World Bank

Environmental Aspects of HVDC Transmission Systems

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Introduction

Colombia is planning to develop non-conventional renewable energy sources mainly in the area near La Guajira. The power is planned to be transmitted to major load centers in Medellin and Bogota area using VSC HVDC transmission system. TransGrid Solutions (TGS) was requested to prepare a report outlining the environmental requirements/considerations related to HVDC transmission system. The report highlights the differences between the HVDC and HVAC from the environmental perspective based on the international guidelines and other issues that need to be considered in site selection of the converter stations and the route selection for the HVDC transmission line. There is no concept issued on the construction environmental aspects basically because it is considered that there are no differences between HVAC and HVDC infrastructure construction systems and technologies.

HVDC Transmission System

An HVDC Transmission system consists of two major components:

- Converter Stations
- Overhead Transmission line or Cable

The converter stations are used to convert power from alternating current (AC) to direct current (DC) at the sending end and then back to alternating current (AC) at the receiving end. The DC power is transmitted from sending end to receiving end either by overhead transmission line or marine cable or combination of both depending on the application. For the Colombia project both the converter stations and the overhead transmission line are required.

Converter Stations

The HVDC Converter stations are always located adjacent to a large AC substation. The environmental issues related to HVDC converter stations are summarized in table below:

Table – Summary of Converter Station Environmental Issues

Equipment	Environmental impact	Mitigation
AC filters in most applications are not necessary		
Converter transformers	Visual Audible noise Oil	Enclosure / housing Sound barriers / low noise design Oil containment, plus oil separators Sprinkler systems
VSC valves	Radio interference Valve halls are large/tall: visual impact EMF (Electro Magnetic Fields)	The converter valves are inside a shielded building. The building can be made aesthetically pleasing
Smoothing reactor (air core)	Audible noise Visual	Sound barrier Enclosure / housing
DC isolating switches	Radio interference	Distance from sensitive area and proper testing

DC and AC ground switches	Audible noise Radio interference	Distance from sensitive area and proper testing
AC circuit breakers	Visual, Audible noise during operation Radio interference	Visual barriers Increased separation, low noise design Distance from sensitive area
valve cooling	Audible noise Coolant leakage	Sound barriers Containment barriers Dry air coolers
Air handling systems, heating and air conditioning	Audible noise	Low noise equipment Enclosures
AC and DC bus and connectors	Radio Interference	Conservative design Corona rings

The environmental issues, during system operation, fall into the following categories:

- Visual
- Audible Noise
- Radio Interference
- Coolant and oils leaks

These issues are also encountered in AC substations. All of these issues have been successfully mitigated in the HVDC systems currently in operation by locating the converter station away from sensitive area, installing sound barriers/enclosures and using low noise equipment.

Overhead DC Transmission Line

The following three parameters characterize the environment near a high voltage transmission line:

- Electric field
- Magnetic Field
- Air ions and charged aerosol concentration

Electric Field

The electric field arises from both the electric charge on the conductors and charges on air ions and aerosols surrounding the conductor in case of HVDC transmission line. The electric fields of an AC line vary at 50/60 Hz whereas the electric field of an HVDC line are static.

The DC electric field and ion current can interact with persons or objects to produce mild proximity effects. Static electric fields can be perceived by human (movement of body hair for instance) but they can not penetrate the organism.

DC electric fields can give rise to shocks (when accumulated body charges are discharged) to a person that contacts large objects near a transmission line. However, studies concluded that there are no sensations or minor irritation similar to "carpet type" shock. Research in animals and human studies lead to the conclusion that there is no basis to conclude that electric field poses a health risk.

Magnetic Field

Research and studies related to magnetic field indicated no significant influence except as related to navigation and orientation of certain bacteria, homing pigeons, honeybees and elasmobranches fish. Human studies considered inquiries with people working on industries with strong magnetic fields (aluminium plants for example). Studies on humans and animals do not indicate that exposures to DC magnetic field up to 20 G would result in adverse outcomes. The magnetic field at the edge of typical right-of-way of an HVDC transmission line in North America is approximately 10% higher or lower than the magnetic field of earth. The earth' magnetic field is less than 1 G.

It should be noted that the magnetic field produced by HVDC lines adds to the earth's magnetic field and can interfere with a magnetic compass.

Air Ions

Studies on the effects of ions on the humans and animals have not provided any reliable evidence of any harmful effects. At the level produced by HVDC transmission lines, the possibility of risk to human health appears remote. Measurements have shown that exposure naturally-occuring ions near a waterfall or seashore would be about the same as adjacent to an HVDC line right-of-way. Studies conducted on group of people living close to HVDC transmission corridor reported no health impacts.

Comparison between AC and DC lines

The table below summarizes the effects of AC and DC transmission lines.

Table – Comparison between Environmental Impacts of AC and DC Transmission Lines

HVAC VERSUS HVDC: POTENTIAL HEALTH IMPACTS OF ELECTRICAL ENVIRONMENT		
	AC	**DC**
Air Ions	Not relevant	No observed effects
Electric Fields	No observed effects	No observed effects
Magnetic Fields	No cause & effect is established	No observed effects

Transmission Line Route Selection

Following studies which should be carried out in order to determine the environmental impact of the overhead line and can be included as part of the application for consents if an environmental impact statement is requested by the relevant authority.

- Water environment,
- Geology and soils,
- Ecology,
- Cultural heritage
- Landscape and visual,
- Community amenity,
- Socio-economics,

- Telecommunications,
- Noise and electrical interference,
- Traffic and transport,
- Electric and magnetic fields,
- Transboundary impacts if the line crosses international boundaries,
- Interrelationship of impacts. This assesses whether any individual mitigation measure impacts on any other part of the environment.

DC Cables

The following environmental issues must be considered in the DC cable route selection

Fishing

Fishing activity and the increasing practice of fish farming have the potential to impact on a cable route for the following reasons:

- The timing of construction. Fishing in some areas may be restricted to certain times of the year. This may be due to the need to maintain species stocks. This may impact on the time during which cable installation may be possible. It may also result in a deviation in cable routing.
- The negative interaction between fishing gear and cables. During the operational life of a cable fishing activity may have a negative effect on cable integrity. This can be mitigated by cable design to include cable armouring and external protection methods such as trenching, cable burial at an appropriate depth, and adding cable protection if necessary.

Liaison with the fishing industry and statutory agencies is recommended.

Marine Biological Environment

Routing of a cable should take into consideration the biological environment. Areas may already have a protected status and research, or survey may uncover benthic features, communities or species which may be of conservation interest. It might then be necessary to route or deviate the cables from the desired cable route to avoid these conservation areas. It should be recognised that the marine environment would extend from the landfall area with its seabird population through the littoral zone and the sub-littoral zone with diversity in flora, fauna and marine life.

The environmental impacts are generally limited to the near proximity of the cable routes and only in the case it may alter the habitat for a long-term is the concern. However, appropriate mitigation measures are available and should be applied.

Marine Physical Environment

Routing of a submarine cable is influenced by the physical environment of the seabed. This will include such aspects as water depth, seabed slope, boulders, seabed geology and the physical characteristics of the landfall. Features such as boulders, sand waves, gravel trains/waves and steep slopes will be avoided to prevent free spans and laying problems. If protection is being considered soft but non-mobile sediment can make trenching or burial a preferred protection method.

Marine Archaeology

Archaeological features will include wrecks which in some instances may be designated as war graves. It will be necessary and prudent to avoid such features. Agreement with the necessary statutory authority may result in providing a minimum separation distance from these items.

Utility crossings

A desk top study of the area of a proposed submarine cable will reveal existing cables and pipelines which may need to be avoided or crossed. Seabed survey is needed to reveal existing installations. The potential effects of submarine power cables on other cables and pipelines will depend on the relative timing of construction. Potential effects can be mitigated by appropriate routing, specifying a minimum separation between utilities and by appropriate construction methods.

Magnetic fields and compass deviations

DC cables produce magnetic fields and this has the potential to affect navigation tools such as magnetic compass specially in shallow waters. The potential effect rapidly falls with increasing depth and can be mitigated in shallow water by laying the high and low voltage cables together if possible. The magnetic field around a cable carrying 1400 A will almost reduce to the surrounding earths field somewhere about 10m away.

1. Introduction

Electrical power is transmitted over considerable distances from generation sources to load centers. In many cases the generating stations are located far away from the load centers. The distance can range any where from several hundred kilometers to several thousand kilo meters depending on the location of the generating resources. Electricity can be transmitted as alternating current (ac) or direct current (dc). The choice between the two alternatives is based on the technical and economic considerations. This report will be dealing with the environmental issues associated with HVDC overhead dc lines and converter stations. HVDC is applied for:

- Bulk power transfer over long distances. Obviously in this situation HVDC is competing with HVAC. However, there may be some important technical reasons to select HVDC. Having said that, from an economic standpoint, HVDC is more economic beyond a certain distance referred to as the break even point. Such distance may vary from one country to another, mainly due to the construction and civil works costs.
- For transmission by submarine or underground cable the breakeven distance is much shorter than for overhead line transmission. It is generally not practical to consider AC cables longer than 50km but DC cable transmission systems with lengths of hundreds of kilometres are feasible.
- DC schemes can provide asynchronous connections allowing power transfer between power systems operating at different frequencies e.g., 50Hz and 60Hz.
- To avoid an increase of short circuit current level in the AC transmission system.
- The power flow through a DC transmission can be precisely controlled. This is not easy to do in an AC transmission system.
- The fast and exact control of the flow of power over an HVDC system can be used to enhance the stability of the power system to which it is connected.
- Integration of renewable energy sources, wind and solar,

HVDC systems requires converter stations located at the sending and receiving ends of the transmission line or cable. To simplify matters, the discussion in this report will only consider a bipolar HVDC system utilizing an overhead line. Further, it is assumed that the dc line is a bipolar line with a dedicated metallic return (DMR). This means the HVDC system does not utilize earth electrodes during monopolar operation. The impact of the location of the converter stations, the route of the transmission line, is part of the licensing and the environmental assessment of process of any energy transmission and substation project.

A brief description of the electrical environment associated with HVDC Converters is presented in Section 2. Issues related to the converter stations are described in Section 3. Section 4 describes the issues related to overhead transmission lines. Section 5 describes the issues related to DC cables.

2. HVDC Technology and Configuration

There are two HVDC technologies presently available: Line Commutated Converters (LCC) and Voltage Sourced Converters (VSC). Most HVDC schemes in commercial operation today are the LCC HVDC schemes employing line commutated thyristor valve converters. However, the voltage sourced converter (VSC) technology utilizing Insulated Gate Bipolar Transistors (IGBT) valves is gaining popularity specially for offshore wind integration projects.

2.1 Configurations

HVDC transmission can be configured in many ways to suit the operational requirements. Some of the most common are outlined below.

All the following configurations presented below are applicable to both an LCC and a VSC HVDC system

The simplest configuration is the back-to-back scheme in which two converters are situated on the same site without a transmission line This configuration is used to form an asynchronous connection between different areas or system. See figure 2-1.

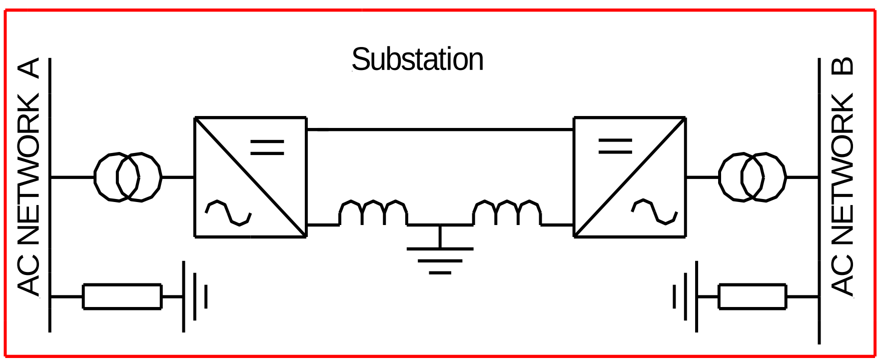

Figure 2-1 Back to back HVDC Scheme

The second configuration is monopolar HVDC systems. Monopolar HVDC schemes use only a single high voltage conductor line or cable. For the return path the earth or sea or a metallic low voltage conductor is used. See figures 2-1 and 2-3.

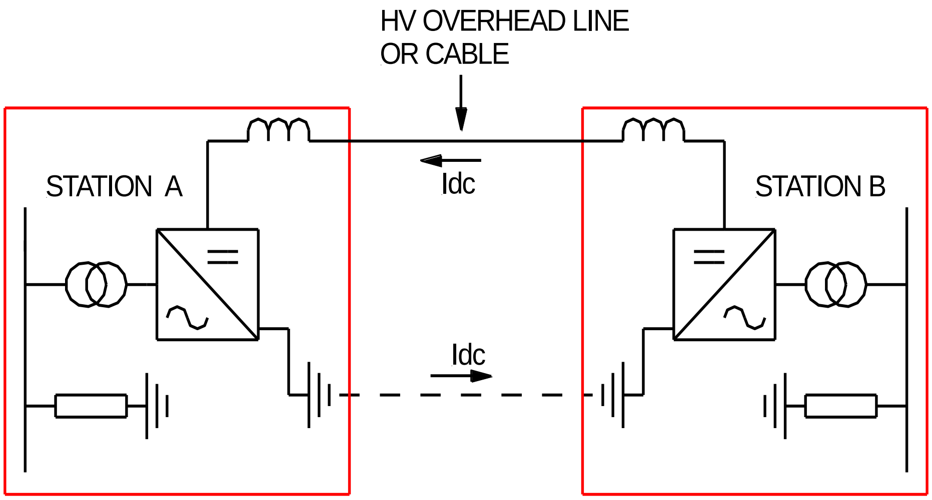

Figure 2-2 Monopolar point to point HVDC scheme with earth return

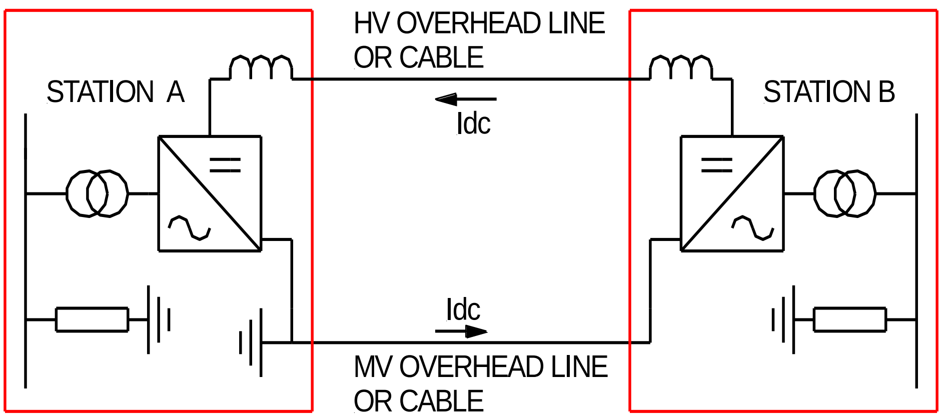

Figure 2-3 Monopolar point to point HVDC scheme with metallic return

The most common configuration is Bipolar HVDC scheme. A bipolar scheme uses two high voltage conductors of different polarity. Bipolar schemes can employ electrodes for periods of unequal pole currents, or for emergency operation when one of the poles is out of operation figure 2-4, or be equipped with a dedicated metallic return(DMR). With a DMR , the grounding is made only at only one terminal, figure 2-5. However, in many bipolar systems, monopolar operation can also be performed utilizing the out of service pole conductor as a return path referred to as permanent metallic return (PMR). For PMR monopolar operation, the converter stations must be designed for it,

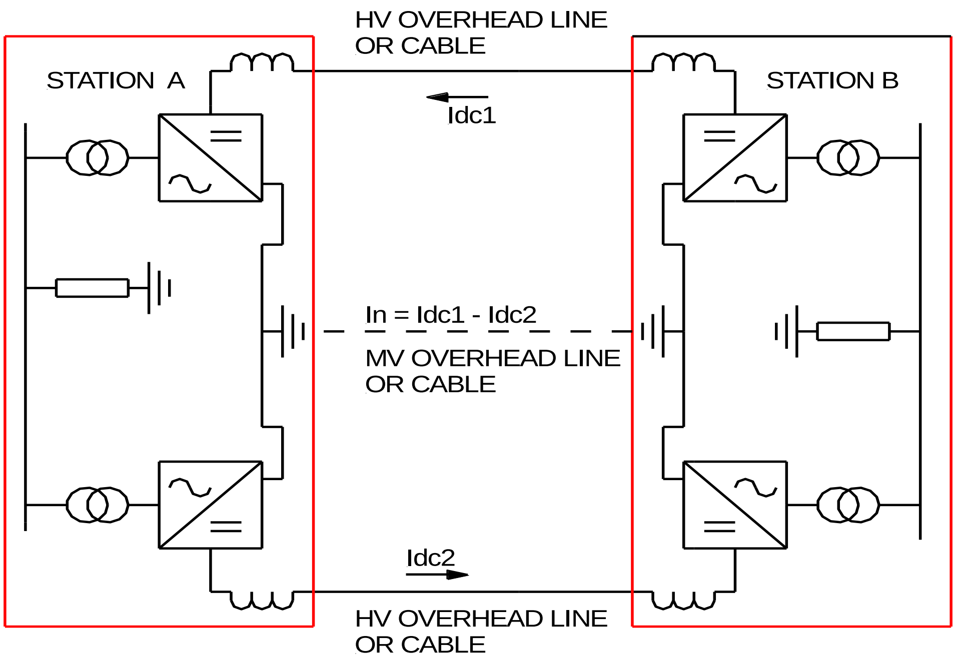

Figure 2-4 Bipolar point to point HVDC scheme with electrodes.

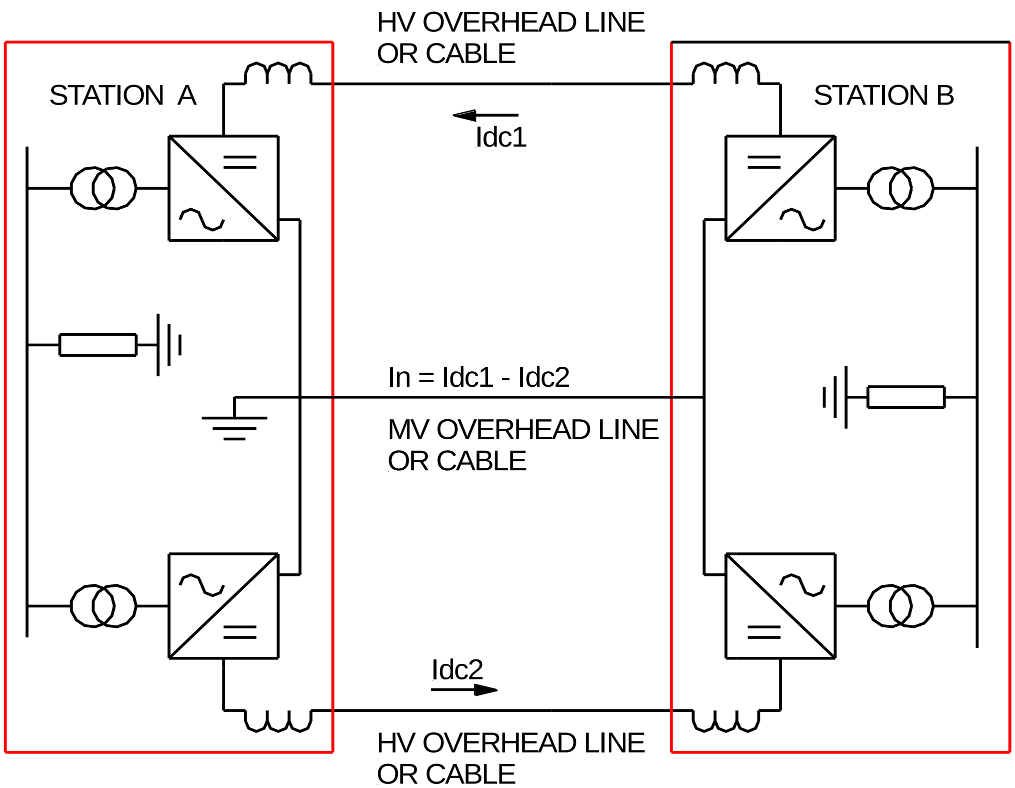

Figure 2-5 Bipolar point to point HVDC scheme with DMR

VSC transmission schemes were commercially introduced in 1999.

VSC converters have been applied utilizing both HVDC cables and overhead lines. One of the most common configurations is the symmetrical monopole as shown in figure 2-6.

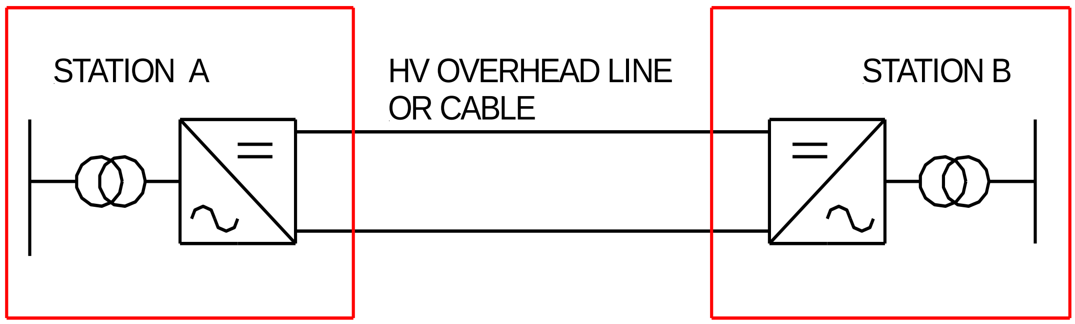

Figure 2-6 Typical symmetrical monopole VSC HVDC scheme

3. Converter Station

3.1 Converter station equipment

In principle the converter stations at each end of the transmission line are identical. There may be very minor differences, but the major equipment are basically similar when it comes to their environmental impact. The main components of a converter station are:

3.1.1 Converter valves:

Currently HVDC utilizing VSC converters is based on the multi-module converter (MMC) technology. The MMC is the prevailing technology in use (Figure 3-1). The converter valves are of modular design. The modules in a VSC converter are assembled in valve structure that also includes the support insulators, the optical fibers, as well as the necessary cooling pipes (Figure 3-2 & figure 3-3)

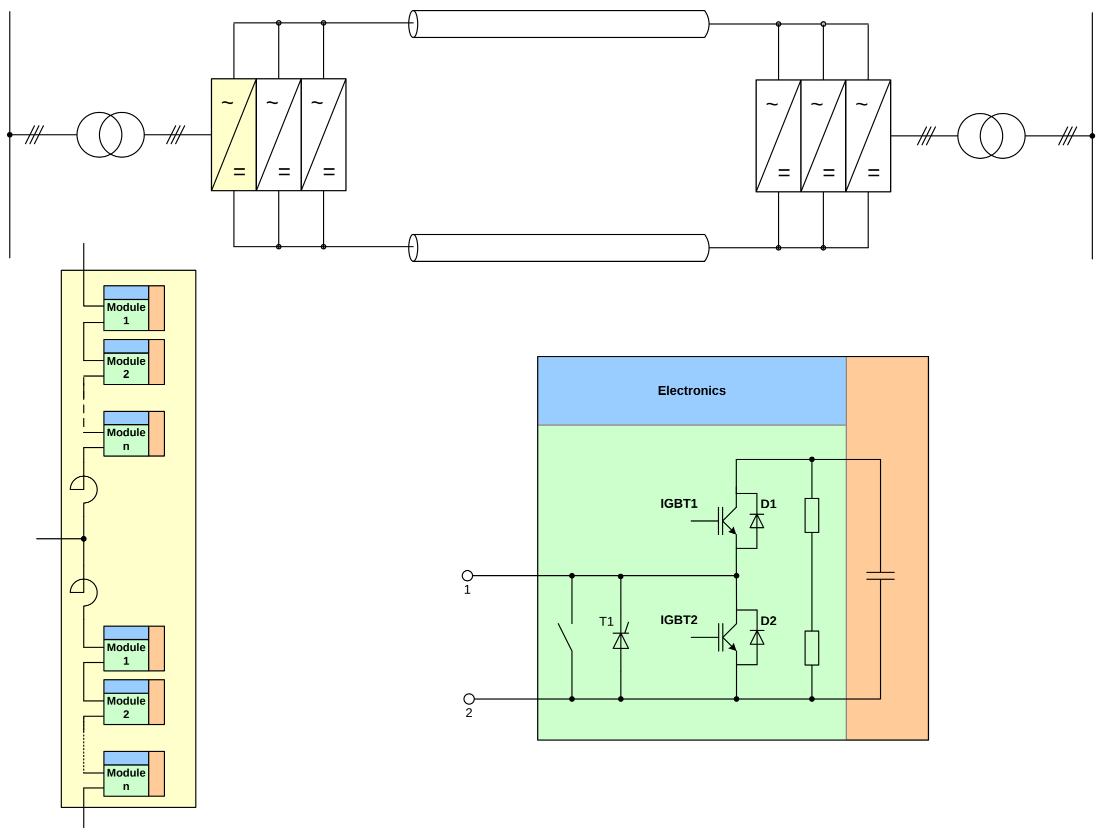

Figure 3-1 MMC concept “Copyright: Siemens”

Figure 3-2 VSC converter valves courtesy of siemens

Figure 3-3 VSC converter valves courtesy of Siemens

The converter valves are an indoor installation in a building referred to as the valve hall. The valve hall also houses other equipment such as the ground disconnects. Valve halls are shielded buildings to keep the radio interference inside the valve hall. {Figure 3-4)

The dimensions of the valve hall are dependant on the dc voltage and the required clearances for maintenance.

Figure 3-4 INELFE 2X1000 MW VSC symmetrical monopoles at Biaxas France-Press release by Siemens

The environmental issues of the converters and the valve halls are:

- Audible noise- MMC converter valves audible noise level is very low when compared to the LCC converters. The reason being that the valves do not include saturable reactors which are the primary noise source in an LCC valve. The audible noise is contained within the valve hall. Therefore, there are no external exposure to it.
- Radio interference-The valve hall is shielded and therefore Radio interference from the converter is mitigated
- Visual impact is important, it can be mitigated.

3.1.2 Valve cooling

The valve cooling system typically consists of two types of components. One is housed indoor and basically consists of pumps, water treatment circuit, water refill system, instrumentation, and expansion vessel. The other is the outdoor equipment which are basically the outdoor radiators and the associated cooling fans. A typical valve cooling contains either pure deionized water or a mixture of de-ionized water and Ethylene Glycol.

From an environmental perspective, two issues arise from valve cooling systems:

1. Noise from the outdoor cooling fans, which is typically mitigated by the choice of the type of fans used,
2. Spillage of the cooling medium (Ethylene Glycol) which is dealt with by careful handling and retaining basins which can collect the spilled liquid for proper handling.

Figure 3-5 Outdoor Valve Cooling radiators and cooling fans

3.1.3 Converter/Interface Transformers

Converter transformers (Figure 3-6) are used to provide isolation between the ac and dc systems and to adapt the AC voltage level to the DC voltage level. DC stations over the years have been designed and built with different configurations of converter transformers [1]. Interface transformers are used in symmetrical monopolar system. Interface transformers are not subjected to dc voltage stresses.

Similar to conventional AC transformers, the converter transformers are oil filled.

The environmental issues associated with transformers include:

- Consideration of weight during transportation to the site. This will affect routing and have a temporary impact on traffic. This is not any different from transporting large AC transformer and is handled by careful planning
- Oil which may leak. It is an environmental concern, that is not different from large AC transformers. Containment pits are part of the design to contain any oil spill (Figure 3-6).
- Fire risks, certainly it is not any higher risk than AC transformers but must be mitigated. Typically, a transformer water deluge system is included plus fire wall barriers between units
- Audible noise. This is mitigated by proper design and specification of the appropriate transformer noise level. The more stringent the requirements the more expensive the mitigation.

Figure 3-6 Converter Transformer

Figure 3-6 transformers with containment pits and barriers

3.1.4 AC-filters

The harmonic profile of VSC MMC converters is quite different from the classical LCC converters. The much lower overall level of harmonic generation is one of the attractive features of VSC MMC. It allows converter stations to be built with very small filters or non at all. This certainly reduces the converter station foot print and its visual impact. Further the classical issue of reactive power necessary for the successful operation of the LCC converter is not an issue in VSC converters. Thus, there is no need of reactive power shunt banks, again reducing the foot print of the converter station as well as eliminating many HV components. DC-filters

Similar to AC filters DC filters are typically not necessary in VSC MMC HVDC stations.

3.1.5 Smoothing Reactors

In VSC MMC converter stations a smoothing reactor is required to limit the rate of change and magnitude of the dc current in the event of a fault. Although the size of the smoothing reactor is much smaller when compared to LCC converters. Typically, the smoothing reactor is dry type (no oil) air cooled and air insulated Figure 3-7.

Figure 3-7 Air Core Dry Type Smoothing Reactor

3.1.6 Phase reactors

The phase reactors are necessary for the operation of the VSC converters. The reactors are located on the ac side of the converter and connected in series between the converter transformer and the converter valves. There are many topologies, however in all applications, the reactors are air insulated, and air cooled (Figure 3-8).

Figure 3-8 Phase reactors

3.1.7 DC switchyard

The DC switchyard includes all the necessary dc switchgear, measuring equipment , busbars and secondary systems. The appearance of the DC switchyard is not any different from any AC switch yard, although by comparison it is much smaller than a typical AC switch yard.

3.1.8 AC switchyard

The AC switchyard of the converter station is not any different from the AC switchyard in any other applications. In fact, in many instances where the converter station is integrated in an existing sub station. The converter station portion is not significant.

3.2 Environmental issues – Converter Station

CIGRE HVDC Committee Working Group B4-44 investigated the environmental issues related to HVDC systems and issued Technical Brochure 508, “HVDC Environmental Planning Guidelines”, Oct. 2012 [2].

Table 3-1 shows a summary of the environmental issues related to the converter stations and proposed mitigation as identified by WG B4-44 [2]. The table has been modified to reflect the issues related to VSC MMC converter stations

Table 3-1 Summary of Converter Station Environmental Issues

Equipment	Environmental impact	Mitigation
AC filters in most applications are not necessary		
Converter transformers	Visual Audible noise Oil	Enclosure / housing Sound barriers / low noise design Oil containment, plus oil separators Sprinkler systems
VSC valves	Radio interference Valve halls are large/tall: visual impact EMF	The converter valves are inside a shielded building. The building can be made aesthetically pleasing
Smoothing reactor (air core)	Audible noise Visual	Sound barrier Enclosure / housing
DC isolating switches	Radio interference	Distance from sensitive area and proper testing
DC and AC ground switches	Audible noise Radio interference	Distance from sensitive area and proper testing
AC circuit breakers	Visual, Audible noise during operation Radio interference	Visual barriers Increased separation, low noise design Distance from sensitive area
valve cooling	Audible noise Coolant leakage	Sound barriers Containment barriers Dry air coolers
Air handling systems, heating and air conditioning	Audible noise	Low noise equipment Enclosures
AC and DC bus and connectors	Radio Interference	Conservative design Corona rings

3.2.1 Site Selection Related to Environmental Aspects

Site selection considerations for converter stations include:

- Land area requirements (sufficient area for equipment, possible further expansion, desirability of having sufficient land to create noise/visual buffers if adjoining sensitive areas e.g., residential),

- Sensitivity of adjoining land uses – important not only for impacts on adjoining land from the station itself (e.g., noise impacts on residential areas) but also the need to find an appropriate line route into and out of the site (e.g., may be an issue if surrounding land has a reserve status),
- Transportation and site accessibility – of critical importance is that the site is accessible for transport of heavy loads e.g., large transformers,
- Geotechnical factors, soil/subsurface conditions – e.g., liquefaction risk or areas having a high-water table are not appropriate,
- Earthquake /seismic risk/geothermal activity e.g., proximity to fault lines or active volcanoes,
- Flooding risk,
- Previous land use – e.g., contamination issues may apply,
- Topography – site should be relatively flat to minimise civil works,
- Ecological – avoidance, if practicable, of areas of ecological value,
- Visual/landscape constraints,
- Historical/archeological/cultural impacts,
- Civil aviation – impacts on flight paths.

The site selection criteria has not changed over the years. In principle converter stations are sited either near the generation or inside an existing AC substation. What has changed over the years are the countries individual environmental regulation that has to be adhered to. Such as noise levels, EM interference and appearance. Some converter stations have been constructed near residential areas without any problem as long as their impact is taken into consideration during the project implementation (figure 3-9, figure 3-10).

Figure 3-9 Haywards Converter station New Zealand

Figure 3-10 Neptune Regional transmission Sayreville substation USA

3.2.2 Audible noise

Converter stations are a source of audible noise [3]. The noise will mainly emanate from transformers and filters. There will also be noise associated with the momentary operation of switching devices.

During the planning phase of any project the allowed limit of noise will be determined by the appropriate authorities and will mainly take into account the proximity of habitable dwellings. The noise limits will be set in accordance with accepted standards for disturbance. It is at this stage that the developer should:

- Determine and prove noise levels and compliance with any level set by law. If necessary, agree with the authorities to build an acoustic model to be used in determining and proving noise levels and compliance with any level set,
- Design appropriate sound attenuation for the main sources of noise based on predicted noise levels for normal operation.

The important noise level is the number at the property line of the converter station. In most of the new HVDC projects that number is between 35 and 45 dBA depending on the location.

As far as the mitigation measures are concerned, it appears that enclosures, noise deflectors and housing the equipment indoors are typical.

3.2.3 Electromagnetic Interference

The issue of magnetic and electric fields within the converter station is dealt with on two levels:

1) General public exposure,
2) Occupational exposure, which is basically the people working at the converter station.

ICNIRP [4] indicate reference levels of electric and magnetic field for AC systems. Two sets of reference levels are given, one related to "general public exposure" and another for "occupational exposure (electricity utility workers)". General public exposure reference levels are smaller than occupational exposure levels by a factor of two for electric field and a factor of five for magnetic field.

In HVDC the reference values for general public exposure to magnetic fields is five times smaller than the reference values for occupational exposure, and both reference values are approximately 500 times higher than the magnetic fields found in a converter station.

As for the DC electric fields, there are no reference values, however, designs take into consideration the perception by human of the field (effect on hair, skin) and strive to minimise such effects.

There are no statistics showing that electrical workers operating HVDC converter stations and in principle exposed to both electric and magnetic fields suffer ill heath issues compared to other occupations [5].

3.2.4 Construction

The construction of an HVDC converter station is not any different from the construction activities of any large ac substation. It involves civil works, steel structures, foundations, and erection of heavy equipment. The issues to be dealt with are:

- Increased traffic on the roads leading to the site,
- The transportation of large and heavy pieces of equipment, mainly the transformers,
- Noise due to site works,
- Unintended spillage of oil during construction,
- Accidents.
- Changes in land covering
- Changes in geoforms, and instability process

These issues are not unique to converter stations and are very typical whether AC or DC stations are being constructed. The mitigation for these issues is as follows:

- Applying the relevant safety rules and regulations,
- Respecting the local transportation permits,
- Having in place a health and safety organisation,
- Having in place spill control mitigation techniques,
- Remaining within the guidelines of noise levels that are applicable to a the construction license.

When prevent, reduce, or mitigate an impact is not option, it is required to design a compensation plan in order to guarantee that the impacted element will be preserved by similar environmental condition through the use of equivalent or similar ecosystems and factors.

3.2.5 Operation

From an environmental perspective, the operation of a converter station is governed by meeting the limits that have been applied in the design in respect of noise, EMF, interference due to harmonic generation. Therefore, during operation, the only remaining issues are safety of both the public and the workers, and dealing with unintended spillages. Such issues are not unique to HVDC converter stations and are covered by the utility and the local and national guide lines and rules such as:

- Health and safety rules

- Spill containment rules

3.2.6 Decommissioning

The issues of decommissioning an HVDC converter station are not unique to HVDC and are similar to the decommissioning of ac substations. The guidelines of the manufacturers for end-of-life disposal should be followed.

In general equipment and materials will be decommissioned and disposed of as follows:

- Transformers, in principle will be drained, the oil reclaimed, stored, processed and reused,
- Steel structures can be salvaged and sold as scrap,
- Switch gear may be reclaimed and used for other applications, any SF_6 can be reclaimed and reused,
- Control cabinets, cables, and such equipment can be dismantled and sold as scrap,
- Capacitors, these days are thin film type and are oil free and certainly PCB free, therefore represent no issue for scrapping,
- IGBT valves will be disposed of as electronic waste.

4. Overhead DC Transmission Line

HVDC utilizing overhead DC lines is a common practice. It is applied for the transmission of bulk power from remote generation. It is also applied for HVDC interconnections between networks. HVDC overhead lines are currently operating at dc voltages of 800 kV with one project at 1100 kV. Obviously overhead lines can transmit large amounts of power for long distances for example 3000 km.

The selection of the optimum transmission line (bipole) alternatives encompasses the different components of the line, so that a global optimization can be achieved. The optimum choice only has a real meaning when electrical, mechanical, civil and environmental aspects are taken into account as a whole set, for which a satisfactory performance and reasonable costs are simultaneously achieved.

Regarding the transmission line itself, its design includes at first the electrical requirements such as power transfer capability and voltage are specified from which the tower-top geometry, the electric field effects, the corona effects, the overvoltage and insulation coordination and the required right of way are established. Then the mechanical design of the towers and foundations, the determination of conductors and shield wires stresses are carried out and finally the economics including direct costs, cost of losses, operation and maintenance cost for the line life, is evaluated.

4.1 DC line configurations

Overhead DC transmission lines include conductors, shield wires, insulator strings and hardware, support towers with or without guy wires, foundations and a grounding system.

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:

- Ccorona losses (CL),
- Radio interference (RI) in the vicinity of the line
- Aaudible noise (AN) in the vicinity of the line
- Eelectric 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.

Some comparison of existing projects performance values is presented in the Table 4-1

Table 4-1 Typical HVDC overhead line performance for actual projects

Project	DC voltage	Audible noise AN	Electric field	Ion current	Ion density
HQ HVDC line	450 kV	55 dBA @the edge of the 60m right of way	30kV/m @ ground level	100 nA/m^2	10^5 ions/cc
Nelson River	500 kV	45 dBA @ 15m from the edge of the right of way	26kV/m @ ground level	70 nA/m^2	
Itaipu	600 kV	40 dBA @the edge of the right of way	40kV/m @ ground level		
Power Grid	500 kV	55 dBA @ the edge of the right of way	40kV/m @ ground level	100 nA/m^2	

It should be noted there are many projects with the same range of numbers

Table 4-2 presents the optimal voltage as a function of station power and line length as per Cigre TB 388 [6].

Table 4-2 Optimum DC voltage as a function of power and line length

Voltage (kV)	For 750 km	For 1,500 km	For 3,000 km
+/- 300	< 1,550 MW	< 1,100 MW	< 850 MW
+/- 500	1,550 – 3,050 MW	1,100 – 2,200 MW	850 – 1,800 MW
+/- 600	3,050 – 4,500 MW	2,200 – 3,400 MW	1,800 – 2,500 MW
+/- 800	>4,500 MW	>3,400 MW	>2,500 MW

Similar AC lines, DC lines are built using the following:

- Conductors
- Steel structures
- Foundations
- Insulators
- Sky wires

Figure 4-1 shows the typical components of a guy dc line tower. Figure 4-2 shows two bipolar dc lines for Nelson River project that have been in operation for more than 45 years at +/- 500kV. Figure 4-3 shows a typical tower of a recently built +/- 800 kV DC line in India, with dedicated metallic return conductor (DMR).

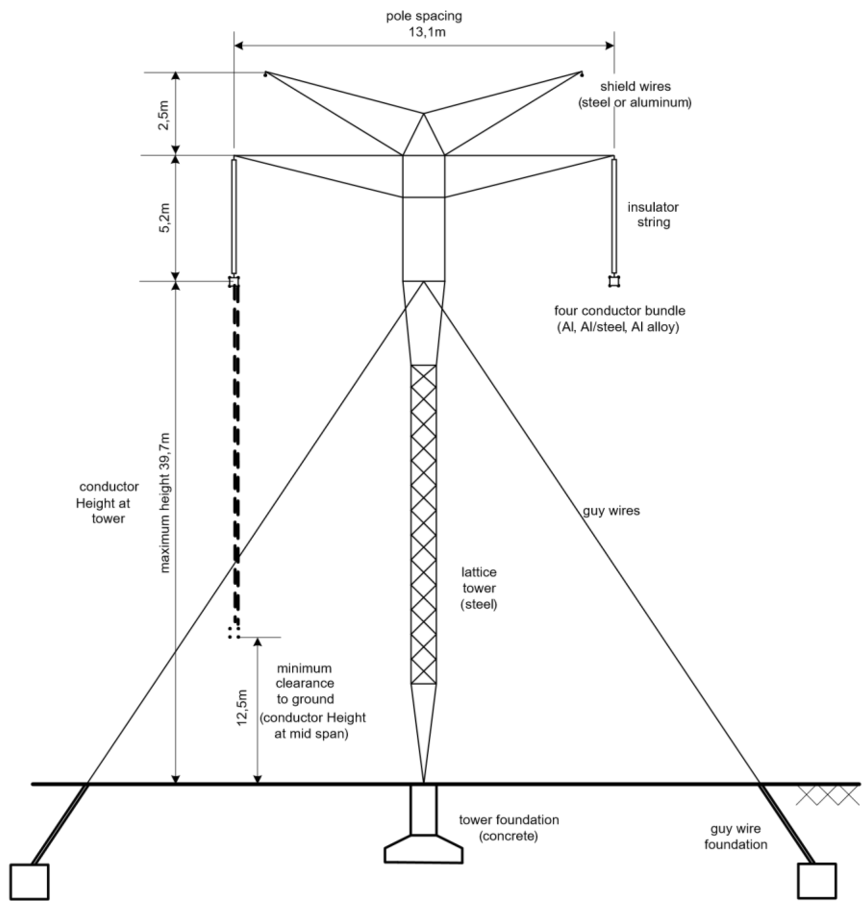

Figure 4-1 Tower of typical guy tower for 500kV DC transmission line

Figure 4-2 Nelson River HVDC lines

.

Figure 4-3 +/- 800 kV Tower For CK2 Project in India with Dedicated Metallic Return Conductor (DMR)

4.2 Environmental issues – overhead lines

4.2.1 Overall Process Description

The key stages undertaken [2] for the selection and routing process for an overhead line in order to mitigate the environmental impact are described below:

1. **Identification of system connection options.**
   The identification, analysis and selection of potential technical options for achieving an effective electrical connection between the generation centre and the load centre.

2. **The technical evaluation of identified connection options.**
   The technical evaluation of each identified option against key performance criteria, with regard to the need for development of a technically feasible, reliable and economically viable overhead line connection option.

3. **The evaluation of preferred study areas, the identification of route corridor options and the selection of a "preferred route corridor".**
   High-level consideration of alternative study areas derived from the preferred connection options and route corridor options within these study areas; taking into consideration the nature of the electricity transmission infrastructure, the strategic objectives of the proposed interconnector, and the environmental imperative to present the lowest reasonably achievable impact on the human and natural receiving environment; and resulting in the joint determination of a preferred electrical connection option and a preferred geographic route corridor for further development.

4.2.2 Selection of the preferred route within the corridor

The following key environmental aspects should be considered in selecting the preferred route for the overhead line.

- Landscape character,
- Consideration of visual aspect from dwellings,
- Use of topography of the landscape and avoidance of higher land,
- Maximising distance from dwellings and other buildings,
- Maximising distance from settlements,
- Maximising distance from community sites,
- Avoidance of woodlands, indigenous land, national parks or other protected areas, large trees, loughs and marshlands,
- Avoidance of waterbodies, wetlands.
- Avoidance of designated sites of outstanding natural beauty and scientific interest etc.
- Avoidance of historic and archaeological sites (both direct physical impacts and maximisation of distance to reduce setting impacts),
- Avoidance of agricultural business area (high productive farm),
- Avoidance of important/rare bird areas and mitigation routes.

Based on these considerations an achievable continuous overhead line route can be determined.

It is preferred to keep the overhead line route as straight as possible, in order to minimise route length and avoid use of angle tower locations as angle towers would be larger towers with a higher level of visual impact.

Following the selection of a line route detailed environmental impact studies along the route should be carried out to assess the impact on the local environment of the construction, operation and maintenance of the preferred line route. Final tower positions can subsequently be determined including the final line route which maximises the potential environmental mitigation measures.

Following studies which should be carried out to determine the environmental impact of the overhead line and can be included as part of the application for consents if an environmental impact statement is requested by the relevant authority.

- Water environment,
- Geology and soils,
- Ecology,
- Cultural heritage
- Landscape and visual,
- Community amenity,
- Socio-economics,
- Telecommunications,
- Noise and electrical interference,
- Traffic and transport,
- Air quality and noise
- Properties and land use
- Fauna and mobilization routes
- Ground covers
- Forest use
- Job opportunities and facilities
- Electric and magnetic fields,
- Transboundary impacts if the line crosses international boundaries,
- Interrelationship of impacts. This assesses whether any individual mitigation measure impacts on any other part of the environment.

National guidelines are normally set out which specify the levels for audible noise, EMF and prevention of interference with communication systems, including radio and television, for overhead lines. These impacts are normally mitigated through design and study models which can determine the expected levels prior to manufacture, construction and operation.

Table 4.3 shows a summary of some of the common environmental impacts and possible mitigation measures.

Table 4-3 Environmental Issues - DC Overhead Lines

Issues	Environmental impact	Mitigation
Corona Effect	Audible noise and radio interference	Proper design
Conductor surface gradient Electromagnetic interference (EMI) Audible Noise	Visual (luminous) and others as below Sound and image noise Noise	Proper conductor bundle design Appropriate right of way (ROW) width, proper conductor bundle design; install dedicated antenna at homes; change the equipment (eg. AM radio to FM radio) Appropriate ROW width; proper conductor bundle design; install sound barrier or dynamic noise cancelation
Electric Field and ions	Perceived effect on skin and hair	Appropriate conductor to ground height Appropriate bundle design
Magnetic Field	Compass deviation, and possible effect on animal and bird orientation	Appropriate conductor to ground height Avoid critical areas
Visual	Aesthetic Bird collisions	Route selection and tower appearance Bird diverters, route selection
Woodlands	Tree removal, effect on habitat, flora and fauna	Route selection Adjusting tower placement and span length to minimize the need for tree removal and trimming along forest edges; Follow guidelines for preventing the spread of invasive plant species and diseases.
Cultural heritage	Damage to components of the archeological heritage	Consultation with local communities and authorities during route selection

4.2.3 Corona Effects

Corona losses occur due to the generation and movement of ions by corona on the conductors. EMI and audible noise (AN) are generated by the pulse modes of corona discharges. The current pulses induced in the conductors and propagating along the line produce RI and TVI, while the acoustic pulses generated by these modes of corona and propagating in ambient air produce AN.

The characteristics of corona-generated radio interference (RI), television interference (TVI), and AN on DC transmission lines differ significantly from those on AC lines. Firstly, while all three phases of an AC line contribute, only the positive pole of a DC line contributes to the RI, TVI and AN. Secondly, the RI, TVI and AN levels of DC transmission lines under foul weather conditions such as rain, which result in rain drops on conductors, are lower than those under fair weather conditions. This is opposite to AC lines where foul weather conditions produce the highest levels.

Corona considerations in the design of DC transmission lines have been discussed in the CIGRÉ Publication 61 [7]. In 2008, JWG B2/B4/C1.17 discussed "The impact of HVDC transmission lines on the economics of HVDC projects" [6] and the above issues were taken into consideration.

The key parameter to evaluate the corona effect is the maximum conductor surface gradient. This parameter is a function of the line voltage and line geometry (pole spacing, conductor height above ground, bundle spacing, and conductor diameter). When the electric field at the surface of a transmission line conductor exceeds a certain value (maximum peak gradient), partial electrical breakdown of the surrounding air takes place, giving rise to corona discharges. Peak maximum gradient is around 30 kV/cm, therefore when the maximum line conductor gradient is below 25 kV/cm [8], there is no major impact in the transmission line design caused by corona effects.

As in the case of RI, there are presently no regulations for AN for HVDC transmission lines. The Environmental Protection Agency (EPA) in the US recommends that the day-night average sound level [9] should be limited to 55 dBA outdoor. Day/night time proportion is 15/9 h; and the noise annoyance at night should have an equivalent effect of 10 dBA lower than during the day.

Usually RI and AN criteria will lead to a certain ROW width. This width can be considered as reference for land use restriction, however, if in specific areas the annoyance is unacceptable, local mitigation can be provided. Uses of noise barriers or noise cancelling acoustic devices are among the options. Anyway, all known measures to decrease audible noise from this source are quite costly.

4.2.3.1 Radio Interference

Radiated noise field strengths should be coordinated with predictions or measurements of local broadcast signal strengths and any local legislation concerning limits of electromagnetic interference (EMI). This applies to the MW (medium wave) and HF (high frequency) bands, namely, 0.3 to 30 MHz, but usually not to the television and FM radio bands [8, 10].

Field surveys or predictions of broadcast signal strengths can be conducted before construction of the line . Noise levels (dry- or fair-weather conditions) from the line can be predicted from published data, laboratory tests, service experience or using simulation packages. Acceptable signal-to-noise ratios should be complied with. The line route should take cognizance of nearby civil, military, and private communications stations. If necessary, specific; case-by-case impact studies should be done on such installations.

Radio interference from HVDC lines in dry conditions is typically 6 to 8 dB lower that that from comparable HVAC lines, provided the dc conductor surface gradient is kept below about 25 kV/cm [8]. Even if the radio interference does not impact on nearby radio stations, the noise should be kept within acceptable limits in order not to pollute the background noise spectrum unnecessarily.

4.2.3.2 Television Interference

Extraneous sparking – as distinct from corona – can cause intermittent TV interference (TVI) in dry conditions. Sources of sparking, such as loose fittings or polluted insulators, need to be identified and eliminated. Such problems are regarded as 'faults' [10,11].

Sparking is rare in well constructed and maintained HVDC plants. For a given gap geometry, dc spark breakdown differs fundamentally from that of ac, in that repetitive breakdown does not occur. A gap will initially break down once with a second breakdown occurring only after the gap capacitance has become charged again. This may take several seconds.

Although the corona phenomenon does generate some radio interference above 30 MHz, the levels fall off rapidly with increasing frequency. Thus, corona is generally not regarded as a source of TVI. However, radio interference above 30 MHz does need to be considered in assessing the impact of a line (whether HVAC or HVDC) eg. on the operation of sensitive radio stations [10].

4.2.3.3 Audible Noise

Audible noise, like radio noise, is produced by corona on transmission line conductors. For ac lines, it takes on two forms: a sizzling or crackling sound called random noise and a single pitch tone called hum. Only the random noise component is present for dc lines. Transmission line random audible noise is rich in high frequency components, which gives it a distinctive sound. Both dc and ac lines have similar corona noise frequency spectra.

The human ear does not have a linear frequency response. As a result, it is necessary to adjust measured noise levels, given in decibels (dB), to obtain correlation with human ear sensitivity. The correlation is provided by frequency response "weighting" curves. The "A" weighting curve is used for most community noise evaluation studies. Noise calculated or measured with a particular weighting curve is identified with the letter of the curve in parentheses, for example 50 dB(A) for A weighting.

Audible noise from ac transmission lines is generally of concern only in wet conditions. Fair weather audible noise can be sometimes heard, but rarely is it able to be measured because of the presence of background noise. On the other hand, the highest noise levels occur during rain, which can itself mask the noise. In contrast, audible noise from dc transmission lines is generally greater during fair weather than for rain. Fair weather audible noise from a dc line is about 5dB higher than the audible noise during rain. Audible noise produced by the dc line during fair weather is 10 to 12 dB below that produced by the ac line during rain.

There are presently no regulations for AN for HVDC transmission lines. Many jurisdictions have noise abatement ordinances which specify noise at the property line. These ordinances take a number of forms. Some are maximum A-weighted levels. Some have different levels for day and night.

The Environmental Protection Agency (EPA) in the US recommends that the day-night average sound level [9] should be limited to 55 dBA outdoor. Day/night time proportion is 15/9 h; and the noise annoyance at night should have an equivalent effect of 10 dBA lower than during the day.

Usually RI and AN criteria will lead to a certain ROW width. This width can be considered as reference for land use restriction, however, if in specific areas the annoyance is unacceptable, local mitigation can be provided. Uses of noise barriers or noise cancelling acoustic devices are among the options. Anyway, all known measures to decrease audible noise from this source are quite costly.

4.2.4 Telephone Interference

The use of fibre-optic and radio systems in modern rural telecommunications systems has tended to reduce the importance of telephone interference caused by an adjacent HVDC (or even HVAC) line. However, as voice-band telephone networks may still be used in the more remote rural areas, mitigation of telephone interference must still be considered and certainly not discounted by the designer.

Overlooking this factor has been known to cause very widespread and disruptive telephone interference [10].

The amplitude of harmonic current flowing into the HVDC line from the convertor is limited by dc harmonic filters and PLC filters, to levels which will not generate interference with PLC communication of the dc line and in adjacent metallic telephone circuits.

4.2.5 Electrostatic (Capacitive) Coupling

Electrostatic coupling (in the absence of corona and space charge) to adjacent unearthed (or floating) conductive objects depends on the potential difference between the line and the object and hence their proximity [10,11].

Unlike for ac coupling, as already mentioned, HVDC coupling does not cause repetitive discharges, but rather static discharge effects that are generally less severe than for ac. A safe dc discharge current limit of 2 mA has been proposed by the National Protection Agency (NPA) in the United Kingdom [12]. Electrostatic coupling can be mitigated by adequate separation of the line from adjacent objects or by earthing the object, or both.

When space charge and ions are present, the resulting partial conductivity of the air allows quasi-continuous dc currents to flow from the line to the object in question. In this way, the public can be exposed to perceptible voltages and painful, but not dangerous, shocks [8]. This is explained further in the description of ionic coupling.

4.2.6 Electromagnetic Coupling

This refers to the coupling caused by the magnetic field generated by the current flowing in ac and dc lines. The first point to note is that, under steady state conditions, the ac current (power frequency and harmonics) induces, by Faraday's law of electromagnetic induction, a relatively small voltage in an adjacent telephone line, for example. The harmonics cause noise voltages to be induced in adjacent telephone circuits (or adjacent power lines) and are dealt with in the same way as the dc harmonic currents. However, in the case of dc, the line direct current does not change with time, so only the harmonic ripple induces noise voltages in the adjacent line.

The second point to note is that when an earth or ground fault occurs on an ac line, the inducing current increases substantially. Therefore, the degree of coupling with the adjacent line also increases substantially (to several thousand amperes), thus causing large voltages to be induced. Such voltages are of the order of 300 V/kA/km of parallel exposure, and last for as long as it takes for the ac protection to interrupt the fault (typically 100 – 150 ms).

A ground fault on a HVDC line, on the other hand, will induce a voltage during the period which the current increases from its prior value to about twice this value. The rate of increase of increase of current (di/dt) is typically in the order of 1500 A/ms, and lasts a few milliseconds. After about 50 ms, both the pole voltage and current are rapidly reduced by the dc control algorithms.

The point to appreciate is that the transient overvoltages induced in the telephone line are much less severe in the dc case than for ac.

4.2.7 Air Ions

Air ions are natural components of the atmosphere. Ions are molecules with extra electrons (negative ion) or missing electrons (positive ion). They may be produced by such activities as storms, sunlight, blowing dust, and corona. High voltage dc lines typically operate in constant corona and produce air ions by the breakdown of the air molecules adjacent to the conductor (corona). The flow of air ion current equals the corona loss current.

Because of the non-alternating nature of direct current transmission, the air ions migrate away from a dc line instead of being tapped near the line conductors as with an ac line. Because both conductors of a dc line have an electric field, both can produce corona and therefore air ions. Most air ions are attracted to the conductor opposite to the one that generated them. Neutralization occurs when air ions combine with those of opposite polarity. Most air ions from HVDC lines are neutralized. Approximately 10% of the ions escape and migrate away from the transmission line, filling the space between line conductors and ground. A unipolar space charge region exists under each of the conductors, and a bipolar space charge region between the conductors. Migration of ions is a function of ion mobility as well as atmospheric conditions. The migrating air ions are carried away by wind, much like dust particles or pollen. Therefore, few air ions produced by the dc line are present on the upwind side of the line. Downwind air ion concentrations have been measured up to 1/2 mile from a dc line, although only for a small fraction of tie.

Early research on laboratory lines indicated that positive pole ion activity is greater than negative pole ion activity, much as positive pole radio and audible noise is greater than negative pole radio and audible noise. Measurements on operating lines have found negative pole ion activity as anticipated, but positive pole ion activity suppressed. The difference in ion production between laboratory lines and operating lines is caused by the effect of elevated air temperature near the conductors resulting from resistive heating of the conductors from the load current. Passage of load current raises the conductor temperature, and therefore decreases the relative air density of the air surrounding the conductor. Ion production is function of relative air density, so by this means line current has an influence on ion production.

The electric field from a dc line is a random variable. In foul weather a charge sheath forms around the conductor, which decreases the electric field near the conductor (reducing audible and radio noise), but increases the ground level field. The electrical environment surrounding a dc transmission line is therefore composed of three parts:

- The electric field which exists in the absence of ions in kV/m, frequently called the electrostatic field.
- Ion current density in Amperes per square meter (A/m^2).

- Space charge density (small air ions and charged aerosols) in ions/cm^3 or charge density in Coulombs/m^3

The total electric field measured near a dc line is the sum of that produced by charge on the line conductors in the absence of ions, plus the effect of the space charge. Migration of the space charge because of the force caused by the Electric field causes an ion current density in the space surrounding the line.

Even under stable weather conditions, the total ground level electric field and ion current density vary over a wide range, making prediction difficult. During fair weather, the effect of the space charge is rarely to decrease the electric field below that expected from line conductor charge alone, and may increase the electric field to a maximum strength 2 to 4 times that due to the line conductors alone. Ion activity generally increases during rain for dc lines, although the maximum electric field and ion current density in rain may not be greater than those in fair weather. The maximum value of ground level electric field including the effect of the space charge is the value of the uniform field given by line voltage divided by conductor height.

The magnitude of ion current is on the order of hundreds of nanoamperes per square meter. The current intercepted by a person standing under a dc line is on the order of a few microamperes, several orders of magnitude below that needed to perceive a shock. The ion current density deposits charge on nearby objects, causing a surface voltage build-up if the object is well insulated from ground. The amount of charge accumulated depends on the size of the object, its location with respect to the line, and its resistance to ground. As a practical matter, people and other objects normally have a sufficiently low resistance to ground to limit the charge accumulation to very low levels. If a sufficiently high resistance exists, a large object may store enough energy to deliver a shock similar to that experienced by walking on a carpet in winter and touching a door knob. This charge is on the order of 5-10 millijoules. There is insufficient current density to sustain a steady current shock. This is in contrast to ac transmission lines, where electric field induction can result in both transient spark and steady state current effects.

DC electric fields induce a static charge on the surface of conducting objects near the line. This may result in discharges similar to insulated objects charged by ion deposition. Perceptible spark discharges may thus occur from both insulated and conducting objects in the field of a dc line.

Hair stimulation and other sensations experienced by the skin may result in human perception of the field. The same phenomenon holds for ac transmission lines. The threshold of perception for the electric field from a dc line is greater than the threshold of perception from an ac line. Thus, a dc Electric field is generally less bothersome to work or be in than an ac electric field of the same level.

While not an environmental effect to the public, electric field and ion current induction are factors for safe live-line maintenance of an energized dc line. Tests have shown that a helicopter-airborne platform can be safely used to perform live-line work.

4.2.8 Electric and Magnetic Fields

With respect to HVDC lines and the environment the following aspects have to be examined:

- Electric Field and Ions,
- Magnetic Field.

ICNIRP is a non-governmental organization formally recognized by the World Health Organization (WHO). ICNIRP issued important publications like the guidelines in [4] and [13].

Electric field and ion current considerations related to DC transmission lines have been discussed in the CIGRÉ Publication 473 [14].

The electric field of an ac transmission line induces voltages on nearby objects by the capacitive voltage divider between line, object, and ground. These objects are typically vehicles, people, animals, sheds, and similar sized bodies. Evaluation of electric field effects of ac lines involves human perception, annoyance, and safety with respect to voltages and currents induced on these nearby objects. The electric field of a dc transmission line is static and therefore unable to induce voltages on nearby bodies by capacitive coupling. Deposition of charge and induction of voltage and current by ion phenomena from dc lines have been addressed in the section 4.2.7.

The DC electric field and ion current can interact with persons or objects to produce mild proximity effects. Static electric fields can be perceived by human (movement of body hair for instance) but they can not penetrate the organism.

DC electric fields can give rise to shocks (when accumulated body charges are discharged) to a person that contacts large objects near a transmission line. However studies concluded that there are no sensations or minor irritation similar to "carpet type" shock. Research in animals and human studies lead to the conclusion that there is no basis to conclude that electric field poses a health risk.

Research and studies related to magnetic field indicated no significant influence except as related to navigation and orientation of certain bacteria, homing pigeons, honeybees and elasmobranchs fish. Human studies considered inquiries with people working on industries with strong magnetic fields (aluminium plants for example). Studies on humans and animals do not indicate that exposures to DC magnetic field would result in adverse outcomes.

It should be noted that the magnetic field produced by HVDC lines adds to the earth's magnetic field and can interfere with a magnetic compass.

4.2.9 Animal studies

Effects of HVDC Transmission Lines on Dairy Cattle

Two studies have been conducted to respond to the concerns of farmers about effects of the electrical environment of HVDC transmission lines on dairy cattle. The first study was conducted by investigators at the University of Minnesota who used the records of the Dairy Herd Improvement Association to study the health and productivity of approximately 500 dairy herds (about 24,000 cows) from farms located near the ± 400-kV CPA/UPA dc transmission line in Minnesota [15, 16]. Six years of veterinary records were examined, from three years before to three years after energization of the line in 1979. For purposes of analysis, the herds were grouped according to distance of the farmstead from the transmission line, with the closest herds less than 1/4 mile of the line, and the farthest between 6 and 10 miles distant. Endpoints selected for study included milk production per cow, herd average of milk production, milk fat content, and measures of reproductive efficiency, among others. Health and productivity of the herds were found to be the same before and after energization, and were also found to be unrelated to distance of the herds from the transmission line.

A more direct test for effects of air ions, dc electric fields, or other aspects of the HVDC transmission line environment was performed by scientists at Oregon State University with the assistance and support of the Bonneville Power Administration (BPA) in the U.S. and the sponsorship of Hydro-Quebec and eight other [17, 18]. Dairy cattle and crops were raised near an HVDC transmission line. Simulated farming and ranching conditions were set up and carefully maintained directly under the ± 500-kV Pacific Intertie in central Oregon and at an identical site 2000 feet away from the line. Exposures of the animals under the HVDC transmission line was 5 to 30 times that of the control herd for electric field, ion current, and density of ions, with average exposures being 5.6 kV/m, 4.1 nA/m^2, and 13,000 ions/cm^3, respectively. After breeding the cattle for three seasons, herds at the two sites were compared. The breeding activity, conception rate, calving, calving interval, and body mass of the two herds did not differ. No deleterious effects on cattle production or health status could be attributed to exposures from the transmission line.

Both humans and animals have been exposed to dc electric fields in experimental laboratory studies. The field strengths used in these experiments have ranged from lower than to higher than near HVDC transmission lines. Some laboratories have reported response to fields, but the large majority of data indicate that dc electric fields produce no biologically important changes.

The effects of Electric fields on reproduction have been investigated in a single study of reasonable quality. Another study [19] exposed mice over two generations to very strong dc electric fields (340 kV/m) for up to eight months. No effects on the number of born or surviving young were found. In this same study, microscopic examination of various organs, blood cell counts, and growth in these offspring revealed no adverse effects of dc field exposure.

Effect of Magnetic field

The effects of static magnetic fields on many biological processes have been examined in animals.

- **Genetic Effects**

A number of studies [20, 21, 22, 23] have examined whether exposure to static magnetic fields produces chromosomal damage. Although a few reports have noted some effects of high intensity magnetic fields, overall the data does not support the conclusion that static magnetic fields induce genetic damage.

- **Cell Growth**

Several well-controlled studies of growth of various cell types exposed to strong dc magnetic fields show no robust or consistent responses on cell growth [24, 25, 26, 27, 28, 29, 30].

- **Reproduction and Development**

A number of studies have been performed to investigate a role of dc magnetic field exposure in development. In the study of Sikov et al [31], pregnant mice were exposed or sham exposed to a uniform field of 10 G or to a gradient (25 G/m) field with a maximum flux density of 10 G, either for the whole or part of gestation. Prenatal surveys of skeletal or internal malformation were done on day 18 of gestation. No differences were observed, though the number of fetuses scored was small. They did not report any differences in developmental landmarks or number of pregnancies or implantation rates. Other reports on mammalian development indicated no adverse effects from magnetic exposure less than 10 G [32, 33]. These field intensities are about 1,000 fold greater than those associated with HVDC transmission.

4.2.10 Human Studies

4.2.10.1 Effect of Air Ions

The effects of artificially generated air ions on humans have been studied for both experimental and therapeutic purposes. In addition, attempts have been made to investigate naturally occurring variations in air ion levels in Israel for a variety of physiological conditions. However, the reported biological and behavioral responses to air ion exposures in all these studies, like the animal studies, are often inconsistent. Positive and negative ion exposures have sometimes been reported to exert opposite effects, but many studies reported no effects.

One of the most comprehensive evaluations of the potential effects of air ions or static fields on human health was a cross sectional study of a densely populated community through which the Pacific Intertie HVDC transmission line passes [34]. The Pacific Intertie was first energized in 1970, and runs from Washington State to the Los Angeles area. At the time of the study (1981), it had been operating at 400-kV for almost 12 years (it now operates at 560 kV). The health endpoints surveyed among the residents included headaches, number of illness days, depression, drowsiness, and respiratory congestion. These endpoints were selected for study based upon the existing animal and human studies.

Participants in the study were divided into groups depending on how close they lived to the HVDC transmission line corridor. The "near" group lived within 0.14 miles of the corridor, and was subdivided into those people who lived right on the edge of the corridor and those who lived beyond the corridor. The "far" group lived between 0.65 and 0.85 miles from the line. The interviews were conducted by home visits, and all members in the household over the age of two were used as subjects. Data were collected on 438 individuals from 128 households. The responses from all the groups were compared, and no differences for any of the endpoint measures were observed, indicating no health impacts. In addition, other less controlled public health surveys have not reported that HVDC transmission lines impact self reported health symptoms [35, 36].

4.2.10.2 Perception of DC Electric Fields and Static Discharge

It is well known that the perception levels of currents in humans are lower in the case of dc than for ac [10, 11]. The average level of perception is about 2 mA in males, and slightly lower in females and children.

The basic reason for the higher sensitivity to dc currents is the following: the time-invariant magnetic field set up by low dc currents in human tissue interferes with or perturbs nerve impulses by causing a corresponding time invariant offset which creates a bias effect. At low currents (microampere to milliampere levels), this is more disturbing to the nervous system than the sinusoidal bias caused by ac currents. This mechanism, however, does not apply at fibrillation and electrocution-level currents [10].

It is important to appreciate that, unlike ac electric fields, a static dc electric field (in the absence of corona and space charge) does not inject/induce a continuous dc current in the body. The presence of space charge, which makes the air conductive, will allow a continuous dc current to flow in the body. However, the resulting currents are below a few microamperes in magnitude, and are not harmful or perceptible.

The familiar 'carpet-type' discharges can occur under HVDC lines, but are not dangerous, painful though they may be. What may be dangerous is ionic coupling to long or large objects such as fences, unearthed telephone and power lines, and pipelines.

The magnetic field under HVDC lines is low (comparable to the earth's magnetic field), and, being time-invariant, does not constitute a coupling or health hazard.

4.3 Consultation

Approvals for overhead line construction are increasingly difficult to obtain due to public objections and major projects face long delays due to extended approval processes. Therefore, it is essential that the main stakeholders including the statutory authorities, the public and the landowners directly affected by the new overhead line are consulted at a very early stage and continually kept up to date with progress. This will identify the main issues of concern including objections which usually include percieved health issues which will need to be addressed as the project develops.

4.3.1 Consultation Strategy

- Public and public representative's consultation,
- Meetings with landowners to negotiate rights of way and agreement for equipment locations,
- Written consultation and public exhibitions during the emerging project stages,
- Written consultations on the final design and preferred route,
- Submit application for approval,
    - Post approval ensures that landowners and those indirectly affected are consulted especially prior to construction through to final operation.

4.4 Operation

Many utilities do a yearly check of the overhead line with a helicopter or from the ground to look for loose parts, damaged glass insulators and the need for logging of trees. The yearly maintenance is usually very limited. A logging activity will cause some noise and driving activity. To reduce traces in the landscape the possibility of using tracks and roads should be a main focus. Recently utilities have started using drones for transmission line inspection.

4.5 Decommissioning

A condition of the permission may be the need to remove the overhead line at the end of its operational life. The environmental impacts to remove this equipment would be similar to the impacts during the construction phase. To take down towers and wires is difficult with respect to personnel safety, and special attention should be given to methods and procedures.

5. HVDC Cable

5.1 Types of cables used for HVDC systems

Three types of cables are used for HVDC transmission

- Self-contained fluid-filled cables
- Mass impregnated cables
- Extruded cables

5.1.1 Self-contained fluid-filled cables

The cables in this category may be any one of the following:

SCFF/SCOF (self-contained fluid-filled / self-contained oil-filled)

The Self-contained fluid-filled cables are used for short distances of up to 50km due to the need for a hydraulic system. The insulation system in these cables is constantly under oil pressure to avoid the formation of cavities when the cables are cooled down and the oil contracts. As these cables contain oil, there is concern about oil spill if the cable is damaged. The resulting clean-up could be very costly, certainly not acceptable by environmental standards, and may result in longer repair time.

Some cable suppliers have discontinued to manufacture SCFF cables. TGS does not recommend this type of cable.

5.1.2 Mass impregnated cables MI

The cables in this category may be any one of the following:

- MI which is based on mass impregnated Kraft paper with high-viscosity insulating compound
- PPL which is based on (polypropylene laminate) impregnated with high viscosity insulating compound

Mass-impregnated cables are the most commonly used with the LCC technology, since they have proven to be highly reliable for more than 40 years. They can be also used with VSC but because of their cost, it would not be an economic solution. They are used up to 500 kV and a maximum conductor temperature of 55 °C. With the PPL insulation, the cable can safely operate up to a conductor temperature of 85°C. There is one project with PPL cable at 600 kV, the Western HVDC link. Since in an MI cable there is no actual free oil or liquid, therefore any damage to the cable does not result in an environmental incident or concern. It is compact design and has been used in deep water applications

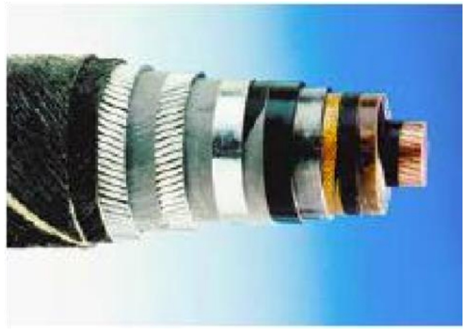

Figure 5-1 MI-submarine cable for HVDC (Photo:Hitachi ABB)

5.1.3 Extruded Cables

Extruded insulation cables consist of an inner semi-conducting screen layer, the insulation compound and an outer semi-conducting insulation screen, extruded simultaneously. A semi-conducting water swelling tape is then applied between the outer semi-conducting screen and the metallic sheath in order to limit water propagation along the cable core in case of cable damage. The metallic sheath is made of lead alloy, over which a layer of polyethylene compound is extruded. The “armouring” includes bedding, armour and serving, applied in one common process. Armour is made of one layer of galvanised steel wires. Serving is made of polypropylene strings that provide a high degree of abrasion protection and reduce cable friction during laying.

Extruded cables are in operation at voltages up to 400 kV and are available up to 525 kV. They are suitable for Voltage Source Converters (VSC), which reverses the power flow without reversing the polarity. As the direction of power is determined by the direction of the current, there is no delay in power reversal. VSC systems with extruded cables with rating up to 1000 MW are already in operation. Extruded cables are not used for LCC systems where voltage reversal is required to reverse the power flow. Their advantages are related to their lighter weight compared to an MI cable of comparative rating.

Figure 5-2 XLPE cable, submarine and land (Photo: Hitachi ABB)

5.2 List of HVDC cable systems

Table 5-1 shows the list of some HVDC cable systems already in operation or planned in the near future.

Table 5-1 List of HVDC Cable systems

System	Voltage kV	MW	Length km	Type of cable	In Service
Italy-Greece	400	500	203	MI	2001
Bass Link	400	500	290	MI	2006
NorNed	450	700	580	MI	2008
BritNed	450	1000	260	MI	2011
SAPEI	500	1000	420	MI	2012
Fenno-Skan 2	500	800	200	MI	2012
Skagerrak 4	500	1400	150	MI	2015
INEFE	320	2 X1000	64.5	XLPE	2016
Dolwin3	320	900	80	XLPE	2018
Western	600	2200	385	MI PPL	2018
Italy-Montenegro	500	1200	415	MI	2019
Nord Link	500	1400	500	MI	2019
NSN Link	550	1400	730	MI	2021
North Connect	500	1400	650	MI	2025

5.3 Service Experience

CIGRE technical brochure 379 [37] is the only information available on the failure of cables. However, this report was prepared in 2009 when most of the HVDC systems at higher voltages were not in operation. The conclusions of the CIGRE TB 379 for submarine cable systems were as following:

- 55% of faults were on AC cable systems and 45% on DC cable.
- 7 cases (14%) are reported to have an unknown cause of failure.

- 16 faults (33%) are reported to have been caused by “other” reasons. This is rather higher than expected.
- 86% of failures were on cable rather than accessories.
- There was insufficient data to quantify a fault rate for accessories.
- 51% of failures were on SCOF cables, with 84% of these being on AC systems.
- Over 50% of faults occurred on unprotected cables. Buried cables are well protected against fishing gear but can still be damaged by anchors penetrating deep into the seabed.
- 30% of faults occurred at water depths up to 10m and 52% at depths between 11 and 50m.
- The average reported repair time of submarine cables is approx. 60 days.

It should be noted that repair time of cables specially submarine cables is impacted by many factors (availability of spare cable and accessories (it should be purchased at the award stage of the project), availability of appropriate vessel, weather conditions etc.) that can lead to a wide spread in times to implement repairs.

HVDC cables are used for submarine applications or land applications, although the cable design is slightly different due to the difference between the ground temperature and the water temperature, as well as the thermal resistivities.

5.4 Cable Design and Configurations

The design of a cable will take into consideration parameters which will include the following:

- Insulation co-ordination with the converter station design
- Load carrying requirements including overload
- DC transmission voltage
- HVDC link configuration
- Water depth
- Protection requirements
- Transition between land and sea transmission
- Environmental issues

The last of the design issues mentioned above, environmental, is becoming more prominent as the marine environment is increasingly the subject of protected status designation. There is also greater public, state and industry awareness of the potential environmental impact of installations at sea.

It is expected that any cable laying project will include the development of an Environmental Impact Assessment (EIA) for submission to the appropriate authorities who in turn may provide a focal point for the collation of views from other parties. An EIA should address all issues relating to the potential impact of the project on the environment and the mitigative measures proposed by the developer.

5.5 Challenges with Cable Option

Major challenges that can be anticipated to selecting cable option for Colombia HVDC project are as following:

1. In general, all modern HVDC VSC systems use extruded cables up to 525 kV.
2. There is only one operating experience of cables at 600 kV connected to an LCC converter
3. There are number of HVDC systems already planned to be built in next few years. Most of these projects are related to offshore wind interconnections. As a result, the cable manufacturers are very busy. This means that early discussions with cable manufacturers are necessary
4. There will be environmental issues (see below) that would require mitigation and could also result in delay of in-service date if not addressed properly.
5. The cable is certainly more expensive than the overhead transmission line option

5.6 Environmental Issues – cable

The CIGRE Technical Brochure TB508 [2] outlines the following environmental issues to be considered in the cable route selection.

5.6.1 Fishing

Fishing activity and the increasing practice of fish farming have the potential to impact on a cable route for the following reasons:

- The timing of construction. Fishing in some areas may be restricted to certain times of the year. This may be due to the need to maintain species stocks. This may impact on the time during which cable installation may be possible. It may also result in a deviation in cable routing.
- The negative interaction between fishing gear and cables. During the operational life of a cable fishing activity may have a negative effect on cable integrity. This can be mitigated by cable design to include cable armouring and external protection methods such as trenching, cable burial at an appropriate depth, and adding cable protection if necessary.

Liaison with the fishing industry and statutory agencies is recommended. It is also possible for the statutory agencies to take a lead role as facilitator in this issue and would have the necessary fishing statistics (fish type, fishing methods, boat size and capacity, potential exclusion zones).

5.6.2 Marine Biological Environment

Routing of a cable should take into consideration the biological environment. Areas may already have a protected status and research or survey may uncover benthic features, communities or species which may be of conservation interest. It might then be necessary to route or deviate the cables from the desired cable route to avoid these conservation areas. It should be recognised that the marine environment would extend from the landfall area with its seabird population through the littoral zone and the sub-littoral zone with diversity in flora, fauna and marine life.

The impact of cable laying, the use of Remotely Operated Vehicles (ROVs) for trenching/ burial activities and the use of rock placement for external protection may impact on small environmentally sensitive areas.

The various impacts act on different components of the ecosystem in different ways. Seabed disturbance and thermal radiation may impact benthic organisms, underwater noise is most relevant for marine mammals, electromagnetic fields may have effects on sensitive fish and marine mammals. The extent of such impacts is determined by the technical design of the cables, the laying equipment, and in the case of power cables, the amount of electrical power transmitted. Some environmental impacts are mainly linked to the installation phase and/or maintenance, repair activities and removal. Their spatial extent is limited to the cable corridor. Others are only relevant during operation.

The environmental impacts are generally limited to the near proximity of the cable routes and only in the case it may alter the habitat for a long-term is the concern. However, appropriate mitigation measures are available and should be applied:

- avoiding sensitive habitats/areas,
- scheduling laying activities to certain times of the year to avoid disturbance of sensitive species, for example, marine mammals or resting/feeding (sea) birds,
- avoidance of heavily contaminated areas in order to prevent the re - introduction of contaminants from sediments,
- In some sensitive areas the impact of cable protection may be reduced by the adoption of external protection (i.e. special anchorage, shields, mattrasses etc.) in lieu of burial protection.

5.6.3 Marine Physical Environment

Routing of a submarine cable is influenced by the physical environment of the seabed. This will include such aspects as water depth, seabed slope, boulders, seabed geology and the physical characteristics of the landfall. Features such as boulders, sand waves, gravel trains/waves and steep slopes will be avoided to prevent free spans and laying problems. If protection is being considered soft but non-mobile sediment can make trenching or burial a preferred protection method.

5.6.4 Marine Archaeology

Archaeological features will include wrecks which in some instances may be designated as war graves. It will be necessary and prudent to avoid such features. Agreement with the necessary statutory authority may result in providing a minimum separation distance from these items.

5.6.5 Utility crossings

A desk top study of the area of a proposed submarine cable will reveal existing cables and pipelines which may need to be avoided or crossed. Seabed survey is needed to reveal existing installations. The potential effects of submarine power cables on other cables and pipelines will depend on the relative timing of construction. Potential effects can be mitigated by appropriate routing, specifying a minimum separation between utilities and by appropriate construction methods.

Agreement between parties should be formalised in an Encroachment Agreement or Crossing

Agreement. These agreements should cover both legal and technical aspects such as

- Notification of work - construction, maintenance and repair,
- Lateral separation distance between utilities which do not cross to minimise interference in the event of repair,
- Vertical separation distance if crossing, or use of stable resilient wrappings to prevent metallic/abrasive/electrolytic contact with other installations,
- Method of separation and subsequent protection of crossing. Separation methods can be as simple as a protective wrapping on the new cable as it is being installed or can involve a pre-dump of rock to provide protection and separation. Post installation protection of the crossing can be provided by rock or concrete mattresses.

5.6.6 Magnetic fields and compass deviations

DC cables produce magnetic fields and this has the potential to affect navigation tools such as magnetic compass specially in shallow waters. The potential effect rapidly falls with increasing depth and can be mitigated in shallow water by laying the high and low voltage cables together if possible. The magnetic field around a cable carrying 1400 A will almost reduce to the surrounding earths field somewhere about 10m away.

5.6.7 Installation

Preparatory work will be necessary at cable landfalls. The timing of any works at landfalls may be restricted due to weather but also for environmental reasons. Landfall preparation may include rock cutting or blasting, the installation of a conduit or beach trenching. All of these may have a potential environmental impact]

Cable laying will involve the mobilisation of an appropriate vessel. The laying vessel will follow a programmed route to ensure the laying of the cable on the seabed along the designed co-ordinates

5.6.8 Protection

Protection requirements should be part of the early design stage and be based on available information about the seabed characteristics and the pre-survey data of the study area. From this data a burial assessment can be made and the impact on cost and the environment assessed. A preliminary licence application for deposits, required for cable protection, can also be made at this early stage.

The protection of a cable may be necessary for a number of reasons including:

- Tidal action,
- Seabed movement,
- Anchor impact,
- Fishing activity,
- Ice problems.

Different types of burial and depth may be adopted along the cable route in relation to the environmental constraints, the seabed characteristics and the kind and level of risk of cable damage

5.7 Mitigation Measures for Environmental Issues

Table 5-2 below outlines the mitigation measures suggested in CIGRE TB 508 [2].

Table 5-2 Environmental issues – cable

Issues	Environmental impact	Mitigation
Routing	Fishing activity Flora and fauna Habitats Cable crossings Sand waves Earth quake fault lines Pipelines Shipping channels (anchors)	Changecable routing to avoid the areas, alternatively protect the cable from fishing equipment by burying it
Biological environment	Conservation interest	Change cable rute to avoid conservation areas
Marine Physical environment	The HVDC cable may be affected	Different routing to avoid difficult seabed characteristics
Archaeology	Wrecks and war graves. Land and marine based antiquity	Change in cable routing
Utility crossings	None	Agreed location and methodologies for crossing and repair.
Magnetic fields	Magnetic compass deviations Fish migration	In bipolar schemes: Laying the cables close to each other Above mitigation or avoid fish migration areas.
Installation of cable	Bird breeding Flora and fauna Fishing activities Farming activity Seagrass damage Disturbance of heavily contaminated areas	Time the installation outside the breeding season Translocation of species Fishing liaison Installation programming Biological stop (time the installation in the winter season) Avoidance areas/control of hazardous sediments

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