

# factsheet

## High Voltage Direct Current Electricity – technical information

### Introduction

High voltage direct current (HVDC) technology is one of the technical options National Grid can consider for the future development of the transmission system in Great Britain.

Although HVDC has some disadvantages, as its integration within an AC system has to be carefully considered and its cost can be higher than the equivalent AC solution, the advantages of HVDC transmission are principally the following:

- the ability to interconnect networks that are asynchronous or that operate at different frequencies
- the ability to transmit power over long distances without technical limitations
- the ability to control power flows on the HVDC connection for all system backgrounds
- the ability to transmit power in either direction as desired by the network operator
- in certain cases the ability to improve AC system stability.

This document provides a technical overview of HVDC technology and the situations in which it is applied as an alternative to alternating current (AC) transmission. It describes the various types of HVDC technology and the components that make up a HVDC connection. It also considers operation and maintenance issues and the costs associated with HVDC transmission.

*Electric power is normally generated, transmitted and distributed as alternating current (AC).*



National Grid owns the high voltage electricity transmission system in England and Wales and operates the system throughout Great Britain at 275,000 and 400,000 volts (275kV and 400kV). The National Grid system is made up of approximately 7,200 kilometres (4,470 miles) of overhead line, 1,400 kilometres (870 miles) of underground cable and around 330 substations.

National Grid has a statutory obligation under the Electricity Act 1989 to develop and maintain an efficient, coordinated and economical system of electricity transmission, and to facilitate competition in the supply and generation of electricity. National Grid also has a statutory obligation to have regard to the preservation of amenity in developing the transmission system.

Electric power is normally generated, transmitted and distributed as alternating current (AC). AC power is well suited to efficient transmission and distribution, as the voltage can be increased or reduced by transformers. HVDC transmission of electricity offers some advantages over conventional AC transmission that leads to its selection in particular applications.

A typical application of HVDC is to transmit power between two independent AC networks that are not synchronised. Examples of this are the 2,000MW England–France interconnector linking the British and French transmission systems and the 1,000MW BritNed interconnector between Britain and The Netherlands.

Unlike AC, there is no technical limit on the length of cable or overhead line that can be used in HVDC connections, so HVDC has advantages for long transmission distances.

### HVDC – how it works

A typical HVDC system is shown in simplified form in Figure 1. A converter at the sending terminal acts as a rectifier and converts the AC power into DC.

A converter at the receiving terminal acts as an inverter and converts the DC power into AC. The connection between the converters may be by overhead line, cable, or both.

Power electronic valves (essentially high powered, electronic switches) within the converters allow the power flow to be controlled. The HVDC system is usually designed so that the converter at either terminal can be operated as either a rectifier or inverter and so the direction of the power flow can be reversed as required.

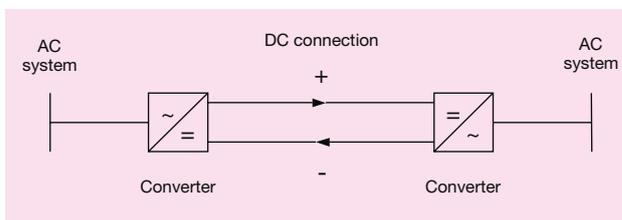


Figure 1: HVDC system

Two main converter technologies have been developed, current source converter (CSC) and voltage source converter (VSC).

## HVDC converter technologies

### Current source converters

Current source converters have been in commercial use since the 1950s. Most HVDC systems now in service are of the CSC type and the technology is well established. A typical current source converter (CSC) electrical diagram is shown below in Figure 2.

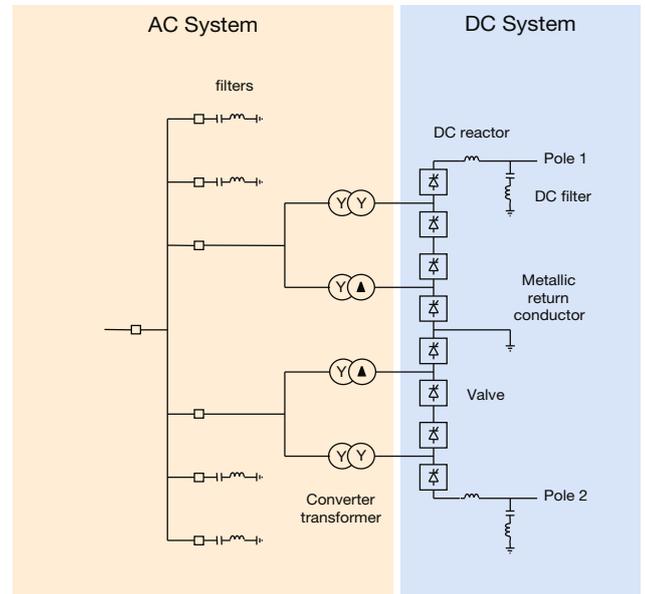


Figure 2: Example current source converter (CSC)

As a consequence of the AC-DC conversion technique utilised in CSC technology, the converter absorbs reactive power from the surrounding AC network and generates harmonic currents, both of which impact on the quality of electrical power. AC harmonic filters and reactive compensation must therefore be provided to maintain the quality of the electrical power. A further consequence is that the converter is dependent on the AC system voltage for its correct operation.

The current flow in the DC circuit is unidirectional. In order to reverse the power flow on a CSC HVDC connection, it is necessary to reverse the polarity of the DC voltage. This is performed by the DC converter control system.

AC harmonic filters are used both to limit AC harmonic currents and to compensate the reactive power absorption of the converter. The filters are switched in and out automatically as required to meet harmonic and reactive power performance limits.

*Unlike AC, there is no technical limit on the length of cable or overhead line that can be used in HVDC connections, so HVDC has advantages for long transmission distances.*

On the DC side of the converter, a reactor is provided to smooth the DC current. The reactor also reduces the peak current in the event of a fault on the DC connection. DC filters may also be required to reduce harmonic voltages on the DC circuit, particularly when the circuit includes overhead lines.

CSC HVDC systems are suitable for operation at high voltages and power transfers. A 6,400MW connection between Xiangjiaba and Shanghai in China, operating at +/- 800kV, went into service in 2010. This connection is made via DC overhead lines which are capable of carrying these high voltage DC currents. Power capabilities via DC cables are presently still limited to lower voltages and power transfer capabilities.

### Voltage source converters

Voltage source converters (VSC) have been used in HVDC transmission systems since 1997. Comparatively few VSC HVDC systems are in service and the technology is still developing in terms of rating and capability. A typical voltage source converter is shown in Figure 3.

VSC converters use insulated gate bipolar transistor (IGBT) valves. The device is self commutating, meaning that the converter is not dependent on the AC system voltage for its correct operation.

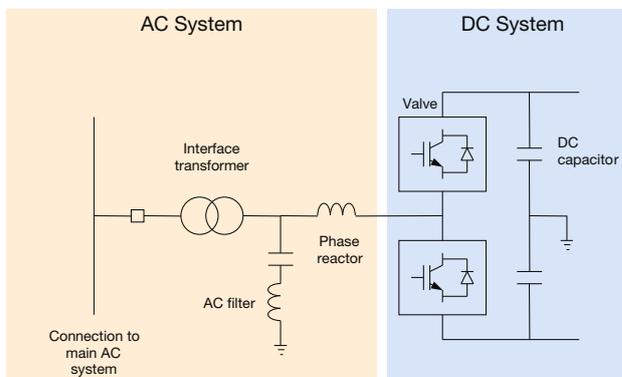


Figure 3: Example voltage source converter (VSC)

The VSC HVDC systems in service so far have been limited to lower voltages and power ratings than CSC systems. The 500MW East-West interconnector between Ireland and Great Britain, operating at +/- 200kV, represented the highest power rating for a VSC HVDC system when it went into service in 2012.

### Comparison of CSC and VSC

The features of current source and voltage source converters are compared in Table 1.

	Current source converter	Voltage source converter
Maturity of technology	Mature	Developing
Valves	Thyristor, dependent on AC system voltage for commutation	IGBT, self commutating
Commutation failure	Can occur	Does not occur
Minimum DC power	Typically 5–10% of rated power	No minimum value
Reactive power exchange with AC system	50% of active power transmitted	Independent control of active and reactive power
Reactive compensation	Required	Not required
AC harmonic filters	Switchable filters required	Less filtering required, filters need not be switchable
Converter transformers	Special design required	Conventional transformers can be used
Reversal of power flow	DC voltage polarity reversal required	Controllable in both directions, no reversal of DC voltage polarity required
Converter station footprint (relative size)	200m x 120m x 22m (100%)	120m x 60m x 22m (~40%)
Conversion losses (per converter end)	0.7% to 0.8% of transmitted power	1% of transmitted power
DC voltage	Up to 800kV available	Up to 350kV available

Table 1: Comparison between current source converter and voltage source converter technology

## HVDC transmission technologies

### Cable types

There are two main types of cable technology suitable for use in HVDC applications, crosslinked polyethylene (XLPE) and mass impregnated (MI) insulation (see Figures 4 and 5). All cables consist of a copper or aluminium conductor surrounded by a layer of insulation (the thickness of which is dependent upon the operational voltage), a metallic sheath to protect the cable and prevent moisture ingress and a plastic outer coating. An additional requirement for cables intended for subsea use is steel armouring, which consists of steel wires helically wound around the cable, increasing the cable's strength and protecting it from the rigours of subsea installation.



Figure 4: MI cable Figure 5: XLPE cable.

Source: Prysmian Cables & Systems Ltd

XLPE insulation is made by extruding the polymer over the cable core, and is the technology now generally used for AC transmission cables. XLPE cables are available for HVDC voltages up to 320kV, this could however increase in the future due to advancements in technology. XLPE cables are unsuitable for use in CSC applications where, in order to reverse the direction of power flow, the polarity must be reversed.

MI insulation is made by winding kraft paper around the conductor until the required insulation thickness is achieved. The cable is then placed in a vacuum chamber and heated to remove any air and moisture. A viscous oil is introduced which impregnates the paper, increasing the electrical strength of the insulation. A recent development uses polypropylene laminated papers, where thin layers of plastic are laminated to the paper layers, allowing the cable to operate at higher temperatures and therefore higher current ratings. HVDC, MI cables are presently available for voltages up to 600kV.

### Cable installations

Generally, at least two cables are required for HVDC underground/subsea transmission, unless an earth/sea electrode is to be used at the converter stations, although it should be recognised there can be environmental issues with such a solution.

In a monopolar scheme, these will consist of a heavily insulated HV cable and a lightly insulated return cable; whereas in bipolar designs both cables operate at high voltages and require heavy insulation.

Because of the reduced power capacity of cables when compared to overhead lines, between four and six cables are required to match the capacity of an equivalent AC or DC overhead line. Existing cable technology limits continuous power transfer on a single cable DC bipole circuit to approximately 2GW, whereas a double circuit AC overhead line may transmit over 6GW.

### Onshore

The same principles and installation techniques for onshore underground AC cables apply to DC, with the exception that reactive compensation is not required for DC transmission and fewer cables are usually needed (minimum of two cables for DC rather than three for AC).

*Offshore cable installation, for both AC and HVDC, requires the use of specially designed cable-laying ships or barges.*



As cables need to be spaced far apart to allow the heat generated to dissipate in the ground, a cable easement corridor of around 12m wide will be required for an HVDC route consisting of four cables, with increased width to account for section joints and access during construction and maintenance (see Figure 6). This causes a significant environmental impact in construction and reinstatement and results in 'land sterilisation', as the cable corridor cannot be used for construction or certain types of agriculture.

### Offshore

In many cases, offshore transmission is better suited to HVDC applications than traditional AC. Using AC, offshore cable voltages are limited to 220kV, limiting power transfer capabilities unless many cables are used. Also, lengths of AC cable are very difficult (and consequently expensive) to joint offshore and reactive compensation cannot be installed mid-route, so transmission distances are restricted.

Offshore cable installation, for both AC and HVDC, requires the use of specially designed cable-laying ships or barges. To protect the cables from anchor strikes, they are preferably buried in the sea bed. Specialist, remotely operated submersible units are needed to cut the trench and install the cables.

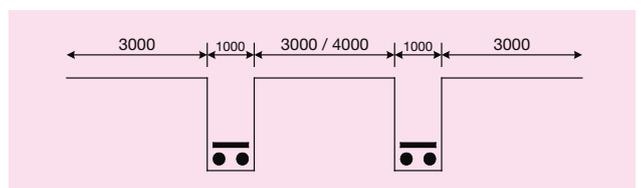


Figure 6: Example cable easement corridor (2 cables/pole)



Figure 7: BritNed CSC converter station

Where there is a requirement for the cables to cross existing subsea equipment such as pipelines, the cables can be protected, for example, by using concrete ‘mattresses’. For longer lengths of submarine cable, lengths of cable need to be jointed together on the ship while at sea. This is a very complex and time-consuming operation, needing highly skilled personnel and a spell of good weather of roughly three days to allow the laying ship to remain stationary while the cable is jointed.



### Overhead lines

Overhead lines rely on the air gap between the conductors and the ground as electrical insulation and to provide cooling for the conductors. Conductors are suspended from towers by insulators made of either ceramics or polymers, although polymer insulators are generally used for HVDC applications because of their improved pollution performance (HVDC systems have a tendency to attract pollution/particulates).

HVDC overhead lines can be used up to 800kV and are capable of transporting more than 6GW on a single bipole route. However, transfers of this level have only been undertaken using CSC technology. As yet, VSC technology has not been proposed to power capabilities beyond 1–2GW.

## HVDC converter station installations

### Converter station current source converters

Figure 7 shows an example of a CSC converter station. Converter stations require a significant amount of land for their construction. CSC converter stations can vary in size due to the requirements of the station however an “average” size station will take up an area of land 200m x 120m, including indoor and outdoor equipment.

DC equipment attracts pollution/particulates from the atmosphere and so the valves and therefore DC switching arrangements, and often smoothing reactors, are housed in large climate controlled buildings nominally 22m high. The converter transformers are outdoors and can generate significant levels of audible noise.

The CSC converter’s requirement for harmonic filtering and reactive compensation make a significant contribution to the size of the converter station (which can be greater than 50% of the overall footprint).

## Operational issues

### Controllability

One of the key benefits of an HVDC system is the ability to precisely control power flows. In AC systems the power, like water, flows along the path of least resistance, which in some cases can result in unequal distribution of power across the transmission system. HVDC systems allow the operator to precisely control the flow across the circuit, which may help alleviate issues on the wider power system.

### Impact of faults on the AC system

AC overhead line systems are very resilient under fault conditions. If an AC overhead line suffers a lightning strike then the power flowing in the network redistributes itself very quickly and without any need for external intervention.

Adjusting power flows on an HVDC link is not instantaneous and requires the intervention of the operator or control system. VSC-based systems are faster at responding to changes in system conditions than CSC-based systems, where polarity reversal must take place to change the direction of power flow.

An additional weakness, specific to CSC technology, is that faults on the AC system can introduce 'commutation failure' in the valves of the converter stations. As CSC converters take their voltage signal from the AC network, disturbances in this voltage, such as might be seen after a fault, can interrupt the power transfer. This may exacerbate the problems on the AC network.

### **HVDC system reliability**

HVDC systems suffer all of the potential issues of AC technology but with additional failure modes introduced at the converter stations.

Overhead lines (OHL) generally experience more faults, such as lightning strikes, than buried transmission systems. A fault caused by lightning generally requires no repair as the air that breaks down for a flashover to occur self heals thus the fault is temporary. It is rare that equipment is damaged badly or needs replacing, but even if damage occurs maintenance is relatively easy on an OHL. Faults on cables on the other hand are permanent as damage occurs in the cable insulation and not the self healing air like on OHLs. Cable faults require extensive excavation to identify the location of the fault and repair it. This is worse for submarine cable systems, where repair means raising the cable from the sea bed, removing the damaged section and replacing it with a new section. A fault on a submarine cable is therefore very serious and can result in the HVDC system being out of service for up to six months.

### **Short-term overload**

A useful characteristic of AC systems is their ability to withstand overloads for a short period of time. AC equipment can exceed its current rating for short periods before the conducting elements become too hot. This can allow the system operator valuable time to reconfigure the network and return power flows to normal levels.

However, in HVDC systems the valve elements heat up very quickly and cannot operate above their rating. This means that the capability of HVDC systems to deal with temporary overload conditions is limited unless the converter station has been designed with this in mind (at extra cost).

### **Multi-terminal operation**

The AC transmission system is protected by high voltage circuit breakers which allow isolation of faulty sections of the network. The same is not true for HVDC systems because there are no commercially available HVDC circuit breakers at present.

Consequently, HVDC systems tend to be point-to-point systems and not interconnected, as any single fault would shut down the entire interconnected HVDC network.

Only a few of the HVDC links in service in the world are multi-terminal applications, each with much less operational flexibility than AC systems. The properties of VSC HVDC systems in theory lend themselves better to multi-terminal operation over CSC systems, although in comparison with CSC, experience with VSC multi-terminal HVDC links is very limited.

This limitation of HVDC systems is fundamental when considering the future expandability of a transmission network. It is a relatively simple matter to, for example, connect a new power station to the AC system, whereas to introduce extra infeeds or outfeeds into an HVDC system is not easily achieved.

### **Voltage source converters**

The footprint of a VSC converter station is considerably smaller than that of a CSC station, as there is no need for reactive compensation equipment. As with CSC stations the footprint of VSC converter stations can vary but an average footprint could be 120m x 60m x 22m. All equipment is generally indoors with the exception of the connection to the AC grid.

To reduce the footprint further, the VSC converter can be constructed on two levels. VSC is the preferred technology for the connection of wind farms located far from the shore where the distance makes an AC connection uneconomic and unfeasible.



## Economics

### Capital costs

The capital costs of HVDC installations can be much higher than for equivalent overhead line transmission routes. It is very difficult to give a direct comparison, however, as the cost of any HVDC and AC project is dependent upon a multitude of project-specific factors such as technology used and route length. Under some circumstances, HVDC may be more economic than equivalent AC transmission; generally the longer the route length the more competitive HVDC becomes. The break-even distance will vary depending upon the installation type but can be over hundreds of kilometres.

### Converter stations

DC converter stations represent a significant portion of the cost of any HVDC installation. AC harmonic filters and reactive compensation add to the cost of CSC stations but in comparison with VSC stations the costs are broadly similar. However VSC converters have presently only been installed at lower maximum ratings than CSC converters so, in terms of capital cost per unit of power, they have generally been more expensive.

### Cables

When used in AC systems, long HVDC cable routes incur a high capital cost. However, DC cables normally:

- require two cables per circuit rather than three
- do not require reactive compensation mid-route
- are more highly rated than equivalent AC cables.

### Overhead lines

As in AC networks, overhead lines are the most economic means of power transmission in HVDC systems.

## Transmission losses

### Converter stations

The process of converting AC power to DC is not 100% efficient. Power losses occur in all elements of the converter station: the valves, transformers, reactive compensation/filtering and auxiliary plant. CSC converter stations incur a loss of 0.7-0.8% per converter station (1-2% for a link including a converter station at each end). VSC converters suffer higher losses in the region of 1% per converter (2% per link).

As there is a cost associated with lost power, these losses can significantly increase the cost of a converter station over its lifetime. When compared to AC transmission, the converter station losses render HVDC transmission considerably less efficient than AC transmission over short distances.

### Cables and overhead lines

Over short distances, the losses in both cables and overhead lines are very small. Losses in AC transmission are in the region of 0.7%–1% per 100km for an overhead line route and 0.3%–0.6% for a cable system. DC transmission losses are slightly less for a given power transfer. Consequently, very long lengths of cable or overhead line are required before the losses in the converter stations are offset and HVDC becomes more efficient than AC.

### Maintenance

Another cost that must be considered when evaluating transmission projects is the cost to operate and maintain the equipment. Maintenance costs for DC systems are generally higher than AC because of the complex converter stations that require regular, specialist maintenance.

### Refurbishment

AC transmission has an expected lifetime of approximately 60–80 years, with mid-life refurbishment of overhead lines, which are the largest capital component, needed after 40 years. In contrast, HVDC systems have a shorter life expectancy of 40 years, and large parts of the converter stations (valves and control systems) are likely to need replacing after 20 years.

## Glossary & Abbreviations

Abbreviation	Meaning
AC	Alternating current
Bn	Billion
CSC	Current source converter
Converter	Part of an HVDC system which either converts AC electricity to DC or alternatively converts DC electricity to AC
Commutation	Part of the process of converting alternating current to/or from direct current
DC	Direct current
GW	Gigawatt (one thousand Megawatts)
HV	High voltage
Hz	Hertz
Inversion	The conversion of DC electricity to AC electricity (as performed by an inverter)
km	Kilometre
kV	Kilovolt (one thousand volts)
MI cable	Mass impregnated insulated cable
MW	Megawatt (one million watts or one thousand kilowatts)
Reactive power	A form of power which is required to maintain voltage on the transmission system
Rectification	The conversion of AC electricity to DC electricity (as performed by a rectifier)
VSC	Voltage source converter
XLPE cable	Cross-linked polyethylene insulated cable