HIGH VOLTAGE DIRECT CURRENT HVDC FOR WIND POWER

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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 in the western Rocky Mountain region, whereas the population and industrial centers are in its central part and on its East and West Coasts. A critical issue is that the electric industry is suffering from a lack of focus on how new technologies can enhance reliability and efficient grid operations. Elsewhere in the world, utility companies are increasingly using advanced technologies in the transmission process, particularly High Voltage Direct Current (HVDC) and the construction of a Smart Grid System optimally coupling the renewable and conventional energy sources to the electrical consumers.

Figure 1. Modern state-of-the-art Yidu High Voltage Direct Current (HVDC) converter station serves the 22,500 MW world's largest hydroelectric power station Three Gorges Dam on the Yangtze River, 403 square miles reservoir project at Shanghai, China. The dam became fully functional on July 4, 2012. Source: ABB.

The Three Gorges Project is one of the essential key projects for flood controlling and water resources regulation in the Yangtze River. China. The project includes a river-crossing dam, underground powerhouses, and navigation structures. Because of the huge size and complicated construction technologies, the project faced a series of challenging engineering issues. In terms of rock mechanics, there are many key technical issues, including the sliding resistance and stability of the dam section along the foundations of powerhouses No.1–5, the slope stability of the double-line five-stage shiplock, excavation of large-scale underground powerhouses, and curtain grouting under the dam. A modern state-of-the-art Yidu High Voltage Direct Current (HVDC) converter station serves the 22,500 MW world’s largest hydroelectric power station.

The 200,000 miles of power lines forming the North American USA and Canada electrical grid are owned by over 500 different competing companies. In the USA, the adoption of advanced technologies emphasizes placing better information from the field into the hands of the system operator, including automated substations. A fractionalized ownership of the grid into power producers and transmission operators, as a result of the process of deregulation, discourages vertical integration in favor of horizontal expansion and is contributing to this failure, since the cost / benefit analysis of these new technologies favors regional rather than local benefits.

The existing outdated and fragile with respect to storm damage infrastructure begs to be replaced and supplemented by a modern, robust and reliable High Voltage Direct Current (HVDC) transmission system. Such a system allows for cables to be buried underground in densely populated, valuable farmland, environmentally-sensitive areas, or below bodies of water for offshore wind production, and is considered as more economical for long-distance transmission than the current vulnerable to storm damage overhead High Voltage Alternating Current (HVAC) transmission system.

NORTH AMERICAN HVDC POWER GRID EXPERIENCE

Figure 2. Pacific Northwest Southwest 800 miles long Intertie using HVDC carries 3,100 MW of power.

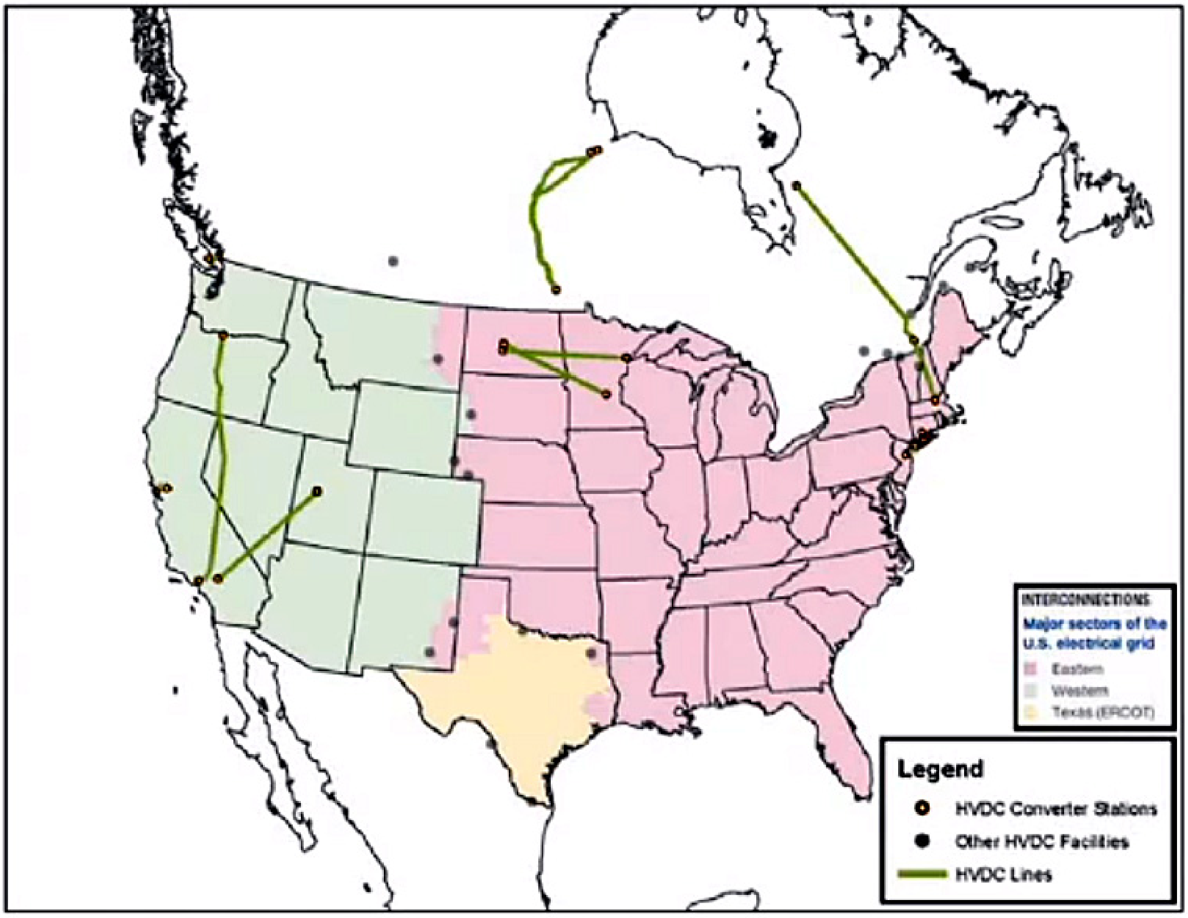


Figure 3. Existing HVDC converter stations and HVDC lines in the North-American power grid system. Shown from left to right are the Trans-Bay Cable, the Pacific Intertie, the Intermountain Power line, the Square Butte, the nelson River I and II, the CU line, the Québec-New England, the Cross-Sound Cable and the Neptune line. The Pacific DC Intertie has been in operation for over 30 years at ± 500 kV. The line is capable of transmitting up to 3,100 MW of power. Currently there are more than 20 HVDC transmission facilities in the USA and more than 35 across the North American grid system.

The Pacific Intertie project is an 846-mile ±500 kV HVDC line, which transmits 3.1 GW of power from the Pacific Northwest, with its vast hydro resources, to the Los Angeles area. This intertie originally went into service in 1970 and was upgraded to its current capacity in 1989. This project is undergoing yet another upgrade, which will further increase its capability.

The Intermountain Power Project (IPP) is an HVDC transmission system, operated by the Los Angeles Department of Water and Power, which moves 1.92 GW of power from south of Salt

Lake City, Utah into the Los Angeles Basin. In 2008, approval was obtained to upgrade the IPP HVDC line to a capacity of 2.4 GW.

The Nelson River Bipole project in Canada connects hydroelectric resources in Northern Manitoba to the population centers in Southern Manitoba. The Nelson River projects have over 3.8 GW of capacity and cover over 550 miles. Manitoba Hydro is planning the addition of a third bi-pole to the Nelson River project.

The Québec-New England project, which delivers 2 GW over 932 miles from the southern Hudson Bay area in Québec to near Boston, Massachusetts, was commissioned in 1990-1992.

The most recent additions in the USA include the Neptune project, which transmits 660 MW over 65 miles, with nearly 50 miles underwater, and connects Long Island and New Jersey; and the Trans Bay Cable, a 53-mile, 400 MW project, which brings power underneath the bay into the San Francisco area. Both of these projects were built by the German Siemens Company.

Other North American grid HVDC projects include the CU Powerline and Square Butte Projects, which bring remote generating resources from North Dakota to Minneapolis, Minnesota and Duluth, Minnesota, respectively; and multiple back-to-back (no overhead line) HVDC projects between the various interconnections.

STRUCTURE OF HVDC GRID SYSTEMS

In the USA, the economic and environmental advantages of long-distance HVDC are sometimes discounted in favor of inferior conventional HVAC technology under the premise that HVDC is a highway with one onramp and one exit ramp; when in reality multiple HVDC converter stations can be built as desired at the wind and conventional energy sources' electricity-feeding nodes, as well as at the load sites. For instance, with Asea Brown Boveri's (ABB) hybrid HVDC breaker technology, it is now possible to have multiple exits along the highway. The hybrid HVDC design has negligible conduction losses, while preserving an ultra-fast current interruption capability [15].

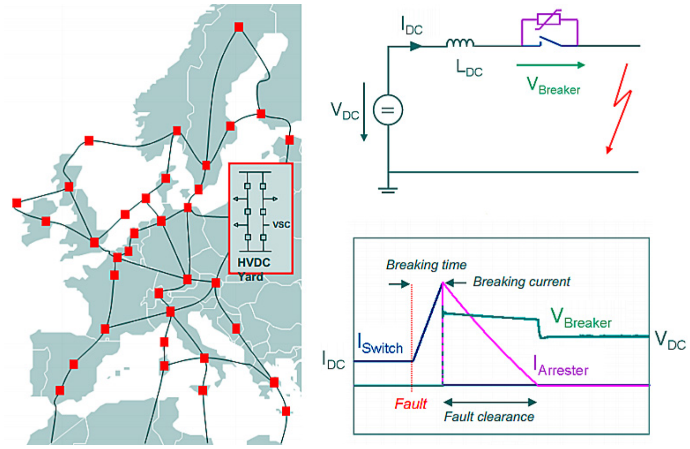


Figure 4. Structure of an HVDC grid system for Europe and North Africa with hybrid HVDC breakers. Total fault clearing time consists of two parts: breaking time corresponds to a period of rising current, and fault clearing corresponds to a period of decreasing current. [15].

Instead of stringing a long-distance HVDC line from, say, Iowa to New York with one onramp and one exit ramp, the line could be interrupted several times to allow the power to flow to load centers along the way, as well as to allow power to be fed from production centers such as wind parks.

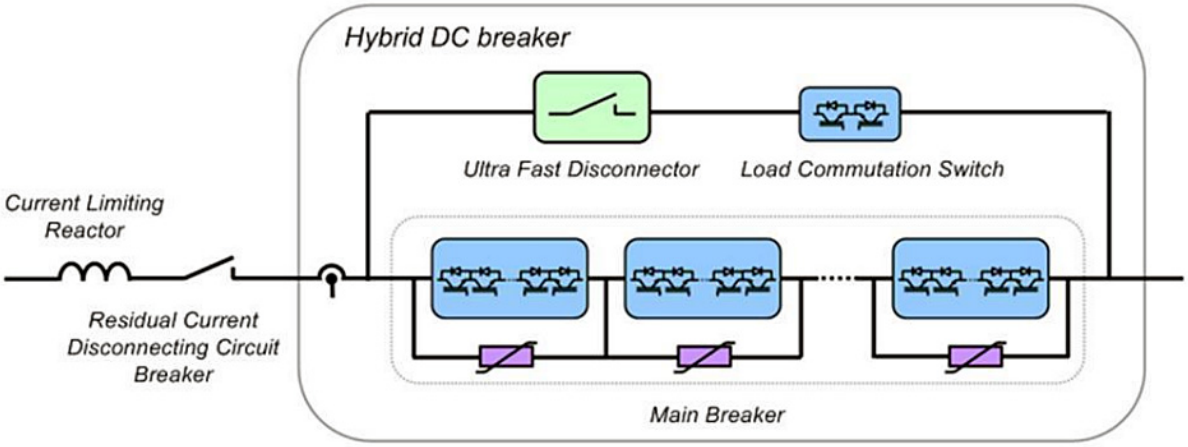


Figure 5. Hybrid HVDC Breaker [15]. Assuming a breaking time of 2 ms, which is possible for semiconductor-based HVDC switches, and an HVDC line fault close to the HVDC switchyard, the maximum rise of the fault current will be 3.5 kA/ms for a HVDC reactor of 100 mH in a 320 kV HVDC grid with 10percent maximum overvoltage. For a given rated line current of 2 kA, the minimum required breaking capability of the HVDC breaker is 9 kA. Source: ABB.

During the short time period representing the occurrence of an HVDC fault, the equivalent circuit includes an infinitely strong HVDC source, an HVDC reactor and the HVDC switch in parallel with an arrester. The electromagnetic transient when the current is broken follows the following scenario:

1. The current starts to rise when the fault occurs.
2. When the switch opens, the current starts to decrease as it is commutated to the arrester.
3. The fault current in the arrester bank establishes a counter voltage, which reduces the fault current to zero by dissipating the fault energy stored in the HVDC reactor and fault current path of the HVDC grid.
4. The protective level of the arrester bank must exceed the HVDC voltage in the HVDC grid.

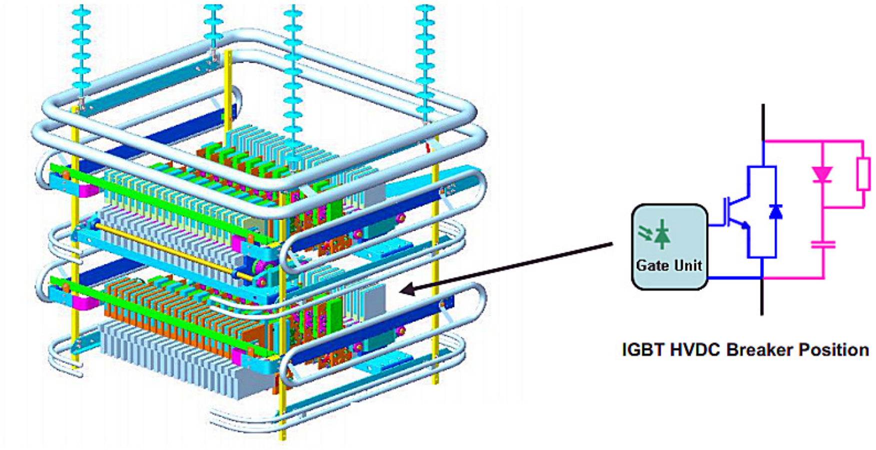


Figure 6. Main 80 kV HVDC circuit breaker cell. The main HVDC breaker consists of several HVDC breaker cells with individual arrester banks limiting the maximum voltage across each cell to a specific level during current breaking. Each HVDC breaker cell contains four HVDC breaker stacks. Two stacks are required to break the current in either current direction. Each stack is composed of up to 20 series connected IGBT HVDC breaker positions. IGBT: Insulated Gate Bipolar Transistor. Source: ABB.

The hybrid HVDC breaker consists of a parallel additional branch as a bypass formed by a semiconductor-based load commutation switch in series with a fast mechanical disconnector. The main semiconductor-based HVDC breaker is separated into several sections with individual arrester banks dimensioned for full voltage and current breaking capability, whereas the load commutation switch matches lower voltage and energy capability.

After fault clearance, a disconnecting circuit breaker interrupts the residual current and isolates the faulty line from the HVDC grid to protect the arrester banks of the hybrid HVDC breaker from thermal overload. During normal operation the current will only flow through the bypass, and the current in the main breaker is zero. When an HVDC fault occurs, the load commutation switch immediately commutates the current to the main HVDC breaker and the fast disconnector opens.

With the mechanical switch in the open position, the main HVDC breaker breaks the current. The mechanical switch isolates the load commutation switch from the primary voltage across the main HVDC breaker during current breaking. The required voltage rating of the load commutation switch is significantly reduced. A successful commutation of the line current into the main HVDC breaker path requires a voltage rating of the load commutation switch exceeding the on-state voltage of the main HVDC breaker, which is typically in the kV range for a 320 kV HVDC breaker.

The transfer losses of the hybrid HVDC breaker concept are significantly reduced to a percentage of the losses incurred by a pure semiconductor breaker. The mechanical switch opens at zero current with low voltage stress, and can thus be realized as a disconnector with a lightweight contact system. The fast disconnector will be exposed to the maximum pole-to-pole voltage defined by the protective level of the arrester banks after first being in open position while the main HVDC breaker opens [14].

Since the auxiliary HVDC breaker is continuously exposed to the line current, a cooling system is required. Besides water cooling, air-forced cooling can be applied, due to relatively low losses in the range of several tens of kW only.

VOLTAGE SOURCE CONVERTER, VSC

Voltage Source Converter (VSC) HVDC transmission systems make it possible to build an HVDC grid with multiple terminals. Compared with HVAC grids, active power conduction losses are low and reactive power conduction losses are zero in an HVDC grid. This advantage makes an HVDC grid more attractive [16].

Fast and reliable HVDC breakers are needed to isolate faults and avoid a collapse of the common HVDC grid voltage since the low impedance in HVDC grids is a challenge when a short circuit fault occurs, because the fault penetration is faster and deeper. In addition, maintaining a reasonable level of HVDC voltage is a precondition for the converter station to operate normally. To minimize disturbances in converter operation, particularly the operation of stations not connected to the faulty line or cable, it is necessary to clear the fault within a few milliseconds.

Plans for large scale use of embedded VSC-HVDC transmission in point-to-point overhead lines is considered in Germany, in the Netzentwicklungsplan Network Development Plan (NEP). New electrical generation from remote sites using wind power renewable sources are supporting the case for VSC-HVDC systems in the areas of active power transmission and reactive power compensation. The hybrid HVDC breaker technology provides the additional benefit of interrupting HVDC line faults.

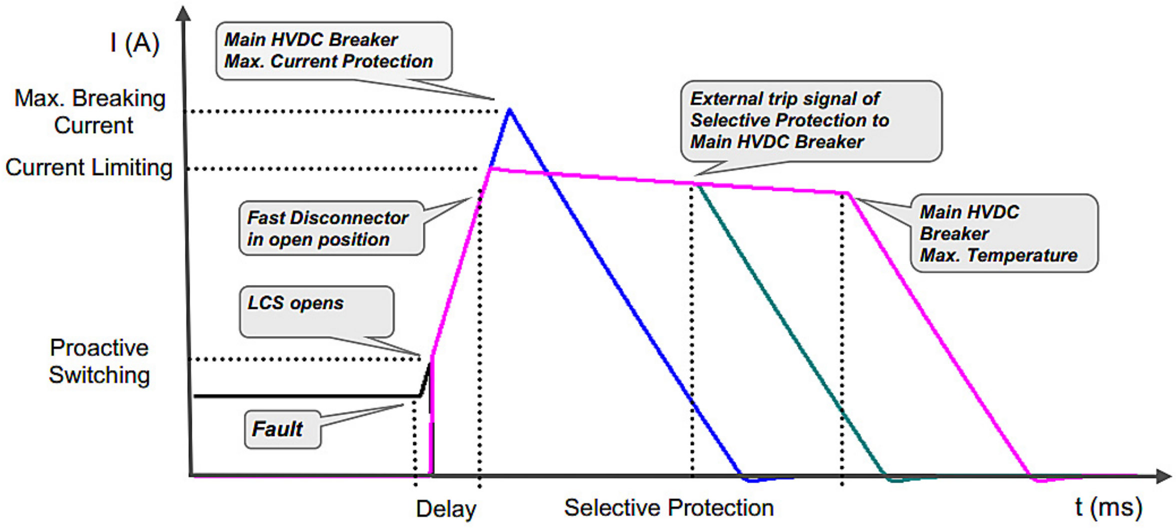


Figure 7. Control of HVDC grid system showing current as a function of time. Response to a fault using hybrid HVDC circuit breakers. LCS: Load Commutation Switch [15].

HVDC BREAKER TECHNOLOGY

Existing HVDC switches have been used for more than 30 years in the neutral switchyard of bipolar HVDC installations. They perform various functions, such as rerouting HVDC current during reconfiguration of the main circuit, or helping to extinguish fault currents.

The Metallic Return Transfer Breaker (MRTB) is used to commutate the current from the ground path to a metal conductor, when there are restrictions on how long an HVDC current can be routed through the ground. Other alternatives are the Ground Return Transfer Switch (GRTS), Neutral Bus Switch (NBS) and Neutral Bus Grounding Switch (NBGS).

The existing mechanical HVDC breakers are capable of interrupting HVDC currents within several tens of milliseconds, but are too slow to fulfill the requirements of a reliable HVDC grid. Building mechanical HVDC breakers is in itself challenging and requires the installation of additional passive components to create a resonance circuit, and generate the current zero crossing so the breaker will succeed in breaking the current once it opens.

The main differences between these transfer breakers and the hybrid HVDC breaker is that the transfer breakers operate considerably slower than the hybrid breaker, and that part of the current is transferred, rather than interrupted. These high-voltage switches or breaker systems use an AC-type of high-voltage breaker; the zero crossing of the HVDC fault current is imposed by discharge of a capacitor bank to generate a current opposite to the fault current, in order to extinguish the arc. These are large outdoor pieces of equipment, situated partly on air-insulated platforms in the HVDC converter station neutral switchyard. The direct voltage for these applications is usually only a few tens of kilovolts (kV).

Semiconductor-based HVDC breakers easily overcome the limitations of operational speed and voltage, but generate large transfer losses in the range of 30 percent of the losses of a voltage source converter station. The hybrid HVDC breaker has been developed to overcome these obstacles,

The fast fault handling enables the converter stations to operate as Stand Alone Static Compensation (STATCOMs) units to stabilize the voltage and increase transmission capacity in the HVAC grid during fault clearance.

NATIONAL PLAN FOR FUTURE NORTH AMERICAN POWER SYSTEM

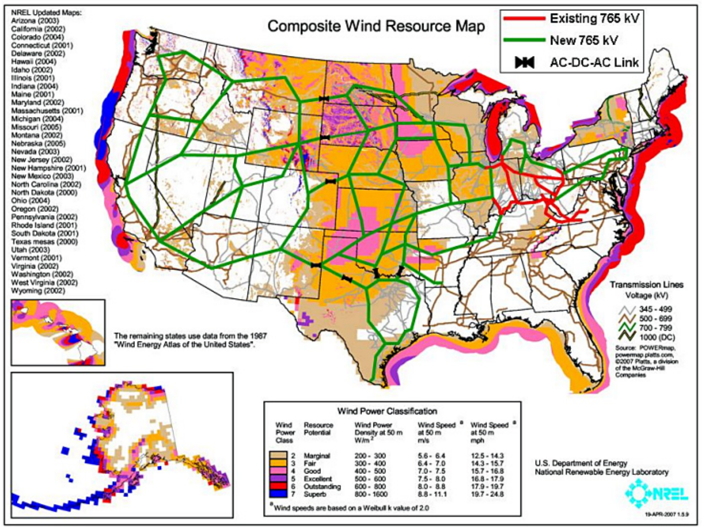


Figure 8. National conceptual recommended 765 kV electric power grid for wind resources with AC-DC-AC links as firewalls between the East and West interconnects. The 200,000 miles of power lines forming the North American USA and Canada electrical grid are owned by over 500 different companies. It is 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 as shown in the diagram. Sources: United States Department of Energy (USDOE), National Renewable Energy Laboratory (NREL), American Electric Power (AEP), American Wind Energy Association (AWEA).

High Voltage (HV) and Ultra High Voltage (UHV) transmission lines carry high-voltage electricity at 64-765 kilovolts (kVs) over long distances to deliver energy from power plants to residences or businesses. Common transmission line voltages in the USA include 64, 138, 161, 230, 345 and 765 kV.

Wind turbines usually generate 11-13 kV AC electricity at the wind resource sites. This is typically converted into 33 kV then stepped up to 138 kV or above, then fed into DC converter stations for long distance transmission at +/- 600 kV, then reconverted in a converter station into AC power for distribution at the consumption sites. Open Cycle Gas Turbines (OCGTs) or Combined Cycle Gas Turbines (CCGTs) are increasingly and necessarily connected to the system to surmount the intermittency of wind energy.

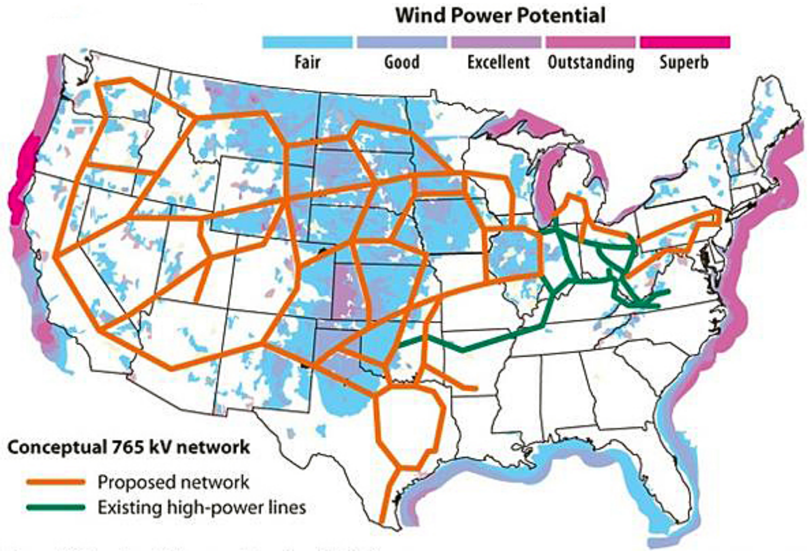
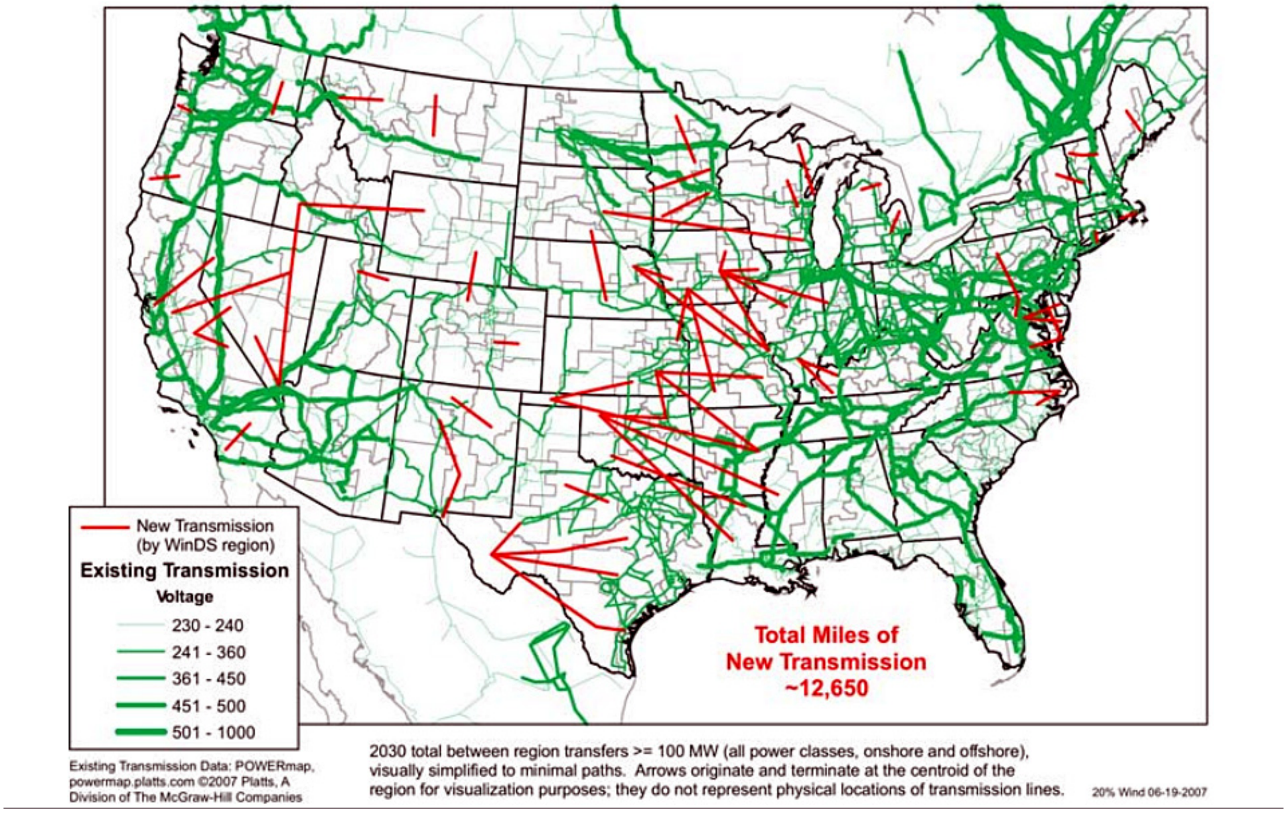


Figure 9. Existing and proposed 765 kV electrical network for the dispatch of electric wind power generation from the North-South USA wind power production corridor to the eastern and western consumption centers. Source: USDOE.



Existing Transmission Data: POWERmap, powermap.platts.com ©2007 Platts, A Division of The McGraw-Hill Companies

2030 total between region transfers >= 100 MW (all power classes, onshore and offshore), visually simplified to minimal paths. Arrows originate and terminate at the centroid of the region for visualization purposes; they do not represent physical locations of transmission lines.

20% Wind 06-19-2007

Figure 10. New transmission lines needed for the transmission of wind power production add up to 12,650 miles by 2030. Source: 20% Wind Energy by 2030.

MODERN SAFE AND RELIABLE USA INFRASTRUCTURE CHALLENGE

The American Society of Civil Engineers (ASCE), in its report on the USA's Infrastructure assesses the status of the USA Electric Grid as follows:

> "The USA power transmission system is in urgent need of modernization. Growth in electricity demand and investment in new power plants has not been matched by investment in new transmission facilities. Maintenance expenditures have decreased 1% per year since 1992. Existing transmission facilities were not designed for the current level of demand, resulting in an increased number of "bottlenecks," which increase costs to consumers and elevate the risk of blackouts."
>
> "Our grids today are more stressed than they have been in the past three decades. If we don't expand our capacity to keep up with an increase in demand of 40 percent over the next 25 years, we're going to see healthy grids become increasingly less reliable. Today, with the grid operating flat-out, any disruption—like the downed transmission line that sparked the 2003 blackout in the Northeast—can cripple the network."

Commenting on the situation in the State of New York in late October 2012 following Hurricane Sandy, concerning the low-reliability disaster and failure-prone fragile electrical grid system in the USA depending on outdated overhead power lines in highly populated areas, the European economic-competitor to the USA view is expressed by Fichtner et. al. [9] as:

> "The power lines in Brooklyn and Queens, on Long Island and in New Jersey, in one of the world's largest metropolitan areas, are not underground, but are still installed along a fragile and confusing above-ground network supported by utility poles, the way they are in developing countries."
>
> "Large parts of America's biggest city (New York) and millions of people along the East Coast could now be forced to survive for days, possibly even weeks, without electricity, water and heat. Many of the backup generators intended for such emergencies didn't work, so that large hospitals had to be evacuated. On the one hand, these consequences of the storm point to the uncontrollability of nature. On the other hand, they are signs that America is no longer the great, robust global power it once was."

In response, the USA will rise to the challenge of reviving its aging infrastructure with modern, safe, reliable, effective and environmentally sound engineering systems. It will remain “the great, robust global power” that it has always been for the benefit of its future generations and the whole world.

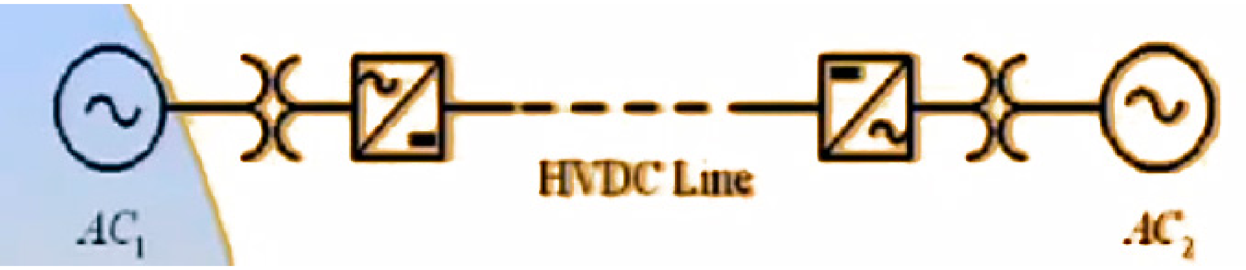


Figure 11. Typical HVDC line includes generators, step-up and step-down transformers and rectifiers[14].

COMPARISON OF HVDC AND HVAC

There exists is a need to supplement the existing electrical grid system with a modern High Voltage Direct Current (HVDC) power transmission, which is characterized with low energy loss and lower capital cost for transmission over long distances. For economic and environmentally-acceptable long distance dispatch of electricity in a Smart Grid context, High Voltage Direct Current (HVDC) is unequivocally superior to HVAC. Because of its economic, technical and environmental superiority, HVDC is presently the favored approach globally for long-distance electrical power dispatch, compared with HVAC which is indisputably presently only reserved for outdated 1800s “developing countries” applications [8, 9]. HVDC technology is capable of:

1. Laying of the HVDC power lines under water bodies for offshore applications.
2. Undergrounding of the HVDC power lines in environmentally sensitive areas, valuable farm-land and urban high population areas.

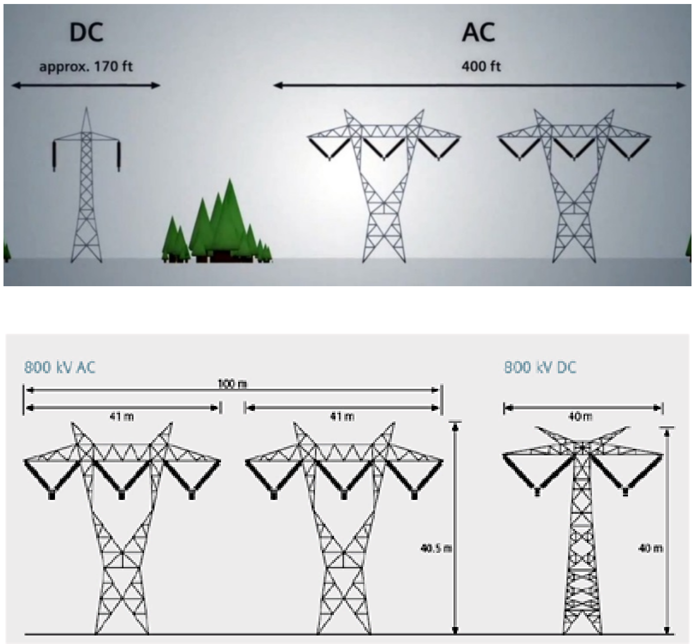
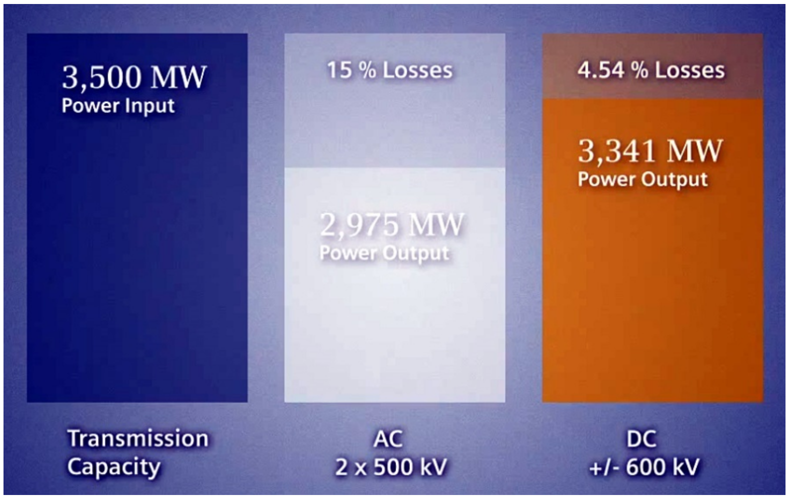


Figure 12. Right Of Way (ROW) and environmental impact of comparable HVDC and HVAC lines for the same amount of power transmission. Typically HVAC requires two to three redundant three-wire systems, whereas HVDC requires a single 2-conductor wires. Consequently the environmental impact of HVDC and the Right Of Way (ROW) of HVDC is less than one half to one third that of HVAC for the same voltage and power. Source: Siemens.

3. An HVDC transmission line requires fewer conductors, right of ways, structural towers and a smaller footprint than a comparable HVAC transmission infrastructure.
4. HVDC can transfer larger amounts of power with lower line losses over long distances using 2 conductors for HVDC rather than three for HVAC lines.
5. HVDC can dampen power oscillations in an HVAC grid through fast modulation at the converter stations and thus improve the grid system stability.
6. Complement existing HVAC networks without contribution to short circuit current power or additional reactive power requirements.
7. Provide the system operators with direct control of the energy flows and managing the injection of intermittent wind power.
8. Unlike HVAC lines, HVDC lines act as firewalls and will not become overloaded by unrelated outages, since the amount of power delivered is strictly limited by the HVDC converters at each end of the HVDC line, thereby reducing the likelihood that outages will propagate from one region to another.



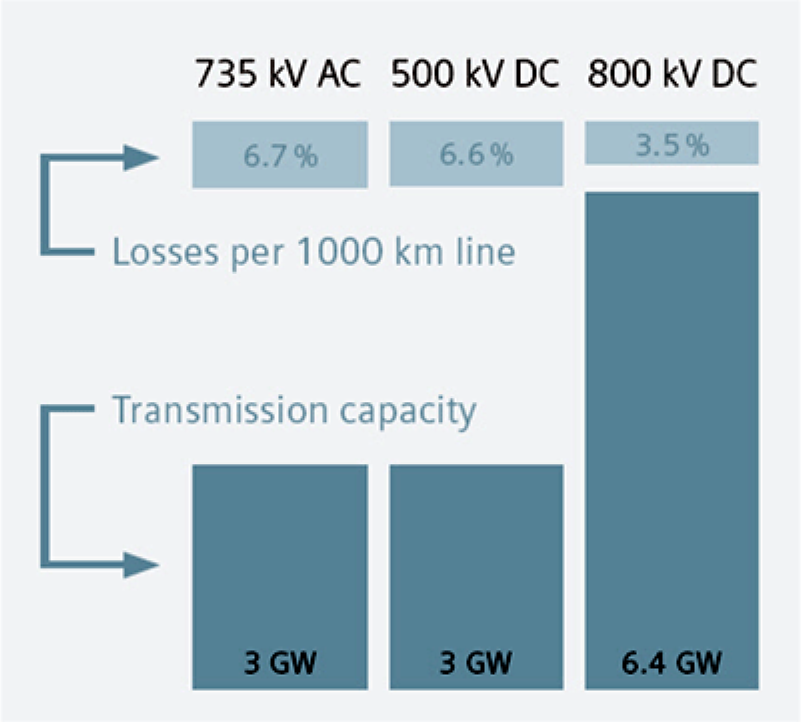


Figure 13. Comparison of transmission losses in HVDC and HVAC. For 3,500 MW of power input, over a distance of 600 miles, the AC losses amount to 15 percent with two 500 kV lines, whereas the HVDC lines would be about one third at 4.54 percent losses. Source: Siemens.

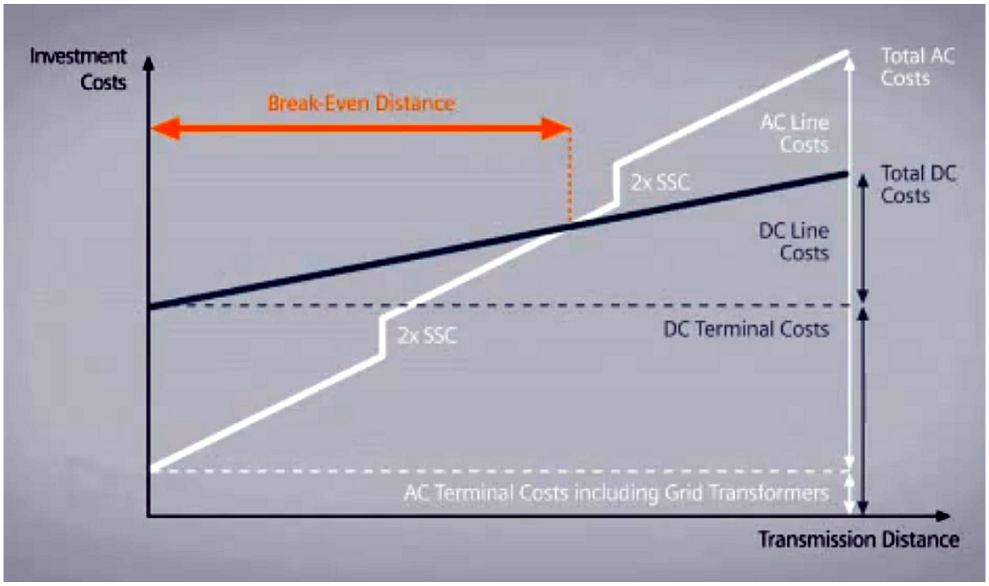


Figure 14. Lower capital costs of HVDC compared with HVAC. HVAC requires AC reactive power compensation stages. Reactive power must be provided by local utilities. Savings of 30-70 percent can be achieved for long distance power transmission by HVDC compared with HVAC. Source: Siemens.

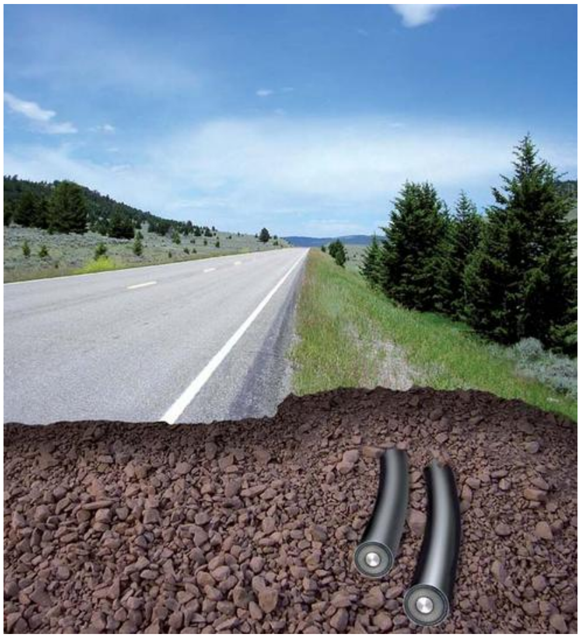


Figure 15. Underground 300 kV HVDC cables can be emplaced underground along existing highways and railroads rights of way in high population, productive farmland and environmentally sensitive areas. Source: ABB.

DENSITY

Density is the number of consumers that an electric utility serves per actual mile of the transmission network that the utility has built and maintains on a regular basis in its service area [11]. Density is an issue that faces the utilities in their duty in providing safe and reliable electricity at the moment the consumer needs it without interruption due to natural or man-made causes.

While highly-profitable Merchant or Investor-Owned Utilities (IOUs) average 34 consumers per mile of line, Rural Electric Cooperatives are less profitable serving only 3-7.5 customers per mile of line. One mile of overhead HVAC electric line costs about $28,000 to build, whereas underground HVAC lines cost twice as much [11]. On the other hand, underground lines cost less to maintain and operate and entail lower power losses over long distances for HVDC.

Bucket trucks cost about $239,000 each and are needed to continuously maintain overhead lines against weather phenomena with a fleet of about 20 trucks needed for a 4,500-miles of transmission lines utility with 25 substations [11]. The distribution cost includes the required facilities, electric poles, wires, transformers, substations, vehicles, equipment maintenance, metering, accounting, billing, member services and the cost of administrative and operations personnel. The “base charge,” earlier called a “facility charge,” averages $40-70 per month per residential serviced home.

Table 1. Density for different utility systems in the USA [11].

Utility type	Density [consumers / mile of line]
Municipal Utilities	48
Merchant, Investor-Owned Utilities (IOUs)	34
Rural Electric Cooperatives	7.5

The adoption of HVDC allows the electrical power transmission cables to be buried underground in highly populated, valuable productive farmland and environmentally sensitive areas. It also allows the electrical power transmission under bodies of water such as for offshore siting of wind parks. In contrast, the underground transmission of HVAC power is impractical over long distances because the capacitance per unit length of the transmission line makes an underground HVAC cable impractical for cable lengths beyond 50-100 kilometers. However, AC lines can be “undergrounded” for short distances and are in fact increasingly buried by the electrical utilities in new residential developments of upscale urban residential neighborhoods in the USA.

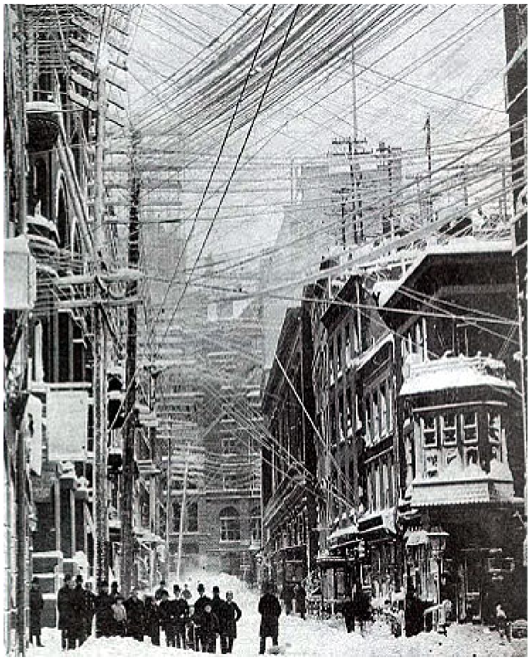


Figure 16. Overhead AC power lines have been installed at the beginning of electricity introduction in New York City in the late 1800s, and dominate the existent fragile infrastructure in the USA.

Ideally, the routing criteria of power lines take into consideration:

1. The avoidance and consideration of offset distance from homes, schools, businesses, cemeteries and other structures.
2. The minimization of impacts to agricultural, mining, aviation and other commercial activities.
3. The avoidance of protected activities and sites such as agricultural areas, wetlands, areas with threatened and endangered species.
4. The avoidance of historical, cultural or archeological significant sites.
5. Avoidance of state and federal lands, recreational areas, water resources, sensitive habitats of protected species.
6. Avoidance of airports and airstrips, schools and churches.

Practically, it is the length of the line and the minimization of the cost of construction that are the predominant factors affecting the power lines projects, raising unavoidable conflicts between the utilities and the affected entities. The costs of developing, constructing and operating the power lines are ultimately recovered from the transmission customers.

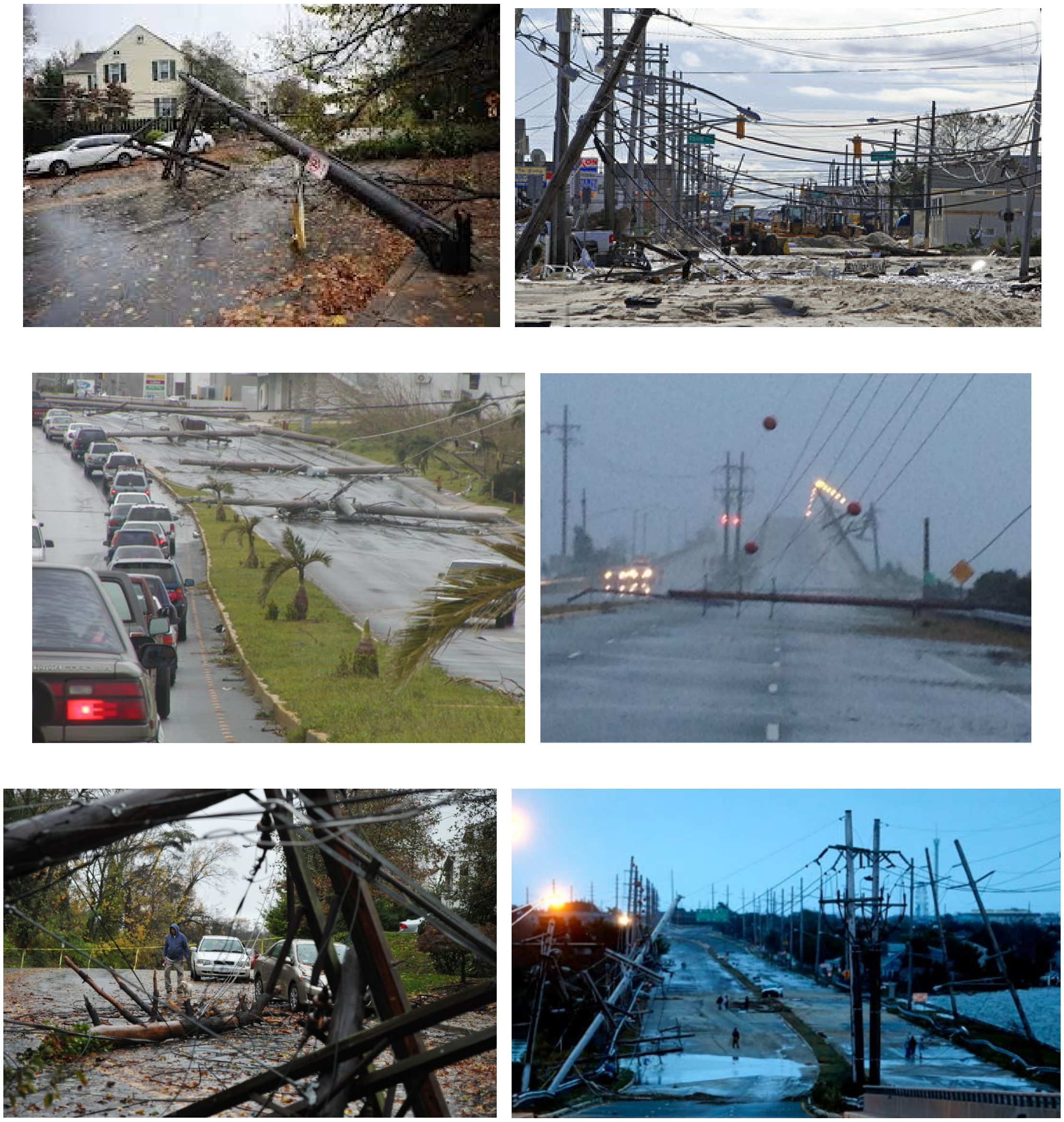


Figure 17. The hazards created by outdated vulnerable and fragile fallen overhead power lines became apparent as a result of Hurricane Sandy affecting the USA's East coast in October-November 2012.

For over 100 years, High Voltage Alternating Current, HVAC has been considered as the choice for electrical power transmission. This was widely replaced by classical current-conversion thyristor-based HVDC technology, which 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.

Voltage Source Converter 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 the classical 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 commutate 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 the transmission and grid infrastructure 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 the production sites to the load centers.

The 200,000 miles of power lines forming the USA electrical grid which are owned by over 500 competing companies and cooperatives are unprepared for a boom in domestic renewable and conventional sources of electricity capacity.

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

Typically, a 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 HVAC 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.

Figure 18. HVDC converter-station configuration. AC filters appear in the foreground, and the valve hall is in the background. Source: IEEE.

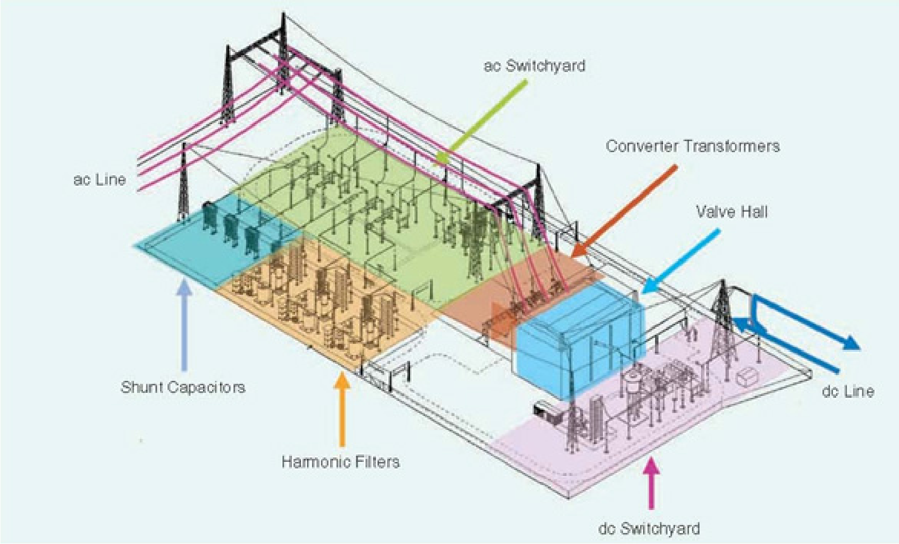


Figure 19. Configuration of a Monopolar HVDC converter-station. AC power uses three lines on the left, and the DC power uses only two lines on the right. Source: IEEE.

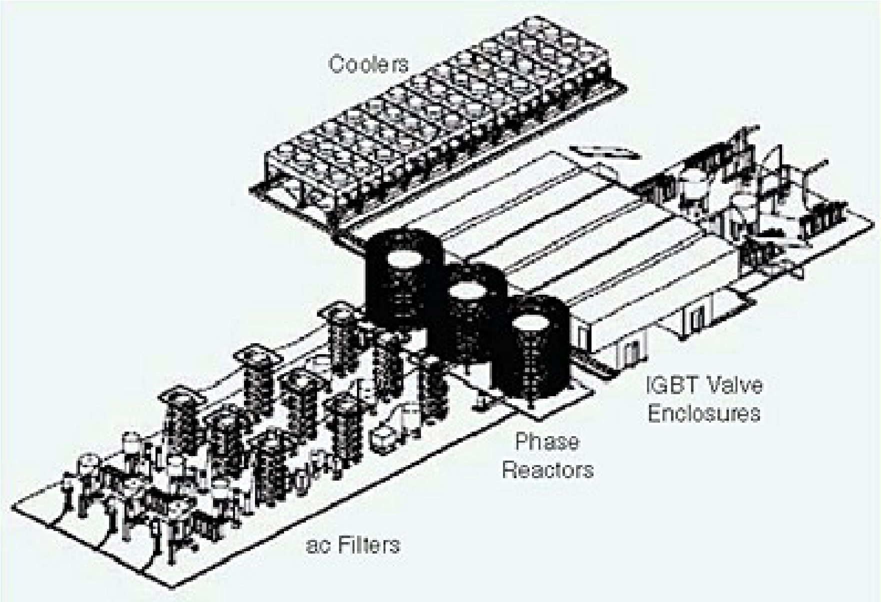
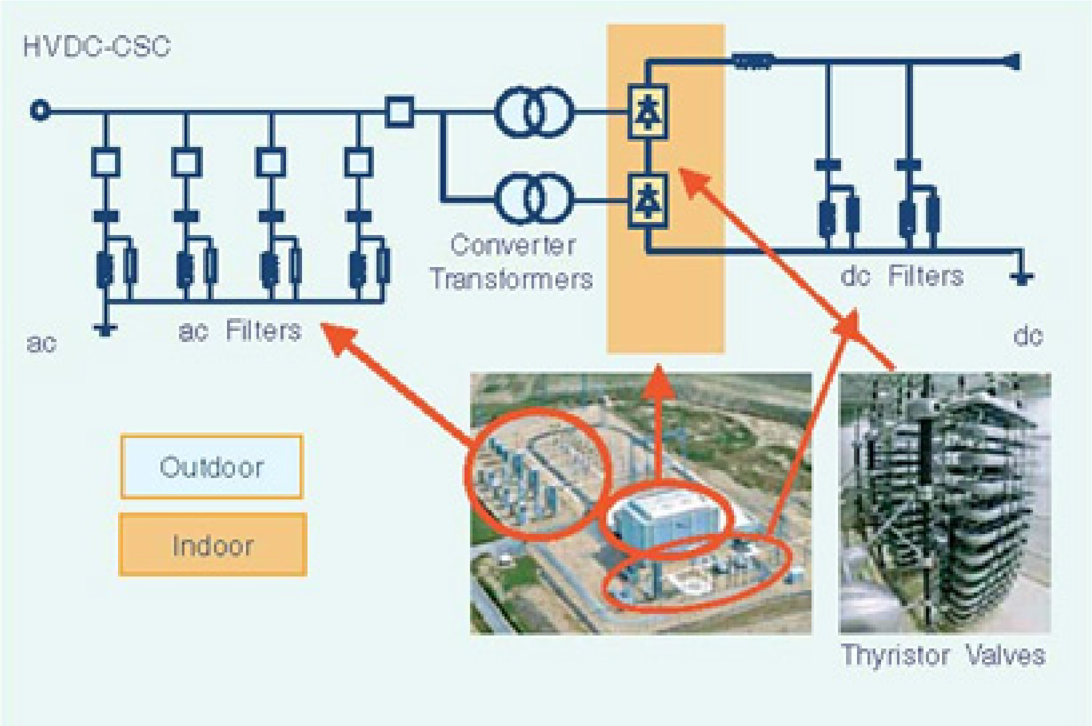


Figure 20. Voltage Source Converter (VSC) station configuration. IGBT stands for Insulated-Gate Bipolar Transistor. Source: IEEE.



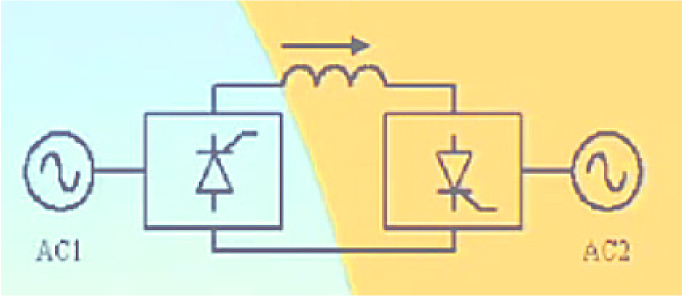


Figure 21. Conventional HVDC with Current Source Converters (CSCs) uses Thyristor valves. Source: IEEE.

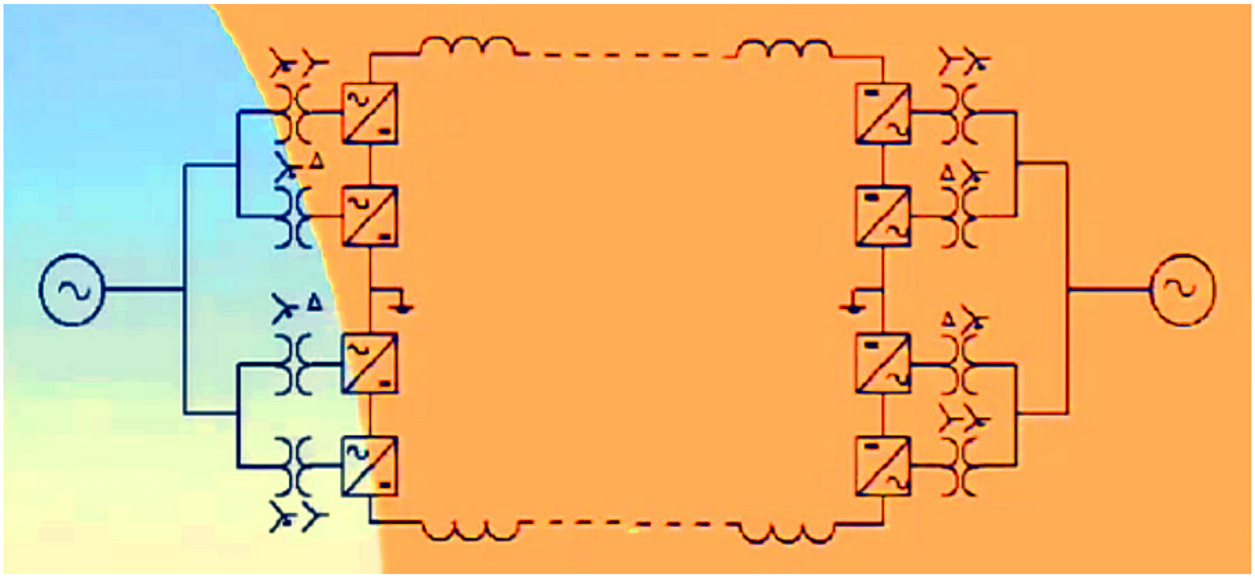


Figure 22. Current link HVDC system using transformers and two poles, one positive above ground and one negative below ground [14]

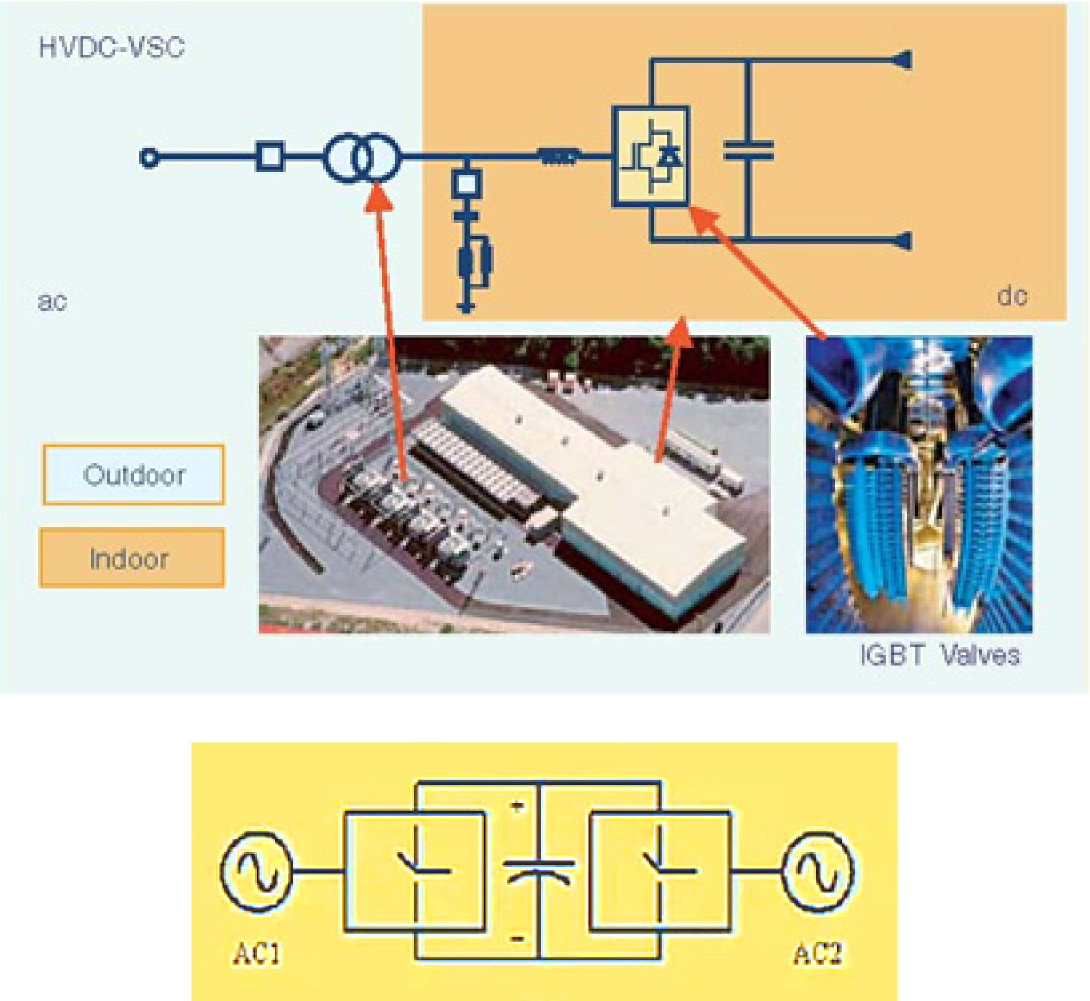


Figure 23. HVDC with Voltage Source Converters (VSCs) uses Insulated-Gate Bipolar Transistor (IGBT) technology. Source: IEEE.

HISTORICAL DEVELOPMENT, HVDC VERSUS HVAC

In the second half of the 19th century a fierce competition arose between the development of Direct Current, DC as advocated Thomas Edison and his financial backer J. P. Morgan, and the development of Alternating Current, AC as advocated by Nikola Tesla who sold his patent to George Westinghouse. Competition flared between Thomas Edison, supported by the financier J. P. Morgan and his DC system and Nikola Tesla and George Westinghouse and their AC system. Thomas Edison used even used scare tactics by electrocuting an elephant with AC power, suggesting that it is used for the execution of convicted criminals and warning people not to introduce it into their homes.

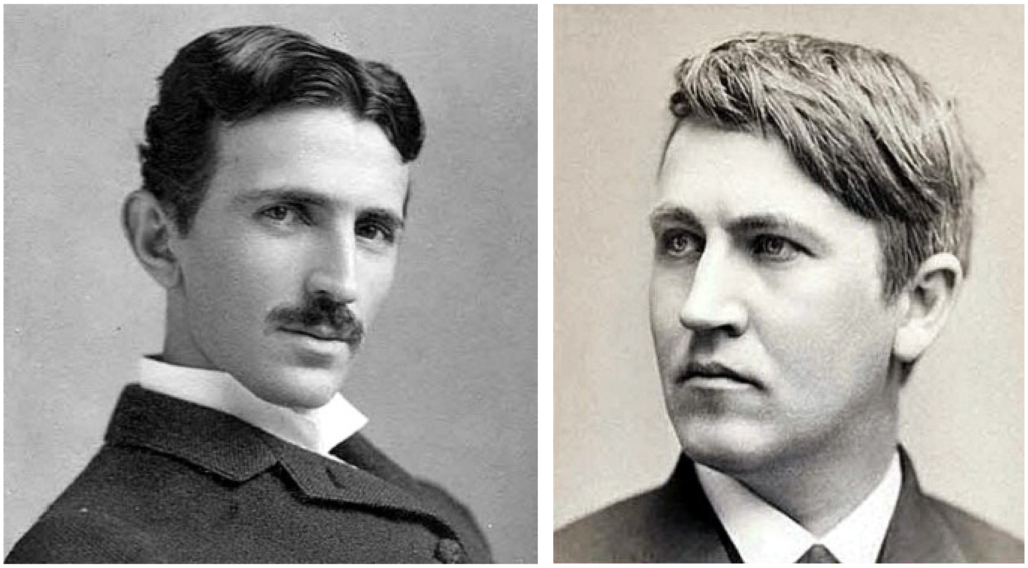


Figure 24. Nikola Tesla advocated AC power, whereas Thomas Edison advocated DC power in a historical rivalry.

The transfer of electricity between regions of the USA has been over HVAC transmission lines in which both the voltage and the current move in a wave-like pattern along the lines and are continually changing direction. In North America, this occurs with a frequency of 60 Hz. In Europe it is 50 Hz. Unlike an HVAC transmission line, the voltage and current on a HVDC transmission line are not time -varying. They do not change direction as energy is transmitted. HVDC electricity is a constant, zero-frequency movement of electrons from an area of negative charge to an area of positive charge.

The first commercial electric power system was built as a DC system by Thomas Edison as the Pearl Street substation in the late nineteenth century to replace gas lighting in the streets of New York. Given some contemporary advantages, AC power became the primary power system in the USA. Some of these advantages are no longer applicable. Technology has advanced to allow the efficient conversion from AC to DC, and DC transmission is currently the preferred solution for moving large amounts power over long distances.

Eventually, AC power transmission over long distance won the contest. In a DC system the electrons travel around the circuit and hence require a thick cable conductor with significant resistive losses. In an AC system, the electrons vibrate back and forth around their position, and hence require a thin cable with low resistive losses. Using a transformer, the AC voltage can be increased and transmitted over long distances without the need for repeater stations along the transmission line.

The AC system at this time 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 initial 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.

The situation is different today. Even though most of the electrical system is constituted of AC elements, the DC transmission system is acquiring increased importance because of its economic advantages over the AC transmission system when involving high voltage and 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. Modern 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 system to connect the generated energy to the power grid. As a result, the High Voltage DC, HVDC transmission system becomes the economically 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 of HVDC transmission power 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, and,
3. Multi terminal Systems.

Figure 25. Huizhou valve hall, Three Gorges Guangdong Transmission, China. Source: ABB.

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 project 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.

Initially, 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 the Asea Brown Boveri (ABB) Swedish and Swiss Company 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.

Figure 26. View of the insides of an HVDC Light valve Insulated-Gate Bipolar Transistor (IGBT) for Voltage Source Converters (VSCs). Source: ABB.

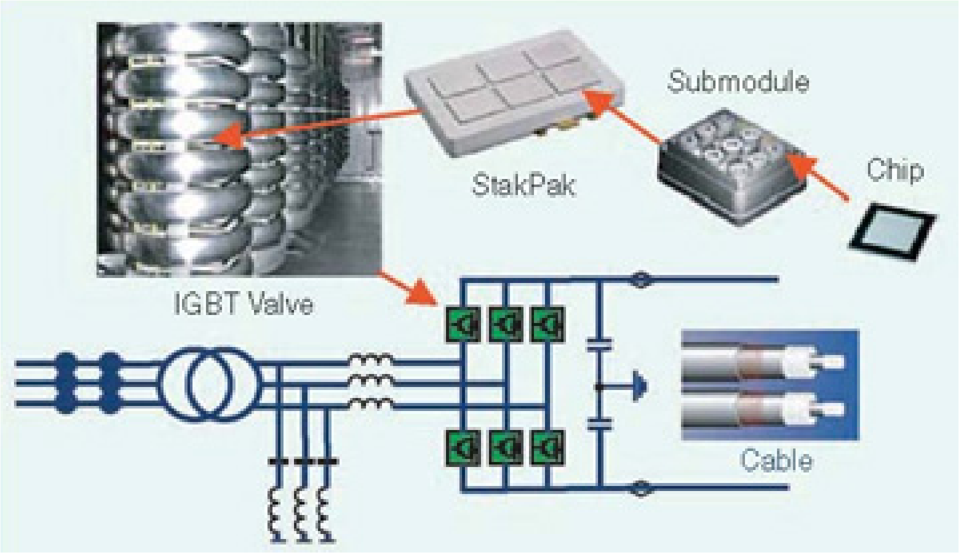


Figure 27. HVDC Insulated-Gate Bipolar Transistors (IGBT) Valve arrangement. Notice that only two cable lines are needed in HVDC instead of three cables in three-phase HVAC. Source: IEEE.

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 occurs. 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 the 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 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 power transfer in an AC transmission line can be estimated from:

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

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 charatcteristic 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 power capability of the line P_{max} can be expressed as:

$$P_{\max} = \frac{V_s V_r}{2\pi L} \tag{2}$$

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 from:

$$dI_C(x) = 2\pi f V(x).dC(x) \tag{3}$$

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:

$$I_C(x) \simeq 2\pi fCV_{rated} \tag{4}$$

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:

$$I_L = \sqrt{I_T^2 - I_C^2} \tag{5}$$

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

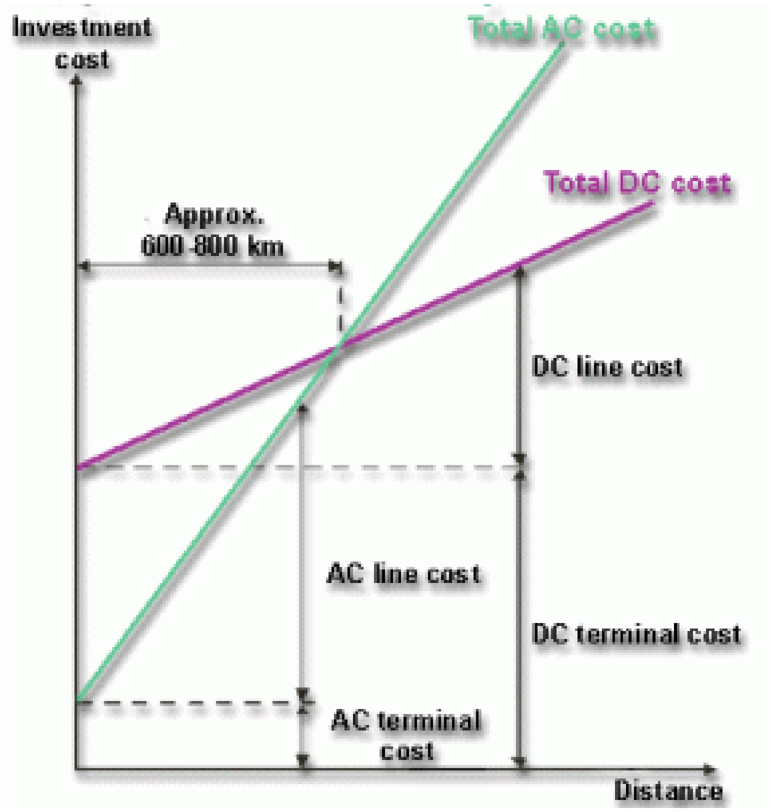


Figure 28. Investment cost breakeven distance for AC and DC electrical transmission. Source: ABB.

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

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

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 be 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.

Figure 29. 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. Source: ABB.

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.

Figure 30. Overhead 500 kV lines use only two conductors in HVDC, compared with 3 conductors in HVAC. Overhead lines can be used in low-population areas. Source: IEEE.

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.

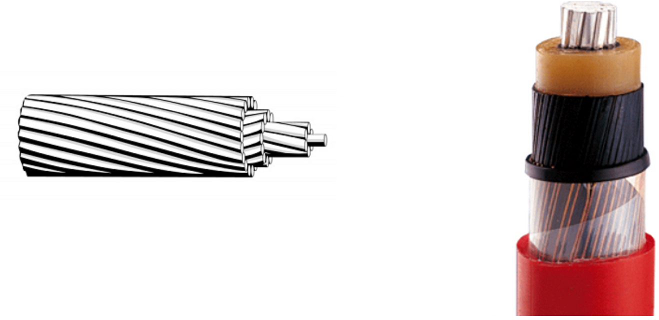


Figure 31. Comparison of overhead and insulated land underground cables with an Al inner conductor. Source: ABB.

Underground HVDC land cables offer multiple advantages to overhead lines:

a. No visual impact, invisible, out-of-sight, out-of-mind,
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, suburban, farmland and environmentally sensitive areas.

3. Lower losses

Losses from overhead power lines are caused by Ohmic resistive heating as well as by corona discharges under high elevation or high humidity condition such as rain. 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.

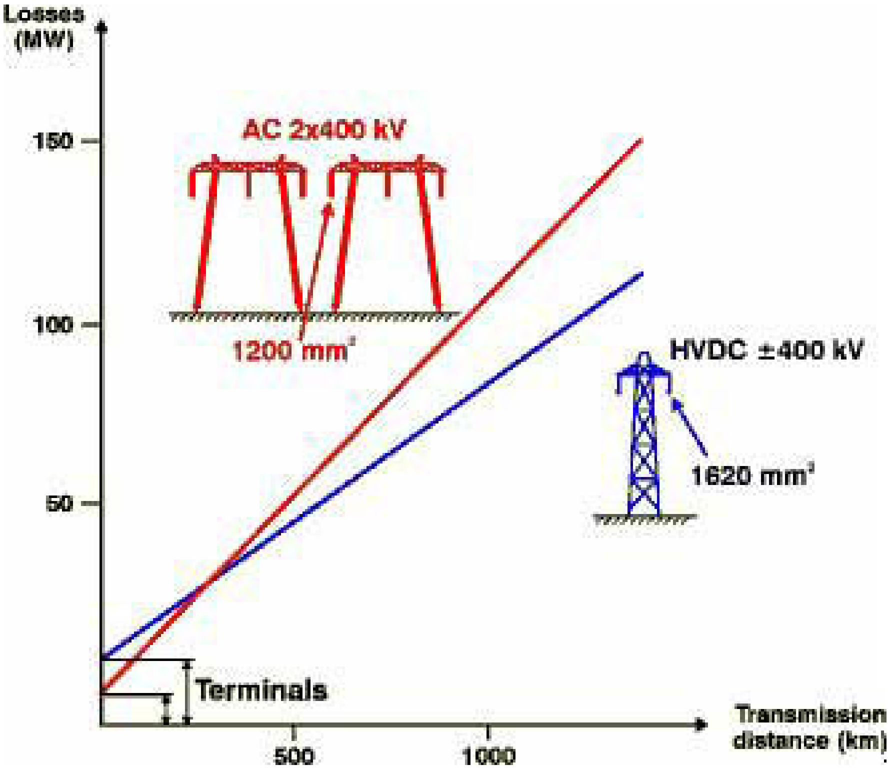


Figure 32. Comparison of the losses for overhead line transmissions of 800 kV with HVAC and HVDC. Notice that HVDC would use just one tower with two lines of +/- 400 kV with 1,620 mm^2 conductor cross section each, whereas HVAC uses two 400 kV towers with three lines each for a total of 6 lines with 1,200 mm^2 conductors cross sectional area each. Source: ABB.

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.

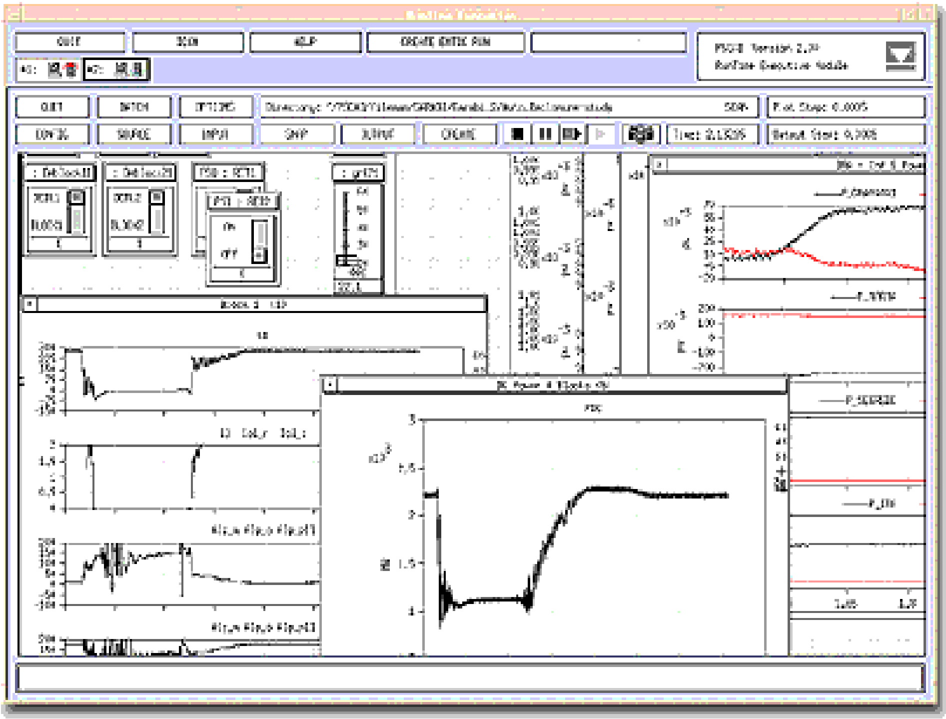


Figure 33. The performance of the inner control loops of the converter and its interaction with nearby network is simulated in a full three-phase representation program such as PSCAD/EMTDC. Source: IEEE.

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. The problem of generated 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 beneficial 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 shaving 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 the 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 alterative 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.

Figure 34. HVDC Light cables pair, 43 mm, 2 kg/m Al conductor 340 mm^2. Source: ABB.

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 CO_2. In particular, Germany's commitments included doubling its share of electricity from renewable energy sources. 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, in addition to the results of the Deutsche Energie Agentur (DENA) or the German Energy Agency network study, have shown that traditional three-phase current technology reaches its limitations in this application. Beyond some transmission distance, 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, Insulated-Gate Bipolar Transistor (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.

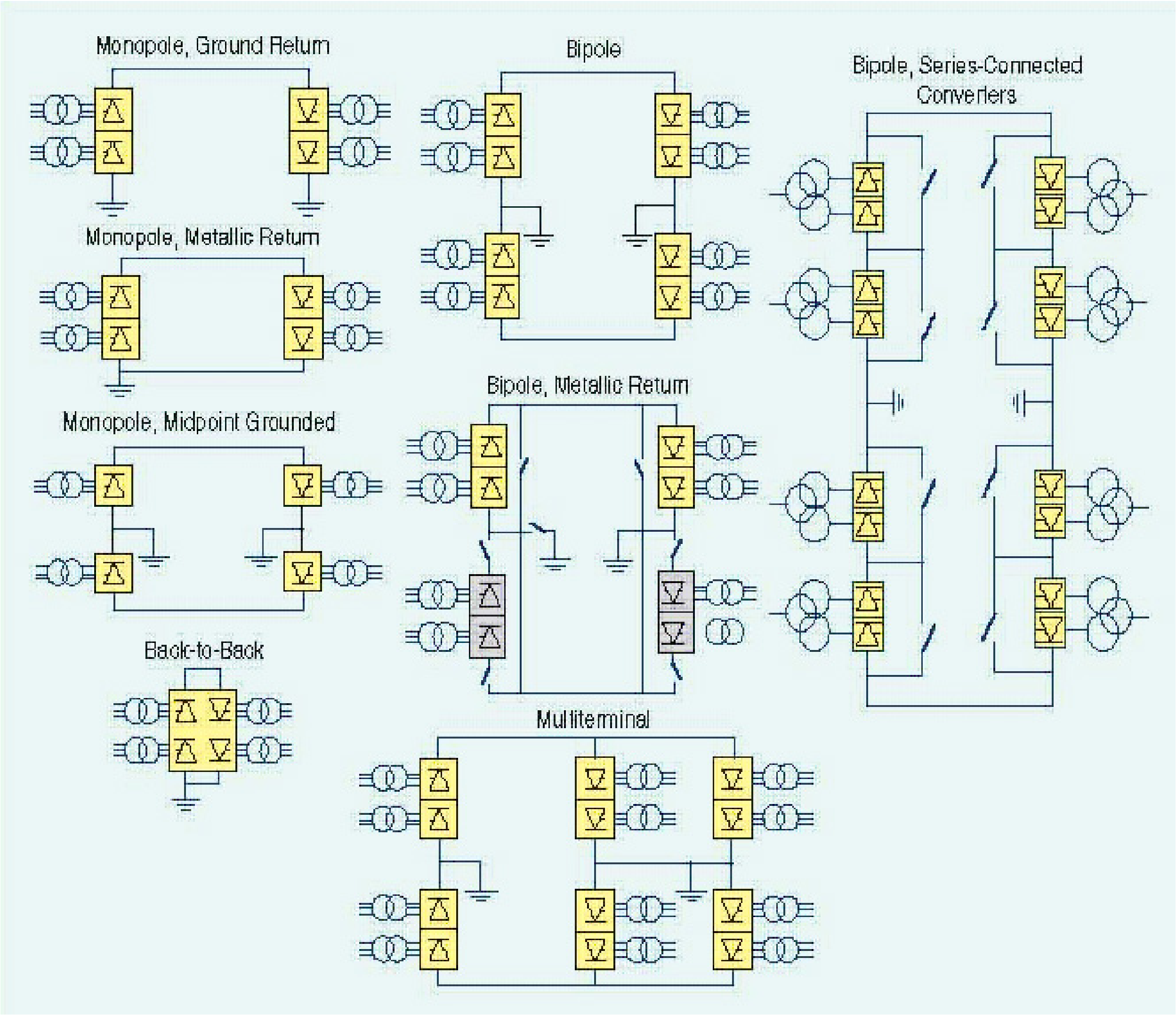


Figure 35. Different HVDC control modes. Source: IEEE.

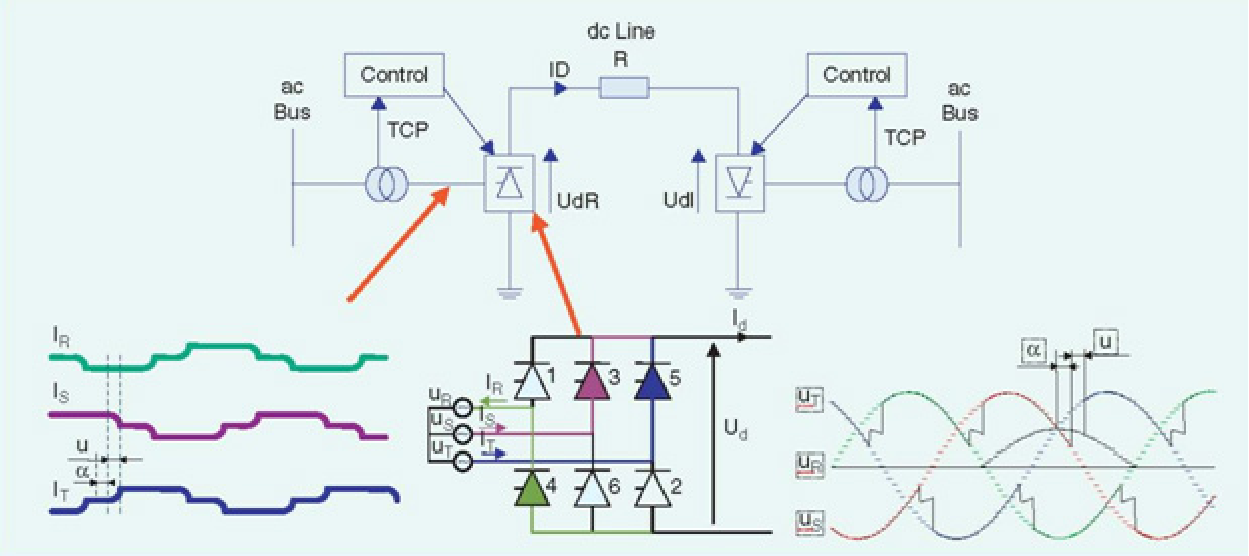


Figure 36. Conventional HVDC control. A mixture of DC and AC lines can be configured. Source: IEEE.

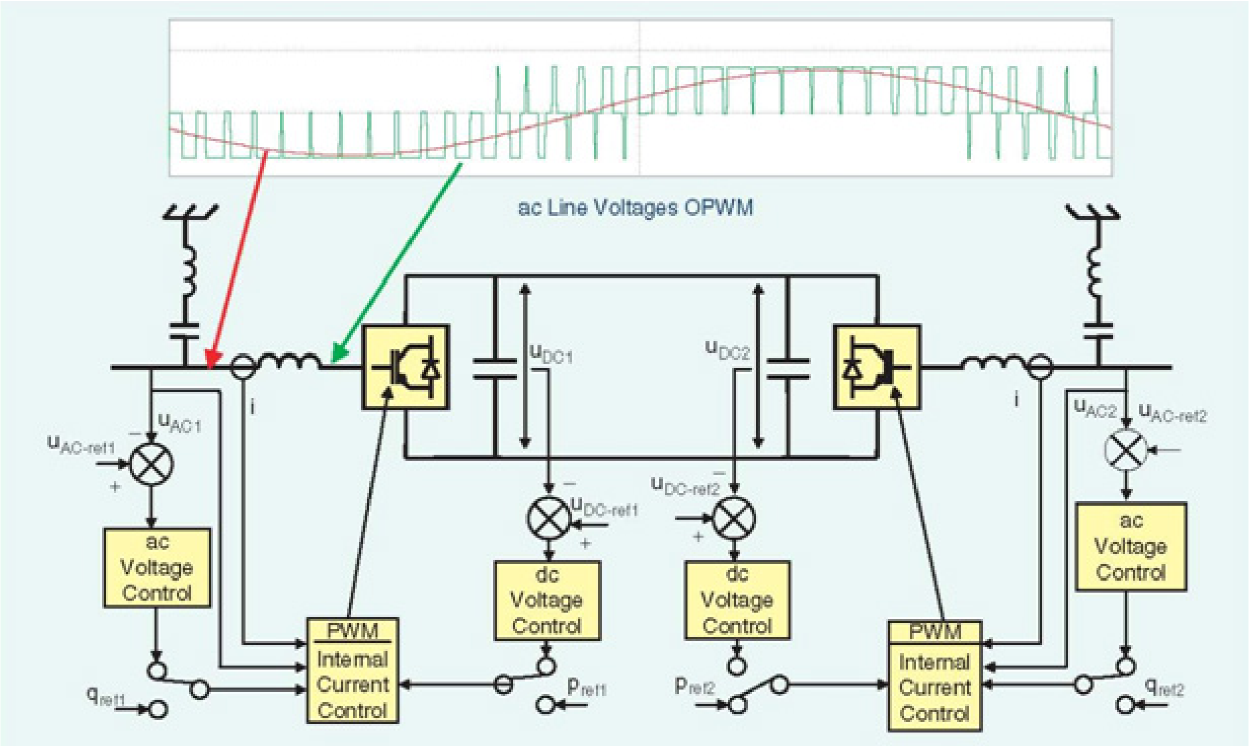


Figure 37. SVC HVDC control schematic. Source: IEEE.

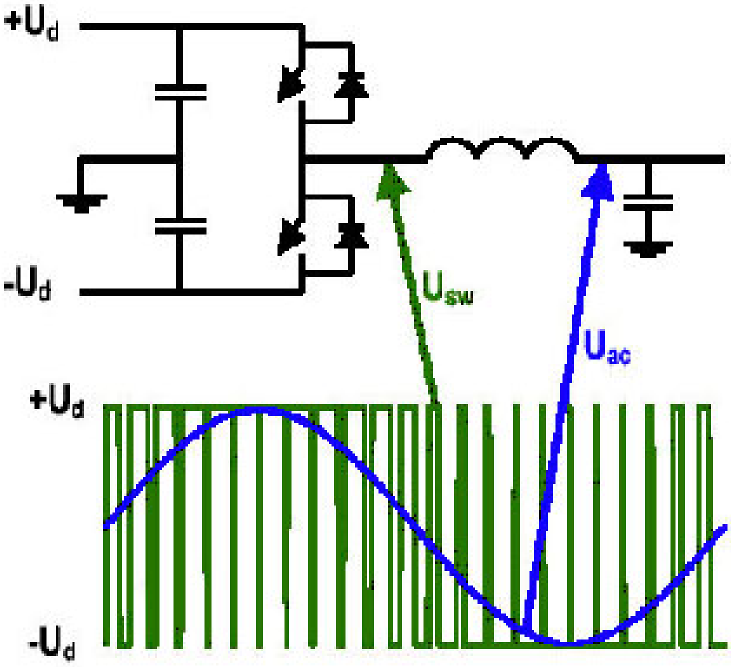


Figure 38. Pulse-Width Modulation, PWM. Source: ABB.

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.

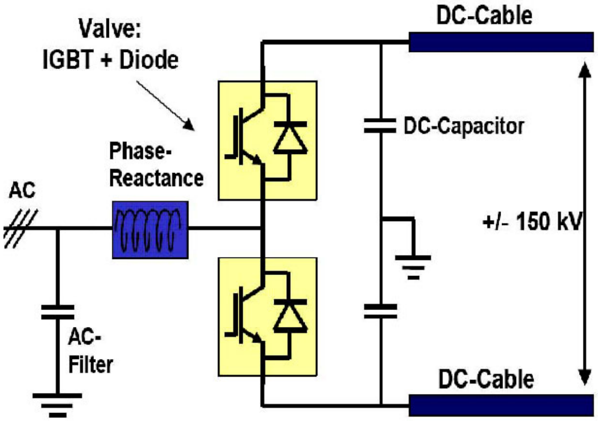


Figure 39. Operational principle of Voltage Source Converter, VSC High Voltage Direct Current, HVDC with a positive and a negative DC cables. Source: ABB.

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.

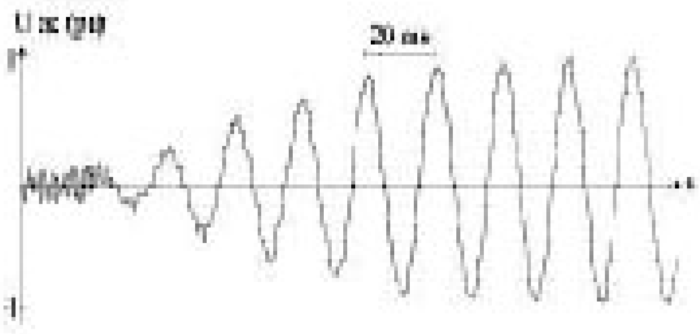


Figure 40. Grid AC voltage start-up of an isolated network at the Hällsjö project. Source: ABB.

LINE COMMUTATED CONVERTER, LCC

In the operation of a Commutated Converter (LCC) facility, current is transferred from one inductive phase to another based on the polarity of the applied voltage across each thyristor valve. The time it takes to transfer the current is called the commutation time.

Commutation requires a relatively stiff voltage source (i.e., one that does not significantly fluctuate in magnitude during a disturbance) in order to ensure the right polarities are applied across the valve. The commutation time is related to the overlap angle where current is building up in the incoming valve and going out in the outgoing valve. The overlap angle increases with increasing DC current and with decreasing AC voltage. If the AC commutation voltage source is not sufficiently stiff or stable, commutation may suffer during faults, periods of voltage distortion, or under-voltage events that affect the commutation voltage.

LATTICE VERSUS POLE STRUCTURES

The lowest footprint of HVDC can only be provided by underwater or underground transmission lines.

Lattice pole structures provide a better strength-to-weight ratio and are generally less expensive than tubular steel poles. Tubular steel poles average about 50,000 pounds for an average span of 1,200 feet while the lattice designs average around 35,000 pounds for an average span of 1,500 feet.

Both structures can be designed for a wide variety of soil and topology conditions; however, the tubular structures will be heavier in all cases. Monopole structures require much larger foundations in terms of depth and amount of concrete, than an equivalent lattice structure; however, the footprint taken up by lattice structures is larger than the footprint of monopole structures. Monopole structures have the potential of being installed much more quickly than lattice structures due to the additional labor requirements in "lacing up" the lattice structures.

When it comes to dead-end structures and heavy angle structures, lattice towers are more efficient and provide significant cost savings over using tubular steel structures. In the case of dead-end and heavy angle structures, it is possible that a design utilizing two tubular structures would be preferred over a single tubular structure to reduce cost and size.

The structure height will be determined by many factors, of which the primary factors are the span length and ground topology. Most structure heights are expected to be between 100 feet and 175 feet tall. River crossings and certain other situations may require taller towers.

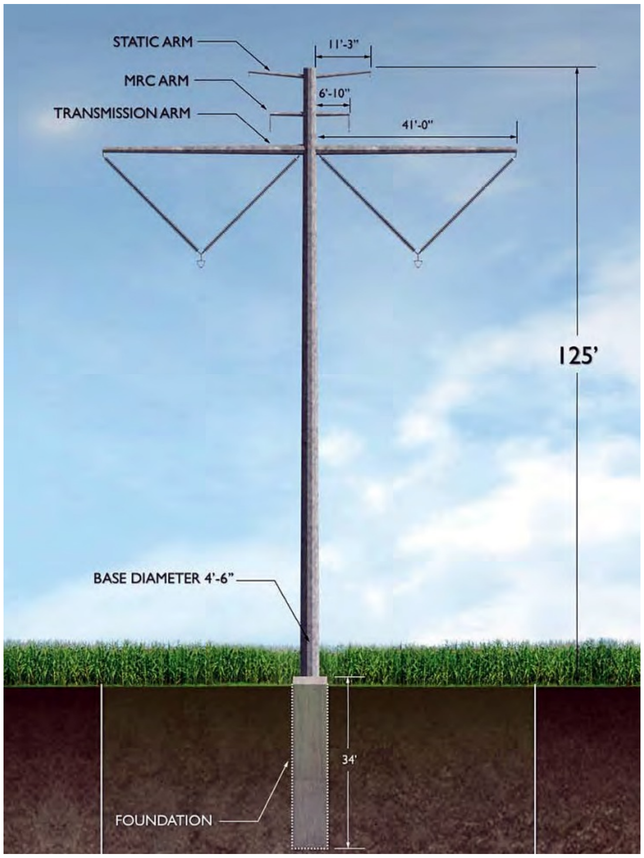


Figure 41. Typical overhead pole structure, 120-160 ft height and 4-7 structures per mile.

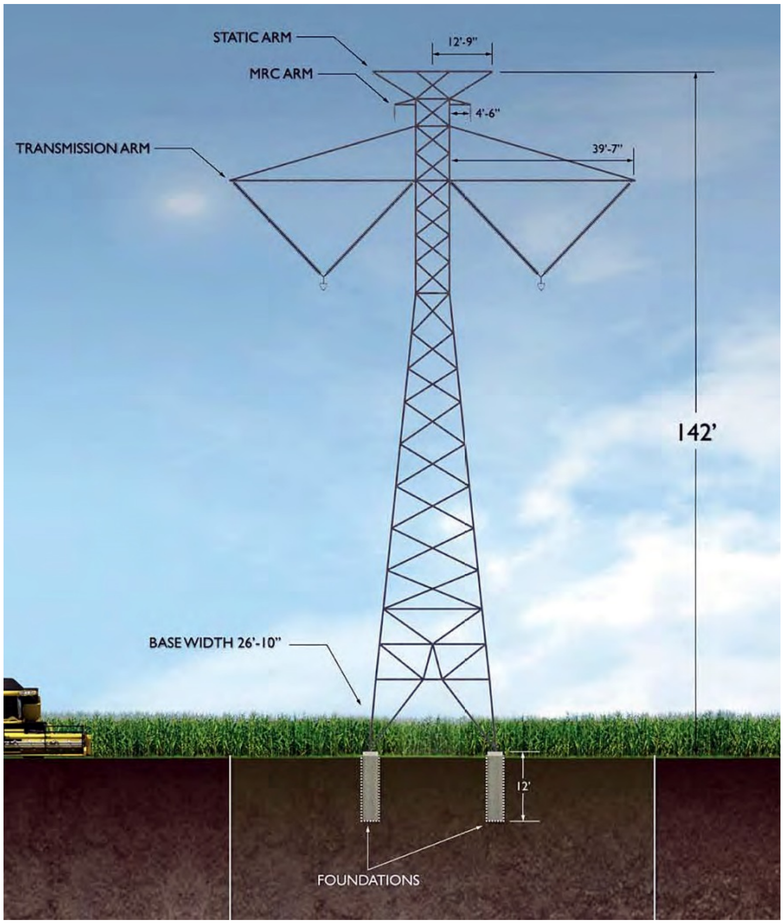


Figure 42. Typical overhead truss structure with a square base and four foundations, 142 ft height and 4-6 structures per mile.

ECONOMIC CONSIDERATIONS

In the economic analysis of power transmission lines several keys metrics are usually taken into consideration. These include:

1. Emissions Production (tons): The total volume of emissions produced by generation units for sulfur dioxide (SO_2), nitrogen oxides (NO_x), mercury (Hg), and carbon dioxide (CO_2).
2. Locational Marginal Price (LMP) in ($/MWhr): The incremental cost of energy averaged across all electrical load buses in a given state.
3. Demand Cost ($): The hourly electrical demand (MWhr) at each bus multiplied by the hourly Locational Marginal Price (LMP) in $/MWhr at that bus summed over all a state's buses for all hours. This represents the total cost to purchase energy to supply a total state's annual demand under Regional Transmission Organization (RTO) settlement rules.

4. Production Cost ($): The total variable cost of generation to supply energy to meet a state's annual demand including fuel costs, emission costs, variable operation and maintenance costs, and unit start-up costs.

OVERHEAD LINES HAZARDS, BLOWOUT

Developers of transmission lines are prohibited from negotiating for transmission line easement Right of Ways until the project complies with notice and hearing requirements prescribed by state law.

HVDC allows for the burial of the power cables underground avoiding the "blowout" hazard and requiring a smaller Right Of Way (ROW).

Overhead power lines are associated with hazards, particularly in the aftermath of storms. These hazards include:

1. Power outages, brownouts and blackouts,
2. Fire hazard from downed lines,
2. Electrocution hazard from downed lines,
3. Fallen limbs,
4. Obscured hazards from snowfall keeping downed lines from being visible.
5. Vulnerability to vandalism, sabotage and terrorism acts.

Two of the primary factors affecting ROW width include maintaining electrical safety clearances and providing access for construction and maintenance of the line. Of the two, maintaining electrical safety clearances is typically the controlling factor for overhead transmission lines.

Wind blowing on transmission line wires will cause them to move away from the center of and towards the side of the ROW. This movement is commonly referred to as "blowout" and can occur in any direction. Therefore, enough ROW width must be established to allow the predicted wire "blowout" movement on both sides of the ROW, while maintaining required electrical clearances from vegetation, structures, and other infrastructure.

The ROW width is typically controlled by the need to provide adequate room for wire "blowout" while maintaining required electrical clearances. The amount of predicted wire "blowout" increases as the span, or distance, between the supporting structures increases.

Figure 43. Downed overhead power lines in the open countryside cause widespread power failures in both rural and urban sites.

Figure 44. Downed overhead power lines constitute a fire hazard in addition to their electrocution hazard.

Figure 45. Burned neighborhoods from fires caused by Hurricane Sandy, October-November 2012.

Figure 46. Loss of power caused by Hurricane Sandy, October-November 2012.

Figure 47. Downed overhead power lines caused by ice and snow storms.

Figure 48. Repair crews from multiple states and utilities reportedly travelled from the West Coast to the East Coast of the USA to help restore the lost power from downed overhead power lines from Hurricane Sandy, October-November 2012.

Figure 49. Downed overhead power lines, Doraville, Georgia, February 12, 2014.

Figure 50. Running electrical emergency generator in power outage presents CO toxicity and electrocution hazards under wet conditions. Bowdoin, Maine, USA December 26, 2014.

Transmission companies try to aim for a substantial 150-275 feet of width for the ROW, as well as wider temporary easements during the construction stage. This allows for repowering or the addition of more lines or the future sale or lease of the ROW to other transmission companies into a "Power Corridor," which is an essentially industrial conversion project. The acreage acquired as a ROW is a valuable "asset" acquired by the transmission company for free on its books, as its acquisition cost is eventually covered by its rate payers. The acquired ROW assets, through financial engineering magic can then be "depreciated" generating virtual "cash flow." This makes the power transmission business a quite-profitable business for entities which can muster enough legal, financial and political clout.

Opponents of overhand power lines refer to the ROWs acquisition process as essentially a "Land Grab," process. In this situation, an underground line is preferable to an overhead line even though more costly initially, but more economical in the long term with reduced storm repair, lower operational losses and maintenance costs. It can be noticed that through political clout, affluent neighborhoods in both rural and urban settings benefit from underground power lines installations, whereas overhead power lines are reserved for the uniformed under-privileged neighborhoods subjecting their residents to frequent storm-related power failures and electrical electrocution and fire hazards caused by the collapsing overhead power lines.

OVERHEAD POWER LINES OPERATIONAL FAILURE

The Pacific Gas and Electric (PG&E) Company in California experienced a power outage on a remote line in northern California immediately before the Camp Fire that devastated northern California in November 2018 ignited. The utility company told the California Public Utilities Commission that it experienced an outage on the 115-kV Caribou-Palermo line in Butte County. According to the California Department of Forestry and Fire Protection (Cal Fire), the blaze started at 6:29 a.m. on Thursday, November 8, 2018 in a spot near that where the fault was reported. The Jarbo Gap had a wind gust to 51 mph due to the canyon effect associated with the Santa Anna Winds. The Jarbo Gap site is about 5.5 miles to the S-SW of the failure site, and located on a ridge. Winds were from the northeast there, with gusts around 50 mph for several hours before the power line failed. The accident location was within a canyon or gap, which was oriented to the northeast upstream from the accident site. The terrain features would have blocked the flow and thus the winds could have been substantially accelerated at the location of the failure. The lines were sparking a full day in advance of the fire.

In the Redding area fire, there were reports of a car with brakes that caught fire alongside the freeway. Fire creates its own wind and ounce it gets hot enough, becomes all but impossible to stop.

PG&E sent a plane to inspect the fault and noticed damage to a transmission tower on the affected line and noticed damage to a transmission tower on the affected line. The tower is about a mile from Pulga, one of several small towns in the region affected by the Camp Fire. That day, PG&E announced it would not turn off power in eight Northern California counties, as it had previously warned it might do in response to dangerous weather conditions. In October 2018, PG&E cut off power to 60,000 customers in 12 counties as a preventive measure.

The utility has historically resisted such measures, saying power cutoffs pose other risks for residents and first responders, such as shutting down hospitals and fire stations. But in December 2017 it began considering adopting shut-offs as part of its wildfire response, and in March 2018, it made switching off power lines part of a formal plan.

The Camp fire was the most destructive in state history, and has destroyed more than six thousand homes and other buildings, killed 42 people and spread to more than 90,000 acres. The company already faces billions in potential liability in connection with previous wildfires in the state. The question of PG&E's liability has hung over the company since devastating fires broke out in 2017 in the Wine Country and other parts of Northern California served by the utility.

State investigators previously said PG&E equipment flaws led to at least 16 fires in Northern California. Investigators said the company violated state safety laws in 11 of the fires. The cause of the Tubbs Fire, which ravaged Santa Rosa and was the state's most destructive fire in history. PG&E plans to invest $6 billion to install 1,300 weather stations and 600 cameras over four years in response to wildfires.

The utility company has been criticized in the past year by residents and state officials after a bevy of wildfires tied to downed power lines swept through the state in October 2017. Investigative reports in May and June from the California Department of Forestry and Fire Protection linked PG&E to 16 fires in 2017 that killed 18 people and destroyed thousands of homes and other buildings.

The PG&E service area covers much of Northern and Central California, and includes 18,000 miles of power lines. It spends up to $70 million per year to clear vegetation near those lines. In three cases, Cal Fire contends PG&E violated state codes by failing to get rid of trees and vegetation near the power lines. The utility has been increasing its efforts: "in response to the increased risk of fire danger brought on by climate change and drought, we are doing more to ensure PG&E facilities are safe and reliable." PG&E paradoxically also has come under fire for cutting down trees near power lines as a safety precaution.

Figure 51. California fires caused by power lines failures in high wind, 2018.

Investigators at the Ventura County Fire Department determined that Southern California Edison power lines ignited the 2017 Thomas fire, a massive blaze in Ventura and Santa Barbara counties that killed two people and later gave rise to a massive mud flow that resulted in at least 20 deaths. Following a 13-month probe by the California Department of Forestry and Fire Protection and Ventura County Fire Department investigators, officials found the fire was started by two power lines that slapped together creating an electrical arc during high winds on the evening of December 4, 2017. The electrical arc deposited hot, burning or molten material onto the ground, in a receptive fuel bed, causing the fire. The common term for this situation is called 'line slap,' and the power line in question is owned by Southern California Edison.

In October 2018, the utility said its electrical equipment likely sparked at least one starting point in the massive fire, which burned 281,893 acres. The loss of vegetation in that area ultimately resulted in the collapse of hillsides north of Montecito during heavy rains on January 9, 2018.

The finding puts the utility on the hook for not only more than $1.3 billion in insurance claims filed by Thomas fire victims, but also for the $400 million in claims filed after the Montecito slides.

In the report released Wednesday on March 13. 2019, investigators said the Thomas fire first began as two separate fires that joined together and burned for 40 days. They determined the utility was responsible for both ignitions. Southern California Edison officials have said they will work with insurance companies to handle the thousands of claims that have accumulated since the fire and mudslide. The company is protected from going bankrupt over the disasters, thanks to a law signed during the summer of 2018 that passes excess liability costs on to utility customers.

High winds would tend to be channeled and strengthened in a Canyon downing the overhead powerlines. One would not think that such winds would take down big high-tension power lines. These could be placed underground in association with HVDC instead of HVAC transmission, at least in sensitive locations.

EXPERIENCE WITH HVDC

GLOBAL EXPERIENCE

HVDC technology has been used and proven for several decades. In North America, there are over 30 HVDC installations, dating back as far as 1968. Of the 30 plus projects, there are 11 HVDC lines in North America that have a combined capacity of approximately 14 GW. The remaining HVDC projects are back-to-back HVDC converters, which function in the same way as an HVDC line but have no overhead or underground line to connect the rectifier and inverter; rather, they are connected directly to each other within the same substation via a DC bus.

Globally, HVDC applications are commonplace and are continuing to increase in applications In India and China, there have been over 16 significant applications of the technology since the early 1990s. In China, there are 11 operating projects with more than 35 GW of capacity, with plans to add an additional 33 projects totaling more than 217 GW of capacity.

India has over 10 GW currently operational and over 6 GW in the planning stage. Australia, New Zealand, Brazil, Japan and Europe have each installed large modern HVDC transmission projects since the late 1960s.

Europe, in particular, has plans for multiple HVDC projects underway to support major off-shore wind applications in the North Sea and the Baltic Sea, as well as around the United Kingdom.

EXAMPLES OF HIGH VOLTAGE DC AND AC TRANSMISSION PLANNED PROJECTS

ILLINOIS RIVER PROJECT

A project is proposed by Ameren Transmission Company (ATXI) to construct a new 345 kilovolt transmission line, called "The Illinois Rivers Project," that will interconnect Missouri, Illinois and Indiana. The project will be routed from a substation near Palmyra, Missouri, across the Mississippi River to Quincy, Illinois, and continue east across Illinois to Meredosia, Pawnee, Pana, Mt. Zion and Kansas across the border to Sugar Creek, Indiana.

As a spinoff from its parent electrical utility Ameren, ATXI proposes the transmission project for wind power resources, as well as clean-coal electricity from the FutureGen-2 international consortium from a unit out of the four mothballed units of the Meredosia coal power plant seeking a Federal Government shovel-ready $1.65 billion project for Carbon Sequestration and Storage (CCS) around the cities of Springfield and Decatur areas in Morgan County, Illinois.

With a modest inventory of 28 miles of transmission lines ATXI, whose parent company has withdrawn from the FutureGen 2.0 project and sought to sell its share of the Meredosia plant, plans to expand its current assets through the acquisition of 375 miles of Right Of Ways (ROWs) to use 345 kV lines. These are reported to be less costly on a dollar / mile basis than the 765 kV AC or +- 600 kV DC lines that are suggested by the USA Department of Energy DOE for wind power transmission. It is reported that the effort may be meant to "pre-empt" the projects of other competing transmission companies, and that the lines and/or rights-of-way may eventually be repowered and expanded to accommodate a capacity closer to that of 765 kV AC or +- 500 or 600 kV DC lines that are commonly used for wind power transmission. The newly acquired lines would be connected to its parent company Ameren's much larger transmission line inventory.

According to the filings with the Illinois Commerce Commission, the acquisition of these ROWs would be considered as assets to the company, to be later charged to the rate payers. The company then plans to depreciate these newly acquired assets to generate sufficient cash flow to obtain a credit rating that it does yet possess for lack of sufficient assets, from the credit rating agencies.

ROCK ISLAND CLEAN LINE LLC PROJECT

The Clean Line Company from Houston, Texas, has been developing the Rock Island Project transmission project, the Plains and Eastern Clean Line transmission project, the Centennial West Clean Line transmission project and the Grain Belt Express Clean Line transmission project.

The Rock Island project was meant to dispatch wind power resources from Iowa to Indiana across Illinois, with two primary converter stations. The "windward" western one would be located in O'Brien County, Iowa and the eastern one in Grundy County, Illinois across about 500 miles in Illinois at +/- 600 kV. No intermediate converter stations were planned along the HVDC transmission line through Illinois, since the project aims at essentially benefiting wind power production in Iowa; even though its power lines pass through Illinois from Iowa to Indiana.

The Rock Island Clean Line LLC Project includes a DC-to-AC converter station, a single circuit 345 kV AC line and a parallel double circuit 345 kV AC line, and a transformation facilities site adjacent or near to the Collins substation.

OTHER TRANSMISSION LINE PROJECTS

The Plains and Eastern Clean Line transmission project would have brought electricity from wind generation sources in western Oklahoma, western Kansas, and the northern panhandle of Texas, to the Tennessee Valley Authority, Arkansas, and the southeastern USA.

The Centennial West Clean Line transmission project would have brought wind and solar resources from eastern New Mexico and Arizona to the Los Angeles Basin in California.

The Grain Belt Express Clean Line transmission project would bring electricity from wind generation sources in western Kansas to load centers in eastern Missouri, the Midwest Independent System Operator (MISO) region of Illinois, the Pennsylvania-New Jersey-Maryland (PJM) market in southwestern Indiana and points farther east.

All of these projects, and others, have the similar rationale of connecting the country's strongest wind and solar renewable resources to load centers via long-distance HVDC and HVAC transmission facilities.

DISCUSSION: ADVANTAGES OF HVDC OVER HVAC TECHNOLOGY

High Voltage Direct Current (HVDC) is a more efficient technology for the long-haul transmission of large amounts of electric power because substantially more power can be transmitted with lower losses, narrower right-of-way, and fewer conductors than with an equivalent High Voltage Alternating Current (HVAC) system.

In general, over long distances, Extra High Voltage (EHV) AC transmission lines require intermediate switching or substations approximately every 200 miles in order to segment the line to handle issues attendant with voltage support, transient over- voltages, and transient recovery voltages. Additionally, EHV AC lines used for long-haul applications exhibit angular and voltage stability limitations, have a higher requirement of reactive power dependent upon loading, and have higher charging currents at light load.

It takes more lines, and thus more right-of-way to move large amounts of power over a long distance with AC than it does with DC. It is solidly established that at distances beyond about 300 miles, HVDC is the most efficient means to move power via overhead lines; however, this can vary depending on a number of factors.

It is noted that HVDC and HVAC facilities can be made complementary when considering the integration of large amounts of renewable power into the electric transmission grid. However, it is unequivocally established that the use of HVDC technology has a number of distinct benefits over HVAC:

1. High Voltage Direct Current (HVDC) lines can be placed underground in high-density-populated and agricultural farming areas and underwater for offshore applications, minimizing their environmental impact. For underground applications it is observed that heat generation leads to a faster drying of the land directly above the buried lines.
2. High Voltage Direct Current (HVDC) lines can economically transfer significantly more power with lower line losses over longer distances than comparable AC lines.
3. High Voltage Direct Current (HVDC) lines complement AC networks without contribution to short circuit current power or additional reactive power requirements.
4. High Voltage Direct Current (HVDC) lines can dampen power oscillations in an AC grid through fast modulation of the AC-to-DC converter stations and thus improve system stability and reliability.
5. High Voltage Direct Current (HVDC) technology gives the operators direct control of energy flows, which makes HVDC particularly well-suited to managing the injection of variable wind generation.
6. High Voltage Direct Current (HVDC) lines, unlike AC lines, will not become overloaded by unrelated outages, because the amount of power delivered is strictly limited by the DC converters at each end of the HVDC line, thereby reducing the likelihood that outages will propagate from one region to another.
7. High Voltage Direct Current (HVDC) lines utilize narrower rights-of-ways and fewer conductors than comparable AC lines, thereby making more efficient use of power transmission corridors and minimizing visual and land use impacts.

APPENDIX I

Thyristor

A thyristor is a semiconductor component that is unidirectional like a diode, but is switched like a transistor. It is widely used to control high currents and voltages in motors, lighting, heating and power applications. Once turned on at the gate, it allows current to flow until it falls below a certain threshold. In an AC circuit, it stops conducting each time the wave crosses over zero and can rectify AC to DC.

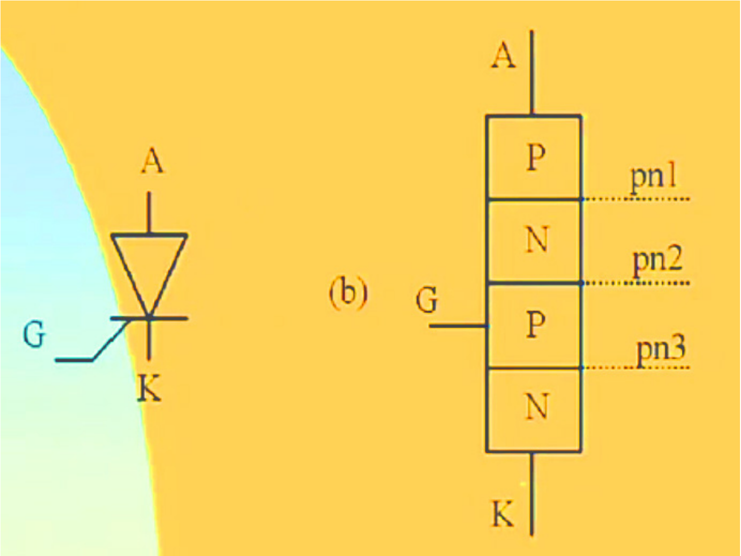


Figure I. Thyristor as a four layer device composed of PN junctions with an anode (A), cathode (K) and a gate (G) [14].

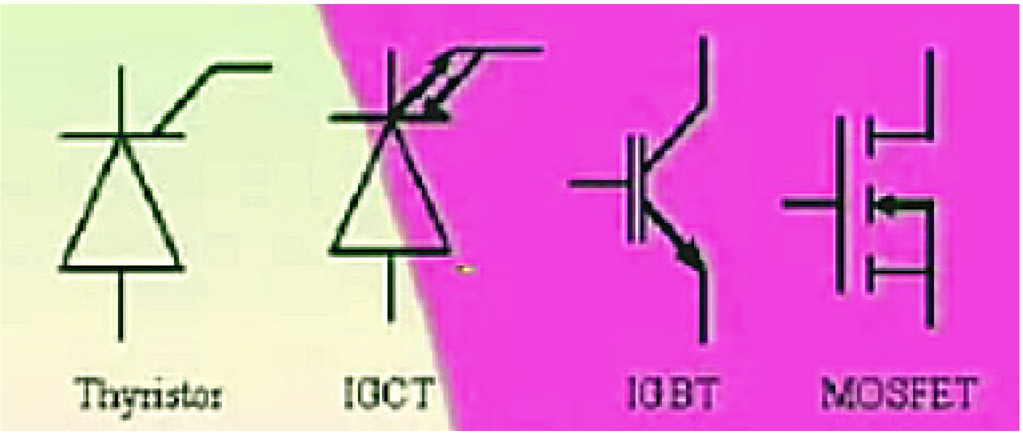


Figure II. Semiconductor diode (Thyristor, IGCT)) and transistor (IGBT, MOSFET) power switching devices [14].

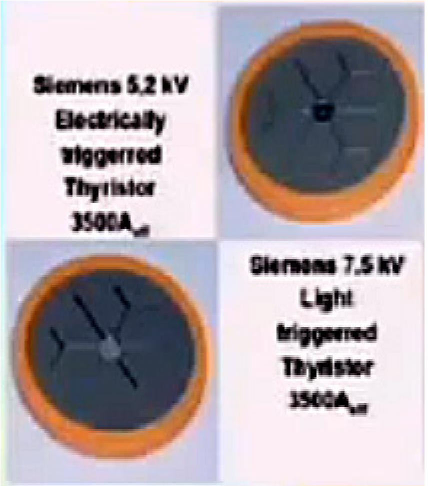


Figure III. Electrical and light triggered thyristors. Source: Siemens.

IGBT, Insulated-Gate Bipolar Transistor

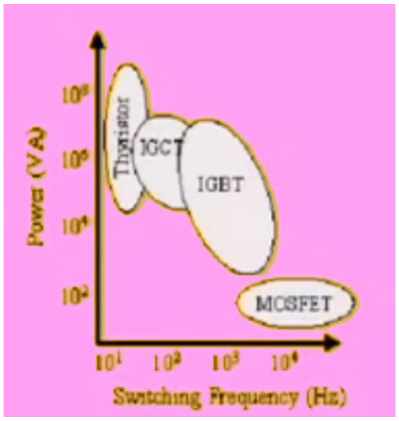


Figure IV. Power and frequency ranges of switching devices [14].

The IGBT (Insulated-Gate Bipolar Transistor) is a three-terminal power semiconductor device primarily used as an electronic switch. It is noted for combining high efficiency and fast switching and is used in the application of inverters to industrial equipment. IGBT modules have evolved from a traditional flat planar chip structure towards a trench gate structure.

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