Presented at Energy Week 2000, Washington, D.C, USA, March 7-8, 2000

High Voltage Direct Current (HVDC)Transmission Systems Technology Review Paper

Roberto Rudervall	J.P. Charpentier	Raghuveer Sharma
ABB Power Systems	World Bank	ABB Financial Services
Sweden	United States	Sweden

Synopsis

Beginning with a brief historical perspective on the development of High Voltage Direct Current (HVDC) transmission systems, this paper presents an overview of the status of HVDC systems in the world today. It then reviews the underlying technology of HVDC systems, and discusses the HVDC systems from a design, construction, operation and maintenance points of view. The paper then discusses the recent developments in HVDC technologies. The paper also presents an economic and financial comparison of HVDC system with those of an AC system; and provides a brief review of reference installations of HVDC systems. The paper concludes with a brief set of guidelines for choosing HVDC systems in today's electricity system development.

In today electricity industry, in view of the liberalisation and increased effects to conserve the environment, HVDC solutions have become more desirable for the following reasons:

- Environmental advantages
- Economical (cheapest solution)
- Asynchronous interconnections
- Power flow control
- Added benefits to the transmission (stability, power quality etc.)

Historical Perspective on HVDC Transmission

It has been widely documented in the history of the electricity industry, that the first commercial electricity generated (by Thomas Alva Edison) was direct current (DC) electrical power. The first electricity transmission systems were also direct current systems. However, DC power at low voltage could not be transmitted over long distances, thus giving rise to high voltage alternating current (AC) electrical systems. Nevertheless, with the development of high voltage valves, it was possible to once again transmit DC power at high voltages and over long distances, giving rise to HVDC transmission systems. Some important milestones in the development of the DC transmission technology are presented in Box 1.

Box 1: Important Milestones in the Development of HVDC technology

- Hewitt´s mercury-vapour rectifier, which appeared in 1901.
- Experiments with thyratrons in America and mercury arc valves in Europe before 1940.
- First commercial HVDC transmission, Gotland 1 in Sweden in 1954.
- First solid state semiconductor valves in 1970.
- First microcomputer based control equipment for HVDC in 1979.
- Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.
- First active DC filters for outstanding filtering performance in 1994.
- First Capacitor Commutated Converter (CCC) in Argentina-Brazil interconnection, 1998
- First Voltage Source Converter for transmission in Gotland, Sweden ,1999

HVDC Installations in the world today

Since the first commercial installation in 1954 a huge amount of HVDC transmission systems have been installed around the world. Figure 1 shows, by region, the different HVDC transmissions around the world. (picture at the end of the document)

Rationale for Choosing HVDC

There are many different reasons as to why HVDC was chosen in the above projects. A few of the reasons in selected projects are:

- In Itaipu, Brazil, HVDC was chosen to supply 50Hz power into a 60 Hz system; and to economically transmit large amount of hydro power (6300 MW) over large distances (800 km)
- In Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network
- In Rihand-Delhi Project in India, HVDC was chosen to transmit bulk (thermal) power (1500 MW) to Delhi, to ensure: minimum losses, least amount right-of-way, and better stability and control.
- In Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, HVDC back-to-back system was chosen to ensure supply of 50 Hz bulk (1000MW) power to a 60 Hz system under a 20-year power supply contract.
- In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby, in consideration of the environmental sensitivity of the project area (an archaeological and tourist area) and improve power quality.
- In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids (of New South Wales and Queensland) to: enable electricity trading between the two systems (including change of direction of power flow); ensure very low environmental impact and reduce construction time.

Details about the above projects are provided elsewhere (under Details of Selected HVDC Applications).

The HVDC technology

The fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end, and from DC to AC (inverter) at the receiving end. There are three ways of achieving conversion:

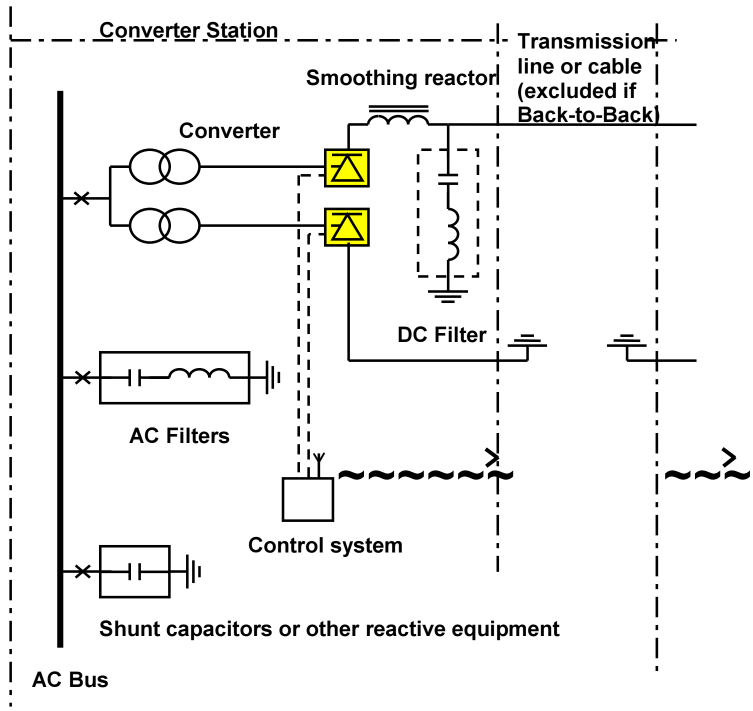
- Natural Commutated Converters. Natural commutated converters are most used in the HVDC systems as of today. The component that enables this conversion process is the thyristor, which is a controllable semiconductor that can carry very high currents (4000 A) and is able to block very high voltages (up to 10 kV). By means of connecting the thyristors in series it is possible to build up a **thyristor valve,** which is able to operate at very high voltages (several hundred of kV).The thyristor valve is operated at net frequency (50 hz or 60 hz) and by means of a control angle it is possible to change the DC voltage level of the bridge. This ability is the way by which the transmitted power is controlled rapidly and efficiently.

- Capacitor Commutated Converters (CCC). An improvement in the thyristor-based commutation, the CCC concept is characterised by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.

- Forced Commutated Converters. This type of converters introduces a spectrum of advantages, e.g. feed of passive networks (without generation), independent control of active and reactive power, power quality. The valves of these converters are built up with semiconductors with the ability not only to turn-on but also to turn-off. They are known as VSC (Voltage Source Converters). Two types of semiconductors are normally used in the voltage source converters: the GTO (Gate Turn-Off Thyristor) or the IGBT (Insulated Gate Bipolar Transistor). Both of them have been in frequent use in industrial applications since early eighties. The VSC commutates with high frequency (not with the net frequency). The operation of the converter is achieved by Pulse Width Modulation (PWM). With PWM it is possible to create any phase angle and/or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Thus, PWM offers the possibility to control both active and reactive power independently. This makes the PWM Voltage Source Converter a close to ideal component in the transmission network. From a transmission network viewpoint, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

The components of an HVDC transmission system

To assist the designers of transmission systems, the components that comprise the HVDC system, and the options available in these components, are presented and discussed. The three main elements of an HVDC system are: the converter station at the transmission and receiving ends, the transmission medium, and the electrodes.



The converter station: The converter stations at each end are replica's of each other and therefore consists of all the needed equipment for going from AC to DC or vice versa. The main component of a converter station are:

Thyristor valves: The thyristor valves can be build-up in different ways depending on the application and manufacturer. However, the most common way of arranging the thyristor valves is in a twelve-pulse group with three quadruple valves. Each single thyristor valve consists of a certain amount of series connected thyristors with their auxiliary circuits. All communication between the control equipment at earth potential and each thyristor at high potential, is done with fibre optics.

VSC valves: The VSC converter consists of two level or multilevel converter, phase-reactors and AC filters. Each single valve in the converter bridge is built up with a certain number of series-connected IGBTs together with their auxiliary electronics. VSC valves, control equipment and cooling equipment would be in enclosures (such as standard shipping containers) which make transport and installation very easy.
All modern HVDC valves are water-cooled and air insulated.

Transformers: The converter transformers adapt the AC voltage level to the DC voltage level and they contribute to the commutation reactance. Usually they are of the single phase three winding type, but depending on the transportation requirements and the rated power, they can be arranged in other ways

AC Filters and Capacitor Banks: On the AC side of a 12-pulse HVDC converter, current harmonics of the order of 11, 13, 23, 25 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network.. In the conversion process the converter consumes reactive power which is compensated in part by the filter banks and the rest by capacitor banks.

In the case of the CCC the reactive power is compensated by the series capacitors installed in series between the converter valves and the converter transformer. The elimination of switched reactive power compensation equipment simplify the AC switchyard and minimise the number of circuit-breakers needed, which will reduce the area required for an HVDC station built with CCC.

With VSC converters there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the AC side are related directly to the PWM frequency. Therefore the amount of filters in this type of converters is reduced dramatically compared with natural commutated converters.

DC filters: HVDC converters create harmonics in all operational modes. Such harmonics can create disturbances in telecommunication systems. Therefore, specially designed DC filters are used in order to reduce the disturbances. Usually no filters are needed for pure cable transmissions as well as for the Back-to-Back HVDC stations. However, it is necessary to install DC filters if an OH line is used in part or all the transmission system

The filters needed to take care of the harmonics generated on the DC end, are usually considerably smaller and less expensive than the filters on the AC side. The modern DC filters are the Active DC filters. In these filters the passive part is reduced to a minimum and modern power electronics is used to measure, invert and re-inject the harmonics, thus rendering the filtering very effective.

Transmission medium

For bulk power transmission over land, the most frequent transmission medium used is the overhead line. This overhead line is normally bipolar, i.e. two conductors with different polarity. HVDC cables are normally used for submarine transmission. The most common types of cables are the solid and the oil-filled ones. The solid type is in many cases the most economic one. Its insulation consists of paper tapes impregnated with a high viscosity oil. No length limitation exists for this type and designs are today available for depths of about 1000 m. The self –contained oil-filled cable is completely filled with a low viscosity oil and always works under pressure. The maximum length for this cable type seems to be around 60 km.

The development of new power cable technologies has accelerated in recent years and today a new HVDC cable is available for HVDC underground or submarine power transmissions. This new HVDC cable is made of extruded polyethylene, and is used in VSC based HVDC systems.

Design, Construction, Operation and Maintenance considerations

In general, the 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 an 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 for VSC based HVDC systems to go from contract date to commissioning. The following table shows the experience for the different HVDC technologies:

Natural commutated HVDC	3 years
CCC based HVDC	2 years
VSC based HVDC	1 year

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, thyristor valves. In all the above, adequate training and support is provided by the supplier during the installation, commissioning and initial operation period.

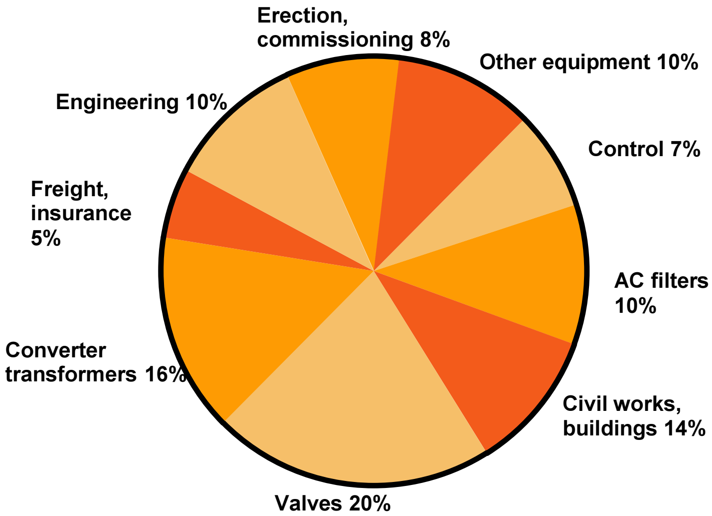
Normal routine maintenance is recommended to be one week per year. The newer systems can even go for two years before requiring maintenance. In fact in a bipolar system, one pole at a time is stopped during the time required for the maintenance, and the other pole can normally continue to operate and 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 plants and 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 Cigré protocol 14-97.

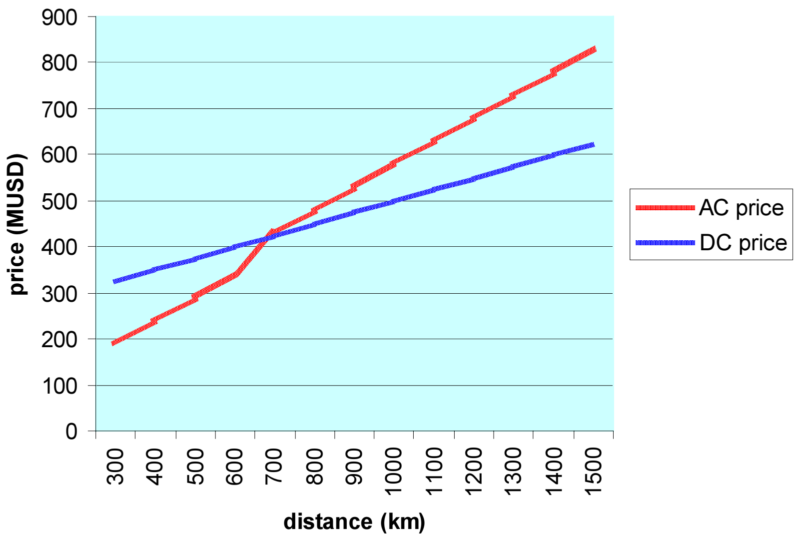
While HVDC systems may only need a few skilled staff for operation and maintenance, several factors influence the number of staff needed at a station. These factors are: local routines and regulations, working conditions, union requirements, safety regulations, and other local rules can separately or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

Cost structure

The cost of an 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 an HVDC system. Nevertheless, a typical cost structure for the converter stations could be as follows:



As a guidance, an example showing the price variation for an AC transmission compared with an HVDC transmission for 2000 MW is presented below.



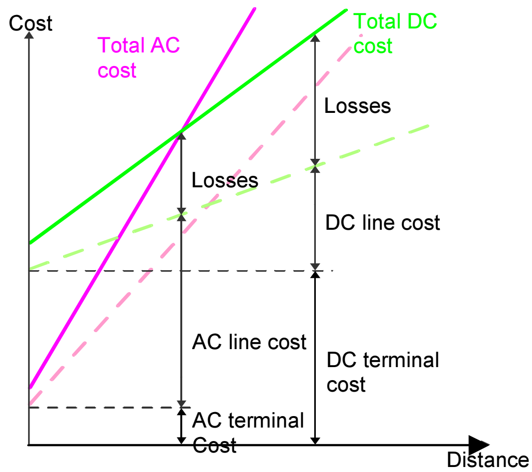
Assumptions made in the price calculations:
For the AC transmission a double circuit is assumed with a price per km of 250 kUSD/km (each), AC substations and series compensation (above 600 km) are estimated to 80 MUSD.
For the HVDC transmission a bipolar OH line was assumed with a price per km of 250 kUSD/km, converter stations are estimated to 250 MUSD.

It is strongly recommended to take contact with a manufacturer in order to get a first idea of costs and alternatives. The manufacturers should be able to give a budgetary price based on few data, as rated power, transmission distance, type of transmission, voltage level in the AC networks where the converters are going to be connected.

The choice of DC transmission voltage level has a direct impact on the total installation cost. At the design stage an optimisation is done finding out the optimum DC voltage from investment and losses point of view. The costs of losses are also very important - in the evaluation of losses the energy cost and the time-horizon for utilisation of the transmission have to be taken into account. Finally the depreciation period and desired rate of return (or discount rate) should be considered. Therefore, to estimate the costs of an HVDC system, it is recommended that life cycle cost analysis is undertaken.

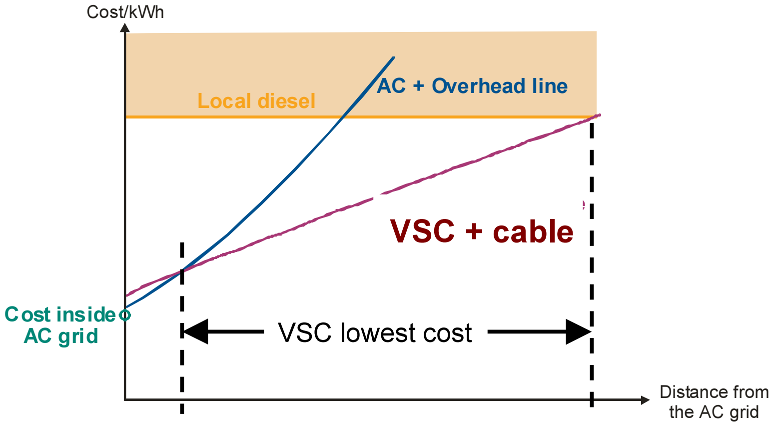
Two different comparisons are needed to highlight the cost comparison between high voltage AC and HVDC systems – one is between thyristor based HVDC systems and a high voltage AC transmission system; and the other between a VSC based HVDC system; an AC system and a local generation source.

Thyristor based HVDC system versus high voltage AC system: The investment costs for HVDC converter stations are higher than for high voltage AC substations. 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. The following picture shows the cost breakdown (shown with and without considering losses).

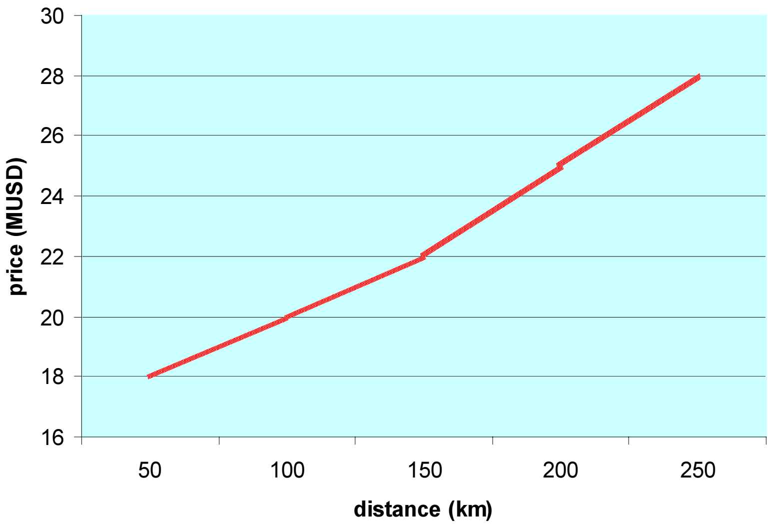


The breakeven distance depends on several factors, as transmission medium (cable or OH line), different local aspects (permits, cost of local labour etc.). When comparing high voltage AC with HVDC transmission, it is important to compare a bipolar HVDC transmission to a double-circuit high voltage AC transmission, especially when availability and reliability is considered.

VSC based HVDC system versus an AC system or a local generation source: VSC based HVDC systems cater to the small power applications (up to 200MW) and relatively shorter distances (hundred of km) segment of the power transmission spectrum. The graph below shows that, the VSC based HVDC system is the better alternative economically when compared to either an high voltage AC system or a generation source local to the load centre (e.g., diesel generator).



As a guidance, a price example for a 50 MW VSC transmission with land cable is presented below.



However, the break-even distance and power transfer level criteria and the comparative cost information should be taken in the proper perspective, because of the following reasons:

- In the present (and future) industry environment of liberalised competitive markets and heightened efforts to conserve the environment. In such an environment, the alternative for a transmission system is an in-situ gas-fired combined cycle power plant, not necessarily an option between an AC transmission and a HVDC one.
- Second, the system prices for both AC and HVDC have varied widely even for a given level of power transfer. For example, several different levels of project costs have been incurred for a HVDC system with a power transfer capacity of 600 MW. What this shows therefore is that, in addition to the criteria mentioned above (power levels, distance, transmission medium, environmental conditions etc.), the market conditions at the time of the project is a critical factor, perhaps more so than the numerical comparisons between the costs of an AC or DC system.
- Third, technological developments have tended to push HVDC system costs downward, while the environmental considerations have resulted in pushing up the high voltage AC system costs.

Therefore, for the purposes early stage feasibility analysis of transmission system type, it is perhaps better to consider HVDC and high voltage AC systems as equal cost alternatives. (Also see the last section on HVDC in Today’s Electricity Industry).

Overview of HVDC Applications

	Long distance transmission over land	Long distance transmission over sea	Interconnections of asynchronous networks	Windmill connection to network	Feed of small isolated loads
Natural commutated HVDC with OH lines	**X**		**X**		
Natural commutated HVDC with sea cables		**X**	**X**		
Capacitor Commutated Converters (CCC) in Back-to-Back			**X**		
Capacitor Commutated Converters (CCC) with OH lines	**X**		**X**		
Capacitor Commutated Converters (CCC) with sea cables		**X**	**X**		
VSC Converters in Back-to-Back			**X**	**X**	
VSC Converters with Land or Sea Cables	**X**	**X**	**X**	**X**	**X**

Details of Selected HVDC Applications

Itaipu - the world's largest HVDC transmission

The Itaipu HVDC Transmission Project in Brazil, owned by Furnas Centrais Elétricas S.A. in Rio de Janeiro (an Elétrobras company), is by far the most impressive HVDC transmission in the world. It has a total rated power of 6300 MW and a world record voltage of ±600 kV DC. The Itaipu HVDC transmission consists of two bipolar DC transmission lines bringing power generated at 50 Hz in the 12600 MW Itaipu hydropower plant, owned by Itaipu Binacional, to the 60 Hz network in São Paulo, in the industrial centre of Brazil.

Power transmission started on bipole 1 in October 1984 with 300 kV and in July 1985 with 600 kV, and on bipole 2 in July 1987. The converter stations were commissioned stepwise in order to match the generating capacity built up at the Itaipu hydropower plant.

HVDC was chosen basically for two reasons: partly to be able to supply power from the 50 Hz generators to the 60 Hz system, and partly because an HVDC link was economically preferable for the long distance involved.

The converter stations Foz do Iguaçu and Ibiuna represent a considerable step forward in HVDC technology. The two stations are unique in their combination of size and advanced technology.

Technical Data:

Commissioning year:	1984-1987
Power rating:	3150+3150 MW
DC voltage:	±600 kV
Length of overhead DC line:	785 km + 805 km
Main reasons for choosing HVDC system:	Long distance, 50/60 Hz conversion

Leyte - Luzon HVDC Power Transmission Project, Philippines

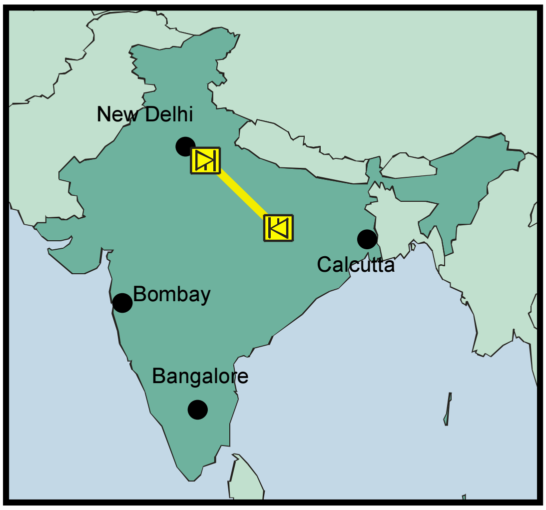
National Power Corporation has constructed a 440 MW, 350 kV monopolar HVDC link to transfer power from the geothermal power plant on the island of Leyte, to the southern part of the main island of Luzon to feed the existing AC grid in the Manila region.

The HVDC interconnection will be beneficial both to industry and the inhabitants of the Manila area, not only through the added power influx, but also through the inherent stabilizing effect of an HVDC link on the AC network. The use of geothermal power contributes significantly to environmental improvements on a national as well as a global scale. The HVDC Link has been in commercial operation since August 10, 1998.

Technical Data:

Power Rating:	440 MW
DC Voltage:	350 kV
Length of overhead line:	430 km
Length of submarine cable:	21 km

Rihand-Delhi HVDC Transmission, India



National Thermal Power Corporation Limited built a 3000 MW coal-based thermal power station in the Sonebhadra District of Uttar Pradesh State. Part of the power from the Rihand complex is carried by the Rihand-Delhi HVDC bipolar transmission link, which has a rated capacity of 1500 MW at ±500 kV DC. Some of the power is transmitted via the existing parallel 400 kV AC lines.

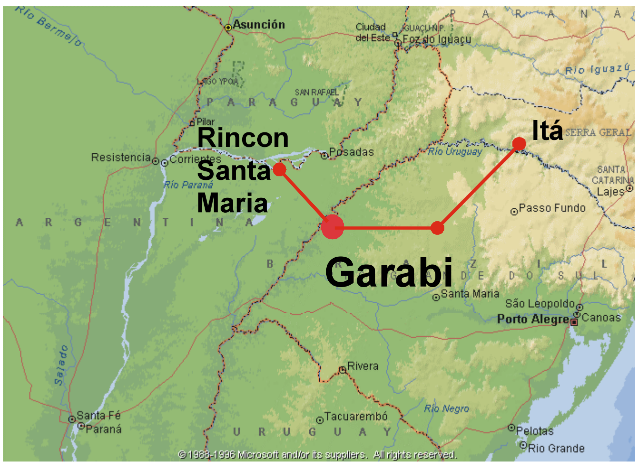
The basic aim of the HVDC link is to transmit the Rihand power efficiently to the Northern Region, meeting urgent needs in the area. There were several reasons why choosing HVDC instead of 400 kV AC. The most important ones were better economics, halved right-of-way requirements, lower transmission losses and better stability and controllability.

The Rihand-Delhi HVDC transmission is the first commercial long-distance HVDC link in India.

Technical Data:

Commissioning year:	1990
Power rating:	1500 MW
DC voltage:	± 500 kV
Length of overhead DC line:	814 km
Main reasons for choosing HVDC system:	Long distance, stability

Garabi – Interconnection of Argentina and Brazil



In South America, de-regulation of the electrical sector has made good progress in the last couple of years.

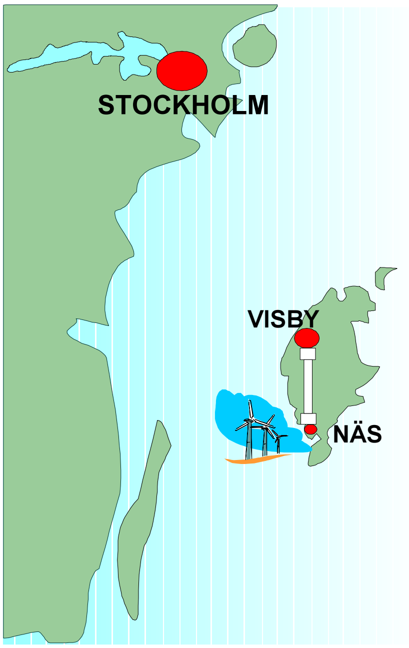
On May 5th 1998 the Brazilian Ministry of Mines and Energy, through Eletrobrás, Furnas and Gerasul in agreement with the Argentine government, signed a 20-year contract for importing of 1000 MW firm capacity with associated energy to Brazil from the wholesale energy market, MEM, in Argentina. The contract was signed with CIEN, "Companhia de Interconexao Energética" who will be responsible for importing. The CIEN group is led by the two ENDESA companies from Spain and Chile, respectively.

On May 18 the CIEN group placed an order for a turnkey package for the complete power transmission system, including engineering, construction, operation and maintenance. The transmission system comprises 490 km of 500 kV AC overhead lines between the two substations of Rincón de Santa Maria in northern Argentina and Itá in southern Brazil. A 1100 MW HVDC Back-to-Back Converter Station will be placed at Garabi, in Brazil, close to the Argentine border. Brazil has 60 Hz frequency and Argentina would be supplying at 50 Hz. Therefore the asynchronous nature of the interconnection. This interconnection is scheduled to start commercial operation at the beginning of year 2000. The cross-border transmission system will permit both countries to utilise electricity resources more efficiently and cost-effectively. The energy purchased by Eletrobrás will be commercialised in the South/Southeast/Central-West interconnected systems. It will contribute to increase the delivery of energy and the reliability in these systems. It will also enable trade in secondary energy between the two countries.

Technical Data:

Power Rating:	1100 MW
DC Voltage:	70 kV

Gotland - Wind Power Evacuation



In recent years the push for renewable forms of energy has brought wind power farms into focus on the Swedish island of Gotland, in the Baltic sea. Today the island needs additional transmission capacity and a better means of maintaining good power quality because wind power capacity has been greatly expanded on the southern tip of the island. But the main load centre is the city of Visby. Moreover, sensitive wildlife environments and the fact that many holiday resorts are located on Gotland demand low visual impact on the surroundings.
Therefore, the VSC´s in combination with underground DC cables was the obvious choice for this project. Accordingly, in 1997, GEAB the local electric supplier, agreed to install the world´s first VSC based

HVDC transmission system on Gotland. GEAB is a subsidiary to Vattenfall AB, which has financed the project together with the Swedish National Energy Administration. Rated at 50 MW, the transmission has linked the wind power park on the southern tip of Gotland (Näs) to the city of Visby (Bäcks), some 70 km away. It will run in parallel with the existing AC connection.

Technical Data:

Commissioning year:	1999
Power rating:	50 MW
DC voltage:	± 80 kV
Length of DC cable:	70 km
Main reasons for choosing HVDC system:	Environmental aspects and power quality.

Direct Link

TransÉnergie Australia, a subsidiary of Hydro Quebec, and the New South Wales distributor NorthPower, awarded the 21 of December 1998 the supply of the equipment for the Directlink interconnection.

Directlink will employ VSC and DC cables to connect the Queensland and New South Wales electricity grids between Terranora and Mullumbimby, a distance of 65 km. The development is to be fast tracked to enable the interconnection to be in service by June 2000.

Directlink will comprise an underground cable along its entire route, obviating the need for overhead transmission and minimising the impact on the environment. It will also follow the existing rights-of-way with no land resumption involved.

The entrepreneurial interconnection will be totally funded by its users. Consistent with this approach, the ultimate size of the interconnection will be approximately 180 MVA - sufficient power to supply the energy needs of 100,000 homes.

Further information is available from the web site at http://www.TransÉnergie.com.au

Technical Data:

Commissioning year:	2000
Power rating:	180 MVA (3 x 50 MW)
DC voltage:	± 80 kV
Length of DC cable:	65 km
Main reasons for choosing HVDC system:	Environmental aspects and short delivery time.

Advantages of HVDC Systems

Modern HVDC systems combines the good experience of the old installations with recently developed technologies and materials. The result is a very competitive, flexible and efficient way of transmitting electrical energy with a very low environmental impact.

It is important to remark that an HVDC system not only transmit electrical power from one point to another, but it also has a lot of value added which should have been necessary to solve by another means in the case of using a conventional AC transmission.

Some of these aspects are:

- No limits in transmitted distance. This is valid for both OH lines and sea or underground cables.
- Very fast control of power flow, which implies stability improvements, not only for the HVDC link but also for the surrounding AC system.
- Direction of power flow can be changed very quickly (bi-directionality).
- An HVDC link don't increase the short-circuit power in the connecting point. This means that it will not be necessary to change the circuit breakers in the existing network.
- HVDC can carry more power for a given size of conductor
- The need for ROW (Right Of Way) is much smaller for HVDC than for HVAC, for the same transmitted power. The environmental impact is smaller with HVDC.
- VSC technology allows controlling active and reactive power independently without any needs for extra compensating equipment.
- VSC technology gives a good opportunity to alternative energy sources to be economically and technically efficient.
- HVDC transmissions have a high availability and reliability rate, shown by more than 30 years of operation.

HVDC in the new Electricity Industry

The question is often asked as to when should HVDC transmission be chosen over an AC system. In the past, conventions were that HVDC was chosen when :

- Large amounts of power (>500 MW) needed to be transmitted over long distances(>500 km);
- Transmitting power under water;
- Interconnecting two AC networks in an asynchronous manner.

HVDC systems remain the best economical and environmentally friendly option for the above conventional applications. However, three different dynamics - technology development, deregulation of electricity industry around the world, and a quantum leap in efforts to conserve the environment - are demanding a change in thinking that could make HVDC systems the preferred alternative to high voltage AC systems in many other situations as well. To elaborate:

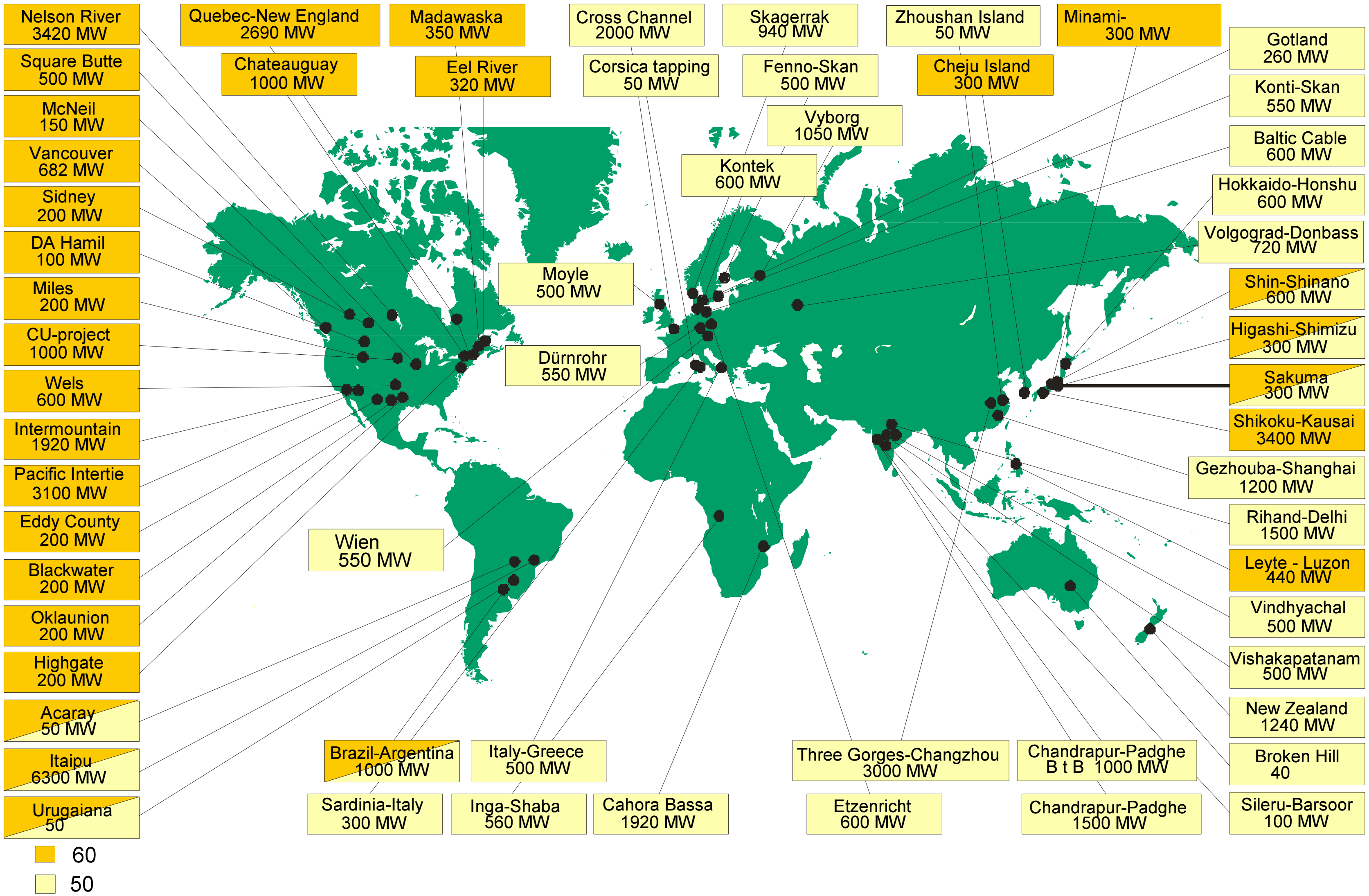
- New technologies, such as the VSC based HVDC systems, and the new extruded polyethylene DC cables, have made it possible for HVDC to become economic at lower power levels (up to 200 MW) and over a transmission distance of just 60 km.
- Liberalization has brought other demands on the power infrastructure overall. Transmission is now a contracted service, and there is very little room for deviation from contracted technical and economic norms. HVDC provides much better control of the power link and is therefore a better way for providing contractual transmission services.
- Liberalization has brought on the phenomenon of trading to the electricity sector, which would mean bi-directional power transfers, depending on market conditions. HVDC systems enable the bi-directional power flows, which is not possible with AC systems (two parallel systems would be required).

- In the past, when the transmission service was part of a government owned, vertically integrated utility, the land acquisition and obtaining rights-of-way was relatively easier, and very often was done under the principle of "Eminent Domain" of the State. With liberalization, transmission service provision is by and large in the domain of corporatized, sometimes privatized, entities. Land acquisition and/or obtaining rights-of-way is now a significant portion of the project's costs. Once these costs are included in their entirety in the economical analysis of HVDC versus AC alternatives, it would be seen that HVDC is much more economical in this regard, since it requires much less land/right-of-way for a given level of power.
- In an environmentally sensitive areas, such as national parks and protected sanctuaries, the lower foot print of HVDC transmission systems becomes the only feasible way to build a power link.

So how should power system planners, investors in power infrastructure (both public and private), and financiers of such infrastructure be guided with respect to choosing between an HVDC and an high voltage AC alternative? The answer is to let the "market" decide. In other words:

- the planners, investors and financiers should issue functional specifications for the transmission system to qualified contractors, as opposed to the practice of issuing technical specifications, which are often inflexible, and many times include older technologies and techniques) while inviting bids for a transmission system.
- The functional specifications could lay down the power capacity, distance, availability and reliability requirements; and last but not least, the environmental conditions.
- The bidders should be allowed to bid either an HVDC solution or an AC solution; and the best option chosen.

It is quite conceivable that with changed circumstances in the electricity industry, the technological developments, and environmental considerations, HVDC would be the preferred alternative in many more transmission projects.


Nelson River 3420 MW
Square Butte 500 MW
McNeil 150 MW
Vancouver 682 MW
Sidney 200 MW
DA Hamil 100 MW
Miles 200 MW
CU-project 1000 MW
Wels 600 MW
Intermountain 1920 MW
Pacific Intertie 3100 MW
Eddy County 200 MW
Blackwater 200 MW
Oklaunion 200 MW
Highgate 200 MW
Acaray 50 MW
Itaipu 6300 MW
Urugaiana 50
60
50
Quebec-New England 2690 MW
Chateauguay 1000 MW
Madawaska 350 MW
Eel River 320 MW
Cross Channel 2000 MW
Corsica tapping 50 MW
Skagerrak 940 MW
Fenno-Skan 500 MW
Vyborg 1050 MW
Kontek 600 MW
Zhoushan Island 50 MW
Cheju Island 300 MW
Minami- 300 MW
Moyle 500 MW
Dürnrohr 550 MW
Wien 550 MW
Brazil-Argentina 1000 MW
Italy-Greece 500 MW
Sardinia-Italy 300 MW
Inga-Shaba 560 MW
Cahora Bassa 1920 MW
Three Gorges-Changzhou 3000 MW
Etzenricht 600 MW
Chandrapur-Padghe B t B 1000 MW
Chandrapur-Padghe 1500 MW
Gotland 260 MW
Konti-Skan 550 MW
Baltic Cable 600 MW
Hokkaido-Honshu 600 MW
Volgograd-Donbass 720 MW
Shin-Shinano 600 MW
Higashi-Shimizu 300 MW
Sakuma 300 MW
Shikoku-Kausai 3400 MW
Gezhouba-Shanghai 1200 MW
Rihand-Delhi 1500 MW
Leyte - Luzon 440 MW
Vindhyachal 500 MW
Vishakapatanam 500 MW
New Zealand 1240 MW
Broken Hill 40
Sileru-Barsoor 100 MW