition to the long-term studies, short-term tests were also performed to determine lateral profiles and frequency spectra of RI and AN. Some tests were also made on positive and negative monopolar corona performance of the three conductor bundles.

Special bipolar tests were carried out on the 6-conductor bundle to determine the influence of conductor height and pole spacing on corona performance. Variable voltage tests were made for each of the line configurations studied in order to determine the influence of conductor surface gradient on corona performance. Finally, the feasibility of using outdoor test cages for monopolar and bipolar corona studies was investigated and the corona and electric field performance of bus configurations required for bipolar DC stations in the range of ± 600 kV to ± 1200 kV was evaluated.

In the second phase of the corona study [22], a comprehensive investigation of the corona performance of the 6-conductor bundle was carried out over a period of more than 12 months, covering all possible variations in weather conditions. The study also included bipolar and monopolar cage tests on a large number of conductor bundle configurations, mainly to determine the generation quantities of CL, RI and AN. In addition, tests were carried out to study the psychoacoustic effects of DC corona noise as well as to make a subjective study of RI to determine acceptable levels of RI from DC transmission lines. Finally, a number of tests were carried out on the electric field and ion induction effects on people and objects located under DC lines.

Starting in 1977, EPRI and the Department of Energy (DOE) in the United States co-sponsored research studies on corona and insulation aspects of HVDC transmission lines at the research center in Lenox, Massachusetts. Although originally intended to cover the range of voltages from ± 600 kV to ±1200 kV, it was soon realized that transmission systems in this voltage range may not be built in the U.S and emphasis was therefore shifted to the range of ± 400 kV to ± 600 kV [23]. The objective of this research program was to characterize electrical effects, including RI, AN, CL, ozone, fields and ions and space charge. Special techniques were developed to measure the space charge densities in the vicinity of the line and particularly the net space charge due to large ions carried downwind from the line [24].

Extensive studies of CL, RI and AN produced by corona on DC lines as well as of the electric field and ion environment, were carried out by the Central Electric Research Institute of Electric Power Industry (CRIEPI), Japan. The Shiobara HVDC test line [25], consisting of a bipolar double-circuit line with a measurement span of 300 m was used for corona studies. Long-term measurements of CL, RI, AN, electric field and ion flow electrification were made since 1982. In addition, studies were also conducted to validate the use of test cages for determining the RI and AN. Test line studies included measurement of small ion mobility characteristics and profiles of large ion densities. The use of shield wires below DC lines to reduce electric field, induced voltages, ion currents and ion density was also investigated.

Following completion of the EPRI project, studies at IREQ were devoted to the design and development of the Radisson-Nicolet ± 450 kV transmission line [26]. On the question of design criteria for ground-level electric fields and ion current densities, not many studies with the necessary scientific rigor have been carried out. In a study at IREQ [27], human subjects were exposed to electric fields and ion currents in a carefully controlled exposure chamber, and tests were carried out using psychophysical principles. The results of this study clearly show that human perception is a function of both the electric field and ion current density.

At BPA, the long-term corona performance of an operating ± 500 kV line was monitored by making measurements of RI, AN, electric field, ion current and space charge densities [28].

Air Insulation

Atmospheric air serves as the principal insulation medium between the conductor-tower, conductor-conductor and conductor-ground-plane gaps of a HVDC transmission line. Of these, selection of the conductor-tower air gap clearance is the most important aspect of air insulation design. In the case of bipolar DC lines, the air gap clearance between the conductors of opposite polarity is equal to twice the conductor-tower clearance plus the width of the tower structure and should, therefore, be able to withstand any overvoltages occurring between the conductors. The minimum conductor height above ground is selected mainly on the basis of ensuring public safety and, consequently, is larger than that required from considerations of insulation withstand. For higher system voltages, ground-level electric field and ion current density levels largely influence the selection of ground clearance.

Selection of the conductor-tower air gap clearance is based on its capability to withstand the maximum operating direct voltage as well as the maximum expected lightning and switching overvoltages. A large amount of data obtained through a number of research studies [29,30] for different gap configurations can be applied to determine the air gap clearances of DC lines, particularly for direct voltages and lightning overvoltages. However, the switching overvoltages to which air gaps of DC lines are subjected are composite in nature, being composed of a DC bias voltage on which switching overvoltages of different polarities get superimposed. Thus, the question of whether the previous data on the flashover and withstand characteristics of air gaps under standard switching waveforms are applicable to DC line design should be examined.

Research studies in Sweden [8] addressed the question of withstand characteristics of conductor-tower air gaps under composite switching overvoltages. In the EPRI-BPA study [20], extensive tests were carried out using simulated conductor-tower air gap configurations to determine the flashover characteristics under direct voltages and investigate the effect of conductor bundling. The switching and composite impulse flashover characteristics of rod-rod, rod-plane and conductor-bundle-plane air gaps under dry and rainy conditions were also investigated and the results compared with previously obtained experimental data.

In the EPRI-IREQ air insulation study [31], the flashover voltages of air gaps encountered on bipolar transmission towers as well as in station bus arrangements required in the voltage range of ±600 kV to ±1200 kV were determined. A full-scale tower structure corresponding to a bipolar DC line was simulated inside the high voltage laboratory. Tests were performed for different conductor-to-tower clearances, with mixed (i.e. switching impulse superimposed on dc) positive polarity voltages applied to one pole and the other pole either grounded or with a negative polarity DC voltage of one per-unit applied to it, to determine the 50% breakdown voltage and coefficient of variation.

In the EPRI-Lenox study [23], the flashover characteristics of a short (0.83 m) rod-plane and conductor-tower gaps were determined under the application of direct voltages as well as composite voltages.

Insulators

Although the insulation design of HVDC transmission lines should generally take into account both the normal operating voltage and the lightning and switching overvoltages, service experience has shown that the flashover characteristics of insulators at the normal operating voltage and under conditions of contamination and/or wet weather conditions play a critical role in selecting the number and type of insulators. The principal reasons for this are that accumulation of contamination on insulation surfaces is more severe under DC rather than AC energization and that for the same severity of contamination the withstand strength of insulators under direct voltages is usually lower than that under alternating voltages.

Some of the earliest studies on the performance of contaminated insulators at direct voltages were carried out in Sweden [7]. Long-term tests with natural pollution were carried out in order to determine the withstand characteristics of line and post insulators. Outdoor test facilities, with bus bars for station insulators and a test line for line insulators, were energized under normal weather conditions including rain, fog, dew, sleet and rime ice, to determine the insulator withstand characteristics. Some tentative steps were also taken to develop artificial pollution tests for insulators. The thesis by Witt [10], based on work carried out at ASEA laboratories and Chalmers University of Technology, addressed the important problem of DC source requirements for pollution tests and characteristics of pollution deposition on insulator surfaces under the influence of electrostatic forces, wind and gravity. The problems resulting from ion migration and electrolysis in the dielectric materials used for DC insulators were also investigated.

In the EPRI-BPA study [20], different laboratory test methods were evaluated to determine the withstand characteristics of contaminated insulators. A large number of suspension and dead-end insulators of different design were tested in the contamination chamber to provide data on their performance characteristics.

In the first phase of the EPRI-IREQ insulation pollution study [32], the state of the art of pollution testing of DC insulators was surveyed which revealed that neither the loading effect (maximum leakage current) of contaminated insulators nor the necessary rectifier parameters were clearly determined in earlier pollution tests. Theoretical investigations combined with extensive laboratory studies on the flashover characteristics of contaminated insulators in a fog chamber lead to the definition of DC source requirements for pollution tests. The main conclusion of this phase of the study was that DC pollution tests require a source with a dynamic voltage drop of less than 5-10% and less than 10% voltage fluctuation under the most severe leakage current pulses that may occur.

In the second phase of the insulator pollution study [33], the specifications of the HVDC laboratory power source sufficient to determine the 50% flashover voltage of heavily contaminated insulators within an accuracy of 5% were determined on a model circuit and the results were generalized on a computer program. The main conclusion of this study was that a controlled cascade rectifier connected in a voltage-doubler arrangement is an adequate power supply for testing insulators under heavy pollution.

A comprehensive investigation of the contamination performance of insulators for use on HVDC transmission lines was carried out in the EPRI-Lenox study [23]. Following a review of the experience on operating HVDC transmission lines, the study presented a discussion of the main factors influencing the deposit of contamination on insulator surfaces. Extensive artificial contamination tests were carried out on different types of insulators representing a wide range of design parameters. Different types of ceramic disc insulators, one type of ceramic long-rod insulator and a few non-ceramic insulators were tested. The main objective of these tests was to develop data that can be applied to the design of new HVDC transmission lines as well as to upgrade the design of existing lines for improved contamination performance. A test facility capable of performing flashover tests on contaminated insulators in artificial and natural fog at voltages up to ± 1100 kV was used in this study.

Influence of the following parameters on the flashover performance was investigated: polarity, equivalent salt deposit density (ESDD), insulator length, type and amount of non-soluble material, type of salt, non-uniformity of contaminant along the insulator string, ratio of the top to bottom ESDD, string orientation and double versus single insulator strings. One of the important conclusions of this study established the linearity of critical flashover voltage as a function of insulator string length.

Additional studies were carried out at IREQ on the HVDC source requirements for pollution tests [34] following which a 650 kV DC source was acquired and extensive contamination tests were carried out on line and station insulators.

In Sweden, studies continued at the Chalmers University of Technology and at the Swedish Transmission Research Institute (STRI), mainly on pollution test methods and performance of insulators and wall bushings. The studies include experience with RTV silicone rubber sheds and shed coatings, development of test methods for artificially and naturally polluted porcelain barrel insulators and field experience of outdoor polymeric insulators exposed to HVDC.

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5
OPERATING ISSUES OF HVDC TRANSMISSION LINES

Introduction

Since the advent of modern HVDC transmission systems more than fifty years ago, several overhead transmission lines at voltages of ± 400 kV up to ± 600 kV have been in operation in different parts of the world. Experience gained in designing, constructing and operating these lines is very valuable for the design of lines at or above ± 800 kV being seriously considered for bulk power transmission. A survey is made of HVDC transmission lines operating in the voltage range of ± 400 kV to ± 600 kV and the results are summarized in this chapter. The design practices adopted and operating issues of the surveyed lines are reviewed.

Case Studies

A questionnaire has been prepared addressing the planning, design, construction, operation and maintenance aspects of a number of HVDC transmission lines around the world. The questionnaire has been sent to several utilities and companies operating transmission lines in the voltage range of ± 400 kV to ± 600 kV. The questionnaire is included as Appendix 5. Responses to the questionnaire were received for HVDC transmission lines operated by four utilities:

- Hydro Québec, Canada
- Manitoba Hydro, Canada
- FURNAS, Brazil
- POWERGRID, India
- ESKOM, South Africa

The experience of each of these utilities in planning, design, operation and maintenance of the lines is summarized below, based on the information received through responses to the questionnaire as well as on some published papers and reports.

Hydro Québec ±450 kV HVDC Line

The HVDC interconnection between Québec and New England evolved from a five-terminal system to a system that can be operated as either a three-terminal system or as two separate two-terminal systems. The main purpose of this interconnection has been to provide an asynchronous link capable of transmitting power up to 2000 MW from the Radisson station at the James Bay hydro-electric complex in northern Québec to Sandy Pond station in New England. The interconnection passes through an intermediate station at Nicolet in Québec. The HVDC transmission line from Radisson through Nicolet to the U.S border is about 1200 km long and has been designed, constructed and operated by Hydro Québec. The transmission line is mostly an overhead line except for a short section of underwater cable used to cross the St-Lawrence River in southern Québec, mainly to prevent an overhead river crossing from interfering with the scenic beauty of the popular tourist region. The interconnection has been in operation since 1990.

The choice of ± 450 kV for the bipolar HVDC line was based essentially on the economics of transmitting 2000 MW over a total distance of about 1600 km. Although the nominal operating voltage is the same for the line sections in Québec and New England, the line designs are not the same. The design and operational aspects of only the line section in Québec are described in this section.

Withstanding the switching surge overvoltages was the main criterion used to select the minimum conductor-tower and conductor-ground clearances, although environmental considerations such as corona, electric field and ion current effects also played important roles in the final choice of pole spacing and minimum height above ground of conductors. Pole spacing of 11 m and minimum conductor height of 12 m were selected for this line.

Selection of the conductor bundle was based on corona performance as well as practical and economic considerations. A bundle of four Bersfort (686 mm^2 ACSR 48/7, 35.6 mm diameter) or Bersimis (689 mm^2 ACSR 42/7 35.6 mm diameter) conductors, with a sub-conductor spacing of 457 mm, was selected on the basis of preliminary corona performance evaluations and because the bundle is largely used on 735 kV AC lines, giving very good field performance. The following corona performance criteria were established for the line design: RI level of 60 dBμ (dB above 1 microvolt/meter) and AN level of 55 dBA at the edge of the 60 m right of way (ROW); maximum values within the ROW of the ground-level electric field of 30 kV/m, ion current density of 100 nA/m^2 and ion density of 10^5 ions/cc. The positive pole is installed on the west side of this north-south line because the dominant wind blows generally from that direction, keeping most of the positive ions produced inside the right-of-way (ROW). Positive ions are generally suspected of a negative impact on people.

Although corona performance in general depends to a large extent on the conductor bundle selected, pole spacing and minimum conductor height have an important influence on the ground-level distributions of electric field, ion current density and ion density. Hydro Québec therefore carried out an investigation at its research institute IREQ to study the influence of line parameters on corona performance. The investigation was carried out on the outdoor test line facility of IREQ in two stages:

1. For a fixed pole spacing, the influence of conductor height on corona performance, and
2. For selected values of pole spacing and conductor height, the long-term statistical corona performance was obtained over a period of about one year.

The results of this study have shown (1) that the RI level was well below the design criterion and the AN level was close to the ambient. The maximum or L_5 values (defined as values exceeded 5% of the time) of ground-level electric field, ion current density and ion density were also within the design criteria set for this line.

In addition to the investigations carried out on the test line at IREQ, long-term statistical measurements of corona performance of the operating Des Cantons-Comerford ± 450 kV HVDC line of Hydro Québec were carried out at a measuring site near Ascot, Québec. Analysis of partial data obtained at the test site has shown that the maximum (L_5) values are as follows: electric field of 22 kV/m, ion current density of 32 nA/m^2, ion density of $52x10^3$ ions/cc, RI level at 15 m from positive pole of 46 dBμ and AN level at 15 m from positive pole of 46 dBA.

The isokeraunic level (IKL) experienced by the line varied between 20 in the south and 5 in the north and the line was designed for lightning outage criterion of 0.1 per 100 km-year. Two 12.5 mm steel ground wires, with a shielding angle of 20º were used for lightning protection. However, for the line section between Nicolet and Des Cantons, the ground wires were insulated and used as the electrode line because the existing ground electrode at Des Cantons is being used for purposes of DC grounding at Nicolet. For this section, two Curlew ACSR conductors, 30 mm diameter, were used as ground wires. The tower footing resistance was less than 25 Ω. Counterpoises are used in the northern part of the line. The line traverses terrain that is almost at sea level, the altitude being less than 500 m.

Porcelain or glass insulators conforming to specified performance criteria were used for insulation on this line. The critical withstand levels for the insulator string under lightning, switching and direct voltages were specified as 1950 kV, 1175 kV and 550 kV respectively. An RIV level of 1000 μV at 1 MHz at an applied voltage of +500 kV was also specified. Pollution surveys along the line route as well as field and laboratory tests at IREQ on different types of insulators were the basis for selecting the number and type of insulators in the string for use on the line. Double insulator strings in V-configuration, with an overall leakage distance of 14 m (specific leakage distance of 3.11 cm/kV) are installed. The insulators were tested, according to IEC 507, to determine that the critical withstand voltage under salt fog conditions of 5g/l was at least 550 kV.

Detailed studies had confirmed that guyed towers were the most economical solution for the Hydro Québec ± 450 kV HVDC line (2). However, in farmlands in the southern region of Québec, only self-supporting towers were used to minimize loss of land at tower locations. Counterpoises are also avoided in farmlands for practical reasons. Consequently, two families of towers were designed and used: guyed towers in the northern region and self-supporting towers in the southern region. Figure 5-1 shows a typical self-supporting tower structure.

Some outages were reported for this line due to pollution and ice melting. Pollution flashovers were also experienced on the line-to-cable junction of the St-Lawrence River cable crossing and required the application of silicone grease, particularly on the positive pole bushing.

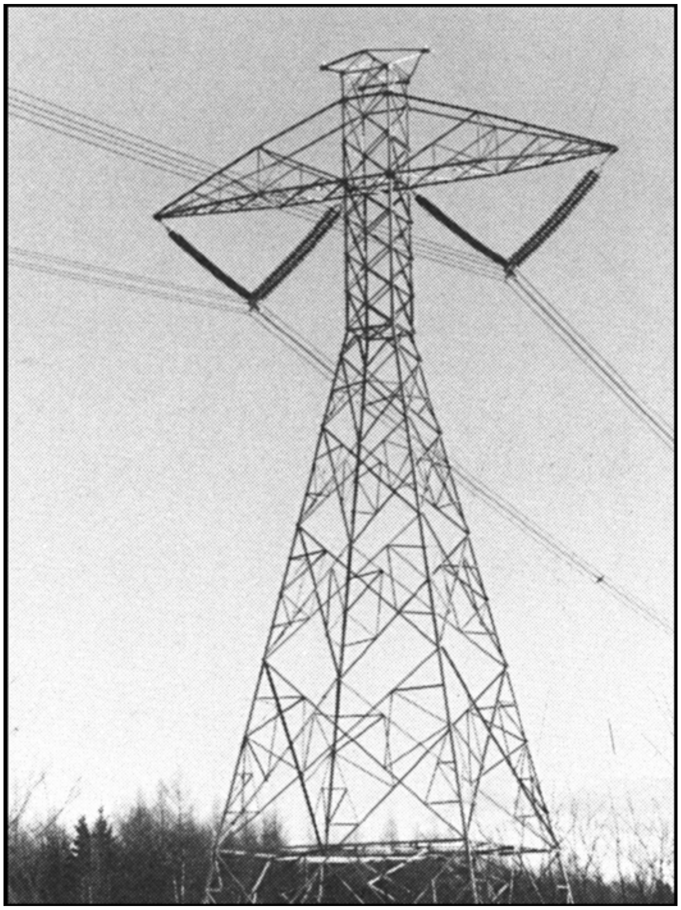

Figure 5-1
Hydro Québec Self-Supporting ±450 kV Tower

Nelson River ±500 kV HVDC Lines

The Nelson River HVDC transmission system of Manitoba Hydro in Canada transmits electric power from the hydroelectric power stations on the Nelson River in northern Manitoba over a distance of about 900 km to the city of Winnipeg in southern Manitoba. The HVDC transmission comprises two bipoles: Bipole 1 used mercury-arc valves, was rated at 1688 MW, ± 463.5 kV, 1800 A and went fully into service in 1977; Bipole 2 used thyristor valves, was rated at 1800 MW, ± 500 kV, 1800 A and its first stage at ± 250 kV was put into commercial operation in 1978. Operation of Bipole 2 at its full rated capacity started in 1985. The mercury-arc valves of Bipole 1 were gradually replaced by thyristor valves with pole 1, completed in 1993 and pole 2 completed in 2004.

The choice of HVDC for this line and the operating voltage of ± 463.5 kV were based on the economics of long-distance bulk power transmission. Selection of air gap clearances for the line was based on switching surge voltage of 1.7 p.u and the standard safety requirements. The choice of 13.4 m (44 ft) for the pole spacing involved considerations of ROW width, conductor clearances to tower and corona loss. The minimum height above ground of conductors was selected as 8.9 m (29 ft), based mainly on safe clearances to vehicles. Ground-level electric fields and ion currents were not considered in the choice of minimum conductor height.

A two conductor bundle, with 1.6" (4.06 cm) diameter ACSR conductors and a bundle spacing of 18" (45.7 cm), was selected taking into account current carrying capacity, I^2R losses and corona performance. Each conductor is capable of carrying 1800 A at a maximum design temperature of 123ºC (254ºF), equivalent to 3600 A per pole. The conductor bundle selected meets, therefore, the requirement that under emergency conditions any pole remaining in service must be able to transmit twice its normal capacity of 1800 A.

Initial studies on the corona loss and RI performance of this conductor bundle were carried out on the test lines of the National Research Council (NRC) of Canada (3). Following construction of the Nelson River HVDC transmission lines, NRC in collaboration with Manitoba Hydro carried out RI measurements at several locations along the length of the line during the period between 1974 and 1978. At the same time as the RI measurements in 1978, system operators were able to arrange power transmission for short periods of time in such a manner that corona losses from the whole length of the line could be measured (4). Results of this study have shown that early predictions of RI and CL obtained using the test lines at NRC were reasonably accurate.

An evaluation of the environmental effects of the Nelson River HVDC lines in operation, including the RI, AN, ground-level electric field, ion current density and ion density, was carried out by Manitoba Hydro in collaboration with IREQ over a few days in September 1979 (5). The main objective of this study was to provide much needed data on the electric field and ion current performance of operating HVDC transmission lines. The two bipolar lines of Nelson River transmission run parallel on the same ROW at a minimum spacing between the lines of 65 m. The ROW width varied between 112 m to 127 m. The two bipoles operate in the “bipole crossover connection” mode (6), with the two negative poles on the outside and the two positive poles on the inside. Such an arrangement is advantageous from the point of view of the RI and AN levels at the edge of the ROW, since on HVDC lines corona-generated RI and AN from the positive pole are much higher than those from the negative pole. For bipolar operation of the line at ± 450 kV, statistical analysis of a large number of measurements obtained in this study has shown that the maximum electric field was 20 kV/m, compared to the space-charge-free electric field of 14 kV/m, and the maximum ion current density was 70 nA/m^2. For ± 450 kV operation, the RI and AN levels at 15 m from the outer conductor (negative pole) were 45 dB at 1 MHz and 40 dBA respectively.

In addition to the short-duration studies mentioned above, Manitoba HVDC Research Center has carried out a comprehensive long-term study, from 1990 to 1993, of the electrical environment of the Nelson River HVDC transmission lines (7). Most of the measured data were obtained with Bipole 1 operating at ± 450 kV and Bipole 2 at ± 500 kV. Statistical analysis of the data obtained over this four year period has revealed that the maximum values (L_5) of the electric field under the positive & negative poles respectively were 20 kV/m & 26 kV/m in fair weather and 31 kV/m & 34 kV/m in foul weather. Similarly, the maximum values of the ion current density under the positive & negative poles respectively were 74 nA/m^2 & 50 nA/m^2 in fair weather and 85 nA/m^2 & 87 nA/m^2 in foul weather.

The IKL along the route of the Nelson River lines varied between 25 in the south and 10 in the north. A single ground wire with a shielding angle of 35º was used on each bipole. The earth resistivity varied in the range of 100 Ω.m to 2000 Ω.m. The tower footing resistance was typically less than 5 Ω. In areas of high ground resistivity, counterpoise wire was used to bring down the tower footing resistance to below 30 Ω. With the overhead ground wire, the lightning outage rate was expected to be 2 flashovers/year/100 miles, while without the ground wire it was expected to be 23.

Insulators with deep skirts and with a high ratio of leakage distance to spacing were used on the lines. Selection of the number and type of insulators in the string was based on tests carried out with cement contamination at the BPA HVDC test center. The specific leakage distance was 2.29 cm/kV.

The altitude along the line route varied between 80 m and 230 m above sea level. The line experiences wind, ice and tornadoes and, therefore, weather was very important in line design. The basic tower configuration for the lines was a guyed single-mast steel structure on tangents and light angles. Conventional self-supporting towers were used for heavy angle and dead-end towers. Figure 5-2 shows the two Nelson River bipolar HVDC transmission lines.

The lightning outage performance of the lines has been good and practically no outages were reported due to switching surges. There have been no known outages due to pollution flashovers on these lines, although there were many in the converter station on wall bushings and a few on support insulators. During the normal operation of the lines, some glass insulators were shot off by rifle fire and all the spacer dampers had to be replaced. There were two incidents where the HVDC system was suspected of causing RI. However, after an investigation, one proved to be an arcing distribution insulator and the other caused by 11th harmonic resonance in distribution circuits. Live line maintenance was used in the past but has been stopped pending reviews of a flashover on a 500 kV AC transmission line.

Figure 5-2
Nelson River HVDC Transmission Lines

FURNAS ±600 kV HVDC Line

The Itaipu hydroelectric power station was a Brazil-Paraguay joint venture with a total installed capacity of 12,600 MW, most of which was transmitted to Southeastern Brazil. Due to the difference in frequencies of the two countries, half the generation is at 50 Hz (Paraguay) and half at 60 Hz (Brazil). FURNAS was given the responsibility to study, design, construct, own and operate the transmission system from Itaipu power station to the South/Southeast region of Brazil. Extensive technical and economic studies (8) have shown that the optimum solution was a hybrid system with half the power generated by the nine 60 Hz generators transmitted by AC lines and the other half by the nine 50 Hz generators transmitted by HVDC lines. A small part of the 50 Hz power is retained for use in Paraguay. The studies have also indicated that 750 kV AC and ± 600 kV DC were the optimum transmission voltages.

Two ± 600 kV HVDC bipoles were required for transmitting the 6,300 MW of power. The two bipoles were designed to operate independently of each other under normal conditions. The two bipolar lines, each approximately 800 km long, follow separate routes, at least 10 km apart and each line can carry the rated output (6,300 MW) of the station using the facility of parallel operation of converters. The two lines went into full rated operation in 1990.

Although the air gap clearances were based on switching surge withstand criteria, the performance of the selected tower configuration was verified under the expected switching and lightning overvoltages as well as the normal operating voltage. For maximum switching surge overvoltage in the range of 1.7 – 2.0 p.u, the risk of failure was estimated between 0.02% and

0.5%. Live line maintenance was also taken into account in finalizing the tower dimensions. The conductor-tower clearance was determined for a wind speed of 136 km/h. Minimum values of pole spacing and height above ground were 15.4 m and 13 m respectively.

A bundle of four Bittern ACSR (45/7) conductors of 34.12 mm diameter, with a sub-conductor spacing of 45.7 cm, was selected on the basis of acceptable corona and electric field performance of the line. The line was designed to achieve a radio signal to noise (S/N) ratio of 17 dB and a maximum AN level of 40 dBA at the edge of the ROW. The criterion for the maximum ground-level electric field, including the space charge influence, was 40 kV/m under normal conditions. No experimental studies were carried out to verify the corona and electric field performance of the line.

The two FURNAS bipolar HVDC lines are located in the States of Paraná and São Paulo. Although an IKL of 70 was used in the initial design of the lines, since the end of 1998 FURNAS has joined a Lightning Detection Network named RINDAT, comprising 26 sensing stations. From the data obtained by this network, the following lightning flash densities were obtained: 2.1 flashes/(km^2.year) in the region between Foz do Iguaçu to Paraná and part of São Paulo, 5.1 flashes/(km^2.year) in the Southeast region of São Paulo and 7.6 flashes/(km^2.year) in São Paulo near Ibiuna. Two galvanized steel wires with a protective angle between 0º and 10º were used for lightning protection. The lines pass through a region with average ground resistivity of 1500 Ω.m. A counterpoise of No. 4 BWG galvanized steel wire or No. 6 copperweld wire were used to bring the average tower footing resistance to 20 Ω. The lightning outage rate of the line was expected to be 1-1.5 outages/km.year. The lines pass through a region with an average altitude of about 800 m and a maximum altitude of about 1000 m above sea level.

Line insulation was provided by I strings of 30 glass disc insulators, each with dimensions of 320 mm x 170 mm and with a leakage distance of 510 mm. The specific leakage distance was 2.5 cm/kV.

The lines were built with 80% guyed and 20% self-supporting towers. Although not designed according to IEC criteria, both lines of the FURNAS HVDC system may be considered to be in compliance with Class 1 of IEC 60826. The ROW of each line is 72 m. Figure 5-3 shows a photograph of the FURNAS ±600 kV HVDC transmission lines.

Figure 5-3
FURNAS ±600 kV HVDC Line

The line routing was based on the following considerations:

i) Reduction in the length of the line, deflections in the line and of interferences with existing obstacles and projected obstacles;

ii) Easiness of access to the line;

iii) Search for a smooth relief line route, the best points of crossing with rivers, roads, lines, telecommunication lines, dams, pipe-lines, gas-lines, etc and for the reduction of parallelism with rivers, roads, lines, telecommunication lines, dams, pipe-lines, gas-lines, etc;

iv) To avoid airports areas and extreme deforestation;

v) To increase the reliability of the system, the bipole 1 was located to the south of the preexisting 750 kV AC lines and the bipole 2 was located to the to the north;

vi) Each one of the bipoles kept a minimum distance of 10km in relation to the two 750 kV AC lines;

vii) In addition to the route of the bipoles, it was also necessary to determine the route of the ground electrode lines.

Early operating experience indicated (9) that the performance of the ±600 kV HVDC lines was generally very good. In the three year period between 1994 and 1996, there were a total of 51 faults, of which only 12 did not restart with success. More recent operating experience has been as follows: about 5 lightning outages in 2006; 51 line outages due to switching surges during the period between 2000 and 2005, of which 48 were monopolar and 3 were bipolar. One line outage was attributed to polluted insulators. In addition, there were other outages due to mechanical failure of hardware, corrosion problems, tower collapses related to high wind speed and flashovers between the conductors and nearby vegetation. The insulator pollution flashover occurred in the vicinity of a cement factory and application of silicone grease to the insulators solved the problem.

The lines were inspected three times a year, including aerial inspection by helicopter, land inspection with tower climbing and quick land inspection without tower climbing. Live line maintenance techniques and tools similar to those on AC lines were used on the DC lines. The tools used were fiberglass sticks, chair, stairs, strain carriers and insulator cradles. Both bare-hand and hot-stick methods of live line working were used. Since the safety distance at 600 kV DC was 5 m, the bare-hand method was used much more than the hot-stick method.

POWERGRID ±500 kV HVDC Lines

POWERGRID is the largest bulk power transmission company in India, responsible for high voltage AC and DC interconnections between the different regions of the country. The first ±500 kV, 1500 MW, 840 km long HVDC transmission lines between Rihand and Dadri (near Delhi) was commissioned in 1991. Subsequently, one more ±500 kV, 2000 MW HVDC interconnection was built between Talcher-Kolar which is operational for the last 5 years. The total length of ±500 kV HVDC transmission lines presently in operation by POWERGRID is about 4370 circuit-km. A third ±500 kV, 2500 MW, 800 km HVDC link between Ballia and Bhiwadi is under installation and is likely to be commissioned by June 2009.

The main purpose of the ± 500 kV HVDC transmission lines in India was bulk power transmission over long distances. Talcher-Kolar HVDC link served as asynchronous connections for controlled power transfer and stability control. The choice of the line voltage was based initially on technical and economic considerations, but for several lines built subsequently it was also based on the experience gained with the first ±500 kV line.

Conductor-tower clearances were adopted based on insulation withstand considerations under switching surge and normal operating voltages. In addition to air insulation and safety, conductor to ground clearance and pole spacing were selected taking into account the ground-level electric field and ion current density. Clearances for live line maintenance were also considered in the tower design. Pole spacing of 12.75 m and minimum conductor height of 12.5 m were used for the Rihand-Dadri line, while the pole spacing for the Talcher-Kolar line varied between 12.5 m and 13.5 m.

Selection of the conductor bundle was based on corona performance as well as technico-economic considerations. A bundle of four Bersimis ACSR (42/7) conductors of 35.05 mm diameter and a sub-conductor spacing of 45.7 cm was selected for POWERGRID's ±500 kV HVDC lines. Taking into account international practices and the comparative levels of 400 kV AC transmission lines operating in the country, the following design criteria were adopted for the corona performance: fair weather RI level of 48 to 50 dB; AN level of 55 to 58 dBA under wet conductor conditions; space-charge-free electric field of 40 kV/m and ion current density of 100 nA/m^2 at ground level. The above design criteria were applied by theoretical calculations using existing empirical methods. No experimental studies were carried out to verify the corona performance of the lines.

The IKL in the regions traversed by the ±500 kV lines was less than 60. Two galvanized steel ground wires of 11 mm diameter were used to provide a shielding angle of 10º for lightning protection. Adequate grounding was provided to keep tower footing resistance to below 10 Ω. The terrain of the line route has altitudes above sea level less than 1000 m and is characterized by hot and humid weather conditions, with foggy conditions occurring in winter in some areas.

Antifog porcelain and glass insulators were specified for the ±500 kV HVDC lines. Suspension V string insulators were used on suspension towers, while quadruple tension strings were used on the tension towers. Based on experience with AC transmission lines in the vicinity, satisfactory pollution performance at an ESDD of 0.45 mg/cm was the criterion for selection of the number and type of insulators in the string. The number of discs used in the string on the Rihand-Dadri line were 38, with a total leakage distance of 20,520 mm (4.1 cm/kV), while on the Talcher-Kolar line they were 41, with a total leakage distance of 22,140 mm (4.5 cm/kV). Solid layer pollution tests according to IEC 61245 were carried out to verify conformity of the performance of the insulators to the specifications.

Self-supporting lattice steel tower structures were used for the ±500 kV HVDC lines. The towers were designed for a limit wind load of 104 kg/m^2 on full projected area on conductors and earth wires. Figure 5-4 shows a photograph of POWERGRID ±500 kV HVDC line.

The operational experience has been generally satisfactory except for the insulator performance in polluted conditions (10). The number of transient faults due to pollution flashover increased during 1992-1995 and then decreased in subsequent years because of an annual program of manual cleaning of insulators in polluted areas with wet cloth, installation of bird guards, reduced voltage operation etc. Investigations are also being carried out to study the feasibility of hotline washing of insulators and the use of polymer insulators.

Figure 5-4
POWERGRID ±500 kV HVDC Line

ESKOM ±533 kV HVDC Line

The Cahora Bassa-Apollo HVDC transmission scheme transmits power from the hydroelectric power station at the Cahora Bassa dam in Northern Mozambique to the Eskom network in South Africa. Of the 2000 MW generated power, about 500 MW can be transmitted via a 330 kV AC line to Zimbabwean transmission network while the remaining power is converted to DC and transmitted about 1440 km via two monopolar HVDC transmission lines separated by 1 km and operating at +533 kV and – 533 kV to the Apollo inverter station about 50 km from Johannesburg. Commissioned in three stages, full commercial operation began in 1979. However, since 1985 power transmission has been interrupted due to damage brought about by civil war in Mozambique (11). The scheme has been re-commissioned in 1997.

The main purpose of this HVDC interconnection was to economically transmit a large block of power over a long distance and across international borders. Based on considerations of technical feasibility, the range of ±400 kV to ±600 kV was selected for economic evaluation and the voltage ±533 kV was chosen as the economically optimum voltage.

The operating direct voltage as well as switching and lightning overvoltages were taken into account in the insulation design of the line. Since the two poles of the bipolar ±533 kV HVDC line are located 1 km apart, they can be considered as two monopolar lines from the point of view of insulation and corona performance. To some extent, fire and power line carrier propagation have influenced the choice of the large pole spacing for this line. The minimum height of conductors above ground was 8.55 m and the minimum clearance from live metal to earth in still air was 3.65 m.

Although the total conductor cross section was selected on the basis of minimum total cost (material cost + cost of losses), the conductor bundle was chosen based on corona performance criteria: corona losses, RI (60 dB above 1 μV/m @ 1MHz at the edge of the ROW), AN (42 dBA at the edge of the ROW) and power line carrier noise. A bundle of 4 ACSR conductors of 31.8 mm diameter was selected based on corona performance criteria.

Statistical variations in ground flash density, stroke current parameters, DC polarity, soil resistivity and tower height were all considered in evaluating the lightning performance of the two monopoles. An insulated earth wire, therefore called a shield wire, was used for lightning protection. The shield wire consisted of an ACSR conductor 17.6 mm in diameter, located at a minimum distance of 10.5 m from the conductors at the tower. A porcelain suspension insulator was used to insulate the shield wire from ground. A double shield wire was used for the first few towers from the station.

Toughened glass insulators, manufactured and tested in accordance with IEC Publication No. 87-1957, were used on this line. The shank of the insulator pin was provided with an alloy ring to protect against possible electrolytic corrosion. The number of insulators in the string varied from 24 at altitudes less than 500 m to 28 at altitudes above 1250 m. The average specific leakage distance was 2.5 cm/kV. Polymeric insulators with good pollution performance are presently being used to replace the older glass insulator strings.

Since the line consists essentially of two monopolar lines with a large separation between them, pyramidal lattice steel structures with a single cross arm and a shield wire on top were used. The line traversed regions with altitudes varying in the range of 250 m to 1550 m.

No major failures were experienced on the line in South Africa. Some glass insulators were damaged but were quickly repaired. No information is available on outages due to polluted insulators, although pollution problems are suspected in some of the unexplainable line faults. Polymeric insulators are used as replacements in suspected areas. Inspections are carried out using both ground patrols and helicopters. Some complaints were received on static shocks from fences and metal installations close to the HVDC lines, probably caused by corona-generated space charges from the lines conductors.

Review of Design Practices and Operating Issues

In all the cases surveyed, the choice of HVDC transmission was based on technical and economic considerations for transmitting large blocks of power over long distances. Additional considerations that influenced the choice of HVDC transmission were the need for providing an asynchronous link between Québec and New England in the case of the Hydro Québec line and the transmission of power generated at two different frequencies in the case of the FURNAS line. In the cases of FURNAS and Nelson River HVDC systems, two bipolar DC lines were required to transmit the full amount of power generated to the load centers. POWERGRID used a number of HVDC lines to interconnect the regional power grids in India.

Four of the five lines surveyed use horizontal bipolar conductor configurations. The two Nelson River lines share the same ROW, with a minimum spacing between the lines of 65 m, while the two FURNAS lines share two separate ROWs at least 10 km apart. The Cahora Bassa line is made up of two monopolar lines separated from each other by 1 km. Some of the main parameters defining the lines surveyed are summarized in Table 5-1.

The overall operating experience of the five lines surveyed is reported to be generally satisfactory. The most common problem reported is pollution flashover of line insulators, although it is still less serious than that of converter station wall bushings. During the winter season in Québec, problems of insulator flashovers due to the combined effect of pollution and icing were reported on the Hydro Québec line. In addition to pollution flashovers of insulators, considerable number of flashovers due to switching surges and a few due to lightning were reported in the FURNAS lines operating at the highest voltage. Pollution flashover incidents were reported to have been reduced on POWERGRID lines by hand washing of the insulators using a wet cloth, by installing bird guards and through reduced voltage operation. FURNAS reported satisfactory experience with live line maintenance of the lines using both bare hand and hot stick methods.

Table 5-1
Summary of the Main Parameters of the Lines Surveyed

Parameter	Hydro Québec Line	Nelson River Line	FURNAS Line	POWERGRID Line	ESKOM Line
Voltage, kV	±450	±500	±600	±500	±533
Power, MW	2000	1688, 1800	6300	1500, 2500	2000
Pole Spacing, m	11	13.4	15.4	12.5 – 13.5	1000
Conductor Height, m	12	8.9	13	12.75	8.55
Conductor Bundle	4x35.6 mm dia	2x40.6 mm dia.	4x34.12 mm dia.	4x35.05 mm dia.	4x31.8 mm dia.
Number of Insulators	29	21	30	38 – 41	24-28
Specific Leakage Distance, (cm/kV)	3.11	2.29	2.55	4.1 – 4.5	2.5
Criteria for conductor selection	Corona	Corona & current carying capacity	Corona	Corona	Corona
Criteria for electrical clearances	Switching surges	Switching surges (1.7 p.u)	Switching surges (1.7 p.u)	Switching surges	Switching Surge
Operating experience	Good Occurrence of pollution & ice-melting failures	Good	Good Occurrences of tower collapses & few lightning & switching surge failures	Satisfactory, except for pollution failures in spite of higher leakage distances	Good

* Conductor height determined on the basis of environmental considerations.

Appendix A5

EPRI HVDC 800 kV PROJECT

QUESTIONNAIRE ON TRANSMISSION LINES

Please answer the questions that you can and briefly. Alternatively please send any reports that contain information on your HVDC Transmission Line.

A. Planning Considerations

1. What planning considerations have influenced the choice of HVDC for this interconnection?

    a) Distance
    b) Different frequencies
    c) Economics
    d) Other (explain if possible0

2. What were the factors considered in the choice of the transmission voltage?

    a) Standard
    b) Technical or strategic (future integration etc)
    c) Economic
    d) Other

3. Has the transmission voltage been upgraded from the initial choice? If yes, explain why.

B. Electrical Design

1. What overvoltage criteria were used to select the conductor-tower and conductor-ground clearances?

    a) Switching surge
    b) Lightning surge
    c) Operating voltage

2. What other considerations were taken into account in the choice of pole spacing and conductor height?

3. What lightning outage criteria were used in the line design?

4. Were any ground wires used? If so, how many and what type of wires were used and what was the basis of their selection?

5. What types of insulators, (disc/long rod, porcelain, glass or non-ceramic) were used and what were the reasons for the choice?

6. What pollution performance criteria were used to select the number and type of insulators?

7. Were any surveys made on the type and severity of pollution along the line route? If so, how were the survey results used in selecting the insulators?

8. Were laboratory pollution tests used as a basis for selection of the type and number of insulators?

9. What were the specific leakage distances (cm/kV) of the insulators selected? Have different specific leakage distances been selected for regions with different severities of pollution?

10. What insulator profiles were selected?

    i) Disc insulators with
        a) Under ribs
        b) Outer ribs
        c) Spherical profile
        d) Aerodynamic profile

    ii) Long rod with
        a) Uniform sheds
        b) Alternate sheds

11. What were the criteria used for the selection of the conductor bundle? Specifically with reference to corona performance, what criteria were used for acceptable radio interference (RI) and audible noise (AN) levels?

12. What prediction methods were used to calculate RI and AN levels of the line?

13. What criteria were used for the ground-level electric fields and ion currents under the line? What methods were used to predict the electric fields and ion currents?

14. Have any tests been performed to determine the corona performance, in terms of the RI, AN and ground-level electric fields and ion currents, of the line configuration?

15. Was prevention of corona on the ground wires a consideration in line design?

16. Were any other electrical criteria used in the line design?

17. If the transmission voltage has been upgraded from the initial choice, how was the line design modified and implemented?

C. Conductor Bundle Configuration

1. Number of sub-conductors
2. Sub-conductor diameter
3. Bundle diameter

D. Bundle Conductor Vibration Control

1. Whether spacer-damper or a combination of spacer and damper installed?
2. Whether field performance tests carried out for selection of damping system?
3. Whether fatigue failures observed on conductors?

E. Special Design Considerations

1. What were the reliability levels selected for the line: Security class I, II or III (Ref. IEC 60826)?
2. At what altitude does the line operate and was altitude a design consideration?
3. What type of terrain does the line traverse (Terrain category I, II or III, Ref. IEC 60826)?
4. What IKL's or other lightning incidence indicators are experienced by the line?
5. What types of weather conditions (wind, ice, cyclones/tornadoes) does the line experience? How important was weather in line design?
6. What ground resistances does the line experience?

F. Operation and Maintenance

1. What has been the line outage experience due to:
   a. Lightning?
   b. Switching surges?
   c. Polluted insulators?
   d. Other (Structural failure, fatigue failure etc.)?
2. Were the outages due to insulator pollution in anyway correlated with the prevailing pollution severity?
3. Were any techniques (washing, application of silicone grease, etc.) used to improve the performance of insulators under conditions of pollution? If so, what were the techniques used?

4. How often were the conductors, hardware and insulators inspected and what techniques of inspection were used?

5. Have any failures occurred during the normal operation of the line and have any of the original insulators, hardware etc been replaced because of poor performance?

6. Have there been any complaints from the public regarding RI, AN, ground-level electric fields and ion currents, visual impact or other factors? If so, how were they resolved?

7. Have live line maintenance techniques been used on this line? If so, what materials and methods were used?

G. Physical Characteristics

1. Please provide drawings and photographs of the line.

2. Please provide the electrical characteristics of the line.

3. Please provide any information that would be useful in the discussion of line routing.

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6
CONVERTER STATION DESIGN AND LAYOUT

Introduction

The layout and design of an 800 kV converter station is dependent on the configuration of the valve groups. In chapter 2, two possible and practical configurations were discussed:

Two 12-pulse series connected valve groups of equal rating per pole. Each 12-pulse vale group will consist of two 6-pulse valve groups in series with one connected to wye-wye transformer and other connected to wye-delta transformer. Both groups operate together as a 12-pulse group and 6-pulse operation is not allowed.

Two parallel connected 12-pulse valve groups that may or may not be equal in rating per pole. As above, each 12-pulse vale group will consist of two 6-pulse valve groups in series with one connected to wye-wye transformer and other connected to wye-delta transformer. From a transformer design point of view it appears that the preferred connection for the upper transformer is a Delta. This gives a greater number of turns on the valve winding and hence allows the designer a greater degree of impulse voltage distribution control for the winding. Both groups operate together as a 12-pulse group and 6-pulse operation is not allowed.

In the following sections the layout and design of the converter stations will be discussed.

Two Series Connected Valve Groups in Each Pole

Converter Building Layout

In this case the assumption here is that the two 12-pulse valve groups in series have equal rating. This means that each 12-pulse valve group is rated for 400 kV DC across its terminals and both groups are obviously rated for the same DC current because of the series connection. However, one 12-pulse group will be insulated at 400 kV from ground and the other 12-pulse group will be insulated at 800 kV from ground.

Certainly this type of arrangement affects the station design and layout. From a converter-building point of view each pole will consist of two adjacent totally independent valve halls, one each for the 12-pulse valve groups. However, the clearances and creepages to ground in the low voltage valve hall will be designed for 400 kV, and for the high voltage valve hall will be designed for 800 kV. The bus work as well as all other equipment insulation levels will be designed accordingly. Naturally, the 800 kV valve hall will be bigger and taller than the 400 kV valve hall.

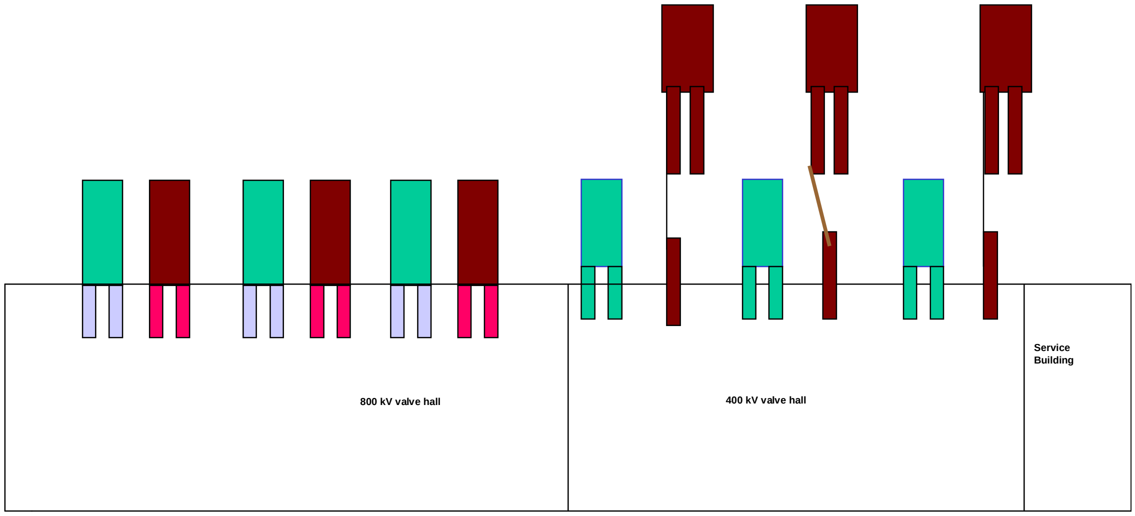
It is interesting that although the clearance and creepage requirements are very important, one of the factors that will influence the width of each valve hall will be the dimensions and orientation of the converter transformers if the valve winding bushings of the transformers are to protrude into the valve hall. As indicated in Chapter 2 the transformers will be designed as two winding single-phase units.

In the layout various options may be adopted depending upon the pollution level of the converter stations and area availability.

- In the case of the lower voltage 12-pulse valve group (400 kV to ground), the converter transformer bushings may or may not protrude into the valve hall and wall bushings may be used.
- Another alternative for the low voltage group is to allow only the 400 kV transformer bushings to protrude into the valve hall for connection to the upper 6-pulse valve group, and use wall bushings for connecting the 200 kV transformer bushings to the lower 6-pulse valve group.
- All the transformers for the 400 kV 12-pulse converter group may be placed outside valve hall and wall bushings may be used for connecting both wye and delta converter transformers to the two 6-pulse valve groups. The spare transformers (one for delta and one for wye) may also be placed along with the main transformers so that in case of any eventuality, the spare can be taken into operation within 4-6 hours.

In the case of the high voltage12-pulse valve group (800 kV to ground), it is recommended to put the valve winding bushings of the transformers through the wall of the valve hall and avoid the use of wall bushings, this is important and critical to avoid external flashovers on the bushings if they were outdoor. This applies to both 600 kV and 800 kV bushings. In figures 6-1 and 6-2 the layout of the converter buildings for both scenarios is shown.

It is clear from figures 6-1 and 6-2 that valve hall dimensions are impacted by the transformer dimensions as well as the layout being adopted. However, it should be kept in mind that the height of the valve hall and clearances to the floors will be different between the high voltage group and the low voltage group.



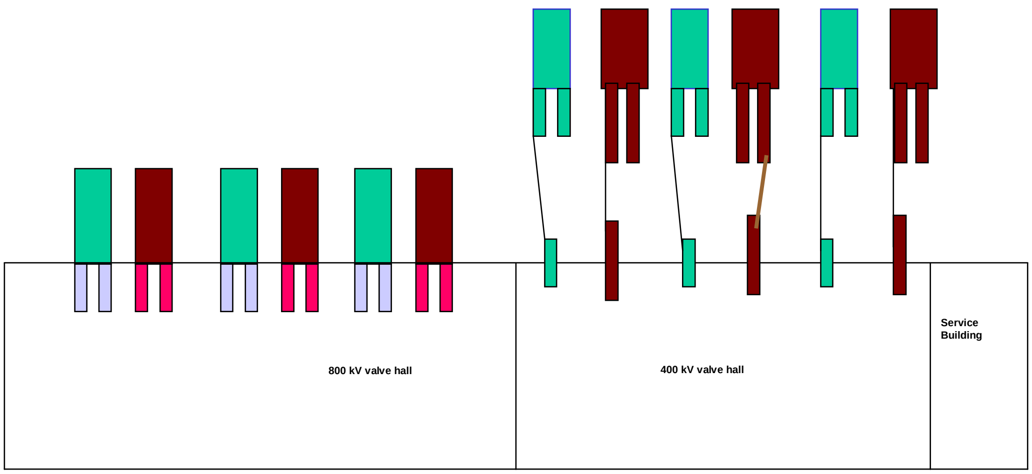


Figure 6-1
Converter Building Layout for One Pole of Two Series Connected Groups. Low-Voltage Valve Group Uses Wall Bushings either Partly or Fully

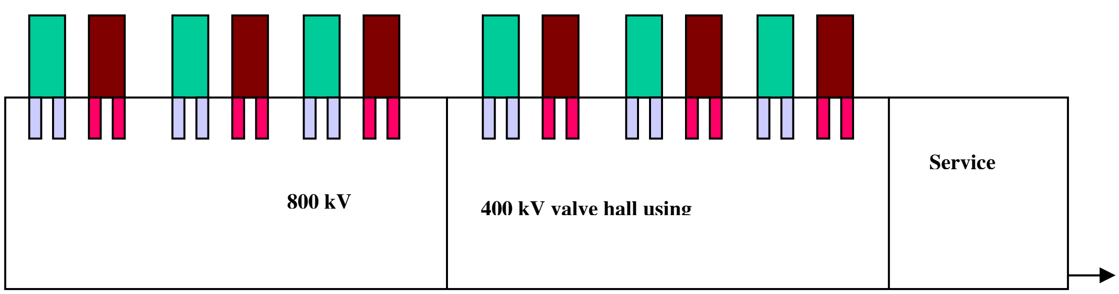


Figure 6-2
Converter Building Layout for One Pole of Two Series Connected Groups. Low-Voltage Valve Group uses Transformer Bushings through the Wall

Neutral Connection and Metallic Return Operation

In the series connected 12-pulse valve group arrangement, the neutral connection between the two poles would be very similar to the existing design of a single bipolar system. In fact, similar to the existing design, equipment such as surge arrestors, surge capacitors and the measuring equipment will be located at the neutral busbar of each pole. It also seems that in the design for the 800 kV systems there is a preference to have two smoothing reactor of half size and locate one half of the smoothing reactors in the low voltage neutral bus of the pole and the other half in the high voltage bus of the pole. This reduces the DC voltage across the valve groups. As far as the metallic return transfer breaker (MRTB) and the ground return transfer switches (GRTS) are concerned, there are no differences to the existing design and requirements except for the ratings. However because of the series connection of the valve groups and the mechanical bypass devices, the metallic return mode requires special switching capabilities in the pole switches. Figure 6-3 shows the general arrangement of the bipole at the rectifier.

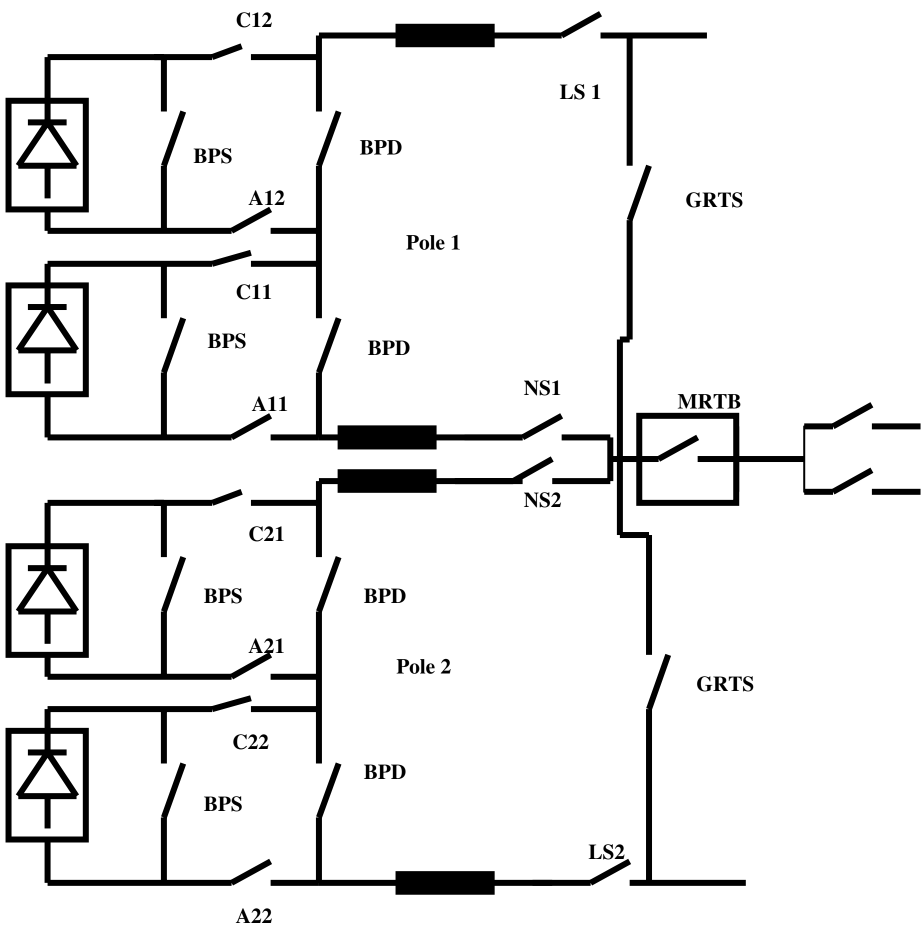


Figure 6-3
The Rectifier Single Line and Neutral Connection

In figure 6-3 when both poles are in operation in balanced bipolar mode then basically the following conditions exist:

All converter valves are deblocked.

LS1, LS2, NS1, NS2, MRTB, A11,C11,A12,C12, C21,A21,C22,A22 and the electrode lines disconnects are all closed.

GRTS in both poles, BPS and BPD in all valve groups are open.

If we now assume that pole 1 is tripped, then the pole 1 converters will be blocked (both valve groups), the groups are isolated meaning that both bypass disconnects for both valve groups are closed. However, the blocked and bypassed pole will be still connected to the DC line through LS1 and to the ground electrodes through the MRTB. It should be noted that the GRTS will be open. This situation is interesting, since the healthy pole will be operating in ground return with the majority of the current passing through the electrode line to the ground electrode. However because of the bypass disconnects being closed, there will be a spill current through LS1 to the line conductor of the shutdown pole. Although this may not be a very high current it will be significant for LS1 if we are interested in going into metallic return where we have to open LS1. The current in LS1 will be dependent on the ratio of the impedances between the main transmission line and the electrode line and the ground electrode.

If we consider the sequence for the use the metallic return, before any switching the majority of pole 2 DC current is passing to the ground electrode through the MRTB and a small percentage is through the bypass disconnects (BPD) of the shutdown pole and through LS1 to the DC line. If we close the GRTS, then the DC current to the metallic conductor is split between the GRTS and the path formed by the two BPD and LS1. Now we need to open LS1 and commutate this current only to the GRTS path. Therefore either LS1 has to have special switching capability to commutate this current that is passing through the smoothing reactor from LS1 path to the GRTS path or if we can deblock at lease one converter in force retard to extinguish this current and open the switch. Once this is achieved then the MRTB can be opened and the current is fully transferred to the metallic conductor.

In order to switch from metallic return to ground return, the MRTB will close which establishes the DC current in the electrode line and ground electrode. The line switch LS1 can be closed which establishes a parallel path to the GRTS through the smoothing reactor and the BPD of the two blocked valve groups. This again requires a special design and rating for LS1 unless the one of the valve groups in the blocked pole can be deblocked into force retard.

Two Parallel Connected Valve Groups in Each Pole

Converter Building Layout

In this case the two converter poles are connected in parallel at 800 kV, this is an interesting configuration because one can deal with it as two independent bipoles connected in parallel or as one bipole with each pole consisting of two converters in parallel. No matter how it is considered, in principle the converters from a DC voltage consideration are all identical since they are all connected between 800 kV on the high voltage DC side and ground on the low voltage side. If the parallel converters are not equal in rating then only the DC current will be different. In the parallel converters both rectifiers can be at the same site or separated to two different sites by a DC line segment as shown in figures 6-4 and 6-5(a),(b). The same will apply to the inverters, both can be at the same site or separated to two different sites. The parallel connection whether located at common sites or separated by DC line segments is in principle a multi-terminal HVDC system. The difference will be the communication requirements and the fact that if located at both sites, the AC system is common. However from a valve hall point of view, all the converter buildings will look the same with 800 kV clearances. In this configuration it is recommended that all the transformer bushings go through the wall of the valve hall. This type of valve hall is similar to most of the current design of one 500 kV converter per pole valve hall except with 800 kV clearances as shown in figure 6-6.

In the parallel connection, even though each valve hall is separate, still the typical arrangement of two valve halls with a service building in between can be adopted.

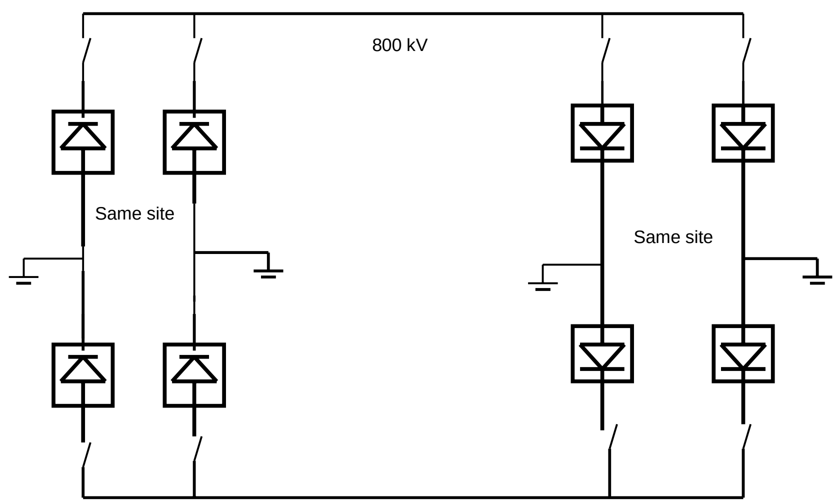
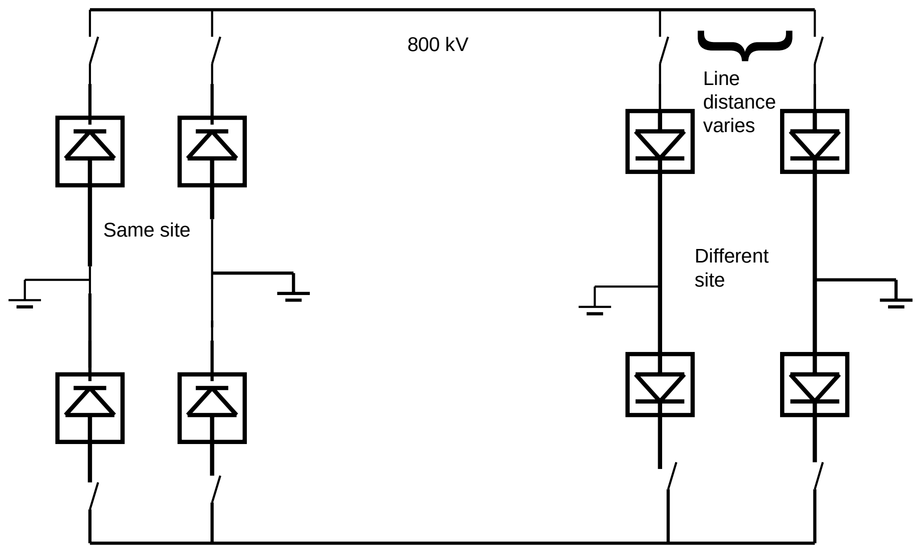
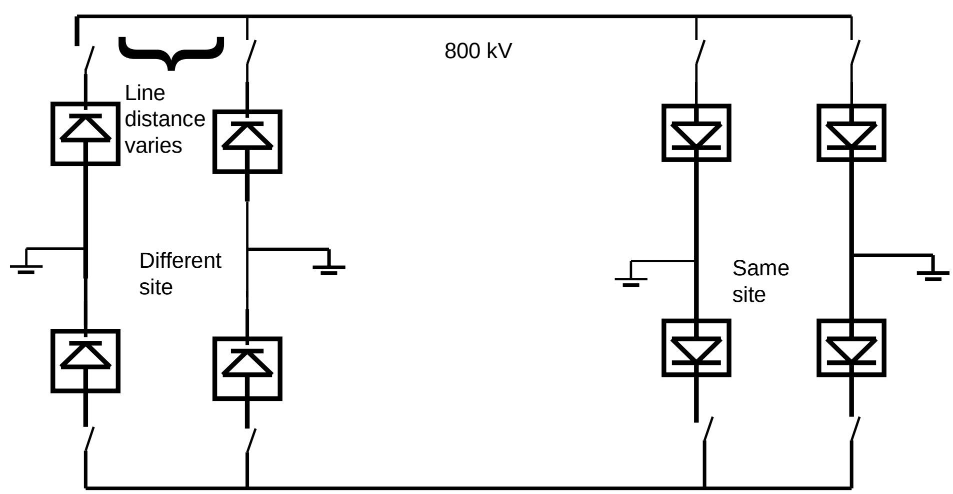


Figure 6-4
The Rectifiers and Inverters Located at the Same Sites



(a)



(b)

Figure 6-5
(a) The Rectifiers Located at the Same Sites and Inverters Located at a Distance;
(b) The Rectifiers Located at a Distance and Inverters Located at the Same Site

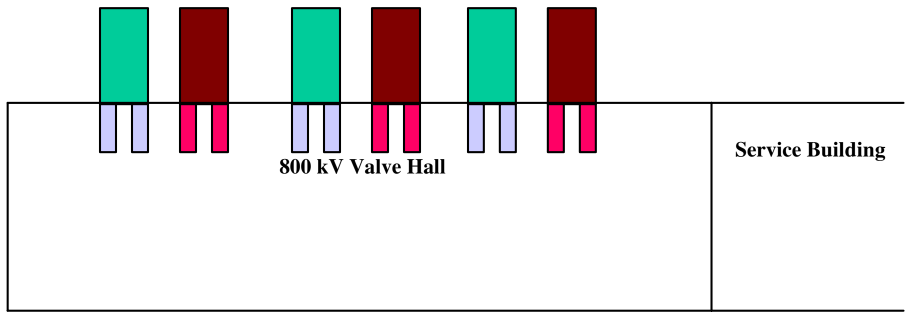


Figure 6-6
Converter Building Layout where All Transformer Bushings Protrude Inside Valve Hall

It is important to note that for Thyristor based converters, reversal of power requires reversal of voltage and multi-terminal scheme would have limitations on power reversal. Multi-terminal scheme is a lot simpler for schemes with unidirectional power flow.

Neutral Connection and Metallic Return Operation

In the parallel connection, the neutral end of the two converters will look very similar. If the two rectifiers or the inverters are located at sites that are separated by a distance, then obviously two electrode lines are required. However, if the rectifiers or the inverters are located at the same site then there is the possibility of having one electrode line for that site. From a reliability point of view, it is recommended to separate the two converters on two separate independent neutral buses and no common connection between both the bipoles except electrode lines connectivity, as shown in figure 6-7.

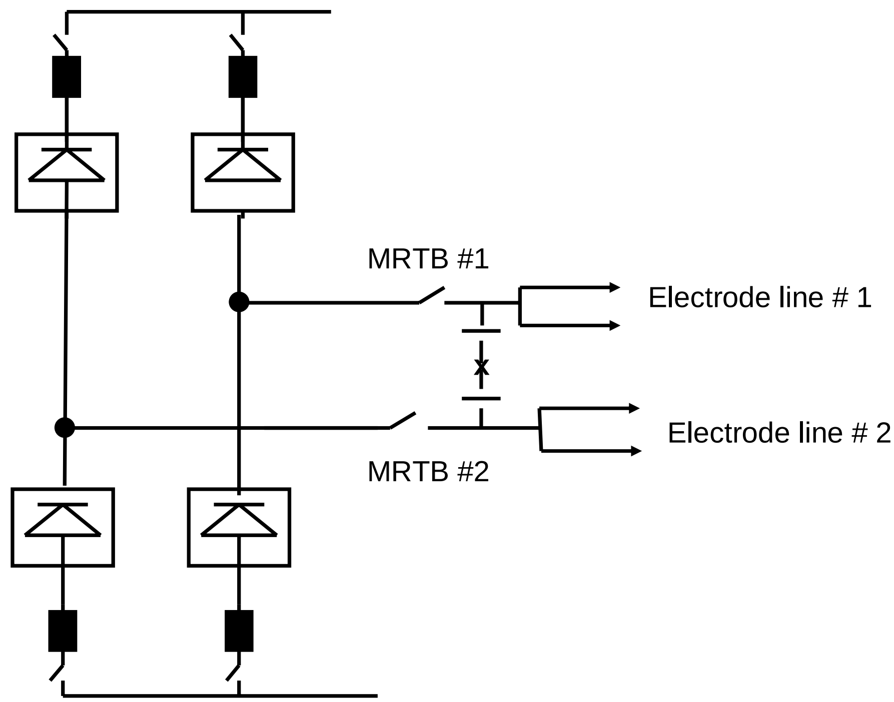


Figure 6-7
Neutral Connection for Parallel Converters at the Rectifier

This separation will make it necessary to have two metallic return transfer breakers (MRTB) and two sets of ground return transfer switches (GRTS). However, the parallel connection presents an interesting situation; the only time the metallic return is actually needed is for the loss of the two parallel converters of the same polarity. If only one converter is removed at one terminal, ground current can be avoided by balancing the currents in the remaining converters. The second factor is the rating of the MRTB. If the two rectifiers are located at the same site then each MRTB should be rated for twice the pole DC current. However if the rectifiers are separated by a DC line segment or the inverters are separated by a DC line segment then the DC current in the MRTB will be determined by the ratios of the DC line resistances and the electrode lines and earth resistances.

It is a well known fact that in any long distance bipolar system one of the most critical locations that can lead to a bipolar outage is the neutral connection between the two poles. The separation of the neutral points in the parallel connection certainly has the advantage that there is no common failure mode that can result in the loss of the complete power.

In the series connected valve groups unless the neutral end connection of the two poles is designed differently, with some redundancy in it, it will be the weakest point from a reliability perspective.

7

THE NEED FOR GROUND ELECTRODES IN AN 800 KV SYSTEM & IMPACT OF THE CONFIGURATION

Introduction

Selection and design of ground electrode station is very important for planning consideration for HVDC systems rating and its overload capability. The ±800 kV overhead transmission systems are normally planned for bipolar configuration. Even, if two monopolar lines are used, the ground electrodes should be designed for planned and forced outages of pole(s). Land electrodes only are considered here as sea or shore electrodes are generally associated with submarine cable systems. In view of large power ratings and very long transmission line associated with ± 800 kV system, continuous current ratings up to overload capability of the electrode during ground return mode of operation for long durations is anticipated. There is not much of difference in design of electrode station from conventional ±500 kV and ±800 kV HVDC system, except that of handling of a much larger current. With DC voltage level of 800 kV, the power transmission capacity is to the tune of 6000 MW in the recent projects being taken up in China and India, the electrode currents to be considered are about 4000A and with overload, it may be close to 5000A. A brief description of the selection and design of land electrodes is given in this chapter.

Reliability Considerations

For loss of ground electrode connection, due to open circuit or short circuit of the electrode line, bipolar operation can continue with converter station ground, until there is large unbalance between two pole currents. Such an unbalance may arise due to commutation failure, DC line faults or tripping of a pole. Such an event will lead to blocking of both poles.

From a system point of view the most important inputs for design of electrode are rated ground current, maximum allowed temperature rise of the soil near electrode, current density at the soil and coke interface, duration of operation at this current and unbalance operation of poles during its service life. The life of the electrode is generally defined in million-Ampere-hours. The rated current of the electrode is usually the rated current of one pole; the duration for which the electrode is used will depend on the duration before switching to metallic return which may be short time of a few minutes. However the time duration may be long in case a line pole is out in case of planned line maintenance. Also it is also important to note the observations made in Chapter 2 “Converter Configuration”, where it is indicated that for parallel converters, including multi-terminal operation, restricts operation in metallic return using the line pole and consequently at high power transfer levels, large unbalance ground currents need to be considered.

In practice, land electrodes have proven to be very reliable and problems related to availability of the bipole have been mainly related to the electrode line, rather than the electrode itself. This leads to the consideration of using two electrode lines, perhaps following different routes, for each bipolar station and electrode as mentioned in the Chapter 6 "Converter station design and layout" where a switching scheme using disconnectors and breaker has been shown to permit paralleling of both bipoles onto a single electrode during outages of any electrode line but this contingency arrangement shall have a risk of tripping both the bipoles in case there is a protective action on neutral side of either bipole.

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 direction of current.

When evaluating the reliability requirements of the electrode system it should be considered that HVDC transmission lines very rarely suffer permanent mono-polar faults. Transient line faults are very quickly cleared and restart of pole automatically. For damaged insulation, operation can continue at reduced voltage. Thus transmission line permanent faults usually involve tower failures where both poles are involved.

Site Selection and Interference Considerations

Selection of proper ground electrode site is of prime importance for the availability and reliability of the bipolar HVDC systems. As the quantum of power being considered is very large, a good earth electrode site shall ensure not only smooth operation but also rule out the requirements of any mitigation measures against adverse effects of ground currents. In order to avoid any operational problems due to geological reasons, it is advisable to carryout a thorough soil investigation for shallow and deep resistivity, thermal conductivity etc. at the proposed location. For these investigations, it would be prudent for the power utility to take assistance for selecting a good electrode site from other organization/ research institutes such as those involved in Geological explorations, oil & gas exploration companies and other organisations involved in Geophysical research and mapping.

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

- Step voltage at electrode site.
- Current density to avoid electro-osmosis in anode operation.
- Touch voltages to fences, metallic structures and buried pipelines nearby.

- Corrosion of buried metallic pipelines, metallic structures or foundations: Corrosion on the buried metal pipe line is proportional to magnitude of DC earth current and for earth electrode site selection, consideration has to be given to distance from buried pipe lines when designing earth electrode for high DC earth current (of the order of 5 kA).
- DC current in power lines, especially via power transformer neutrals.
- DC current in telephone circuits.
- Effect on the cathodic protection of the buried metallic pipe lines.

The main mitigation method for these possible interference issues, except step voltage, is to locate the electrode station at a distance from sub-stations, buried metallic pipelines, etc. This is a very important factor when selecting the site for the electrode location.

The type of soil may have a great influence upon the electrode design. In the CIGRÉ 2006 Session, an interesting presentation was brought up, showing how the type of soil (of volcanic nature or not) may influence the voltage rise curve against distance to electrode. This is shown in Figure 7-1.

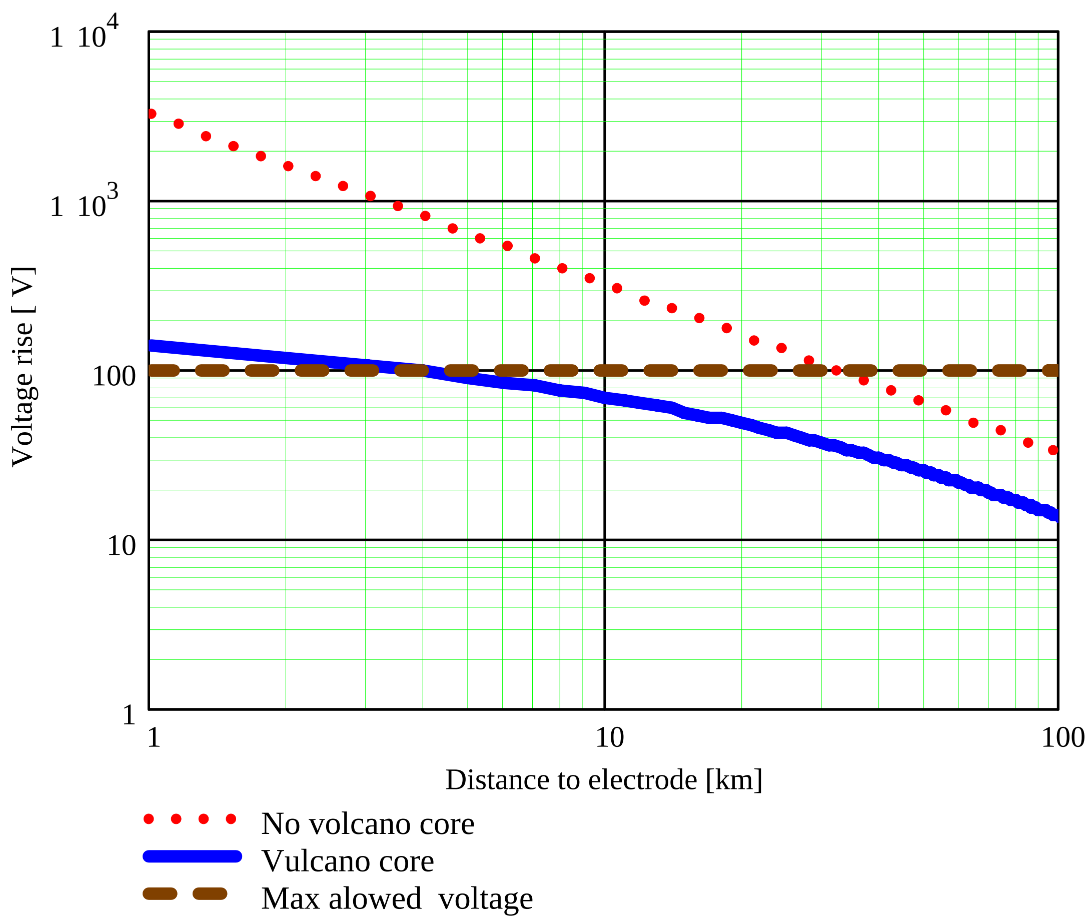


Figure 7-1
Voltage Rise with Distance to Electrode, for Different Soils (Courtesy: ABB)

This is due to the resistivity of earth with deepness. It is known that earth presents the characteristics shown in Figure 7-2, which calls for a more detailed investigation when designing the electrode scheme, for ±800 kV DC high current applications.

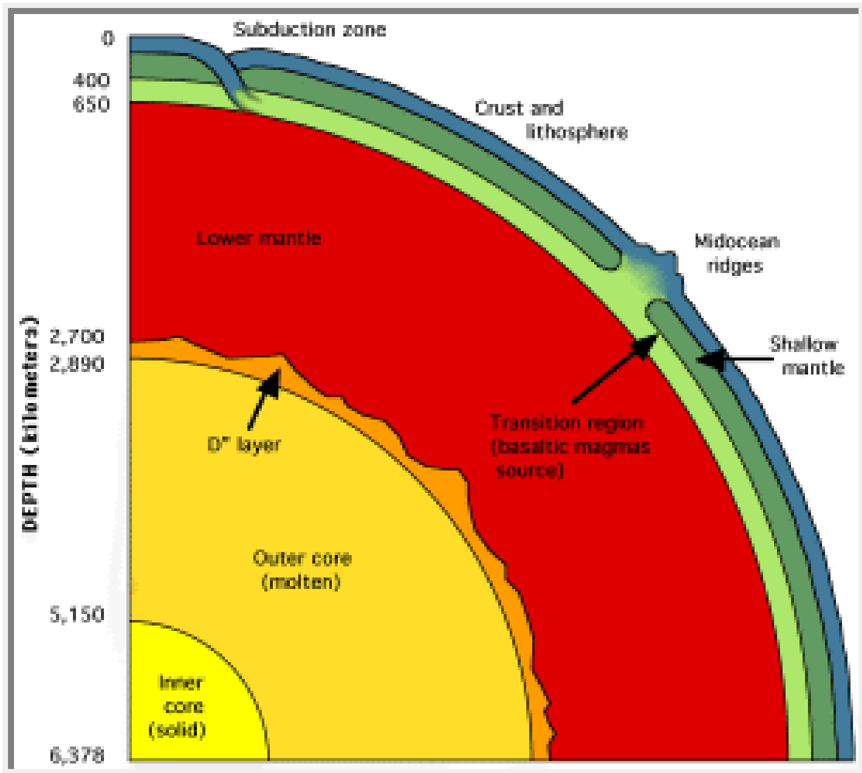


Figure 7-2
Earth Soil Composition with Depth (Courtesy: ABB)

It is also necessary to ensure that during ground return mode of operation, current penetrates deep into the earth near the electrode station so that the grounding resistance/potential rises in the vicinity of the electrode are within acceptable limits. Soil resistivity decreasing with depth at the proposed electrode station site can minimize the possibility of taking mitigation measures against any interference effect during ground return mode of operation. For this purpose, it is important to know the resistivity profile of the electrode stations up to the depth of at least 10 kms at different location distributed over a radius of 20 km from the proposed electrode station.

To map the resistivity profile, detailed geophysical studies to determine shallow resistivity (up to 150 meters depth) and deep resistivity structures (up to 10 kms depth) should be carried out at the proposed electrode station. Shallow resistivity measurement data is useful for designing the earth electrode to take care of safe step and touch potential during continuous large DC earth current. Deep electrical resistivity structure up to the depth of 10kms around proposed Earth electrode station sites may be delineated by using Magnetotelluric (MT) method. There are basically two types MTs, namely: Natural Source MT, and Controlled Source MT. In Natural Source MT method, natural Electromagnetic (EM) waves are used to delineate the earth's electrical resistivity structure from a few hundred meters to several hundred kilometers depending on the frequency of the signal. In case of Controlled Source MT a current source of variable frequency is used to inject the current into ground. Depending upon frequency of the injected current, the penetration of the current into the earth takes place. In these methods, orthogonal components of the electric and magnetic fields are simultaneously recorded to get detailed information about the deep subsurface structure and the nature of lateral extension of the structure. MT measurements are to be carried out at different locations in an area of 20kms x 20kms to get an idea of the deep resistivity structure around the electrode station.

In addition to resistivity measurements, the thermal conductivity and moisture content should also be measured. These two parameters vary considerably and therefore require prolonged measurements over a period of time. With high moisture contents in the soil and designing electrode with current density > 1 A/m^2 at the interface of the soil and coke, shall tend to dry up the soil due to electro-osmosis while electrode working as anode. Many projects have performed a pilot test electrode program in order to confirm correct site selection before going for a full fledged electrode construction. This involves a small electrode operating as an anode, but with the design value of the 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 of the soil near coke and water loss can be obtained. Also, depending on length of temporary line, interference effects can be evaluated.

Design of Electrode Station

The design criteria for electrode station is typically 50 years, same as that of useful life of the HVDC systems of which they are a part with the need to define currents in operation and times for which they are expected (in Million ampere-hour) to operate. This should take into account the operating modes and reliability criteria, as well as normal unbalance current, of the order of 1.5% of rated current (depending upon the accuracy of the DC current measuring device(s)). As these are very much specific to each project, the same has to be calculated by the Utilities while specifying the requirement.

The electrode resistance may appear to be an important parameter, however in practice; the ohmic value is always very low in relation to line resistances, of the order of 0.3 to 0.4 Ω, and seldom a defining parameter.

The type of operation of the ground electrode depends on which of the two poles has been out of service, therefore all the electrodes shall be designed for both types of operation, anodic and cathodic.

The ground current magnitude and time duration for normal operation and overload condition is an important factor for land electrode because of the thermal time constant of the soil. The maximum temperature of the soil must not exceed 85 °C in order to prevent steam formation of water. This steam while trapped inside the soil might develop excessive pressure and at times, the electrode can even explode. Overheating will effectively reduce the moisture content of soil. In order to replenish the moisture content of the soil, drip irrigation may be adopted over the entire electrode in case of prolonged ground return mode of operation.

The current density is also an important factor for preventing excess stress on the surrounding soil, and drying out caused by electro-osmosis; it should not exceed 1 A/m^2.

Lightning strike or any other events that trigger transient over current do not have much significant at the electrode station but have an impact at the neutral bus of the terminal because of high impedance offered by the line to lightning strikes. The potential of the station neutral would be increased in the event of transient over current which has to be taken care while considering insulation level and providing metal oxide arrestor at the station neutral bus.

The permissible touch and step voltages{3} to which an individual may be subjected when the electrode is energized by the DC current are determined, based on standards such as IEC standards 60479-1 and 60479-2 and IEEE standard 80. Based on IEEE standard, the maximum tolerable step voltage for a human being is:

$$E_{step} = I_b(1000+6\rho_s)$$

Where I_b is the maximum permissible body current and ρ_s the surface soil resistivity. When a current I_{CU} is injected into horizontal electrode of length of l, buried at a depth h, the maximum potential gradient is given by:

$$E_{max} = \rho\, I_{CU} / 2\, \pi\, l\, h$$

Typical values of potential gradient, touch and step potential are given below. However it must be remembered that not only the conditions of the site and surrounding area should be considered but due consideration should also be given to local regulations regarding safety and interference.

Potential gradient on surface: 2–20 V/m - Mitigated by depth above electrode.

Step voltage at electrode site: 2–8 V/m - Mitigated by depth or fencing higher areas.

Touch voltages: 20 V typical - Mitigated by distance or section insulation of, say, fences, pipes.

The most significant parameters giving the major dimensions of the electrode are current density at coke-soil interface and temperature rise of the soil near coke. Most land electrodes have been constructed by burying a coke, or a derivative of coke, in a trench or well to form the electrode, with an iron or mild 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. The feeder cables to the MS electrode must be insulated and able to withstand corrosion.

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.

Conclusion

As stated above, the loss of ground electrode connection will result in loss of the Bipole when the two poles are loaded unevenly and there is a large un-balance current flowing through ground for a considerable time. Further, the ground electrode permits operation of a healthy pole of a bipolar HVDC system in ground return mode in case metallic return operation is not possible due to outage of other pole conductor. However due care and proper geophysical investigations with regard to selection of sites for electrode stations is required. This will enable trouble free operation during ground return mode of HVDC system without any impact on nearby transformers, buried pipelines, etc.

For ±800 kV DC applications, ground electrode design plays a major role as regard to reliability and system security issues, due to the large amount of power being transmitted by the link.

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] W.Ruan, J .Ma, J Liu,F.P. Dawalibi & R D Southey: - 2005 Safe Engineering Services & Technologies Ltd

8
TEST GUIDELINES FOR MAIN EQUIPMENT

Introduction

The final testing of all equipments is an essential part of quality assurance during the manufacture of the equipments. Tests include type, routine and special tests carried out in accordance with the relevant standards or as per customer requirements. The tests give an indication of the capability of the equipment to meet the specified requirements such as current carrying capability, dielectric withstand and operating characteristics, reliability, maintenance requirements and long life.

The equipment which is directly affected by the 800 kV voltage level is the equipment connected to the pole bus, i.e., thyristor valves, converter transformers, wall bushings and DC yard equipments like smoothing rector, DC filters, instrument transformers, bypass switches and pole disconnectors. The main focus for research and development in 800 kV HVDC systems has been the converter transformer, bushings and external insulation.

Unlike AC systems, standard test values for HVDC equipment are not available. The required withstand voltages for HVDC equipments are derived based on the station configuration and the insulation co-ordination principles outlined in IEC 60071-5. By using a suitable configuration of surge arresters, the stresses on the equipments can be lowered to arrive at economically and technically viable withstand voltages. However this should be done with detailed studies and adequate care so as not to keep very low insulation margins as this could lead to equipment failure which could prove to be very costly and also seriously affect the reliability and availability of the HVDC system.

Factory Tests

For all equipments, usually two categories of tests are required:

Type Tests

The purpose of type tests is to verify the design of the equipment. Generally the first built unit of a particular design will be subjected to type tests. In case, type test reports, are available for identical equipments, the requirement for type test can be waived provided there has not been any change in the design. These type test reports should not be more than five (5) years old.

Routine Tests

The purpose of routine tests is to control the quality of equipment and component manufacture. Therefore every individual unit has to undergo all prescribed routine tests. Routine tests for the equipments are given in relevant standards like IEC, IEEE, etc.

In addition, special tests if any agreed between manufacturer and customer should also be conducted.

Additionally for HVDC applications, system tests under the following two categories are also required:

Factory Acceptance Tests

The purpose of factory acceptance tests is to verify the functionality requirement. The system functionality need to be evaluated for all kinds of predefined conditions and fine tuning / adjustment / improvement made when necessary.

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. These tests consist of sub-system and system tests and are carried out after installation of the equipments at the site. The sub-system tests cover the major sub-systems like valve cooling, AC&DC filters, HVDC converter, auxiliary systems, communication, etc. After completion of sub-system tests, System tests covering power transmission tests, transient & dynamic control tests, measurement of electric field and RFI, etc should be conducted. The recommended value for the electric field should be less than 20 kV/m and ion current density should be less than 20nA/sq m at ground level in the DC yard. After completion of all system tests, trial operation of the HVDC system should be carried out.

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 basic guiding principles should be to make sure the test requirement thoroughly represent the operation stresses but also should not overstress the equipment during tests.

Test Requirement of Main 800 kV DC Equipment

The dielectric test requirement for the 800 kV DC equipment are perhaps the only tests which are directly affected by raising the voltage levels from the present levels to 800 kV. Most of the other tests which are more of thermal and mechanical in nature are not directly impacted by the voltage but are more specific to a particular project. As already stated, unlike AC equipment where required test values are well standardized, the required dielectric test values for DC equipment depends on the station configuration and insulation coordination study results for the specific project. A document titled "HVDC converter stations for voltages above ±600 kV" was prepared in December 2002 by CIGRE WG 14.32, where dielectric test requirement levels for main 800 kV DC equipment are indicated, however, no project of 800 kV was envisaged during that period and no detailed studies were carried out. Recently due to the need of introduction of 800 kV HVDC projects in China and India, manufacturer's research and development work on different converter station configurations have resulted in reduced equipment insulation levels for the purpose of economic design. The series / parallel converters with reactor(s) in the neutral bus of the DC yard with the options of placing surge arrester at the different position for economic reasons are also under consideration. However, it is prudent to indicate the minimum dielectric test requirement levels for main 800 kV DC equipment.

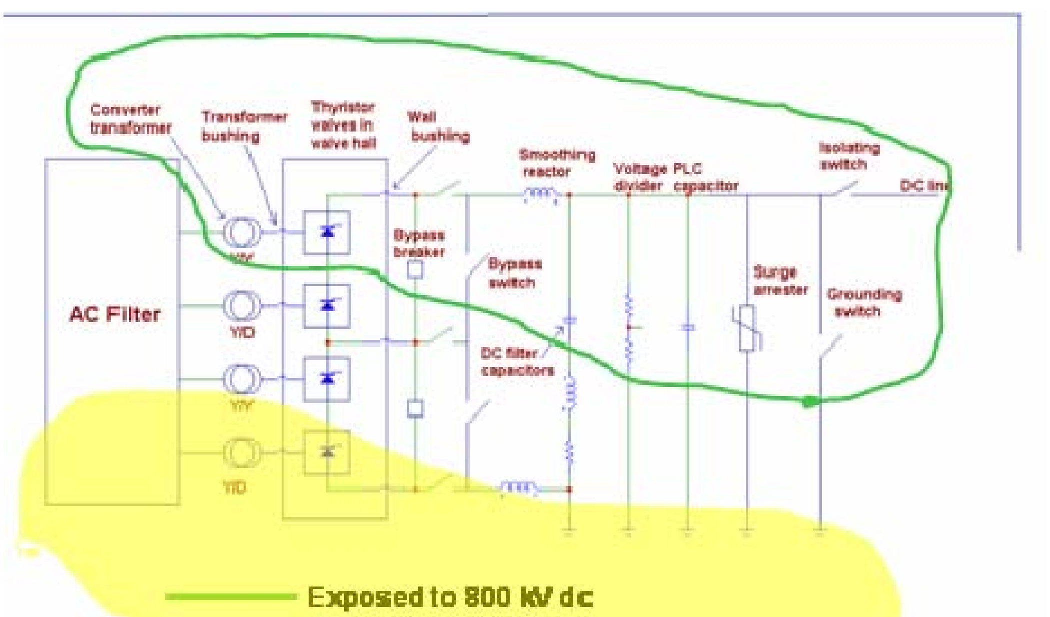


Figure 8-1
Equipment Energized at 800 kV DC Voltage Level (Courtesy: ABB)

The dielectric test requirements for the HVDC equipment connected to the pole bus are described in the subsequent sections.

Converter Transformers

The dielectric tests on converter transformers should be carried out in accordance with IEC 61378-2. Different values of switching and lightning impulse withstand voltages for the valve side (s) of the converter transformers have been proposed in different reports as indicated below:

	DC Voltage (kV)	LIWL(kV)	SIWL(kV)
WG B4-45 (draft)	800	1800	1600*
CIGRE14.32	800	1990	1891
EPRI	800	1950	1800

* Proposed, yet to be discussed and finalized

It has been observed in previous HVDC projects that different utilities use different criteria for calculating the LIWL and SIWL voltages for the upper valve side of the converter transformers. Keeping this in view and the voltages mentioned in the above table, it can be seen that LIWL ranges from 1800 to 1990 kV and SIWL ranges from 1600 to 1891 kV. Keeping in view that 800 kV HVDC systems are yet to be made operational, it is recommended that the following test voltages may be adopted for upper valve side of converter transformers:

LIWL	SIWL	AC 60 mins withstand	DC withstand	Polarity reversal
1950 kV	1800 kV	As per IEC 61378	As per IEC 61378	As per IEC 61378#

The requirements of polarity reversal test particularly with regard to the duration are under discussion within the CIGRE JWG A2-B4. The recommendations of CIGRE JWG A2-B4 shall be adopted as and when they are published.

The values of LIWL and SIWL can be revised to lower levels after gaining some experience of operation at 800 kV HVDC.

In addition to the tests proposed in IEC 61378, another test recommended is a 12 hour, no load, 110% overvoltage test at rated frequency and with partial discharge measurement at 30 minute intervals. Partial discharge shall not exceed background level at any time.

Thyristor Valves

Testing on thyristor valves is divided into two parts:

- Operational tests
- Dielectric tests

The operational tests are performed in a back to back or synthetic test circuits on a reduced number of thyristors as per IEC60700-1 and IEEE857 and are not different from the current practice for HVDC systems up to 600 kV.

Based on the procedures outlined in IEC 60071-5 and the values being adopted for converter transformers, the following dielectric withstand voltages are specified for the 800 kV thyristor valves:

Lightning Impulse	Switching Impulse	DC withstand
1950 kV	1800 kV	1280 kV (1 minute) 1040 kV (3 hours)

In addition to the above tests, seismic testing is also recommended due to the increased dimensions and weight of the valves in the valve hall.

Smoothing Reactor

The smoothing reactors can be oil immersed or air cored air insulated. The test levels for 800 kV smoothing reactors (oil) are as follows:

LIWL	SIWL	DC (2 hours)	Polarity Reversal
1950 kV	1800 kV	1.5 Udn	1.25 Udn

DC Switchyard Equipment

The switching and lightning impulse levels for various DC yard equipment like post insulators, disconnectors, grounding switches, DCCT's and voltage dividers are as follows:

LIWL	SIWL
1950 kV	1800 kV

The DC test voltages will be in line with the existing practice for ±500 kV and ±600 kV HVDC systems.

DC Bushings

The DC bushings shall be tested in accordance with IEC 62199. The proposed test voltages are as follows:

LIWL	SIWL	DC (2 hours)	Polarity Reversal
1950 kV	1800 kV	As per IEC 62199	As per IEC 62199

R&D Efforts

As 800 kV HVDC systems are being built for the first time, a certain amount of research and development is required particularly with respect to converter transformer insulation systems and for DC bushings. It is therefore recommended that HVDC manufacturers develop prototypes of transformer insulation barrier systems and subject the same to dielectric testing using a 800 kV DC bushing on the valve side of the transformer prototype. A test set up where other equipment such as disconnectors, DCCT's and voltage dividers are subjected to prolonged period of 800 kV DC voltage would also be useful to study the behavior of equipment at 800 kV HVDC systems.

Figure 8-2
800 kV DC Bushing (Courtesy of Siemens)

Conclusion

The increase in DC voltage to 800 kV from the present levels mainly effects the dielectric testing of the equipment connected to the pole bus and therefore the dielectric test requirements for these equipments have been covered above. It is now important that test laboratories upgrade their equipment and facilities for these test voltages so that this does not become a bottleneck during the execution of the 800 kV HVDC projects. It may be further mentioned here that based on the experience gained after commissioning and operation of the first few 800 kV HVDC links, the test levels proposed can be reviewed and if necessary revised for more economic design without compromising the equipment safety.

9
DC LINE DESIGN

Introduction

Electrical design of HVDC transmission lines consists mainly in selecting the air insulation clearances between the energized conductors and the various elements at ground potential in the vicinity, the choice of the number and type of insulators required to support the energized conductors and selection of conductor bundle and its height above ground. The main objectives are to obtain a line design with reliable performance over the operating life of the line, acceptable environmental impact and minimum overall cost. Since the introduction of overhead HVDC lines more than forty years ago, there has been continuous evolution in the design practices and criteria. An overview of these practices and criteria presently used and their applicability to HVDC transmission lines at voltages of ±800 kV and above are presented in this chapter.

Air Insulation

Design of air insulation comprises selecting the conductor-tower, conductor-conductor and conductor-ground air gaps to withstand the maximum operating voltage of the line as well as the switching and lightning overvoltages to which the line may be subject. The design procedure requires knowledge of two basic sets of information:

1. the maximum operating voltage and the shapes and magnitudes of the switching and lightning overvoltages;
2. the flashover and withstand characteristics of the air gaps associated with HVDC lines under direct, switching and lightning voltages.

Voltage Stresses

The highest levels of switching surges on bipolar DC lines occur on the unfaulted pole due to a pole to ground fault on the other pole due to lightning or polluted insulator flashover. Overvoltages originating in the AC system or in the converter station are generally limited by lightning arresters. The magnitude and shape of the surge voltage on the unfaulted pole due to a ground fault on the other pole depends on the fault location along the line as well as the equipment connected at the line ends such as harmonic filters etc. The shape of surges generated depends to a large extent on the circuit parameters defining the transmission line and the terminal equipment, while the magnitude of the surge depends on the location of the fault. For a given fault location, the magnitude also varies at points along the line. Digital or analog simulation techniques may be used to determine the shapes and magnitudes of switching overvoltages generated on HVDC lines.

For the experimental determination of the dielectric breakdown and withstand characteristics of air gaps, the switching surges on DC lines are represented by a standardized waveform of a 250 µs/2500 µs double-exponential transient superimposed on the direct voltage of the line. The peak amplitude of the switching surge is, therefore, given as $V_p = (V_{dc} + V_t)$, where V_{dc} is the operating direct voltage of the line and V_t is the peak of the superimposed transient voltage. At any given point along the line, the peak amplitude V_p may be considered as a random variable, represented by a probability distribution function $P(V_p)$. Simulator studies of HVDC transmission systems have indicated that the highest values of V_p can range between 1.5 p.u and 2.2 p.u.

The information required to characterize the impact of lightning on transmission lines consists of:

1. the waveform and distribution of stroke current amplitudes;
2. lightning incidence statistics.

Lightning current and voltage waveforms are standardized [1] and the statistical distribution of current amplitudes is obtained on the basis of measurements [2]. Lightning flash characteristics in different regions of the world have also been obtained through extensive measurements [3]. Different regions are generally characterized by the number of thunderstorm days per year or the ground flash density (GFD) expressed as the number of lightning flashes per square kilometer per year.

Insulation Strength

Studies were carried out to determine the breakdown characteristics of rod-rod and rod-plane air gaps up to 3 m long under positive and negative direct voltages [4]. The results show that at the positive polarity, flashover voltages under dry and artificial rain conditions are nearly the same and there is very little dispersion in the results. The withstand voltage is about 480 kV/m for rod-plane gaps and 550 kV/m for rod-rod gaps. At negative polarity, the dry withstand voltages are much higher, from 1000 to 1400 kV/m for the gap spacings tested. However, under artificial rain, the withstand voltages are reduced to values in the range of 500 to 600 kV/m. Extensive testing was performed at the DC Test Center of BPA [5] using simulated conductor-tower air gap configurations and direct voltages of both positive and negative polarities. Gap spacings of up to 1.75 m were tested. The results have shown that the flashover voltage of conductor-tower air gaps are close to the rod-plane and rod-rod data at positive polarity but not at negative polarity. In tests carried out at EPRI [6] on a simulated conductor-tower air gap, the lowest flashover voltage reported for all cases including ambient air, air with dust, ions, fog or rain was 420 kV/m.

Early studies on the flashover characteristics under switching surges superimposed on direct voltages were also carried out on rod-rod and rod-plane air gaps [4,7]. Studies on conductor-tower gaps, for lengths up to about 10 m, were carried out at IREQ [8,9]. The critical flashover voltage $V_{50\%}$ at positive polarity for the gaps tested varied from 300 kV/m for a 4 m gap to 225 kV/m for a 9.6 m gap. It should be noted that the switching surge withstand strength in kV/m decreases as the gap length increases. The coefficient of variation c, defined as the standard deviation σ of the distribution expressed in percentage of $V_{50\%}$, $c = \frac{\sigma}{V_{50\%}} \times 100\,\%$, is about 4% for all gap lengths. Studies on conductor-tower air gaps under direct as well as under switching surges superimposed on direct voltages have shown that the occurrence of corona on either the conductors or the tower structure will have a significant impact on the withstand strength.

For calculations of lightning outage rates, the flashover voltages obtained for wet insulator strings under lightning voltages [10] show that the gradients for critical flashover are 560 kV/m for positive polarity and 605 kV/m for negative polarity. A coefficient of variation of 3% is recommended for lightning flashover.

Design Procedures

There has been a steady evolution in the design procedures used for determining the air gap clearances of HVDC transmission lines. Early line designs used deterministic methods for evaluating the minimum gap clearances necessary, based on the available data on rod-plane flashover characteristics and the prevailing safety regulations [11,12]. The procedure consists essentially in estimating the highest switching overvoltage V_s (usually 1.7 p.u) and then determine the air gap clearance that can provide 99.9% withstand probability, i.e. $V_s = V_{50\%}$.(1-3σ), where $V_{50\%}$ is the critical flashover voltage of the selected gap. Additional safety factors may be added in selecting the air gap clearance to take into account other factors. The clearance determined as described above actually corresponds to the maximum expected swing of the conductor towards the tower, which can be determined knowing the insulator length (in the case of an I-string) and maximum wind forces on the conductors. The conductor tower clearance d at zero wind conditions may then be determined as the sum of the minimum clearance required to withstand the switching surges plus the conductor swing displacement. Finally, the pole spacing is obtained as (2d + w) where w is the width of the tower structure.

The design procedure described above can be improved as more accurate information on the voltage stresses as well as on the insulator strength of conductor-tower gaps become available through the efforts of research and testing. For example, the data on the flashover and withstand characteristics of actual conductor-tower air gaps rather than rod-plane gaps should be used, particularly for switching surge withstand, to improve the design procedure.

For HVDC lines at and above ±800 kV, statistical rather than deterministic design procedures described above may be more appropriate. Statistical design procedures require the following basic sets of information:

1. For the transmission line and the HVDC system under consideration, the probability distribution function $P_s(V_s)$ of the highest switching surge voltages occurring along the length of the transmission line;
2. Probability distribution function of the flashover voltage V_f for different values of conductor-tower air gaps, $P_f(V_f,d)$;
3. Index of acceptable flashover rate R_f for the line.

The first set of information is obtained through studies using analog or digital simulators. Using appropriate models to simulate the transmission line and the relevant components at the converter and inverter terminals, magnitudes of switching surges at different points along the transmission line are determined for monopolar line to ground faults simulated at different points along the line. The location at which the highest magnitudes of switching surges occur (probably at the center of the line) is determined and the probability distribution $P_s(V_s)$ at this location is also determined. Actually, the distribution $P_s(V_s)$ applies not just at a single point along the line but over a certain length l_s of the line. Depending on the average span length of the line, l_s corresponds to a number N of parallel conductor-tower air gaps that need to be taken into account for risk of failure calculations.

The second set of information required is the probability distribution $P_f(V_f,d)$, of flashover voltage V_f, determined by testing conductor-tower gaps with lengths d. The experimental data should cover the range of atmospheric conditions experienced by the proposed transmission line and the gap lengths required for HVDC lines at and above ±800 kV. The third information required is the specification of acceptable risk of failure R_f for the line, which is usually specified as the number of allowable flashovers for a given number of switching operations. For example, specification of $R_f = 10^{-4}$ means that one flashover in 10,000 switching operations.

Given the probability distribution for a single conductor-tower air gap, the probability of flashover for N parallel air gaps is obtained as

$$P_N(V_f,d) = 1-\left[1-P_f\left(V_f,d\right)\right]^N \quad \textbf{Eq. 9-1}$$

The risk of failure for switching surge flashover of the line is then calculated as

$$R_f = \int_0^{\infty} P_N\left(V,d\right)\cdot P_s\left(V\right)dV \quad \textbf{Eq. 9-2}$$

The calculations described by equations (1) and (2) are carried out for different values of gap spacing d. The value of d corresponding to the specified risk of failure R_f is then selected as the required minimum conductor-tower gap spacing. Subsequent calculations of conductor swing and pole spacing are carried out in the same way as described for the deterministic method.

The statistical design methodology described above is based on that described in the EPRI Red Book [3] for AC lines. Similar methodology is also used, as described in the next section, for selecting the length of the insulator string for a specified pollution flashover performance.

Lightning performance of HVDC transmission lines may be evaluated using methods developed for AC lines [3]. Special features of the performance of bipolar HVDC lines derives from the fact that the operating voltage of the two conductors is of opposite polarity and has an amplitude that is comparable to the withstand strength of the insulation. Also, since the polarity of lightning currents is generally negative, lightning flashovers occur predominantly on the positive pole of the line.

As in the case of AC lines, lightning outage of a DC line may occur due to:

1. lightning strikes the ground wire causing the tower potential to rise and resulting in *back flashover* of the line insulation, usually across the insulator string;
2. lightning strikes the energized conductor because of *shielding failure* causing a flashover to ground.

The mechanism of back flashover occurs usually at high amplitudes of lightning current, while shielding failures occur at low amplitudes. For a given HVDC line configuration and values of shielding angle between the ground wire and the energized conductor and tower footing resistance, the outage rates due to back flashover as well as shielding failure may be calculated using methods described in reference 3, by taking into account the fact that the conductors are at a constant direct voltage rather than the alternating voltage with a time average value of zero.

Insulators

Because of the comparatively lower levels of internally generated switching overvoltages occurring in HVDC transmission systems, pollution performance at the operating direct voltage is the main criterion for the selection of insulator strings. Since the length of the insulator string is selected on the basis of air insulation withstand for switching overvoltages, the length of the leakage path along the insulator surface is generally larger for DC than for an equivalent AC line.

Since the early stages of development of HVDC transmission lines, it was recognized that pollution performance of insulators on DC lines differs significantly from that on AC lines, mainly because of differences in

a) the mechanism and extent of pollution deposits on insulator surface,
b) the mechanism of flashover of polluted insulators in the presence of atmospheric moisture and precipitation.

Experimental studies have been carried out to understand the process of contamination deposit on insulators energized at direct voltages [13,14]. Electric forces acting on charged contamination particles determine the amount and distribution of pollution on the insulator surfaces.

Environmental pollution consists of both soluble and non-soluble contaminants. The soluble component is generally some kind of salt, usually sodium chloride (NaCl) and when dissolved in the surface layer of water, increases the surface conductivity of the insulator. Non-soluble contamination such as dust or kaolin does not affect the surface conductivity of the insulator but may influence the absorption of moisture on the insulator surface. The contamination severity is generally characterized by equivalent salt deposit density (ESDD), which corresponds to the equivalent amount of sodium chloride on the surface area of the insulator, in mg/cm^2, which has the same conductivity as the actual deposit dissolved in the same amount of water [15]. The non-soluble deposit density (NSDD) is the amount of non-soluble deposits expressed as the weight of these deposits per unit area of the insulator surface in mg/cm^2. The pollution performance of insulators is generally expressed only as a function of ESDD.

Research carried out by EPRI [16] identified the following factors as influencing contamination deposit on DC insulators:

- The ratio of accumulated contaminant on DC to AC insulators may range from 1 to 6 or more;
- There is no conclusive evidence of any differences between contamination deposit at positive and negative polarities;
- The distribution of contaminant along a string of DC insulators is nonuniform, with more contaminant on insulators near the high voltage conductor;
- On individual insulators energized at direct voltage, the ratio of top surface to bottom surface ESDD may vary between 0.1 and 1.0 depending on string orientation and environmental conditions.

A number of experimental studies have, therefore, been carried out to determine the flashover characteristics of strings of different types of insulators as functions of the different parameters described above.

Voltage Stress and Insulation Strength

As in the case of air insulation, design of insulators for use on HVDC transmission lines requires firstly information on the voltage stresses imposed on the insulators and secondly the withstand strength of insulator strings when exposed to the environmental conditions that may prevail along the proposed line route. The first information is rather simple because all the insulator strings along the length of the line are subject to the same operating direct voltage. The second information is rather complex, however, since environmental conditions may vary significantly along the length of the line and the insulation withstand characteristics depend in a complex manner on a large number of parameters defining the insulator shape, pollution severity and weather conditions. For a given type of insulator and string length, the flashover probability distribution function $P(V_{50\%},c,S_p)$ may be obtained from artificial contamination tests, where V is the 50% flashover voltage, c is the coefficient of variation and S_p is the pollution severity expressed as ESDD. If different types of insulators are being considered, the probability distribution function for strings of each insulator type is required. Insulation design consists, therefore, of selecting the number and type of insulators required to achieve a specified risk of failure R.

Design Considerations

Insulation design for withstanding the operating direct voltage of HVDC transmission lines consists of selecting the number and type of insulators in the string for ceramic insulators or the type and length for nonceramic insulators that result in the specified risk of failure for the line under the prevailing conditions of pollution along the line. Due to the lack of experimental data and operating experience, design of early HVDC transmission lines was based on deterministic methods. The maximum contamination severity that the line might experience is determined either through site surveys or through the operating experience of AC transmission lines in the region. The number and type of insulators is then selected through tests at the maximum pollution severity to withstand the operating voltage of the proposed line. A certain safety margin is provided between the maximum operating voltage and the minimum insulator withstand voltage.

The use of statistical design methods leads to a more optimal selection of insulators that meet specified reliability criteria, but require more detailed information on pollution severity along the proposed line route as well as probability distribution of the flashover characteristics of insulators as a function of pollution severity. From the data on the probability distribution for one insulator string, the distribution function for N insulator strings in parallel may be determined using equation (1). Similar to the case of air insulation, the risk of failure for insulators along the line may be obtained [17,18] by multiplying the probabilities of occurrence of flashover, pollution severity and wetting of the insulator surface (required to initiate the flashover process) and integrating over the range of pollution severities and wetting periods, similar to what is indicated in equation (2). The calculated risk R gives the risk of flashover as a function of the number of wetting periods in a year.

Application of statistical design methods for insulator selection is difficult because of the limited availability of experimental data on the influence of various parameters on the performance of insulators. An alternative approach has, therefore, been suggested [16] in which design guidelines are proposed that are based on the results of extensive laboratory and field studies on different types of insulators. The proposed guidelines recommend specific leakage distances (cm/kV) required in areas of different pollution severities and are shown in Table 1. From laboratory tests conducted by EPRI [7], the specific leakage distances in Table 1 apply equally to vertical strings, V strings and horizontal strings because no significant effect of string orientation was found.

Table 9-1
Guidelines for Design of Ceramic Insulators

	Contamination Severity, mg/cm^2			
	Very Light < 0.005	Light 0.005-0.02	Moderate 0.02-0.05	Heavy >0.05
Specific Leakage Distance (cm/kV)	2.0 – 2.5	2.5 – 3.2	3.2 – 4.0	4.0 – 7.0

Caution should be exercised, however, in applying these guidelines because the classification of contamination severity may be somewhat arbitrary and leakage distance alone is not sufficient to characterize insulator performance.

For HVDC transmission lines at and above ±800 kV, application of the simple design guidelines described above may not be adequate. The insulator strings required at these higher voltages satisfying the proposed design criteria may be quite long. Detailed experimental studies and new insulator designs may, therefore, be necessary for developing economically optimum line designs.

Corona

As in the case of AC lines, conductor selection for HVDC transmission lines is based on corona performance considerations, mainly the corona loss (CL), radio interference (RI) and audible noise (AN). The main difference between the impact of corona on the design of AC and DC lines arises because the highest levels of RI and AN occur on AC lines during rain and on DC lines during fair weather. In addition to CL, RI and AN, the design of HVDC transmission lines should also take into account the possible environmental impact of ground-level electric fields and ion currents.

Any procedure for the corona design of HVDC transmission lines requires two sets of information:

1. Methods for predicting the CL, RI, AN and the ground-level electric fields and ion currents as functions of line voltage and parameters such as the number and size of conductors in the bundle, pole spacing and conductor height as well as of prevailing weather conditions;
2. Design criteria for CL, RI, AN and ground-level electric fields and ion currents.

Prediction Methods

Similar to AC lines, the corona performance of DC lines is a complex function of corona physics, conductor surface conditions and the prevailing weather conditions. Development of prediction methods for the corona performance of HVDC lines requires theoretical as well as experimental studies [19]. Long-term measurements covering the weather conditions occurring in different seasons of the year, made on experimental as well as operating transmission lines are an essential basis for the development of prediction methods.

Compared to the vast amount of data available for AC lines, there have been only a few studies carried out to obtain the data necessary to develop prediction methods for DC lines, particularly for lines above ±500 kV. Long-term measurements on operating DC lines are necessary for validating the accuracy of any prediction methods developed, but very few studies have been carried out so far. Existing empirical formulas [19] should, therefore, be used with caution, particularly for the design of HVDC transmission lines at and above 800 kV.

Design Criteria

Corona losses may have an impact mainly on the economic choice of overall conductor cross section. An optimum conductor cross section is generally determined to give the minimum overall annualized cost of the line, which includes the capital cost of the line and the cost of power losses in the conductor comprising the I^2R losses and corona losses. However, as the operating voltage of the line increases, the importance of corona losses compared to the I^2R losses decreases. Corona losses play only a minor role, if any, in determining the economic conductor cross section for HVDC lines at and above ±800 kV.

For lines above about ±200 kV, it may be necessary to split the total conductor cross section determined on the basis of economic considerations, into a number of sub-conductors in a bundle, in order to obtain acceptable levels of RI and AN. The height of the conductor bundle determines the acceptable levels of ground-level electric fields and ion currents.

Psychophysical methods with human subjects were used to develop design criteria for RI, AN and ground-level electric fields and ion currents from HVDC transmission lines. These criteria should be applicable to lines at all voltages, including those at and above ±800 kV.

As in the case of AC lines, design criteria for RI from DC transmission lines are based on its impact on radio reception in the AM broadcast band. A number of studies have been carried out to determine acceptable signal-to-noise ratios (SNR) for corona-generated RI from AC transmission lines and the results used to develop standards and guidelines [19]. Comparatively fewer studies have been carried out [15,20], however, for RI from DC lines. Based on the results of the most comprehensive of these studies [20], the following SNRs are obtained for AC and DC corona:

DC fair weather	:	21 dB
DC foul weather	:	26 dB
AC fair & foul weather	:	22.5 dB

At present, there are no standards or regulations that set limits to RI specifically from DC transmission lines. However, the similarities as well as the differences between the characteristics of RI from AC and DC transmission lines may be used to develop guidelines for DC lines. The similarity is that acceptable SNR's for RI from both AC and DC lines are roughly the same. However, while RI from AC lines in foul weather (rain or wet snow) is 10-20 dB higher than in fair weather, foul weather RI from DC lines may be 5-10 dB *lower* than in fair weather [19].

RI design guidelines for HVDC transmission lines may be developed taking due account of the particularities of DC corona and an appropriate methodology for establishing RI limits.

The AN from DC lines has a wide-band frequency spectrum and does not have any pure tones (hum) components that characterize AN from AC lines. Similarly to RI, the AN from DC lines *decreases* in foul weather (rain, wet snow) compared to that in fair weather. Any regulations or guidelines for limits to AN from environmental noise sources are generally based on an evaluation of subjective human responses to the noise determined using Psychoacoustic methods [21]. The results of a comprehensive study [20] to evaluate the subjective human response to AN from DC lines indicates that the threshold annoyance level for AN from both AC and DC lines is about 51 dBA. The results of this study may be used to develop design criteria for corona-generated AN from DC lines. At present, there are no noise control regulations for AN from power lines. However, there are some regulations for general environmental noise sources. In the U.S, the Environmental Protection Agency (EPA) recommends that the day-night average sound level (L_{dn}) [22] be limited to 55 dBA outdoors and 45 dBA indoors. Since highest levels of AN occur in fair weather, when people are likely to be outdoors, a lower limit in the range of 45-50 dBA may be more appropriate for HVDC transmission lines.

Review of scientific literature [23] has established that the electric field and ion current environment produced by HVDC transmission lines does not pose any risk to human health. However, this environment can produce nuisance and annoyance effects in humans by causing stimulation of skin and hair and tingling or sometimes even painful sensations. In the absence of any health effects and the rather low probability of occurrence of any induction or shock effects, design criteria for HVDC transmission lines can be based only on human perception of DC electric fields and ion currents.

There is very little published scientific literature on human perception of DC electric fields and ion currents. In one recent study [24], however, the threshold of human perception was studied in a specially designed exposure chamber on human subjects using well-established psychophysical methods. The results obtained in this study show that human perception is a function of the magnitudes of both the electric field and ion current density. In the absence any ion current, the perception level for electric field alone was found to be 40 kV/m. However, when both fields and ions are present, as in the case of practical HVDC transmission lines, perception threshold is defined by an electric field of 25 kV/m and ion current density of 100 nA/m^2 respectively. Results of this study may, therefore, be used to develop appropriate design criteria for ground-level electric fields and ion currents for HVDC transmission lines at and above 800 kV.

Design Procedures

Procedures for the design of HVDC transmission lines, from the point of view of corona performance, have steadily evolved since the introduction of the first lines in modern power systems. Early DC line designs took into account only the CL and RI aspects of corona performance. As experience was gained in operating DC lines and higher transmission voltages were being considered, AN and ground-level electric fields and ion currents assumed increasing importance as design considerations.

The design procedure, particularly for lines at and above ±800 kV, follows the steps described below:

- The total conductor cross section is determined on the basis of economic considerations;
- Two or three bundles with the number and diameter of sub-conductors corresponding to the total economic conductor cross section are selected for evaluation;
- For each conductor bundle and a range of values of pole spacing and conductor height, the conductor surface gradients are determined and, using available prediction methods, the RI, AN and ground-level electric field and ion current density profiles are determined;
- The conductor bundle is selected on the basis of acceptable RI and AN criteria; A six-conductor bundle may be required for ±800 kV lines;
- For the conductor bundle selected, the minimum height of conductors above ground is determined on the basis of acceptable levels of ground-level electric fields and ion currents.

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10
DC LINE RESEARCH AND TESTING REQUIREMENTS

Introduction

While the presently available data may be used for a conservative design of ±800 kV lines, research and testing are necessary to obtain the information required for the optimum and more reliable electrical design of HVDC transmission lines to meet specified criteria for air insulation, insulator and corona performance, particularly for the design of lines at and above ±800 kV. Research studies are required for understanding the physical processes involved while extensive testing is necessary for obtaining the data used for line design. Methods for predicting different aspects of performance are developed on the basis of experimental data obtained as well as theoretical considerations. Research and testing are also necessary to develop the design criteria for acceptable air insulation, insulator and corona performance of HVDC lines. A summary of research and testing carried out so far is presented in Chapter 4. Requirements for any additional research and testing for the design of future HVDC transmission lines at and above ±800 kV are presented in this chapter. Availability of test facilities for this purpose is also discussed.

Air Insulation

As discussed in Chapter 9, the critical stress for air insulation on HVDC transmission lines is produced by switching impulses superimposed on the operating direct voltage of the positive pole, generally by a ground fault on the negative pole. Air insulation design for HVDC lines at and above ±800 kV requires, therefore, detailed simulation studies to determine the probability distribution of switching overvoltages produced by pole-to-ground faults at different points along the length of the transmission line. Since ±800 kV HVDC lines are generally very long and transmit large amounts of power, it would be necessary to determine as accurately as possible the probability distribution of voltage stresses in order to achieve the specified reliability of the line.

It has been well established that the withstand strength of air insulation is much higher under direct voltage stress than under switching overvoltages. However, most of the direct voltage flashover data has been obtained for rod-rod and rod-plane air gaps and very little for conductor-tower air gaps. It would be useful, therefore, to develop a database on the flashover characteristics under direct voltages of conductor-tower air gaps under conditions of clean dry air as well as in the presence of dust, ions, fog and rain in the gap. Such data would provide a useful comparison with the available rod-plane data presently used and may be useful in other aspects of line design.

The critical data required for DC line design are the flashover characteristics under switching overvoltages of conductor-tower air gaps. However, in early studies [1, 2] such data was obtained only for rod-rod and rod-plane gaps. It should be noted that the switching withstand voltage is a function of occurrence of corona and hence depends on the conductor geometry, surface condition of the conductor and the tower leg as well as on atmospheric conditions. Data for conductor-tower gaps has been obtained in more recent studies [3] for gap lengths up to about 10 m, which may be quite adequate for the air insulation design of HVDC transmission lines at the highest voltages presently foreseen. It would be desirable, however, to carry out other independent studies on conductor-tower gaps to replicate and confirm the results of the earlier study, as well as with specific or close to specific conductor intended for the project.

Many advances have been made over the last twenty years in understanding the mechanisms of lightning overvoltages on transmission lines and methodologies have been developed for evaluating the lightning outage rates of high voltage AC transmission lines [4]. These methodologies are also applicable to HVDC transmission lines, just by taking into account the fact that line conductors are energized at direct rather than alternating voltages. Computational studies should, therefore, be made to determine the lightning outage rates of lines at and above ±800 kV as functions of tower geometry, ground wire shielding angle and tower footing resistance. Results of such studies would be useful in the design of future HVDC lines to meet specified lightning outage criteria.

Insulators

For HVDC transmission lines, the critical consideration in the design of insulators is their performance at the operating direct voltage under conditions of pollution. Extensive research studies have been carried out over the past forty years on different aspects of the pollution performance of insulators for use on HVDC transmission lines. The studies included:

- Laboratory and field investigations of pollution deposition on insulator strings under direct voltages;
- Mechanism of pollution flashover of insulators under direct voltages;
- Requirements of power supply for pollution testing of insulators for HVDC lines;
- Influence of various parameters such as non-uniform distribution of contaminants on individual insulators as well as on the insulators in a string, equivalent salt deposit density (ESDD), non-soluble deposit density (NSDD), wetting conditions and dimensions and shape of insulators;
- Flashover and withstand performance of different types of insulators.

The large amount of information obtained from these studies is useful in the design of HVDC transmission lines. The studies have also demonstrated the linearity of the pollution withstand voltage with the insulator length, at least up to voltages of ± 600 kV.

Presently available information may be adequate for deterministic methods of insulator design for HVDC lines up to ±800 kV. Additional studies and testing are necessary, however, to develop and implement statistical design methodologies, particularly for lines at and above 800 kV. Studies are also required to:

- Monitor the pollution severity on operating HVDC transmission lines;
- Investigate the surface charging of DC insulators which may be responsible for anomalous flashovers on existing HVDC lines and which may be a more serious problem for long insulator strings required for HVDC lines at and above ±800 kV;
- Evaluate the influence of non-soluble materials on the pollution flashover characteristics of DC insulators;
- Obtain the experimental data necessary for the application of statistical methods of insulator design;
- Study the pollution performance of non-ceramic insulators, with emphasis on ageing characteristics;
- Evaluate the pollution performance of long insulator strings required for HVDC lines at and above ±800 kV;
- Develop methods for hot-line washing of insulators and other methods for in-service diagnostics and improvement of the pollution performance of DC insulators.

Corona

Research and testing has been a necessary prerequisite for the corona design of some of the HVDC transmission lines in operation today. Notable examples include:

1. Studies on the outdoor test lines at the National Research Council (NRC) of Canada for the design of Nelson River ±500 kV HVDC lines;
2. Studies at the Dalles test line of Bonneville Power Administration (BPA) for the design of the ±500 kV Pacific Intertie;
3. Studies at the Institut de Recherche d’Hydro Québec (IREQ) for the design of the Québec-New England ±450 kV HVDC interconnection.

In addition to research and testing carried out before the line design, follow-up studies have also been made to monitor the corona performance of all the lines listed above after they have been built and in operation. Other HVDC transmission lines have been designed, built and operated based mainly on the information obtained in different studies and also on the operating experience of other HVDC lines.

As mentioned earlier, corona design of HVDC transmission lines requires the prediction methods as well as design criteria for the different corona effects: corona loss (CL), radio interference (RI), audible noise (AN) and ground-level electric fields and ion currents. Prediction methods developed so far for these corona effects are based on comparatively limited experimental data obtained either from test lines or from operating HVDC lines and are, therefore, also limited in their applicability and accuracy [5]. Additional research and testing are necessary to improve the accuracy of the prediction methods and make them applicable to HVDC lines at and above ±800 kV. Studies may also be necessary to validate some of the design criteria.

As transmission voltages increase, the importance of CL in the economic choice of conductor bundles decreases. Thus, although it would be useful to obtain CL data in any future corona studies at voltages above ±800 kV to improve the accuracy and applicability of prediction formulas, existing methods may still be used in the design of lines up to the highest voltages being contemplated.

Unlike CL, the importance of corona-generated RI, AN and ground-level electric fields and ion currents as design considerations increases with the line voltage. Two types of studies may be carried out to obtain the data for improving the accuracy and applicability of the prediction methods:

1. Long-term measurements of RI, AN, and ground-level electric fields and ion currents of operating HVDC transmission lines at voltages between ±400 kV and ±600 kV. Measurements should be made to cover the different seasons and weather conditions in a year;
2. Studies on experimental lines to determine the long-term corona performance of a few selected conductor bundles for use on HVDC transmission lines at and above ±800 kV.

It is important in both types of studies to equip the test sites with appropriate instrumentation to measure accurately in an outdoor environment, the following parameters at a few points along a line perpendicular to the transmission line and at mid-span: RI, AN, ground-level electric field, ion current density and, if possible also the ion density. In addition to the parameters listed above, it is also necessary to measure on a continuous basis the following weather parameters: atmospheric pressure, temperature and relative humidity as well as rates of rain and snow precipitation. An optional parameter that can be measured in both types of studies is atmospheric aerosol density.

Some psychophysical studies have also been carried out [5] to determine the subjective response of humans to corona-generated RI, AN as well as electric fields and ion currents from HVDC transmission lines. The information obtained from these studies, combined with local weather patterns and any existing environmental regulations, may be used to develop appropriate design criteria for HVDC lines in a given region or country. This would require, however, analysis of the various factors involved such as that carried out to establish RI design criteria for AC transmission lines in Canada [6, 7]. Additional psychophysical and analytical studies may also be necessary to develop design criteria for HVDC lines at and above ±800 kV.

Research and Test Facilities

Special facilities are required to carry out research and testing for obtaining the data necessary to design of HVDC transmission lines at and above ±800 kV. Different test installations, voltage sources and measuring equipment are required for air insulation, insulator and corona studies.

Air insulation studies may be carried out in either an indoor or outdoor test facility. The test installation consists essentially of a mockup tower configuration simulating a conductor bundle to tower gap. The tower may be simulated by a lattice steel structure with a crossarm and insulator string to support the conductor bundle. It should be possible to vary the conductor-tower gap over a range of values required for the transmission voltages being considered. A full bipolar tower head configuration would be required to study the influence of the negative pole on the positive conductor-tower gaps. Previous studies [3] have shown, however, that this influence is quite small, being of the order of 3% or less. Tests using a monopolar conductor-tower air gaps may, therefore, be quite adequate. The DC power source required for flashover tests should be capable of providing the highest transmission voltage being considered plus a 10% to 20% margin. A 10-20 mA current rating is generally adequate for DC sources used for flashover tests under dry conditions, while a current rating of 50–100 mA would be required for testing under wet conditions. An impulse generator capable of producing peak switching impulse voltages in the range of 0.7 to 1.2 times the highest transmission voltage is necessary for carrying out flashover tests with switching impulse superimposed on direct voltage. Adequate HV protecting devices (ex. HV diodes) should be used to protect the two HV sources in the parallel connection to the test objects. The measuring equipment consists essentially of accurate voltage dividers. Equipment for producing artificial rain or dust environment may also be necessary.

Studies on flashover characteristics of polluted insulators for use on HVDC lines require a pollution chamber sufficiently large to allow testing long insulator strings at the highest transmission voltages being considered. A strong DC power source is required for carrying out pollution tests [8-11] and the test voltage is brought into the pollution chamber through a wall bushing capable of withstanding the highest test voltage. The pollution chamber should be equipped to carry out clean fog as well as salt fog tests according to IEC specifications. Apart from the test voltage, measurements are also required of the fog parameters inside the chamber, ESDD on insulator surfaces etc.

The test installation required for corona studies on conductor bundles is a full-scale experimental bipolar HVDC line capable of supporting different conductor bundles with six to ten sub-conductors. The length of the experimental line should be between a few hundred meters to one or two kilometers to allow RI measurements within the AM radio frequency band. The line should also permit variation of pole spacing and conductor height. Two DC power sources are required to energize the bipolar line, with voltage rating about 20% above the maximum transmission voltage being considered and current rating sufficient to supply the expected maximum corona losses on the line. Instrumentation is required to measure the voltage applied to the line, CL, RI and AN as well as the electric field, ion current density and ion density at ground level. Some of these parameters (RI, AN, etc.) should be measured simultaneously at several points to obtain lateral profiles at the center of the experimental line. In addition to the corona performance parameters described above, measurements should also be made of weather parameters, mainly the ambient temperature, pressure, relative humidity, wind speed and direction as well as the rate of rain- or snow-fall. Long-term measurements should be made covering the different weather conditions occurring in a year for each conductor bundle tested in order to obtain useful statistical description of the corona performance.

Facilities to carry out some or all aspects of research and testing required for HVDC transmission lines at and above ±800 kV are available at the following research centers: EPRI Lenox Laboratories (U.S.A), IREQ high voltage test facilities (Canada), STRI high voltage laboratories (Sweden) and CPRI UHV Research Laboratory (India). However, in some cases upgrading of voltage sources and measuring instrumentation may be necessary before proceeding with research and testing at and above ±800 kV.

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