

Background Paper on Transmission Options for the RGI Workshop on:

Transmission Technologies and Technical Developments: Cable vs. Overhead – AC vs. DC – Innovations

Summary

The focus of this background paper discusses High Voltage (HV) transmission technologies that are currently available commercially. The objective of this document is twofold; to present an overview of HV transmission options within the context of a pan-European electricity grid largely penetrated by renewable energy sources, and to relate them to the main parameters that developers of such a project need to consider (without focusing on environmental considerations¹). This paper is written as support to the RGI Technical Workshop and aims at giving to the participants of the workshop a broad but general overview on transmission technologies.

Electricity is transmitted at High Voltages (HV > 110 kV), Extra High Voltages (EHV > 220 kV) or Ultra High Voltages (UHV > 500 kV) to reduce the energy lost in long distance transmission. Transmission options can be categorized according to three defining characteristics; the type of current transmitted {AC vs. DC}, how it is transmitted {Overhead Line (OHL) vs. Underground Cable (UGC) / Submarine cable}, and what type of conversion is required for DC transmission {Line Commutated Converter (LCC) vs. Voltage Source Converter (VSC)}. The options that arise from these characteristics are:

- HVAC Overhead Line
- HVDC Overhead Line (LCC or VSC)
- HVAC Underground / Submarine Cable
- HVDC Underground / Submarine Cable (LCC or VSC)

There is no clear winner that should be applied in all cases. When choosing a transmission option the decision should not be made between AC or DC transmission and Overhead Lines or Underground Cables, but it should be a decision that takes into account all parameters collectively. This constitutes the close collaboration of experts in the fields of high voltage cables, high voltage transmission system design, landscape architecture and civil engineering. The choice between overhead and underground is more project-specific as elements of the project's location need to be taken into account and tested against these options. For example, in some cases underground transmission could be preferred in locations where planning consent is difficult. On the contrary, overhead transmission can provide a cost effective and reliable option when permitting is possible. The choice between AC and DC is an operational one in terms of which option would be more appropriate from the system's perspective. For example, in some cases over long distances DC transmission is the option that could provide the least costs, least losses option, while for shorter distances AC could prove to be the preferred option.

¹ A workshop focusing on the environmental and health considerations of HV transmission technologies will follow this workshop in the coming weeks.

About the Renewables-Grid-Initiative

The mission of the Renewables-Grid-Initiative (RGI) is to promote effective integration of 100% electricity produced from renewable energy sources. RGI was launched in July 2009 by a coalition of Transmission System Operators (TSO's) and Non-Governmental Organizations (NGO's). RGI's members originate from a variety of European countries, as it consists of TSO's from Belgium (Elia), UK (National Grid), France (RTE), Germany (50Hertz), Netherlands (TenneT), and NGO's such as WWF International, Germanwatch and RSPB (UK). RGI advocates national and EU authorities to strive for an efficient, sustainable, clean and socially accepted development of the European network infrastructure for both decentralised and large-scale renewable energies.

Integration of Renewables to the High Voltage Transmission Network

The nature of electricity requires the continuous balancing of generation and demand in order to maintain system stability. Today the structure of the system consists of three layers; generation, transmission and distribution. This implies the formation of a network connecting the three layers together and enabling the transferring of electricity from the point of generation to the point of consumption. Electricity is generated in bulk through large-scale power plants and transferred through the electricity network to demand centres. The transmission and distribution form what is termed the electricity grid. The generated electricity is transmitted in high voltages to local substations and subsequently distributed to numerous loads. To ensure generation very closely matches demand at all times transmission networks are interconnected nationally, regionally or even continentally. They typically consist of transmission circuits and substations. The transmission structure enables multiple alternate routes for power flow should a fault occur. Overall, a high voltage transmission network needs to take into account safety, reliability and operational constraints while preserving the efficient transmission of electricity.

The liberalisation of the electricity market on all levels and the emergence of renewable energy sources have created additional requirements for the operation of the system. Long distance high voltage transmission has become a necessity in order to allow remote renewable energy sources to be utilized to replace fossil fuels. This necessity has in effect brought the debate of high voltage transmission options at the forefront. A high voltage transmission conductor can carry Alternating Current (AC) or Direct Current (DC) and transmitted through Overhead Lines (OHL) or Underground / Undersea Cables (UGC). When designing the future architecture of the high voltage transmission network, the variability and dispersity of renewable energy generation from sources such as wind and solar, needs to be taken into account. For example, wind generation in Northern Europe can be complemented by solar generation in Southern Europe during different times of the day. Hence, the high voltage transmission network needs to be able to transfer bulk amounts of electricity from one region to another. The current composition of the high voltage transmission network of AC overhead lines needs to be expanded to allow the smooth and efficient integration of high shares of renewable energy generation required to decarbonise the European power sector. Hence, when designing this grid expansion, the choice between AC vs. DC and Overhead vs. Underground needs to be re-defined to fulfil the requirements and fully benefit from a grid penetrated by high renewable generation.

Overhead Lines and Underground/Submarine Cables

Overhead Lines

The transmission lines across Europe consist almost completely of overhead lines. It represents the most common solution that provides high performance levels at a low cost. Depending on whether AC or DC is transmitted, the components of an overhead line may vary. Common equipment typically found in an overhead line are the supporting structure, the metal conductor (typically aluminium), and insulation. Overhead lines are supported by a tower that can be made from either wood, steel, concrete, aluminium and reinforced plastics. The purpose of this structure is to keep the high voltage conductors away from their surroundings and from each other. Their design requires minimum safety clearances. Each structure's design is project-specific and depends on the weight of the conductor they have to support and other factors such as the usage of area under the line and its structure, level of rigidity, angle, terminating line, river / road crossings, sag of the conductor². Adverse weather conditions of high wind and low temperatures (icing of lines) can lead to power outages (wind speeds of the order of 40 km/h can permit conductors to surpass operating limits resulting in loss of supply). Also, oscillatory motion of the line can occur (galloping). Typically, failures arising from such conditions are easily located and quickly repaired.

Underground / Submarine Cables

Electricity transmission can also be utilised through cables running underground or undersea. Currently, underground transmission represents a very small fraction of HV transmission across Europe and it has been utilized when overhead transmission is not deemed possible. Underground cables are insulated with a medium (e.g. oil, paper) where the cable can be directly buried or installed in tunnels. The main reasons for choosing tunnels is to facilitate forced cooling systems for oil-filled cables and ease of access for the cable.

In more detail, there are a number of cables that could be used, including:

- Low-density polyethylene (LDPE)³
- Cross-linked polyethylene (XLPE)⁴
- High-pressure fluid-filled paper insulated pipe type cable (HPFF)⁵
- Self-contained fluid-filled paper insulated cable (SCFF)⁶
- Self-contained fluid-filled paper-polypropylene laminate (SCFF-PPL)⁷
- Gas-insulated Line systems (GIL)
- Mass-impregnated (MI)⁸

The choice between overhead lines and underground cables lies predominantly on the trade-offs between three key areas; cost, operational features and environmental concerns. Typically, overhead transmission is less expensive to build and quicker to repair but it requires wider right-of-way⁹ that could cause permitting problems.

² The sag of the conductor is the vertical distance between the highest and lowest point the wire is supposed to oscillate. It varies depending on the temperature.

³ LDPE: dry dielectric where the inner conductor is covered with polyethylene

⁴ XLPE: same as LDPE except that it has been chemically cross-linked to raise its maximum operating temperature from 70 °C to 90 °C

⁵ HPFF: three unsealed, paper insulated cores pulled into a single steel pipe which is filled with an insulating fluid

⁶ SCFF: same as HPFF with the exception of a flexible extruded metallic sheath applied to the cores enabling them to be laid separately directly into the ground

⁷ SCFF-PPL: variation of SCFF using PPL tapes that effectively reduce the capacitance and dielectric losses

⁸ MI: paper tape insulation impregnated with high viscosity dielectric fluid

⁹ Right-of-way reflects the land needed to build, operate and maintain the overhead/underground line/cable. It provides a safety margin for surrounding structures and vegetation

Application Considerations

Underground transmission is used in urban areas or sensitive locations but could have higher cost and greater operational limitations. Specifically, underground transmission can be used in a number of applications including:

- urban areas where they are densely populated
- areas planning consent is difficult
- rivers and natural obstacles
- land with natural or environmental heritage

Besides the above areas where underground transmission excels over overhead lines, there is a number of more technical areas that it excels over OHL:

- less prone to severe weather conditions (lightning, wind, ice and snow)
- right-of-way (narrower surrounding space required for safety, maintenance and repair)
- safer (no shock hazards or threat to wildlife through collision)
- less visual impact

On the other hand, there are a number of areas where underground cables have a disadvantage towards OHL:

- more expensive¹⁰
- worse maintainability and reparability¹¹ resulting to longer outage times and thus lower availability
- longer construction time
- less operational¹²
- less flexible¹³
- significant impact due to cable routeing (land use, natural and cultural heritage, etc)

¹⁰ The life-cycle cost of an underground cable can be two to four times the cost of an overhead line for voltages up to 150kV. For higher voltages it can be significantly higher.

¹¹ When repairing underground cables, they can not be maintained “live” and it takes days or weeks for the process while OHL maintenance can be performed “live” in a short period of time.

¹² The added equipment required for UGC result to more complex control and modes of failure

¹³ An overhead line is much easier to be adapted to system changes (reinforcing the network, modification to system topology, etc).

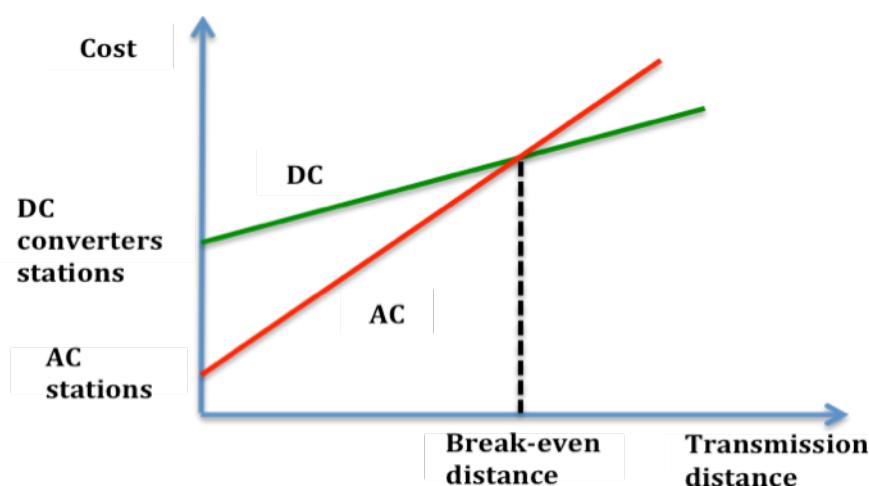
HVDC and HVAC

HVAC Transmission

The vast majority of EHV transmission in Europe consists of 3-phase HVAC transmission. It is the most common solution as it fulfils two important criteria; it represents the most cost effective technically feasible option, and it can be easily transformed to comply with the required voltage levels of the transmission and distribution networks of the electricity grid. It is because of this ease of operation and efficiency that AC has prevailed over DC over the past decades.

HVDC Transmission

DC is less simplified than AC transmission as it requires converter stations at both ends of the transmission line to convert AC to DC (and vice-versa) and transform voltage to the desired level of the rest of the AC network. These stations increase costs and losses. However, DC can be more economical over long distances as it can carry more power per conductor compared to AC. The stations costs and the transmission distance form the two variables that determine the break-even point between AC and DC as illustrated in the graph below:



The fundamental operation of a HVDC system is that the AC is rectified at the transmitting end and inverted at the receiving end. An HVDC system can be utilized through a monopolar or bipolar point to point connection. However, in future an increasing number of multi-terminal connections¹⁴ could be used.

In more detail, the main components of HVDC system can be:

- transformer (adjusting the voltage level of the AC source to the required entry voltage level of the converter)
- converter (conversion from AC to DC or from DC to AC)
- the smoothing reactor (prevention of intermittent current and resonance in the DC circuits, and limitation of DC fault currents)
- AC and DC side filters (absorb harmonic currents and supply reactive power)
- DC transmission circuit (lines, cables, etc)
- control and protection equipment

¹⁴ In essence a monopolar connection is the equivalent of a single AC circuit. A bipolar connection is used to provide redundancy and increase reliability that was worsened due to the added equipment and their complexity. Multi-terminal systems are more rare and difficult to design and control.

One of the most crucial parts is the converter. DC transmission, based on Line Commutated Current-Sourced Converters (LCC/CSC), has been employed for the past 50 years with intense development of such projects only over the last couple of decades. Voltage Source Converters (VSC) have come into use over the past few years enabled by the development of Insulated Gate Bipolar Transistors (IGBT) and turn-off thyristors (GTO).

Losses

Transmitting electricity at higher voltages reduces the energy lost to resistance. A higher voltage reduces the current and subsequently the resistive losses in the conductor¹⁵. Losses can also be reduced by increasing the diameter of the conductor and effectively reducing its resistance. However, larger conductors are heavier and more expensive.

In AC transmission, the inductance and capacitance of the conductor can be substantial. The resulting reactive current flow causes extra losses to the transmission circuit. Capacitor banks and other components (phase-shifting transformers, static VAR compensators, Flexible AC transmission systems¹⁶) are used to control reactive power flow to reduce losses and stabilize system voltage.

In DC transmission, the majority of the losses originate from the converter. For a long transmission line (>500 km) or interconnector, HVDC exhibits lower losses¹⁷ as compared to HVAC. However, for shorter lines the losses of the converter stations surpass AC line losses¹⁸. There is yet not enough operational experience of DC embedded systems to derive any useful comparative conclusions.

Limitations

Electric current passing through a conductor causes heating of the conductor. The amount of electricity that can be transmitted at a certain voltage level depends on the length of the line.

For short AC lines (<100 km), the limit is thermal and is governed by the amount of current and the resulting line losses causing overheating. Overheating the line can cause an increase of its sag and reduce the mechanical strength and life of the line.

For intermediate length AC lines, the limit is set by the voltage drop or rise in the line. Large voltage drop or rise may damage equipment and affect the operation of the system.

For longer AC lines (>500 km), system stability sets the limit. Maximising the power transmitted through an AC line whilst maintaining line stability, reduces the length of the line. The allowable product of line length and maximum load is proportional to the square of the system voltage.

In AC underground or submarine transmission operational problems can occur because of the interaction between the current and the cable that can cause voltage distortion and large amounts of reactive power. This in effect would limit the real power transmitted through the cable.

For DC transmission, the limit is not influenced by the length of the line. The limit is rather constant and is set by thermal and voltage drop limits.

Another source of losses present in both AC and DC overhead transmission is due to the corona discharge¹⁹. For EHV, bundle conductors are used to avoid corona losses.

¹⁵ An increase in voltage requires the same amount of current reduction. Hence, the losses (I^2R) are reduced proportionally to the square of the amount of current reduced.

¹⁶ A flexible AC transmission system (FACTS) as defined by IEEE is “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability”.

¹⁷ Losses are lower in HVDC as compared to HVAC because there is no skin effect and reactive power flow (increases with circuit length)

¹⁸ Converter station losses for DC transmission vary with the square of the transmitted power while HVAC has fixed station losses

¹⁹ Corona discharge occurs at extra high voltages (>200 kV) from the creation of ions in the air when a strong electric field is present. This in essence can cause power losses and audible noise.

Application Considerations

So far, HVAC has been used in the vast majority of applications. However, HVDC is becoming increasingly attractive for cases where bulk electricity over long distances (>500 km) needs to be transmitted or for interconnections between asynchronous grids. In the latter case it stabilizes control issues of AC electricity flow²⁰. It is also used for long submarine cables (>50 km) because AC can no longer be applied at these distances. Theoretically, HVDC can be used for all kinds of electricity transmission. However, the necessary converting stations are costly. In practice, long distance transmission favours HVDC against HVAC as it is less expensive and incurs lower losses. On the contrary, for shorter distances HVAC is preferred.

In more detail, the advantages of DC over AC transmission are:

- bulk electricity transmission from and to remote areas without any intermediate steps
- increasing the capacity of an existing transmission grid using existing rights-of-way
- connecting asynchronous AC systems and improve system stability²¹
- reduced line cost
- lower losses for long transmission lines
- synchronize and transfer AC generated by (remote) renewable energy sources²²

The disadvantages of HVDC as compared with HVAC lie among the following areas:

- conversion (inverters are expensive and have limited overload capacity)
- switching & control (control of added equipment is complex and requires active regulation, particularly in the case of multi-terminal systems)
- availability (lower availability than AC systems due to the extra conversion equipment)²³
- operation & maintenance (DC equipment are system-specific and less standardized)
- more land required for the station²⁴
- less flexible

²⁰ AC transmission between two regions would require continuous real-time adjustment of the relative phase of the two grids. When using HVDC, the AC flow from one region would be converted to HVDC and then transmitted over the distance between the regions before converted back to locally synchronized AC.

²¹ HVDC can prevent failures to propagate from one part of the transmission network to another. Additionally, the magnitude and direction of electricity flow can be regulated by the system operator as required for the further stabilization of the AC networks. Lastly, reactive power flow and AC voltage control can be achieved through a HVDC link.

²² This in effect mitigates the intermittent nature of renewable energy sources by averaging and smoothing the outputs of dispersed wind/solar power plants.

²³ There is concern that if a more wide application of HVDC is applied across Europe's transmission network, the current high availability provided by HVAC overhead lines could be decreased.

²⁴ Transformers and filters are placed outdoors as it would be too expensive to place them along with the control equipment in a temperature controlled building.

Overview of Transmission Options

HVAC Overhead Lines

HVAC overhead lines use air to provide most of the insulation. Aluminium alloy is used as the conductor material, composed of several strands. At high voltages that are commonly used for the transmission of electricity, suspension-type strain insulators²⁵ are used. Overhead lines can be equipped with a shield wire that can serve for three purposes; act as lightning protection, ground conductor and include optical fibres for communication and control of the system. Thicker wires would lead to a relatively small increase in capacity due to the skin effect²⁶.

This option is most suitable for short to medium length transmission lines (200-500km) at a lower cost than other alternatives. It reflects a proven technology that provides voltages and power of the order of 500kV and 1000-3000MW per circuit respectively. Their capacity can be doubled by installing a double circuit on the same tower. This approach increases slightly the wideness of the right-of-way and the height of the tower but cost-wise is cheaper than two single circuit lines.

Overall, AC overhead lines are an efficient and economic option for transmitting electricity over short and medium distances. Over longer distances they are less efficient and have higher losses that need to be compensated by the application of FACTS technologies.

Below is a summary of the advantages and disadvantages of HVAC overhead transmission:

Advantages	Disadvantages
<ul style="list-style-type: none"> • proven technology • lower cost compared to other options • increased capacity at low incremental cost by double circuit • ease of connection to the existing grid • high level of reliability • easy and quick to repair, operate, manage 	<ul style="list-style-type: none"> • visual pollution • FACTS may be needed over long distances • concerns about electromagnetic interference (EMF) • larger right-of-way

HVAC Underground / Submarine Cable

HVAC underground transmission can be split to installations of over 300kV and under 300kV. Currently, there is more operational experience for cables up to 300kV than for higher voltages where the technology has developed to a commercial phase only the past decade. Most cables for AC underground transmission are insulated by cross-linked polyethylene (XLPE) or by self-contained fluid-filled cable systems (SCFF). Some cables may have a lead or aluminium jacket in conjunction with XLPE insulation to allow for fibre optics to be integrated.

The choice of cable technology depends on a range of factors including reliability, local manufacturing support, and cost. XLPE offers the best ratings and the minimum charging current. Most concerns relating XLPE are related to their application on voltages and power of the order of 400-500 kV and 900MW per circuit respectively, where there has not been a lot of operational experience. The predominant cables used for these ratings are fluid-filled type. Moreover, the world production capacity for XLPE cables is limited.

²⁵ Insulators are needed to provide electrical insulation and support both the full span of the conductors' load and additional weight due to ice or wind. They can be used as a set of multiple units made of porcelain, glass or glass-reinforced polymer. The number of units depends on a number of factors such as operating voltage and surges (due to switching or lightning), altitude and environmental factors (fog, pollution, etc).

²⁶ The skin effect causes most of the current to flow close to the surface of the wire. It is a phenomena caused by eddy currents where AC current tends to avoid traveling in the centre of a conductor. Therefore, the current density near the surface of the conductor is greater than that at its core. This effectively limits the cross-sectional conductor area available to carry alternating electron flow, increasing the resistance of that conductor above what it would normally be for DC.

The transmission capacity of such cable types depends predominantly on the thermal properties and the type of the location. A double circuit of underground cable can be installed to increase the capacity to similar levels to a single overhead line circuit.

Due to the high capacitance of an underground cable, more reactive power is produced resulting in the need of FACTS technologies at the receiving end and perhaps at an intermediate point.

Both SCFF and XLPE cable types are highly reliable but in case of a fault the outage time can take up to 2 months. Because of the long outage times, double cables are installed which increases significantly the overall costs.

Overall, HVAC underground transmission is commonly used for short distances (< 50km) in projects where overhead transmission is not possible (densely populated areas, limited right-of-way, undersea, etc). For longer underground transmission HVDC transmission is less costly and is preferred.

Below is a summary of the advantages and disadvantages of HVAC underground transmission:

Advantages	Disadvantages
<ul style="list-style-type: none"> • low visual pollution • safer (minimal weather-related outages) • applicable to: <ul style="list-style-type: none"> • intensively populated urban areas • areas where land is unavailable or planning consent is difficult • rivers and natural obstacles • land with natural or environmental heritage • narrow right-of-way 	<ul style="list-style-type: none"> • lack of operational experience with extra high voltages (> 300kV) and long distances (> 50km) • low maintainability and reparability and thus low availability compared to overhead AC transmission • very expensive due to duplication of cables • higher amounts of reactive power compensation required as compared to overhead AC transmission • complex cable routeing (difficult to dismantle, significant impact on environment)

HVDC Line Commutated Converter (LCC) Overhead Line

The components of a HVDC overhead line are similar as with AC lines. The most significant difference lies in the design of the tower's structure. Because of the nature of AC and DC transmission, 2 conductors are needed for DC instead of 3 for AC for each circuit. This results to a significant reduced tower size and right-of-way.

HVDC LCC is the conventional method of high-voltage DC transmission. The main equipment required for such a system are:

- thyristors²⁷ converter: conversion from AC to DC current and the inversion from DC to AC
- transformer: adjustment of the voltage level and isolation from the DC to the AC system
- AC filters: reduction of AC harmonic currents and supply reactive power
- control and protection equipment

Typically, this configuration is operating at voltage and power ratings of the order of 500kV²⁸ and 2000-3000MW per converter respectively.

Many items of the system are duplicated in order to minimise loss of transmission in case of a fault. This along with the high converter cost results in higher overall costs as compared to an AC system. With increasing transmission distance, the two cost lines converge.

²⁷ A thyristor functions like a diode (allowing current flow in one direction when voltage is applied) with an additional mode of operation; when it is in the conducting state it "holds" the current until "triggered" through a current threshold value

²⁸ For Ultra-HV DC transmission of the order of 800kV and 6000MW, two different configurations are under development in China and India. These configurations are intended for bulk power transmission from remote locations with the lowest possible transmission losses and transmission width. This configuration would be applicable only for very large systems

Overall, HVDC LCC overhead transmission is preferable for bulk power transmission over long distances (>500km). However, there are cases of shorter distances where HVDC may be preferred such as its ability to connect asynchronous systems, optimal power flow control or flexible increase in power capacity.

Below is a summary of the advantages and disadvantages of HVDC LCC overhead transmission:

Advantages	Disadvantages
high capability of bulk power transfer reduced right-of-way less losses less visual pollution better power flow control link asynchronous grids	high converter station cost less flexible lower availability

HVDC Line Commutated Converter (LCC) Underground Cable

The equipment used in underground HVDC LCC are essentially the same as with an overhead line with two cable types that can be used for underground HVDC; self-contained fluid-filled cables (SCFF) and Mass Impregnated (MI) cables.

The most used application is 500kV, 600MW (per converter) submarine interconnectors projects for distances higher than 40km where the majority of such projects use DC transmission. Further applications have not been yet developed for two reasons. Firstly, replacing the overhead line with an underground cable incurs a substantial increase in overall costs. Secondly, there is no suitable cable for higher voltage and power ratings.

HVDC Voltage Source Converter (VSC) Overhead Line

VSC technology has been in use for many years but has only recently been employed for HVDC due to the availability of high voltage, high power transistors.

HVDC VSC serves the same purpose as HVDC LCC; that is to rectify AC to DC current on the transmitting end and invert on the receiving end. The main difference in its converter structure is that VSC uses transistor switches (IGBTs) instead of thyristors. This implies that the converter can be self-commutating and that no synchronization to the network frequency is required.

HVDC VSC is applied to similar applications as with HVDC LCC (interconnecting asynchronous grids, bulk power transfer).

Overall, HVDC VSC is a relatively new technology without a lot of operational experience. As with other HVDC configurations, its main application is to transmit bulk electricity. However, the added benefit of VSC over LCC is the capability of multi-terminal configurations that VSC can offer. Multi-terminal operation has not yet been fully applied but its benefits²⁹ position it as a suitable solution for the integration of diverse renewable energy sources. While currently, HVDC VSC is providing voltage and power ratings lower to the ones of LCC, it is expected that VSC technologies will reach overhead transmission voltages, up to 640kV and 2400MW per converter.

²⁹ A multi-terminal system can reduce the number of converter stations, lower investment and transmission losses, adapt easily to changing network conditions and increase network availability

Below is a summary of the advantages and disadvantages of HVDC VSC overhead transmission:

Advantages	Disadvantages
multi-terminal operation possible less visual pollution high capability of bulk power transfer link asynchronous grids less right-of-way no reactive power demand less area required as compared to LCC capable of providing continuous variable power in both directions	minimum commercial operational experience high converter cost – suitable only for long distances lower power ratings higher converter losses less standardized than AC systems

HVDC Voltage Source Converter (VSC) Underground Cable

The main difference between the HVDC VSC underground solution as compared to the overhead one, is the DC filters and reactors required for the cable. Both MI and XLPE cables could be used in HVDC VSC underground transmission for voltage and power ratings that could reach in the near future 300kV and 1000MW per converter respectively. Currently such VSC systems have been used for underground and submarine applications at voltage and power ratings up to 150kV to 200MW per converter respectively.

Overall, due to the current shortcomings of the available cables the use of HVDC VSC underground is limited.

Below is a summary of the advantages and disadvantages of HVDC VSC underground transmission:

Advantages	Disadvantages
less visual pollution capable of providing continuous variable power in both directions no reactive power demand	higher converter cost and losses as compared with LCC low cable capacity