

HIGH VOLTAGE DIRECT CURRENT POWER TRANSMISSION

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INTRODUCTION

An engineering challenge exists in the USA in that its best wind resources are situated in a North-South corridor encompassing the western Rocky Mountains regions, whereas the population and industrial centers are in its central part and on its East Coast. Similarly, the best solar energy resources exist in a East-West corridor including the desert south-west.

We suggest that there is a need to supplement the existing electrical grid system with High Voltage Direct Current, HVDC power transmission, which is characterized with low energy loss and lower capital cost for transmission over long distances.

For over 100 years High Voltage Alternating Current, HVAC has been considered as the natural choice for electrical power transmission. Classical thyristor based HVDC became available in the mid 1950s and has been exclusively used for large scale bulk power transmission links over long distances, or for interconnecting asynchronous grids. Lately, the Voltage Source Converter VSC HVDC, also known as HVDC Light, is emerging as a feasible robust economical alternative. It offers a superior solution for a number of reliability and stability issues associated with the connection of sustainable energy projects in harsh environments such as offshore wind power, desert, or mountainous situations.

VSC HVDC transmissions are attractive for connecting remotely located wind power locations to the main grid. This is partly because the capacitance per unit length of the transmission line makes an AC cable impractical for cable lengths beyond 50-100 kilometers. In this case a significant amount of reactive power is generated, and low frequency resonances may cause instability phenomena. Further, in thyristor-based HVDC transmissions, a synchronous compensator or a Static Synchronous Compensator, STATCOM may be required at the wind farm location to maintain a smooth line voltage for the thyristors to commute against. This problem does not exist in VSC HVDC in which Pulse Width Modulated, PWM transistors are used with an inherent voltage controlling ability.

Electrical generation is growing four times faster than transmission and grid development in the USA. Many wind power parks projects in the USA have remained on the drawing boards and have not been built because there is no way to move that electricity from there to the load centers. The 200,000 miles of power lines forming the USA electrical grid which are owned by over 500 companies are unprepared for a boom in domestic electricity capacity.

High Voltage Direct Current, HVDC and HVDC Light are highly efficient alternatives for transmitting bulk power and for special purpose applications.

In an HVDC system, electric power is taken from one point in a three phase AC network, converted to DC in a converter station, transmitted to the receiving point by an overhead line or cable and then converted back to AC in another converter station and injected into the receiving AC network.



Fig. 1: Yidu station at the 3,000 MW Three Gorges project Shanghai China.

Typically, an HVDC transmission has a rated power of more than 100 MW and many are in the 1,000-3,000 MW range. HVDC transmissions are used for transmission of power over long or very long distances, because it then becomes economically attractive over conventional AC lines.

With an HVDC system, the power flow can be controlled rapidly and accurately as to both the power level and the direction. This possibility is often used in order to improve the performance and efficiency of the connected AC networks.

The classical HVDC technology is used to transmit electric power over long distances by overhead transmission lines or submarine cables. It is also used to interconnect separate power systems, where traditional Alternating Current AC connections cannot be used.

HVDC Light is an underground and submarine cable power transmission technology that offers additional benefits compared to the classical HVDC.

HISTORICAL DEVELOPMENT, DC VERSUS AC

In the second half of the 19th century a fierce competition arose between the development of Direct Current, DC as advocated Thomas Edison, and the development of Alternating Current, AC as advocated by Nikola Tesla and George Westinghouse.

Thomas Edison in the late 1830s invented the light bulb and designed a DC system to power it with many remaining bugs. He hired another inventor, Nikola Tesla to fix the bugs

which he does, but Thomas Edison did not fulfill his promises of compensating Nikola Tesla. Tesla quits and develops AC, and Edison does everything possible to disprove Tesla's claim that AC could be stepped up in voltage and transmitted over longer distances than DC. Edison's DC could not be stepped up in voltage and transmitted long distances, and required large power plants every square mile and thick cables. George Westinghouse hires Nikola Tesla and purchases his AC patent and sells power at \$2.5/kWhr. Tesla ends his life living in a hotel room as a pauper.

The AC system had the advantage to be more economical and simpler than the DC system, and hence predominated. A simpler aspect was the easy transformation of the magnitude of the electric voltage and current signals. Whereas the DC system needed expensive elements and a complex circuitry to transform the electrical signals, the AC system just needed a simple AC transformer with an easier and cheaper fabrication cost.

In addition, the initially lower voltage DC system was unable to transmit electrical power over long distances. This was the main drawback of the DC system in its initial competition against the AC system. Today, even though most of the electrical system is constituted of AC elements, the DC transmission system is acquiring increased importance because of its economical advantages over the AC transmission system when involving high voltage and very long distance transmission.

Over long distances, an AC transmission line reduces dramatically in its transmission capability. This is based on the fact that at long distances, the reactive power circulating in the line becomes extremely high, hence reducing the transmission load margin or the static voltage stability. As a consequence, a long distance AC transmission line has also a significant increase in the transmitted power losses.

Grid power systems have evolved into complex systems with several elements and interconnections as well as large amounts of electrical power transfers between them. New electrical power generation needs require the tapping of new energy resources such as onshore and offshore wind farms that are situated far away from the consumption centers. This requires an effective transmission to connect the generated energy to the power grid. As a result, the High Voltage DC, HVDC transmission system becomes an attractive option in these cases.

HIGH VOLTAGE DIRECT CURRENT, HVDC TRANSMISSION

HVDC is a well proven technology employed for power transmission all over the world. About 70,000 MW HVDC transmission capacity is installed in more than 90 projects. There are three different categories of HVDC transmissions:

1. Point to point Transmission,
2. Back to back stations,
3. Multi terminal Systems.



Fig. 2: Huizhou valve hall, Three Gorges Guangdong Transmission China.

The development of HVDC technology started in the late 1920s, and only after some 25 years of extensive development and pioneering work the first commercially operating scheme was commissioned in 1954. It was a link between the Swedish mainland and the island of Gotland in the Baltic Sea. The power rating was 20 MW and the transmission voltage was 100 kV.

Mercury arc valves were used for the conversion between AC and DC, and the control equipment was using vacuum tubes.

A significant improvement came around 1970 when thyristor valves were introduced in place of the mercury arc valves. This substantially reduced the size and complexity of HVDC converter stations.

The use of microcomputers in the control equipment in today's transmissions has also contributed to making HVDC the powerful alternative in power transmission that it is today.

In 1995 ABB announced a new concept for HVDC converter stations: HVDC with Capacitor Commutated Converters (CCC) that further improved the performance of HVDC transmissions.

In 1997 a completely new converter and DC cable technology called HVDC light was introduced.

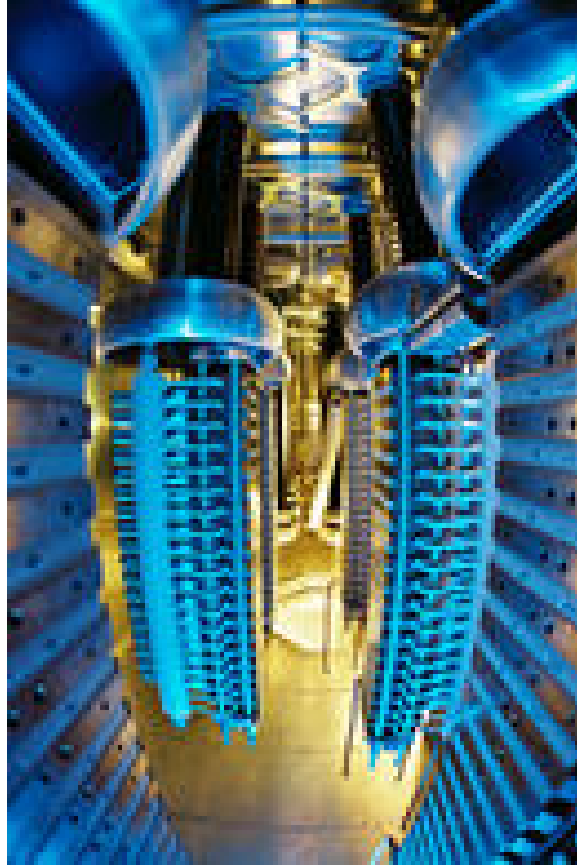


Fig. 3: View of the insides of an HVDC Light valve.

COMPARISON OF HVAC TO HVDC

TECHNICAL CONSIDERATIONS

In overhead transmission lines, in order to improve the transmission capability, it is required to increase the line voltage. As a result, a reduction of the active power losses is obtained. Through the years, the rated voltage has been increased up to 1,200 kV. Although there are some lines of 1,000 kV and 1,200 kV, the 765 KV is standard highest rated voltage used in the electric industry.

Although they are widespread throughout the world, the AC transmission lines have inherent problems when it is required to transmit power over very long distances. When the transmission line length is considerably long, the use of high voltage is not sufficient to increase the transmission capability.

When the line losses are neglected, the maximum transfer in an AC transmission line can be estimated from:

$$P_{\max} = \frac{V_s V_r \cdot SIL}{\sin\left(\frac{2\pi\ell}{\lambda}\right)} \quad (1)$$

where:

V_s is the voltage at the sending end of the line,

V_r is the voltage at the receiving end of the line,

SIL is the Surge Impedance Loading, the characteristic loading of a line, [MW],

λ is the wave length of the transmission line,

ℓ is the line length.

When the transmitted power through the line is close to the maximum transfer, the system can have instabilities and can even lead to a blackout.

In overhead AC transmission lines and at very long distances, there exists a high reactive power absorption. The line inductance parameter becomes very large. Using a lumped transmission line model, the maximum capability of the line P_{\max} can be expressed as:

$$P_{\max} = \frac{V_s V_r}{2\pi L} \quad (2)$$

where: L is the equivalent lumped inductance of the line.

When L becomes large, the maximum power transfer in the AC transmission line is reduced. One corrective technique to increase P_{\max} is to use series reactive compensation. This compensation reduces the equivalent series inductance of the line by connecting a series capacitor. However, the longer the AC transmission line is, the more expensive the required compensation equipment is.

UNDERGROUND AND UNDERWATER HVAC LINES

In underground and underwater AC transmission lines, because of the use of cables, the line has a high capacitance which reduces the load carrying capability of the line. The capacitance effect is distributed throughout the whole line.

The differential charging current at a distance x from the sending end can be estimated by:

$$dI_c(x) = 2\pi f dC(x)V(x) \quad (3)$$

where:

$I_C(x)$ is the charging current,
f is the electric frequency,
dC(x) is the differential capacitance,
V(x) is the line voltage at the distance x.

When a lumped line model is used, the total charging current can be approximated as:

$$I_C(x) \approx 2\pi f C V_{rated} \quad (4)$$

where:

I_C is the total charging current,
f is the electric frequency,
C is the equivalent lumped line capacitance,
 V_{rated} is the rated voltage of the line.

As the line must carry this charging current as well as the useful load current, an increase of the charging current will decrease the available cable capacity to transmit the useful load current.

If I_T is the maximum rated current, the available capability to transmit the useful load current is defined by:

$$I_L = \sqrt{I_T^2 - I_C^2} \quad (5)$$

The additional current circulating in the cables or the charging current will also increase the active power losses in the line.

It is thus important to notice that an underground or underwater line increase its available cable capability by using direct current instead of alternating current, since the frequency in Eqn. 4, $f = 0$, which implies that the charging current $I_C = 0$.

On the other hand, an overhead line can increase its maximum power transfer also by using direct current since in this case, under steady state operation, Eqn. 1 is no longer valid. In both cases, the maximum power transfer is limited by the maximum rated current I_T .

ECONOMICAL CONSIDERATIONS

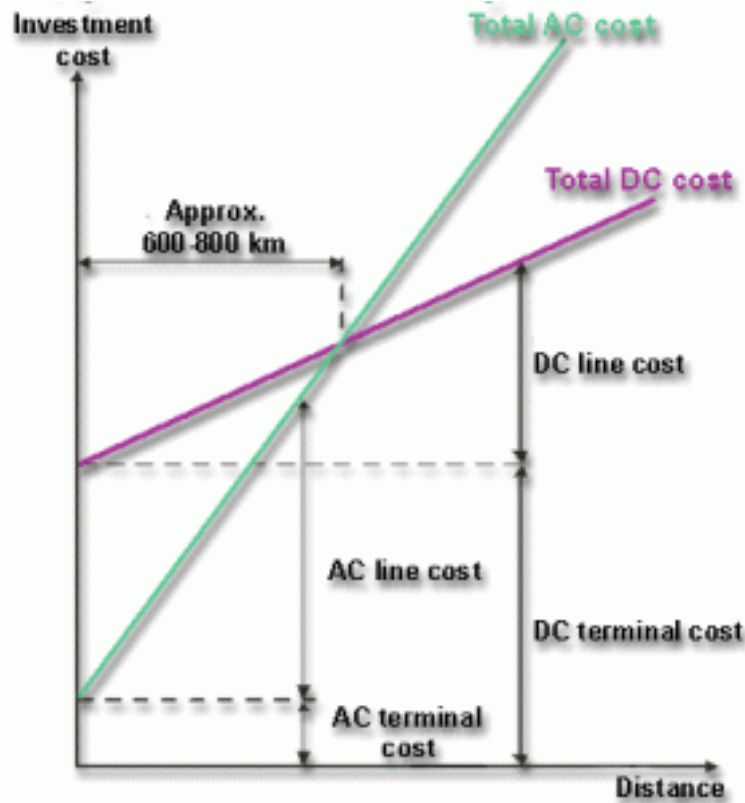


Fig. 4: Investment cost breakeven distance for AC and DC electrical transmission. Source: ABB.

The cost of an AC and an AC transmission line depends on the length of the transmission distance. Considering the total cost:

$$\text{Total cost} = \text{Investment cost} + \text{Operational cost} \quad (6)$$

There exists a critical transmission line length at which the total AC cost is equal to the total DC cost. This is typically 600-800 km. Below this critical length, the DC transmission line is more expensive than the AC transmission line, primarily due to the higher terminal cost. Beyond this critical point, at longer distances, the cost of the specialized equipment of the DC transmission are surpassed by the cost of the AC line pertaining to the expensive equipment necessary for reactive compensation and the reactive power losses because of the charging currents.

ADVANTAGES OF HVDC

Power stations generate alternating current, AC, and the power delivered to the consumers is in the form of AC. Yet it is sometimes more suitable to use direct current, HVDC, for transmitting electric power.

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 of HVDC, but the most common arguments favoring HVDC are:

1. Lower investment cost

An 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. But above a certain distance, the so called "break-even distance", about 600-800 kilometers, the HVDC alternative will always give the lowest cost.

The break-even-distance is much smaller for submarine cables of typically about 50 km in length than for an overhead line transmission. The distance depends on several factors, both for lines and cables, and an analysis must be made for each individual case.

The importance of the break-even-distance concept should not be over-stressed, since several other factors, such as controllability, are important in the selection between AC or HVDC power transmission.

In general, a DC line can take more power than an AC line of the same size. A bipolar overhead line for DC needs only two insulated conductors instead of three conductors for AC. As a result only two 3,000 MW HVDC lines were needed for the Three Gorges to Shanghai transmission in China, instead of five 500 kV lines that would have been used if AC transmission had been chosen.

2. Long distance water crossing

There are no technical limits for the length of a HVDC cable.

In a long AC cable transmission, the reactive power flow due to the large cable capacitance will limit the maximum possible transmission distance. With HVDC there is no such limitation, making HVDC the only viable technical alternative for long cable links.

The 580 kilometers long NorNed link was the longest underwater high voltage cable in the world by 2007, surpassing the then present Baltic Cable transmission between Sweden and Germany with its 250 km.



Fig. 5: Layers of a submarine electrical power transmission cable. These cables are mass impregnated (MI) cables suitable for HVDC. The cable has a copper conductor and the insulation is made of oil impregnated paper. There is a lead alloy sheath outside the insulation. Mechanical protection is achieved by steel tape and steel wire armoring. A typical 450 kV HVDC cable has an outer diameter of approx. 13 cm.

Some HVDC links need an underwater cable between the converter stations. The first HVDC project, the link to Gotland in 1954, was using an HVDC submarine cable, and many of all the HVDC projects unite networks that are separated by water.

The 200 km Fenno-Skan HVDC submarine cable interconnecting Sweden and Finland since 1989 has a capacity of 500 MW and a rated DC voltage of 400 kV. Later cable links such as the Baltic Cable and Swepol have a capacity of 600 MW and a rated DC voltage of 450 kV. An extruded polymer cable has been developed for HVDC Light.



Fig. 6: Underground 300 kV HVDC cables can be emplaced along highways.



Fig. 7: Cross section through a land underground cable.

- Underground HVDC land cables offer multiple advantages to overhead lines:
- a. No visual impact, invisible,
 - b. Maintenance free,
 - c. Low electrical losses,
 - d. Environmentally friendly,
 - e. Unaffected by weather conditions such as high winds or icing,

f. Ideal for highly populated areas.

3. Lower losses

HVDC transmission losses come out lower than the AC losses in practically all cases.

An optimized HVDC transmission line has lower losses than AC lines for the same power capacity.

The losses in the converter stations have to be added, but since they are only about 0.6 percent 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.

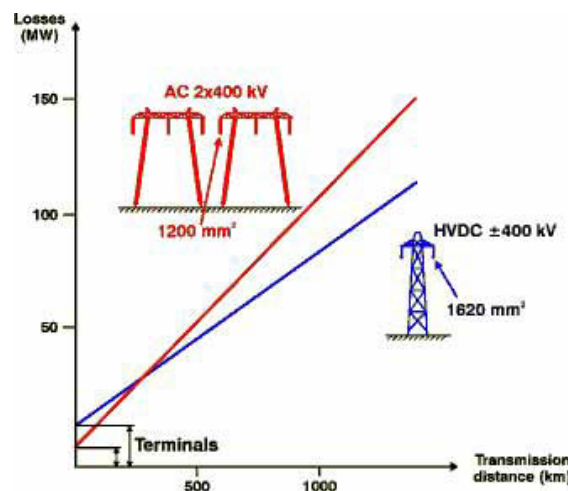


Fig. 8: Comparison of the losses for overhead line transmissions of 1200 MW with AC and HVDC.

4. Asynchronous interconnections

Several HVDC links interconnect AC systems that are not running synchronized with each other. For example the Nordel power system in Scandinavia is not synchronous with the UCTE grid in western continental Europe even though the nominal frequencies are the same.

The power system of the eastern USA is not synchronous with that of western USA. The reason for this is that 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 of 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.

In the majority of HVDC projects, the main control is based on a constant power transfer. This property of HVDC has become more important in recent years as the margins in the networks have become smaller and as a result of deregulation in many countries. An HVDC link can never become overloaded.

In many cases the HVDC link can also be used to improve the AC system performance by means of additional control facilities. Normally these controls are activated automatically when certain criteria are fulfilled. Such automatic control functions could be constant frequency control, redistribution of the power flow in the AC network, or damping of power swings in the AC networks.

In many cases such additional control functions can make it possible to increase the safe power transmission capability of AC transmission lines where stability is a limitation.

Advanced semi conductor technology, utilized in both power thyristors and microprocessors for the control system, has created almost unlimited possibilities for the control of the HVDC transmission system. Different software programs are used for different kind of load flow and stability studies. For more detailed investigations of the performance of the inner control loops of the converter and its interaction with nearby network is simulated in a full three-phase representation program such as PSCAD/EMTDC.

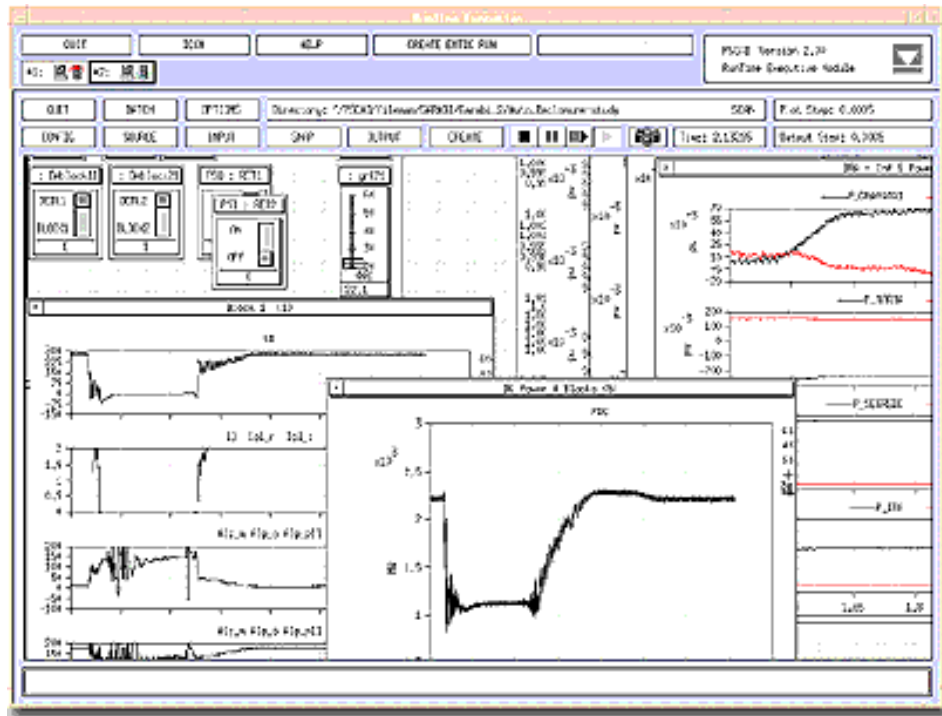


Fig. 9: The performance of the inner control loops of the converter and its interaction with nearby network is simulated in a full three-phase representation program such as PSCAD/EMTDC.

6. Limit short circuit currents

An HVDC transmission does not contribute to the short circuit current of the interconnected AC system.

When a high power AC transmission is constructed from a power plant to a major load center, the short circuit current level will increase in the receiving system. High short circuit currents is becoming an increasingly difficult problem of many large cities. They may result in a need to replace existing circuit breakers and other equipment if their rating is too low.

If, however, new generating plants are connected to the load center via a DC link , the situation will be quite different. The reason is that an HVDC transmission does not contribute to the short circuit current of the interconnected AC system.

7. Environment Benefits

a) Positive effects on the power systems

Many HVDC transmissions have been built to interconnect different power systems by overhead lines or cables. By means of these links the existing generating plants in the networks operate more effectively so that the building of new power stations can be deferred. This makes economic sense, but it is also good for the environment.

There is an obvious environmental benefit by not having to build a new power station, but there are even greater environmental gains in the operation of the interconnected power system by using the available generating plants more efficiently.

The greatest environmental benefit is obtained by linking a system, which has much hydro generation to a system with predominantly thermal generation. This has the benefit of saving thermal generation, predominately at peak demand, by hydro generation. Also the thermal generation can be run more efficiently at constant output and does not have to follow the load variations. This can be done easily with the hydro generation.

b) Reduced Right Of Way, ROW, for a DC line.

One bipolar HVDC overhead line can be compared to a double circuit AC line from reliability point of view. Therefore a single HVDC line with two conductor bundles has less environmental impact than a double circuit AC line with six conductor bundles. It requires less space and has less visual impact.

c) Minimum Environmental Impact.

The HVDC Light technology has made it possible to use extruded polymer cables for DC. This has made the use of land cables an interesting alternative over traditional overhead lines in the 50 - 550 MW range for rather long distances.

The HVDC Light cables have insulation of extruded polymer. The insulation is triple extruded together with the aluminum conductor screen and the insulation screen.



Fig. 10: HVDC Light cables pair, 43 mm, 2 kg/m Al conductor 340 mm².

In HVAC there has been a change of technology going from paper insulated cables to extruded cables. The preference of extruded cables for applications in HVDC has been obvious for a long time. Several reports have been published in the past about the existence of space charges in the insulation leading to uncontrolled local high electric fields causing dielectric breakdowns. Another reason has been uneven stress distribution due to temperature dependent resistivity causing overstress in the outer part of the insulation.

The HVDC Light cable development has overcome these problems and has resulted in an extruded cable for HVDC that is an important part of the HVDC Light concept. The cables are operated in a bipolar mode, one cable with positive polarity and one cable with negative polarity.

The cables are installed close in bipolar pairs with anti parallel currents and thus cancelling out the magnetic fields.

The cables are designed with a copper or aluminum conductor surrounded by a polymeric insulating material, which is very strong and robust. The water sealing of the cable is designed with a seamless layer of extruded lead and finally two layers of armoring steel wire in counter helix for the mechanical properties of the cable.

In general terms the different reasons for using HVDC can be divided in two main groups:

1. HVDC is necessary or desirable from the technical controllability point of view.
2. HVDC results in a lower total investment, including lower transmission losses and/or is environmentally superior.

In many cases, projects are justified on a combination of benefits from the two groups. Today the environmental aspects are also becoming more important. HVDC is in that respect favorable in many cases, as the environmental impact is less than with AC. This is due to the fact that an HVDC transmission line is much smaller and needs less space than AC lines for the same power capacity.

The system characteristics of an HVDC link differ a lot from AC transmissions. One of the most important differences is related to the possibility to accurately control the active power transmitted on a HVDC line. This is in contrast to AC lines, where the power flow cannot be controlled in the same direct way. The controllability of the HVDC power is often used to improve the operating conditions of the AC networks where the converter stations are located.

Another important property of an HVDC transmission is that it is asynchronous. This allows the interconnection of non-synchronous networks.

HVDC IN WIND POWER GENERATION

According to the Kyoto Protocol, the European Union committed itself to reducing the emissions of greenhouse gases like CO₂. In particular, Germany's commitments included doubling its share of electricity from renewable energy sources by 2010. One important element in achieving this goal is the German federal government's strategy for offshore wind power generation with a goal of 20,000 MWs of wind power capacity.

The main priority here is creating appropriate solutions for the transmission of the power from the offshore facilities to the mainland and feeding it into the existing high voltage power grid. Technical studies, plus the results of the Deutsche Energie Agentur or the German Energy Agency (Dena) network study, have shown that traditional three phase current technology reaches its limitations in this application. Beyond some transmissions distances three phase current network links using submarine cables were no longer technically feasible, nor can the stability of the networks concerned be assured in all control states by traditional means for the ratings involved.

In this situation the HVDC Light technology as an enhancement of the traditional HVDC technology now incorporating the present day semiconductor components and control technologies, is under consideration. Instead of the traditional thyristors, IGBT components are now being used, and microprocessor based and computerized control systems have replaced the old analog controls.

The result of this development process is an entirely new generation of HVDC transmission equipment, which has eliminated certain characteristics of traditional HVDC

transmission systems and is branded as HVDC Light. The new technology scores in terms of the following characteristics: relatively small compact installations, low harmonic loads, complete decoupling of the two networks connected with respect to malfunctions or failure of one network, and no reactive power problems etc.

HVDC Light can be supplied up to a unit output of currently 500 MW. This power can be transported over large distances with low losses using just one two pole DC cable, ability to decouple each of the two networks from a malfunction in the other grid, and to keep it running operating in this case too, as specified in the new grid connection rules drawn up by several transmission system operators.

PULSE WIDTH MODULATION, PWM, RECTIFICATION, INVERSION AND CONTROL

In VSC based HVDC, the usage of series connected transistors has allowed the connection of voltage source converters to networks at voltages that were earlier unreachable. This could be used for power transmission, for reactive power compensation, and for harmonic/flicker compensation. Even in weak grids, with fast vector control, such a converter provides the ability to control the active and reactive powers independently, while imposing low levels of harmonics.

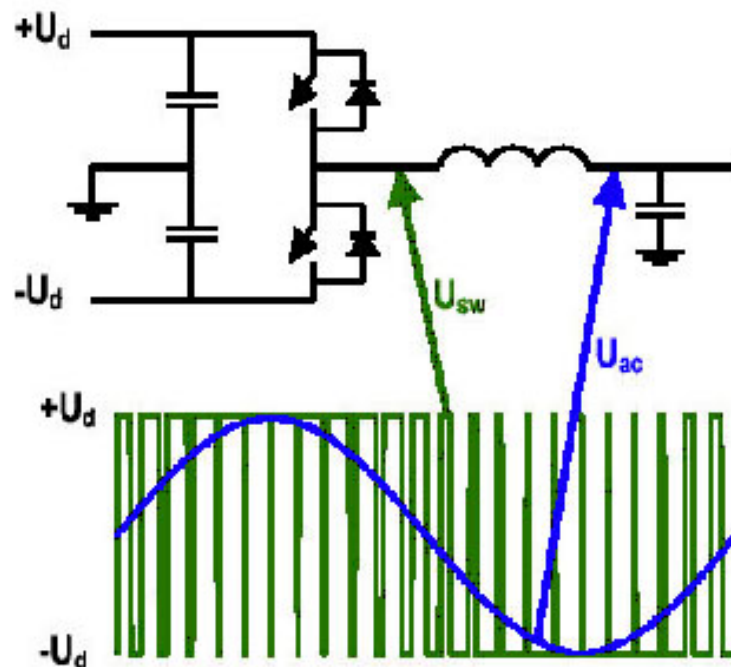


Fig. 11: Pulse Width Modulation, PWM.

Pulse width modulation is a close to ideal component in a transmission network and is

used for the generation of the fundamental voltage. From a system's perspective, it acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously. In addition, it does not contribute to the short circuit power, as the AC current can be controlled. Consequently, both the magnitude and phase of the voltage can be freely and almost instantaneously controlled within prescribed limits. This allows the independent and fast control of the reactive and active power flows.

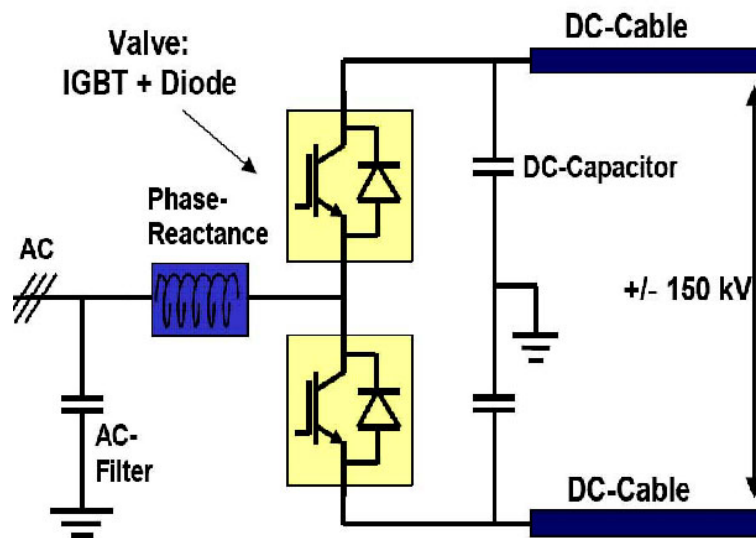


Fig. 12: Operational principle of Voltage Source Converter, VSC High Voltage Direct Current, HVDC with a positive and a negative DC cables.

Usually, each connected station controls its reactive power contribution, both inductive and capacitive, independently of the other station. The active power can continuously and almost instantaneously be controlled from full power export to full power import. The flow of active power in the DC cables must be balanced, which means that the active power entering the HVDC system must be equal to the active power leaving it. A difference in power would imply that the DC voltage in the system would rapidly increase or decrease, as the DC capacitance increases its voltage with increased charge, and vice versa. With a normal design the stored energy is equivalent to around 2 ms power transmission on the system.

To achieve this power balance, one of the connected stations has to control the DC voltage. The other station can adjust arbitrarily the transmitted power within the power capability limits of the system design, whereby the station that controls the DC voltage will adjust its power to ensure that the balance or constant DC voltage is maintained. The balancing is attained without telecommunication between the stations, just based on measurement of the DC voltage.

FREQUENCY VARIATION

The voltage source converter HVDC design is based upon a two level bridge that is grounded by a midpoint capacitor. This ensures both steady state and dynamic operation with low levels of induced ground currents. In an offshore wind farm environment, there is no need for any cathode protection.

A Voltage Source Conversion HVDC station normally follows the AC voltage of the connected grids. The voltage magnitude and frequency are determined by the control systems of the generating stations. For a wind power application the converter station could control the grid frequency and voltage to a reference value set by an overall wind farm control system in order to optimize the wind power production should such a solution be preferred.

Operation with variable frequency in one end and fixed grid frequency in the other does not require main circuit equipment that differs from the normal design. In general, the design principles adopted for normal transmission system applications also applies for wind farm applications.

ISLAND OPERATION

In case of a voltage collapse or a “black-out”, the converter can instantaneously switch over to its own internal voltage and frequency reference and disconnect itself from the grid. The converter can then operate as an idling “static” generator, ready to be connected to a “black” network.

The ability of a VSC converter to generate a voltage that can be changed very quickly in amplitude and phase, offers the possibility of energizing a network after a blackout. This is especially useful when it comes to energization of a remote wind farm network. The converter transformer would be equipped with a special auxiliary power winding for self-supply of the converter station, and the control system will have special schemes for detecting a network blackout. If such an event occurs, the converter will automatically trip the connection to the grid, and continue to operate in “house-load” operation, supplied through the DC cables from the main grid.

The converter can also be started manually in a black-start mode, if needed. The network restoration sequence starts with the offshore station running without load. The voltage and frequency are decided by the converter, which in this case operates in frequency control mode as a generator. The AC voltage can be smoothly ramped up by the VSC thereby preventing transient over voltages and inrush currents. The wind turbine generators can be automatically connected to the remote network after detecting the correct AC voltage for a certain time.

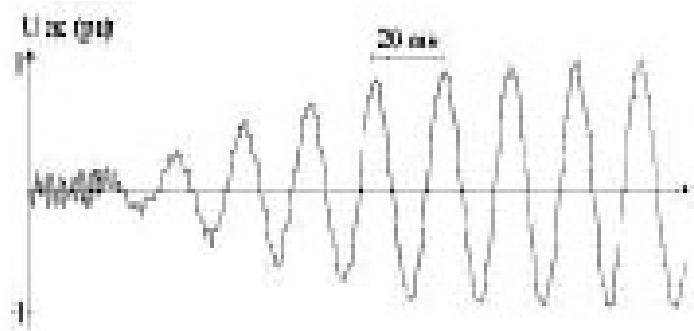


Fig. 13: Grid AC voltage start up of an isolated network at the Hällsjö project.

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