

Transmission and Distribution Networks: AC versus DC

D.M. Larruskain¹, I. Zamora¹, A.J. Mazón¹, O. Abarrategui¹, J. Monasterio²

¹ Department of Electrical Engineering
University of the Basque Country - Bilbao (Spain)
phone:+34 946 014472, fax:+34 946 014300,

² Avnet Iberia S.A.U.

e-mail:ieplaesm@lg.ehu.es, iepzabei@bi.ehu.es, iepmasaj@bi.ehu.es,
gauoihan@yahoo.es, jorge.monasterio@avnet.com

Abstract The fast development of power electronics based on new and powerful semiconductor devices has led to innovative technologies, such as HVDC, which can be applied to transmission and distribution systems. The distribution voltage level is smaller than the transmission one, thus the power electronics are less expensive in distribution.

The technical and economical benefits of this technology represent an alternative to the application in AC systems. Some aspects, such as deregulation in the power industry, opening of the market for delivery of cheaper energy to customers and increasing the capacity of transmission and distribution of the existing lines are creating additional requirements for the operation of power systems. HVDC offer major advantages in meeting these requirements.

Key words: direct current, alternating current, power transmission, distribution.

1. Introduction

The transmission and distribution of electrical energy started with direct current (DC) in the late 19th century, but it was inefficient due to the power loss in conductors. Alternating current (AC) offered much better efficiency, since it could easily be transformed to higher voltages, with far less loss of power. AC technology was soon accepted as the only feasible technology for generation, transmission and distribution of electrical energy.

However, high-voltage AC transmission links have disadvantages and engineers were engaged in the development of a technology for DC transmissions as a supplement to the AC transmissions. The invention of mercury arc rectifiers and the thyristor valves, made the design and development of line-commutated current sourced converters possible.

High Voltage Direct Current (HVDC) transmission finally proved to be technically feasible. The world's first commercial HVDC transmission link, was built in 1954 between the Swedish mainland and the island of Gotland, with a rating of 20 MW, 200 A and 100 kV.

HVDC transmission based on current sourced converters has been in use for 50 years. The Insulated Gate Bipolar Transistors (IGBT) with high voltage ratings have accelerated the development of voltage sourced converters for HVDC applications in the lower power range. Voltage Sourced Converter (VSC) HVDC transmission has come into use in the last years.

This paper presents a comparison between the AC and DC transmission system technology. Economical, technical and environmental considerations of the AC and DC power flow are studied. It reviews the underlying technology and discusses the HVDC systems from a design, construction, operation and maintenance points of view. The paper also presents a numerical analysis of the power increase that can be achieved on an existing distribution network when a 3-phase link is substituted by DC link.

2. The HVDC technology

The HVDC transmission systems are point-to-point configurations where a large amount of energy is transmitted between two regions. The traditional HVDC system is built with line commutated current source converters, based on thyristor valves. The operation of this converter requires a voltage source like synchronous generators or synchronous condensers in the AC network at both ends. The current commutated converters can not supply power to an AC system which has no local generation. The control of this system requires fast communication channels between the two stations.

A. Components of HVDC transmission system

The most relevant components that comprise a HVDC system, are the following:

- The Thyristor or IGBT valves make the conversion from AC to DC and thus are the main component of any HVDC converter. Each single valve consists of a certain amount of series connected thyristors (or IGBTs) with their auxiliary circuits.

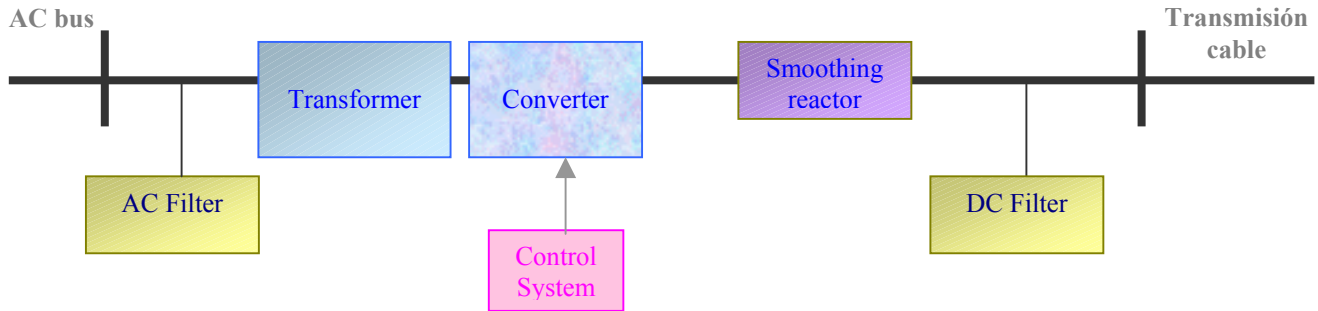


Fig. 1 HVDC system components

- The Converter Transformers transform the voltage level of the AC busbar to the required entry voltage level of the converter.

- The Smoothing reactor, which main functions are:

- Prevention of the intermittent current
- Limitation of the DC fault currents
- Prevention of resonance in the DC circuits

- The Harmonic Filters, on the AC side of a HVDC converter station, which have two main duties:

- To absorb harmonic currents generated by the HVDC converter
- To supply reactive power

Also DC filter circuits have to be used. Besides Active Harmonic filters can be a supplement to passive filters due to their better performance.

- Surge arrester, which main task is to protect the equipment of over-voltages.

- DC Transmission circuit, which include DC Transmission line, cable, high speed DC switches and earth electrode.

- Control and Protection.

A HVDC station requires considerable land because the transformers, filters and phase correction capacitors are placed outdoors. However, the valves and control equipment are placed in a closed air-conditioned/heated building, this distribution is due to the fact that the completely enclosed system requires a large building and is too expensive.

B. Feasibility of HVDC transmission

A HVDC system can be 'monopolar' or 'bipolar'. The monopolar system uses one high voltage conductor and ground return. This is advantageous from an economic point of view, but is prohibited in some countries because the ground current causes corrosion of pipe lines and other buried metal objects. However, in Europe, monopolar

systems are in operation. Most of them are used for submarine crossings.

The bipolar system uses two conductors, one with plus and one with minus polarity. The mid point is grounded. In normal operation, the current circulates through the two high voltage conductors without ground current. However, in case of conductor failure, the system can transmit half of the power in monopolar mode. Besides, this operation can be maintained for a limited time only.

Recently, ABB and Siemens started to build HVDC systems using semiconductor switches (IGBT or MOSFET) and pulse width modulation (PWM). The capacity of a HVDC system with VSCs is around 30-300 MW. Operating experience is limited but many new systems are being built worldwide. The PWM controlled inverters and rectifiers, with IGBT or MOSFET switches, operate close to unity power factor and do not generate significant current harmonics in the AC supply. Also the PWM drive can be controlled very accurately. Typical losses claimed by ABB for two converters is 5%.

3. HVDC Operation and Maintenance

In general, basic parameters such as power to be transmitted, distance of transmission, voltage levels, temporary and continuous overload, status of the network on the receiving end, environmental requirements etc. are required to initiate a design of a HVDC system.

For tendering purposes a conceptual design is done following a technical specification or in close collaboration between the manufacturer and the customer. The final design and specifications are in fact the result of the tendering and negotiations with the manufactures/suppliers. It is recommended that a turnkey approach be chosen to contract execution, which is the practice even in developed countries.

In terms of construction, it can take from three years for thyristor-based large HVDC systems, to just one year,

depending on the different technologies, to go from contract date to commissioning.

To the extent that the term operation denotes the continual activities that are aimed at keeping the system availability at designed levels, modern HVDC links can be operated remotely, in view of the semiconductor and microprocessor based control systems included. There are some existing installations in operation completely unmanned. Moreover, modern HVDC systems are designed to operate unmanned. This feature is particularly important in situations or countries where skilled people are few, and these few people can operate several HVDC links from one central location.

Maintenance of HVDC systems is comparable to those of high voltage AC systems. The high voltage equipment in converter stations is comparable to the corresponding equipment in AC substations, and maintenance can be executed in the same way. Maintenance will focus on AC and DC filters, smoothing reactors, wall bushings, valve-cooling equipment, semiconductor valves. In all the above, adequate training and support is provided by the supplier during the installation, commissioning and initial operation period.

Normal routine maintenance is recommended to be one week per year. The newer systems can even go for two years before requiring maintenance. In fact in a bipolar system, one pole at a time is stopped during the time required for the maintenance, and the other pole can normally continue to operate. Depending on the in-built overload capacity it can take a part of the load of the pole under maintenance.

In addition, preventive maintenance shall be pursued so that the equipment will achieve optimally balanced availability with regard to the costs of maintenance, operating disturbances and planned outages. As a guideline value, the aim shall be to achieve an availability of 98 % according to Cigrè protocol 14-97.

While HVDC systems may only need a few skilled staff for operation and maintenance, several factors influence the number of staff needed at a station. These factors are: local routines and regulations, working conditions, union requirements, safety regulations, and other local rules can separately or together affect the total number of personnel required for the type of installed equipment.

4. HVDC system costs

The cost of a HVDC transmission system depends on many factors, such as power capacity to be transmitted, type of transmission medium, environmental conditions and other safety, regulatory requirements etc. Even when these are available, the options available for optimal design

(different commutation techniques, variety of filters, transformers etc.) render it is difficult to give a cost figure for a HVDC system. Nevertheless, a typical cost structure for the converter stations can be as shown in Fig. 2.

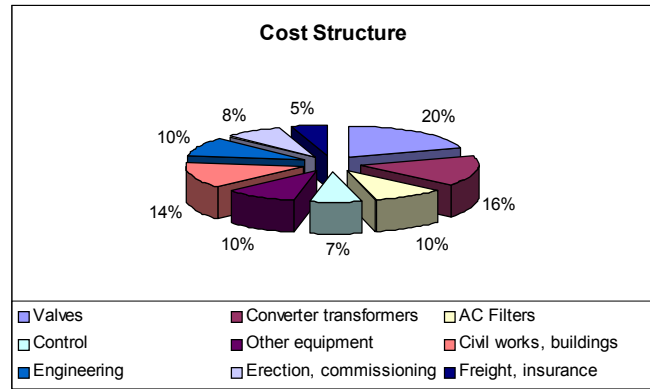


Fig. 2 Cost Structure

The cost of the traditional HVDC system is high because of the need for filters, capacitors and other auxiliary equipment. The traditional HVDC system is designed for the transmission of large amounts of energy measured in hundred of megawatts. This system is not economical less for than 20 MW loads.

The price must be based on few data, as rated power, transmission distance, type of transmission and voltage level in the AC networks where the converters are going to be connected. When the voltage is lower the price goes down, so in distribution networks the total cost is lower than in the transmission ones.

Following, an example of approximate cost is shown. These values can be used only to compare different systems:

- **HVDC system** 50 MW, 100kV, Thyristor converter. Approximate per unit value is: 500 EUR/kW
- **HVDC Light** 50 MW, +/-84kV, IGBT converter pair. Approximate per unit value is: 150 EUR/kW
- **Transformer** 50MVA, 69kV/138kV. Approximate per unit value is: 7,5 EUR/kVA

For a bipolar line HVDC transmission, a price of 190 kEUR/km is assumed, converter stations are estimated to 190 MEUR. Besides, for a double circuit AC transmission a price of 190 kEUR/km (each) is assumed, AC substations and series compensation (above 600 km) are estimated to 60 MEUR.

It should be pointed out that the relationship between the cost and capacity (MW) is not linear, because the cost of the control system, communication system, auxiliary

electrical supply are more or less independent of the size of the converter. Similarly the size of the place and building also has a lower limit. The cost figures indicated can be reasonably used above 10 MW.

5. DC versus AC.

The vast majority of electric power transmissions use three-phase alternating current. The reasons behind a choice of HVDC instead of AC to transmit power in a specific case are often numerous and complex. Each individual transmission project will display its own set of reasons justifying the choice.

A. General characteristics

The most common arguments favouring HVDC are:

- 1) Investment cost. A HVDC transmission line costs less than an AC line for the same transmission capacity. However, the terminal stations are more expensive in the HVDC case due to the fact that they must perform the conversion from AC to DC and vice versa. On the other hand, the costs of transmission medium (overhead lines and cables), land acquisition/right-of-way costs are lower in the HVDC case. Moreover, the operation and maintenance costs are lower in the HVDC case. Initial loss levels are higher in the HVDC system, but they do not vary with distance. In contrast, loss levels increase with distance in a high voltage AC system

Above a certain distance, the so called "break-even distance", the HVDC alternative will always give the lowest cost. The break-even-distance is much smaller for submarine cables (typically about 50 km) than for an overhead line transmission. The distance depends on several factors, as transmission

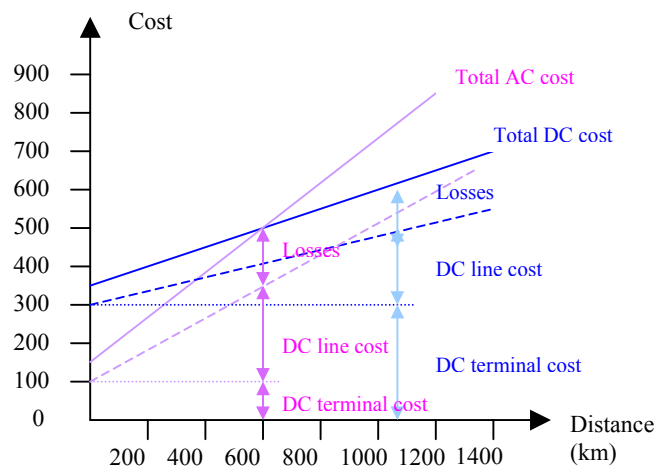


Fig. 3 HVAC-HVDC cost

medium, different local aspects (permits, cost of local labour etc.) and an analysis must be made for each individual case (Fig. 3).

- 2) Long distance water crossing. In a long AC cable transmission, the reactive power flow due to the large cable capacitance will limit the maximum transmission distance. With HVDC there is no such limitation, why, for long cable links, HVDC is the only viable technical alternative.
- 3) Lower losses. An optimized HVDC transmission line has lower losses than AC lines for the same power capacity. The losses in the converter stations have of course to be added, but since they are only about 0.6 % of the transmitted power in each station, the total HVDC transmission losses come out lower than the AC losses in practically all cases. HVDC cables also have lower losses than AC cables.
- 4) Asynchronous connection. It is sometimes difficult or impossible to connect two AC networks due to stability reasons. In such cases HVDC is the only way to make an exchange of power between the two networks possible. There are also HVDC links between networks with different nominal frequencies (50 and 60 Hz) in Japan and South America.
- 5) Controllability. One of the fundamental advantages with HVDC is that it is very easy to control the active power in the link
- 6) Limit short circuit currents. A HVDC transmission does not contribute to the short circuit current of the interconnected AC system.
- 7) Environment. Improved energy transmission possibilities contribute to a more efficient utilization of existing power plants. The land coverage and the associated right-of-way cost for a HVDC overhead transmission line is not as high as for an AC line. This reduces the visual impact. It is also possible to increase the power transmission capacity for existing rights of way. There are, however, some environmental issues which must be considered for the converter stations, such as: audible noise, visual impact, electromagnetic compatibility and use of ground or sea return path in monopolar operation.

In general, it can be said that a HVDC system is highly compatible with any environment and can be integrated into it without the need to compromise on any environmentally important issues of today.

B. Power carrying capability of AC and DC lines

It is difficult to compare transmission capacity of AC lines and DC lines. For AC the actual transmission capacity is a function of reactive power requirements and security of operation (stability). For DC it depends mainly on the thermal constraints of the line.

If for a given insulation length, the ratio of continuous-working withstand voltage is as indicated in equation (1).

$$k = \frac{DC - \text{withstand} - \text{voltage}}{AC - \text{withstand} - \text{voltage}(rms)} \quad (1)$$

Various experiments on outdoor DC overhead-line insulators have demonstrated that due to unfavourable effects there is some precipitation of pollution on one end of the insulators and a safe factor under such conditions is $k=1$. However if an overhead line is passing through a reasonably clean area, k may be as high as $\sqrt{2}$, corresponding to the peak value of rms alternating voltage. For cables however k equals at last 2.

A line has to be insulated for overvoltages expected during faults, switching operations, etc. AC transmission lines are normally insulated against overvoltages of more than 4 times the normal rms voltage; this insulation requirement can be met by insulation corresponding to an AC voltage of 2.5 to 3 times the normal rated voltage.

$$k_1 = \frac{AC - \text{insulation} - \text{level}}{\text{rated} - AC - \text{voltage}(E_p)} = 2.5 \quad (2)$$

On the other hand with suitable converter control the corresponding HVDC transmission ratio is shown in equation (3).

$$k_2 = \frac{DC - \text{insulation} - \text{level}}{\text{rated} - DC - \text{voltage}(V_p)} = 1.7 \quad (3)$$

Thus for a DC pole to earth voltage V_d and AC phase to earth voltage E_p the relations (4) exist.

$$\text{Insulation - ratio} = \frac{\text{insulation - length - required - for - each - AC - phase}}{\text{insulation - length - required - for - each - DC - pole}} \quad (4)$$

and substituting (1), (2) and (3) equations, we obtain equation (5) for the insulation ratio.

$$\text{Insulation - ratio} = \left(k \times \frac{k_1}{k_2} \right) \times \frac{E_p}{V_d} \quad (5)$$

DC transmission capacity of an existing three-phase double circuit AC line.

The AC line can be converted to three DC circuits, each having two conductors at $\pm V_d$ to earth respectively.

Power transmitted by AC:

$$P_a = 6E_p \times I_L \quad (6)$$

Power transmitted by DC:

$$P_d = 6V_d \times I_d \quad (7)$$

On the basis of equal current and insulation

$$I_L = I_d \quad (8)$$

$$V_d = \left(k \times \frac{k_1}{k_2} \right) \times E_p \quad (9)$$

The following relation shows the power ratio.

$$\frac{P_d}{P_a} = \frac{V_d}{E_p} \left(k \times \frac{k_1}{k_2} \right) \quad (10)$$

For the same values of k , k_1 and k_2 as above, the power transmitted by overhead lines can be increased to 147%, with the percentage line losses reduced to 68% and corresponding figures for cables are 294 % and 34% respectively.

Besides, if the AC line is converted, a more substantial power upgrading is possible. There are several conversions of AC lines to DC lines proposals [2], these conversions are carried out as a simple reconstruction. The most feasible of them is Double Circuit AC Conversion to Bipolar DC, it implies tower modifications that maintain all the conductors at a height above ground of 1 to 2 meters below the original position of the lowest conductor during the whole construction phase. Two new crossarms are inserted at the level of the old intermediate crossarm.

No change is made to the conductors, the total rated current remains the same, which means that the transmitted power increases proportionally to the adopted new DC line-to-ground voltage. The conversion of lines where an increase of phase to ground voltage can be higher than 3, is possible when all the conductors of one AC circuit are concentrated in one DC pole.

The line to line (LL) AC voltage is doubled for use with DC, thus the transmitted power will increase by 3.5 times.

$$U(DC) = 2U_{rms}(AC) \quad (11)$$

Table I: Transmitted power and losses for the original double circuit AC lines and the converted DC lines

AC

Voltage (kV)	0,7 A/mm ²		1.0 A/mm ²		1.4 A/mm ²	
	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)
33	26	11.0	37	16.1	52	22.6
132	130	3.5	180	4.9	262	7.1

DC

Voltage (kV)	0,7 A/mm ²		1.0 A/mm ²		1.4 A/mm ²	
	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)	P (MW)	Joule % of P (per 10Km)
66	89	3.8	127	5.4	178	7.6
264	440	1.2	636	1.7	890	2.4

Table I shows the transmitted power and relative losses as a function of current density for distribution networks with a 25 mm diameter conductor. Only Joule losses are taken into account, because they are the most important in distribution voltage levels. The numerical values are function of the defined factors, and are proximate values that show the magnitude order of the power increases that can be achieved.

6. Conclusions

The construction of new overhead electric lines is increasing difficulty, thus there is a need to look at alternatives that increases the power transfer capability of the existing right of ways.

It is technically feasible to achieve a substantial power upgrading of existing AC lines through their conversion for use with DC, by using the same conductors, tower bodies and foundations, but with changes in tower head and insulation assemblies.

When using existing AC lines to transmit DC power, the lines are already built, so that cost can be saved. The distribution networks cost is lower than the transmission ones, because of the lower voltage level applied to the semiconductor cost. It

is also remarkable the fast development of multiterminal DC systems.

DC transmission has many more advantages, such as stability, controlled emergency support and no contribution to short circuit level.

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