Direct current for long-distance transmission

In the past, electrical energy was transmitted across great distances using high-voltage alternating current or three-phase current. Historically, the reason for this was the ability to transform the alternating current as needed to the required voltage in each case. It was stepped up to high voltage for transport and then stepped back down to lower voltage on site for regional or local distribution. Most notably, Tesla and Westinghouse in the United States and Oskar von Miller in Germany recognized this advantage of alternating current, which made electrification of the world possible in the first place. However, the situation is now beginning to change because, upon closer examination, transporting energy via alternating current also has some disadvantages. Today, high-voltage direct-current transmission (HVDCT) is increasingly used to transport large volumes of electricity over long distances with lower losses. HVDCT is also used for back-to-back links, (i.e., for connecting asynchronous grids), because if multiple alternating-current power sources are interconnected, the frequency and phase angle must be perfectly synchronous.

Long-distance transmission of alternating current results in greater losses!

Due to ohmic resistance, losses occur in all power supply grids, whether AC (alternating current) or DC (direct current). In AC power supply grids, other losses occur in addition to these ohmic losses. The relatively large losses with AC compared with DC result from three different phenomena specific to alternating current: **capacitive resistance**, **inductive resistance**, and the **skin effect.**

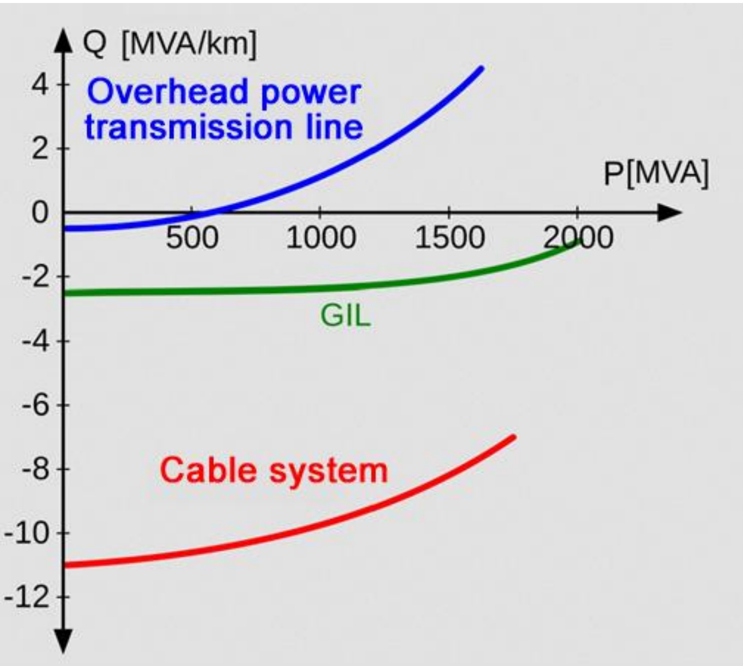


Fig. 1: Reactive-power demand Q 89n MVA/km of a 380 kV AC power line as a function of the transmitted power.

Graphic from wdwd – own work, diagram based on data set from: “380 kV Salzburg line, assessment by B. R. Oswald, Institute of Electric Power Systems and High-Voltage Engineering at the University of Hannover, 12/27/2007” (license: CC BY-SA 3.0), edited by Siemens Stiftung

Capacitive loss is caused by the constant switching of the current direction, which happens 50 times per second in the local power supply grid. This has an effect similar to charging and discharging a capacitor (of a capacitance), for which additional charging currents (called reactive currents) are needed. The resulting effect is as if an additional capacitive resistance occurs. In other words, a portion of the power output is moved back and forth in the grid as **“reactive power**” (“reactive” = cannot be used).

Not only can this “reactive” power not be used, and it does “clog” the line, so to speak, it is also subject to ohmic losses. This capacitive effect is particularly relevant to buried and submarine cables. Due to the dielectric properties of water and soil, which vary widely from those of air, these cables have a greater capacitance effect and thus cause higher losses.

Inductive loss is caused because a certain portion of the power supply grid (the line itself or particular consumers) acts as a coil. As a result, additional currents flow in order to generate and reverse magnetic fields in these coils. This also leads to unusable reactive current that is subject to ohmic losses.

The third source of loss is **the skin effect**. Due to the laws of physics, alternating current does not use the full cross section of the cable. AC generates eddy currents in the cable that generate magnetic fields inside the cable, and these magnetic fields slow down the current flow. The reduced effective cross section of the cable brought about by the skin effect depends on the frequency of the current. A cable for alternating current thus has higher resistance than a cable for direct current with the same cross section.

In high-voltage alternating-current grids, transmission losses of approximately 6 percent to 10 percent are calculated per 1,000 km. In high-voltage direct-current grids, which are subject only to ohmic losses, the losses are calculated at approximately 4 percent per 1,000 km.

How does high-voltage direct-current transmission (HVDCT) work?

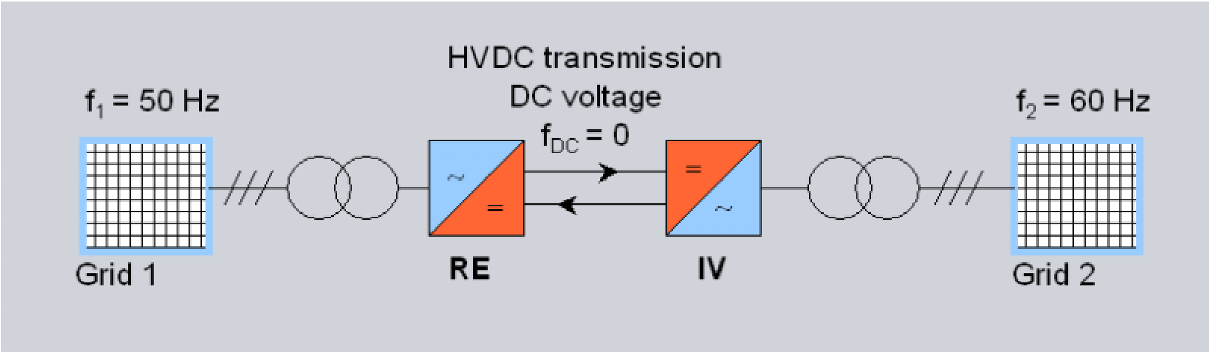


Fig. 2: HVDCT block diagram; RE: rectifier, IV: inverter

For HVDCT, the power generated by the power plant (maximum 60 kV) is first stepped up to 800 kV, for example. It is then converted to direct current voltage with a rectifier (for example, a thyristor). This direct current of 800 kV is then transmitted over distances of 1,000 or more kilometers with relatively low losses. At the destination, the direct current is converted back to alternating current with a power inverter (thyristor) and fed into the AC grid. The frequency and phase angle are adapted precisely to the AC grid.

HVDCT also used for synchronized linking of power supply grids

This HVDCT technology is also advantageous when different electric power sources or power supply grids are linked. The alternating current recovered from the direct current can be easily fed into the grid with the frequency and phase synchronized, thanks to the exact electronic control of the conversion process.

This became apparent, for example, during the big blackout in North America in 2003 when the Quebec supply system remained intact thanks to this protection function of its HVDCT links, while Ontario, which is connected synchronously to the United States, bore the full brunt of the blackout.

A blackout like the one in Europe on 11/4/2006 that affected consumers from East Frisia in northern Germany to Morocco could also be reliably prevented in the future by building Europe-wide HVDCT backbones (main connection lines).

Meanwhile, HVDCT technology is also used for synchronous infeed of wind power into the grid. Due to the strongly fluctuating wind speeds, the effort to control the speed of the wind turbine generators was extremely high. (The frequency of alternating current supplied from a three-phase generator depends on the rotational speed. For exactly 50 Hz, it would have to be held constant at 3,000 rpm with a two-pole generator.) Today, the alternating currents with relatively low voltage and fluctuating frequency generated by wind turbines is first stepped up and rectified, inverted, and then fed into the grid with the frequency and phase synchronized. Offshore wind farms are now also linked with the onshore power grid via HVDCT.

When is HVDC transmission worthwhile?

An HVDCT system is economically viable for overhead power transmission lines with a length of 600 km or more and a power capacity of about 1,000 MW. This break-even point is derived from the following parameters of the different transmission technologies:

- HVDCT technology: low transmission losses, low line costs but high basic costs for the power converter system.
- Alternating current (AC) technology: higher transmission losses, higher line costs, but low basic costs at the beginning and end of the transmission line.

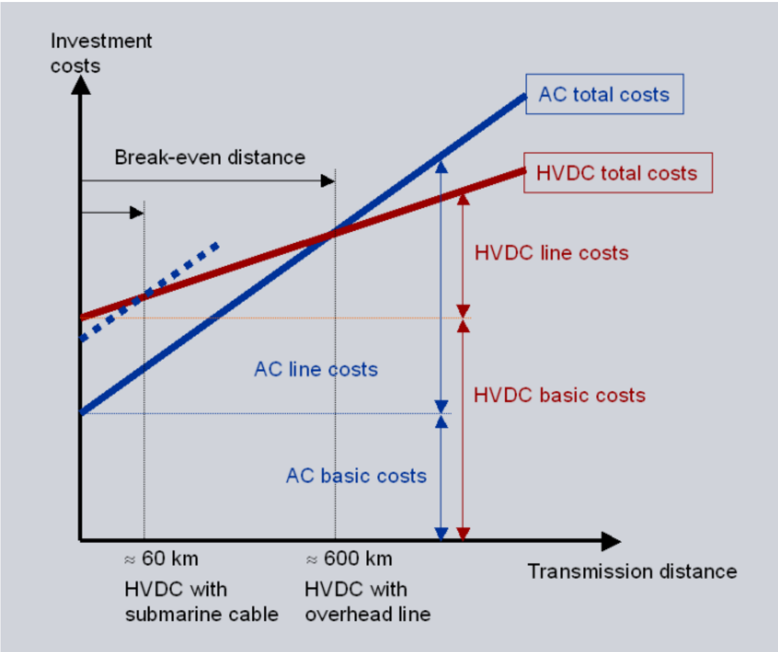


Fig. 3: Cost/break-even distance

When large amounts of power need to be transported via submarine cable, for example from an offshore wind farm, then the break-even point is as low as 50 to 70 km. For this it is sufficient to use a single-conductor cable if the earth or seawater is incorporated in the circuit as the return conductor.

For reasons of environmental compatibility (fish migration, etc.), however, return conduction underground or through the sea is generally avoided in new submarine cable projects by using at least two cables.

Fewer lines, smaller right-of-way width, and weaker stray fields thanks to HVDCT

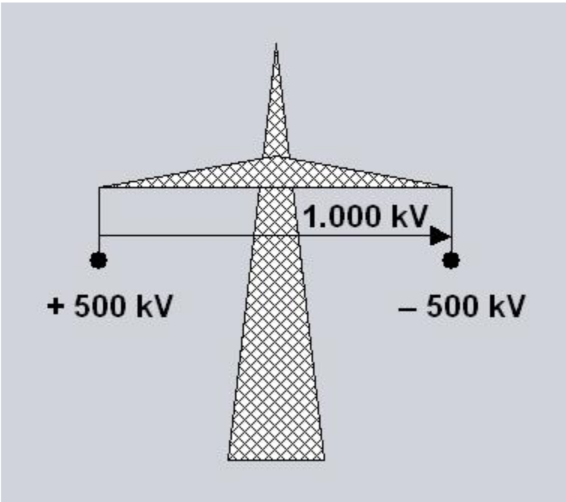


Fig. 4: Bipolar power transmission with direct current voltage

Another advantage of HVDCT technologies is the lower number of required lines.

At least three lines are necessary for three-phase power systems. In practice, two redundant systems with three lines each are often operated in parallel. With alternating voltage, the distribution of each phase on multiple lines reduces the skin effect and decreases the corona discharges. (A corona discharge is an unwanted electrical discharge in a nonconductive medium, for example, in air.)

In contrast, only two lines are necessary for HVDCT. The space requirement and thus the costs are reduced considerably, especially compared with overhead power transmission lines with masts and cross arms.

Even in the case of underground and submarine cables, with a comparatively low space requirement, the lower number of required HVDCT lines pays off. In addition, due to the relatively high capacitance coefficient with three-phase power technology, underground and submarine cables are used only for routes of maximum 50 km.

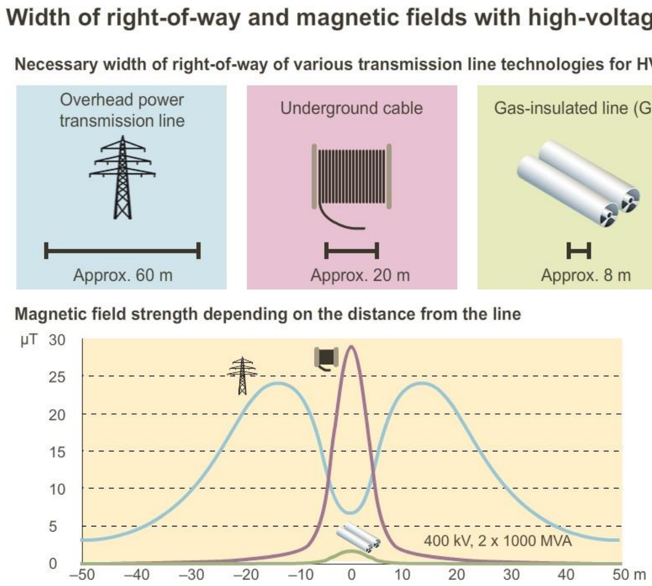


Fig. 5: Bipolar power transmission with direct current voltage

If only the costs are considered, the overhead power transmission line is the best solution.
However, land usage, the blight on the landscape, and the exposure of the population to electrical and magnetic fields are important criteria for planning major long-distance transmission routes.

In view of these aspects, HVDCT technology using underground cables is probably the best compromise.

The electronics behind HVDCT

The first commercial direct-current transmission project – when rectifiers and power inverters based on mercury vapor were still used – was implemented in 1951 on the Kashira–Moscow route in Russia (100 kV, 100 km overhead power transmission line, 30 MW), using the German Elbe/Berlin plant of the Elektrowerke AG, dismantled after the war ended. The world's first large-scale HVDCT project using rectifiers and power inverters based on silicon (thyristors) was the transport of electric power from the Cahora Bassa hydroelectric plant in Mozambique across 1,414 km to Johannesburg in South Africa at 533 kV transmission voltage and with a power capacity of 1,920 MW.

Thyristors convert alternating current into direct current and vice versa

A rectifying valve allows only those portions of the alternating current that have the right polarity to pass through. The design of a thyristor corresponds essentially to that of a diode. In the nonconducting direction, no current at all is allowed to pass. In the forward direction, the thyristor can be switched to the conductive state via control voltage at the gate. The advantage of this is that the thyristor combines the functions of rectifier and high-power switch in one component.
In order to improve the controllability of thyristor technology, the functionality of power electronics components has been further developed so that today there are highly advanced components available for use in HVDCT systems.

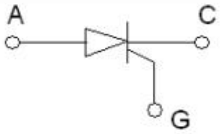
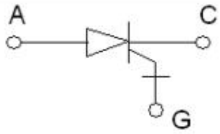
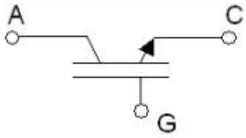
Valve type	Thyristor	IGCT	IGBT
Circuit symbol			
	A = Anode; C = Cathode; G = Gate		
Control	On: Current pulse to G Off: Zero current between A and C	On/Off through current pulse to G	Controlled by variable voltage at G – C

Fig. 6: Comparison of power electronics components

Thyristors that can be triggered electrically (special development for 6-inch thyristors for large-scale projects in China with up to 4.5 kA rated current and HVDC transmission power capacities up to 7,200 MW at ±800 kV) as well as thyristors that can be fired via laser light up to a wafer size of five inches (4 kA rated current) are used.
The specific feature of the thyristors fired by laser light is a special wafer-integrated overvoltage protection circuit that guarantees maximum reliability in operation.
The latest developments in HVDCT are IGBT (insulated gate bipolar transistor) modules. These modules are self-commutated, that is, even when there is no system voltage present, they can generate an “electronic” system voltage from the DC in fine stages “synthetically” and practically free of harmonics.
This blackstart capability enables collapsed grids to be completely restarted with the aid of the other still “healthy” grid without any assistance from power plants or generators. The application range of this modern MMC technology currently extends to about 1,000 MW; in other words, it is suitable for medium power capacities both for underground lines and overhead power transmission lines.

The advantages of HVDC transmission at a glance

HVDC transmission is technically considerably more demanding than conventional alternating-current high-voltage transmission, but it has some key advantages:

- It is the only cost-effective way of transporting large amounts of power over long distances. All reactive power losses of inductive or capacitive nature due to alternating current and the skin effect are eliminated. HVDCT is economically viable for distances upwards of 600 km. In the case of submarine cables, HVDCT is competitive for distances of 50 to 70 km or more, and for long submarine cables there is no alternative to it.
- The line costs for an HVDCT link are lower than with conventional long-distance AC lines because only two conductors need to be provided. The power line masts can therefore be of considerably narrower construction.
- The HVDCT system is the only option for linking technically incompatible grids with different control processes or grid frequencies. This is an import decision-making criterion in many countries such as China or India, where there are generally a number of regional grids that are incompatible. The ability to regulate power rapidly in an HVDCT system helps stabilize existing three-phase systems that it connects or is routed parallel to.
- HVDCT is therefore particularly suitable for use as a stabilizing, highly economical “energy highway” for transporting large volumes of electrical energy. This is the case in Germany, for example, with the three planned north-south expansion lines that are designed to uniformly distribute wind power in Germany.