by Joe Mooney, POWER Engineers, Inc, and Brian K. Johnson, University of Idaho, USA

HVdc Transmission and Integration into an AC Grid

High voltage, direct current (HVdc) transmission has been in commercial operation since the 1950's. The vast majority of HVdc systems have two terminals, one acts as a rectifier and transfers power from an AC system to the DC system and the other acts as an inverter and transfers power from the dc system to ac system. Some HVdc system always transfer power the same direction from a remote power source to a load center. Others can transfer power in either direction at different times of the year with the converters exchanging rectification and inversion roles. The dominant technology used for HVdc has been line current commutated (LCC) systems utilizing thyristor-based technology. LCC systems require significant reactive support from the ac system at the rectifier and inverter terminals as well as current harmonic filtering. LCC HVdc systems are capable of high capacity in terms of voltage levels and power flows. There are LCC systems in operation today at voltage levels of ±800 kV (one conductor at +800 kV and the other at -800 kV) and 8000 MW. In addition, there are plans for future HVdc systems operating at ±1100 kV and 10,000 MW.

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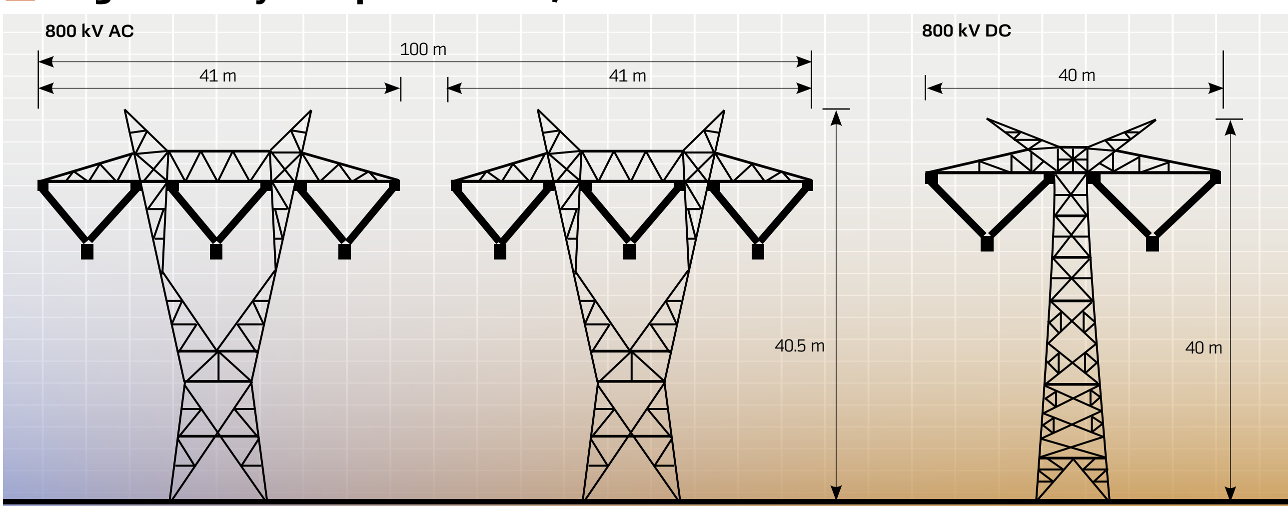
1 Right-of-way comparison of 6,000 MW HVdc and AC circuits



In the late 1990's, power electronic technology that had been used for years in variable speed motor drives began being used in HVdc applications. Insulated-gate bipolar transistors (IGBT) were developed that had voltage ratings and current capabilities needed for HVdc applications.

The first of these was put into service in 1997. HVdc converters utilizing this technology are referred to as Voltage Source Converters (VSC). Two of the main improvements with VSC systems are the ability to control reactive power flow and the reduced harmonic filtering requirements.

Since 1997, VSC systems have been dominating the HVdc market for installations up to 1000 MW and they are becoming the standard for new installations. VSC HVdc systems raise the possibility of creating a HVdc grid, with several multi-terminal systems now in operation and consideration of a European HVdc supergrid.

LCC and VSC systems respond differently to disturbances and events on the AC and DC power system. Due to the high level of control that is available in a VSC system, the rectifier and inverter can respond as "ideal sources" in nearly any fashion desired by the controls engineer, and can often be viewed as current regulated voltage sources.

That means the response of VSC systems to AC system faults and dynamic conditions is much different than conventional AC system sources, such as AC generators. An LCC system, on the other hand, is largely passive in its response and there is very little control action an LCC system can take for AC system faults.

However, as with a VSC system, LCC converters can respond very quickly to other abnormal system conditions, such as power swings, and take corrective actions to help keep the power system stable and intact.

Benefits

HVdc transmission has many benefits that make it an attractive alternative to traditional AC transmission lines. HVdc is excellent for transmission of large blocks of power over great distances. The Pacific HVdc Intertie was constructed to make the inexpensive renewable hydro power from the Northwest available to the California market. In addition, in the winter time when loads were low in California, power could be shipped to the Northwest when loads were high. HVdc transmission is becoming the primary mode of transporting hydroelectricity and coal generation from western China to the load centers in the East. By the end of 2016 there will be 34 LCC HVdc lines in China and many more are planned. In addition there are presently five VSC HVdc projects in China, with two more scheduled for completion by the end of 2018. The longest transmission system in the world is the recently completed Rio Madeira HVdc system at 2375 km (1476 mi) with two ±600 kV, 3150 MW transmission lines based on LCC converters.

HVdc can also be used as an isolation point between AC systems or a point of interconnection between isolated ac systems, even systems operating at different frequencies. The US East and West grids have been interconnected via HVdc back-to-back systems for decades. The same is also true for ERCOT. Although these connections allow the transfer of real power, the regions are still isolated from each other due to the nature of HVdc. There is a proposal for building an HVdc "Super Station" near Clovis, New Mexico that will be used to create a three-way tie between the Western and Eastern interconnects and ERCOT via an HVdc network with an ultimate design capacity of 30 GW. The Super Station will serve as a market hub for exchanging renewable energy between the three regions.

HVdc transmission has seen explosive growth around the world in the last 15 years with many new installations.

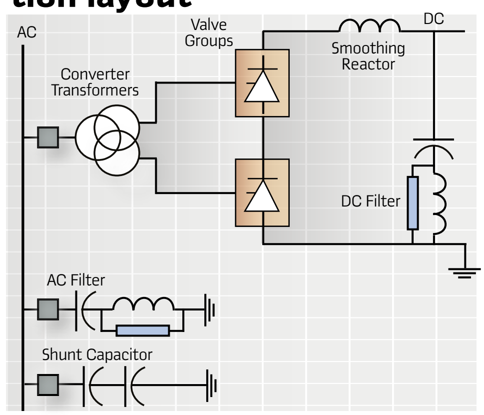
HVdc transmission lines often require smaller rights-of-way than their AC equivalent. A HVdc bipole transmission line only requires two current carrying conductors. In comparison, an AC transmission system carrying the equivalent amount of power would require multiple lines with three conductors per tower. To illustrate this point, Figure 1 shows a comparison of right-of-way needs for 6000 MW transmission system utilizing ±800 kV DC and 800 kV AC. Using HVdc would require a single bipole transmission line and using AC would require two transmission lines resulting in about half the right-of-way requirements for the HVdc line.

HVdc is ideal for underground and undersea cable because there is no distance limitation like there is with AC transmission. Cable applications on AC systems are typically limited to tens of miles due to the need to compensate for the cable charging current. With HVdc systems there is no charging current so the cable length has no physical distance limitation. In addition, the cost of underground and undersea HVdc cables are less than equivalent voltage cables used on AC systems.

HVdc Converter Technology

Line Commutated Converter (LCC): Modern LCC HVdc converters (also referred to a HVdc classic) use solid-state devices called thyristors to

2 "Classic" converter station layout



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control switching of the AC voltage to produce a DC output (known as rectification) and develop the AC current from the DC (known as inversion). Thyristors require a control signal to start conducting current (switch on) and the thyristor turns off when the current flow through the device reverses. The thyristors are connected in series to form valve groups and multiple valve groups are connected in series to develop the needed DC voltage and/or in parallel to develop the needed DC current (increase power transfer at a given voltage).

Early HVdc Classic designs used mercury-arc valves to control switch of the AC voltage to produce a DC output. The first system of this design went into service in 1954 connecting the Swedish mainland to Gotland Island via a submarine cable. The system operated at 100kV and had a capacity of 20MW.

One of the most significant HVdc systems using mercury-arc valves was the Nelson River Bipole 1 commissioned in 1971 with an operating voltage of ±460kV and a 1850MW capacity connecting hydroelectric generation in Northern Manitoba to load centers Winnipeg, Manitoba. The first thyristor-based HVdc link was again a Gotland link in 1967. Figure 2 shows a simplified layout of a typical LCC-based converter station. The main components are:

- AC harmonic filters
- AC reactive support
- Converter transformers
- Valve groups
- DC filter
- DC Smoothing Reactor

The LCC converter topology requires a stiff current on the DC system (which is created using the smoothing reactor) and a stiff AC side voltage to support the transfer of current between phase legs in the converter. Due to the nature of the commutation process, LCC-based converters require harmonic filtering on the AC and DC system and the AC system must provide a significant amount of reactive support. The filtering and reactive support requirements tend to make LCC-based HVdc system less attractive. Harmonics and reactive support are discussed in the next section.

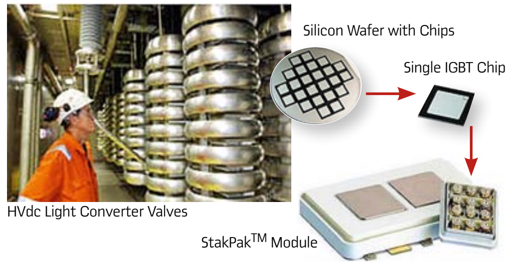
The converter transformers are typically single-phase, three-winding type with one secondary winding connected wye and the other connected delta. The secondary voltage on the converter transformer is rated at voltage to provide the appropriate DC voltage. The converter transformers have a unique winding configuration since the secondary windings see a standing DC offset, and are manufactured specifically for HVdc applications.

The valve consists of multiple thyristors connected in series. Modern thyristors are rated up to 10kV and 6000 amps. The series connection allows for very high voltage outputs and the parallel connections increase current output and power transfer capability. Figure 3 shows a typical valve hall with three valve groups, thyristor stack which makes up one tier in a valve, and a thyristor. There may be multiple valve groups in an HVdc converter depending upon the design. The thyristor can only carry current in one direction. It can block voltage in both directions when it is off.

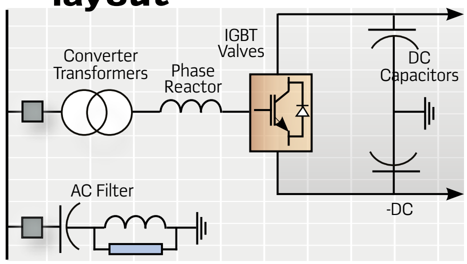
3 Typical components

Figure 3: A typical LCC valve, thyristor stack, and thyristor.

4 Layout components



5 Simplified VSC station layout



The HVdc conversion process generates voltage harmonics on the DC system and current harmonics on the AC system. The DC filter is required to limit interference from these harmonic on adjacent telecommunication systems. In cable applications, the filters are typically not required as the cables are shielded and block the interference caused by the conversion process. All overhead applications require DC filters.

The shunt connected AC harmonic filters exhibit capacitive behavior at the system power frequency. There are often three AC filter banks, tuned notch filters at the 11th and 13th harmonics, and a high pass filter for harmonics above the 13th. The total capacitive compensation requirement at each terminal an LCC system is approximately 50% of the real power rating of the converter.

The short circuit capacity of the ac system as compared to the HVdc power transfer must be relatively high in order for a LCC-based converter to operate correctly. Operating experience has shown that that the short circuit capacity must be 2.5-3 times the HVdc power transfer capability (referred to as the short circuit ratio) to ensure reliable operation. Therefore, LCC-based systems are not good choices for weak system interconnections, such as systems where the dominant sources are wind generators.

The LCC-based convertor is also limited on minimum power transfer. Again, the limit is related to the short circuit capacity of the AC system. Typically, minimum power flow in a LCC-based converter is about 10% of the rated power transfer capability.

One method for reducing the short circuit capacity requirement is to use Capacitively-Commutated Converter (CCC) stations. The CCC-based system is a LCC-based system with series capacitors installed on the secondary of the converter transformers (between the converter transformer and the valve groups). A CCC-base system lowers the short circuit capacity requirement to 1-2 times the HVdc power transfer capability. There are a limited number of CCC installations in North America, mostly at back-to-back converter stations.

Voltage Source Converter (VSC)

The heart of the VSC-based system is the Insulated Gate Bipolar Transistor (IGBT). The primary difference between the LCC-based system and the VSC-based system is that the IGBT can be switched on and off by control action where the thyristor can only be switched on. Therefore, the VSC allows for control of the reactive and real power flow, thus removing the need for reactive support on the AC system. In addition, the VSC switching method minimizes low frequency harmonic content such that only high-frequency filters are required on in the AC system.

VSC technology has been used in motor drives and low voltage power electronics for years. The application of VSC technology in HVdc transmission was introduced as HVdc Light® by ABB in 1997 and the first system went into service in 1999. Siemens introduced their version of VSC technology called HVdc PLUS (Power Link Universal System) in 2007 and Alstom Grid has a VSC technology called MaxSine™.

The VSC converter topology requires a stiff DC voltage source, which is created by DC capacitors and a stiff AC current source, which is created through a combination of the transformer leakage with additional inductance to supplement it.

Figure 5 shows a simplified layout of a typical VSC-based station. Figure 4 shows the HVdc Light VSC valves and IGBT modules. The IGBT can control current in both directions, but can only block voltage in one direction when it is off. The main components of the VSC system are:

- AC filter
- Converter transformer
- Phase reactor
- Valve groups
- DC Capacitor

High-frequency voltage harmonics are generated by a VSC system. The harmonic frequencies are a function of the switching frequency of the VSC. The only filtering that is required is a high-pass filter that removes the high frequency components.

Newer VSC topologies based on modular multilevel converters (MMC) have significantly reduced filtering requirements.

With current configurations, a VSC-based system does not require a special converter transformer since the transformer secondary does not see a standing DC offset. As a result standard transformers are use in VSC applications. This could change if future system designs use a bipole configuration to increase system reliability. A series reactor is necessary to limit the rate of rise of current seen by the IGBTs. In older VSC HVdc configurations, this also acts as a low pass filter to separate the AC fundamental frequency voltage from the raw Pulse Width Modulated (PWM) voltage waveform. The series reactor is an air core device that is also of standard manufacture.

The operation of a VSC terminal is slightly different than a HVdc Classic terminal. Each VSC terminal can independently control the real and reactive power flow. However, as the power flow must remain balanced (e.g., the power going into the DC line must equal the power coming out plus the converter and line losses), one terminal controls the DC voltage level and local AC reactive power, while the other terminal controls the system's real power transfer and the AC reactive power flow at that terminal. The VSC is able to control the power flow because it is able to achieve fast control of the magnitude and angle of the power frequency AC voltage.

VSC HVdc systems installed until a few years ago use a Pulse Width Modulation (PWM) technique. Using PWM it is possible to create any phase angle or magnitude, within the design limits, by changing the PWM pattern. In addition, the VSC can rapidly respond to the system's requirements, typically within 50 mil-

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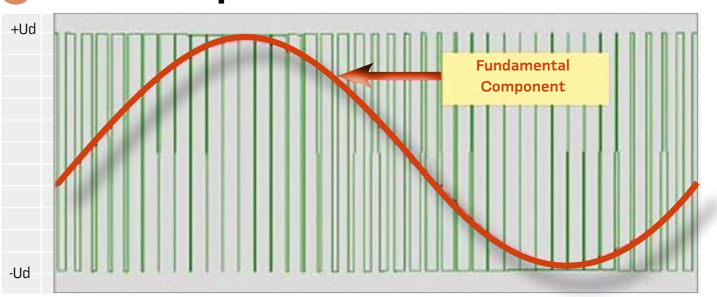
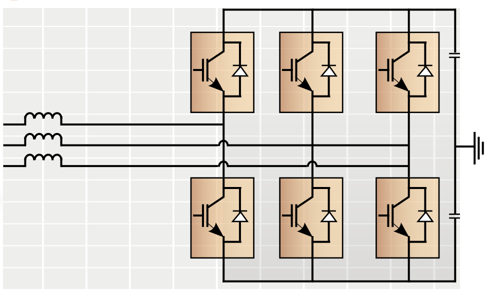
As with a VSC system, LCC converters can respond very quickly to other abnormal system conditions, such as power swings, and take corrective actions to help keep the power system stable and intact.

6 PWM Output from the VSC



7 Two-level VSC converter topology



This topology has the disadvantage that each switching instance requires switching the full DC voltage on and off, leading to large voltage harmonics at the switching frequency and large turn-on and turn-off losses.

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liseconds, changing real and reactive power flow and voltages levels. Figure 6 shows the voltage output from a two-level VSC. Figure 7 shows a two level converter bridge.

The two-level converter topology has the disadvantage that each switching instance requires switching the full DC voltage on and off, leading to large voltage harmonics at the switching frequency and large turn-on and turn-off losses. New VSC designs use a different approach.

A converter is made from a large number of simple submodules connected in series. Figure 8 shows a diagram of a MMC. The converter in the figure has 12 submodules per phase. Each submodule is a single phase voltage source converter in a half-bridge topology as shown in the inset.

The AC voltage waveform is produced by switching modules in and out of the circuit in steps. MMC converters for HVdc have 200 or more standardized submodules per phase. This has the advantage of reducing voltage harmonics and reducing switching losses. MMCs have minimal AC filtering requirements.

As mentioned previously, a VSC converter can control reactive power as well as real power. Figure 9 shows a typical P-Q diagram for a VSC converter. One of the primary benefits of a VSC converter is the ability to provide system reactive and voltage control unlike an LCC system that requires significant amounts of external reactive support. Another benefit is the ability to operate as a black-start source. This is helpful for remote generation resources, such as offshore wind, or for providing restoration power in case of a significant power outage.

A VSC converter can control reactive power as well as real power.

Operation of HVdc Systems

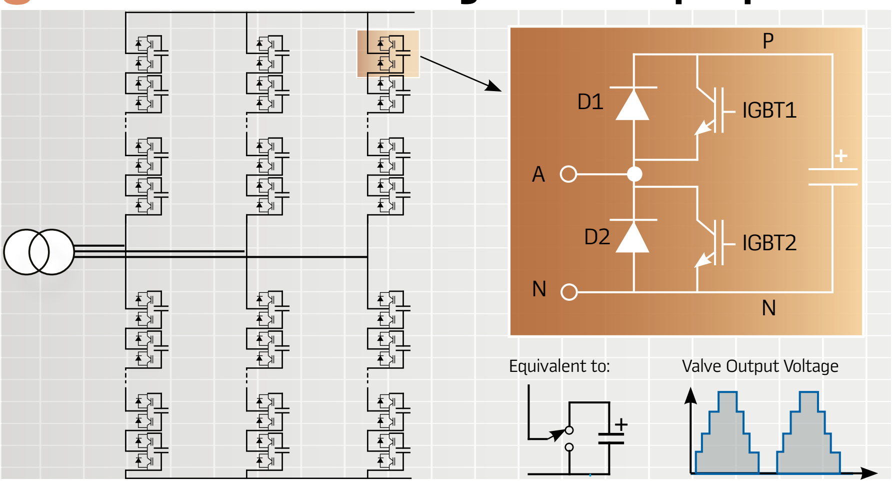
An HVdc transmission line typically consists of two current carrying conductors, one for the positive pole and another for the negative pole. In some applications there is only one pole, either positive or negative, and the second conductor is needed for the current return path. When the line is operated with two high-voltage poles it is referred to as Bipole operation (see Figure 10). When there is one high voltage pole it is referred to as Monopole operation. In monopole operation the current return path can be through another conductor, referred to as metallic return (see Figure 11a), or it can be through earth via a ground electrode (see Figure 11b). Ground return is common with undersea cables. And while a ground return is available for land based systems, there are generally severe restrictions on operation in most countries. A bipole system can operate as a monopole system when one of the main DC poles is out of service due to a planned or unplanned outage. When a converter terminal is taken out-of-service for maintenance, the main conductor associated with that pole can be used as a current return path (see Figure 11a).

LCC and VSC systems respond to differently to disturbances and events on the AC and DC power system.

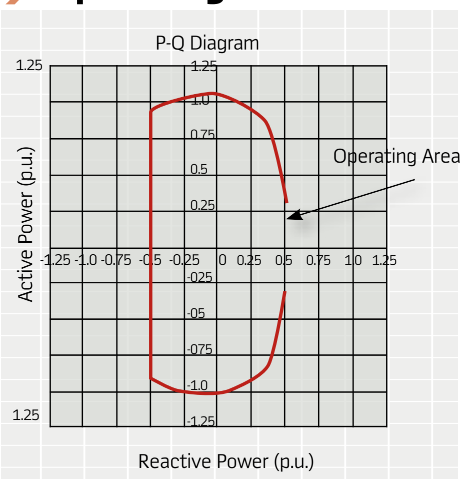
Response to DC Faults

For DC line faults, LCC and VSC systems behave differently. For a DC line fault, an LCC system will "block" the faulted pole allowing the arc to extinguish and restore the faulted pole to operation in the 0.5 to 0.7-second time range. Only one converter terminal will be able to feed the fault, since the thyristors can only conduct in one direction, and the other terminal will take control action. While the faulted pole is blocked, the system is operating as a monopole system utilizing earth return (see Figure 11b). The DC smoothing reactor limits the rate of rise of the DC fault current.

8 MMC with 12 half bridge modules per phase



9 Operating characteristic



VSC systems cannot interrupt DC line faults since the IGBTs have an uncontrolled conduction path in the body diode. In present systems, all DC line faults are cleared by opening breakers on the AC side of the system, typically on the high-side of the converter transformers. The inability to interrupt DC line faults is one of the disadvantages of VSC systems because any DC line fault results in a total shutdown of the HVdc system and an extended outages (i.e., minutes of outage time versus less than a second). As a result, nearly all VSC systems use underground or underwater cables to reduce exposure to DC side faults. All of the major HVdc vendors are working on HVdc circuit breakers, with an objective of being able to clear faults within 2-5 ms.

Integration Considerations

Faults on the AC system can also have an impact on the operation of the HVdc converter. Low-voltage faults near an LCC inverter terminal can result in the converter experiencing a commutation failure. A commutation failure happens when the voltage across the thyristor does not have a high enough reverse polarity to stop current flow in the thyristor. Current continues to flow in the wrong path of the DC bridges and the converter is effectively short circuited on the DC side and no power is transferred until the commutation failure is corrected. Fortunately, once the fault is cleared there is a high probability that the commutation failure will self-heal and the converter resumes normal operation. If not, then remedial action may be required to trip generation and/or load. A VSC system does not experience commutation failure and can ride through faults a short duration, typically 100 milliseconds or less. That means a VSC system is relatively immune to AC system faults.

In addition, loss of an HVdc pole in a bipole system can result in the loss of a significant amount of load transfer. Consider a 3000 MW bipole HVdc line, loss of one pole means the loss of 1500 MW of transfer capacity. The load on the outaged HVdc pole will transfer to the surrounding AC systems, if there is one, or will result in excess generation or load. The application of HVdc systems require detailed study to determine the impact to the AC system on a monopole or bipole loss. Remedial action schemes may be required to separate system, drop generation or drop load to keep the AC system stable.

Loss of an AC line (or lines) does not have the same impact on an HVdc system. Power flow on an HVdc system is controlled and set to a specific value. The only way to change power flow is via some intervention, either human or some automated action. That means that loss of AC lines do not result in automatic power transfer to the HVdc system unless it is a predefined and programmed control action.

AC System Faults

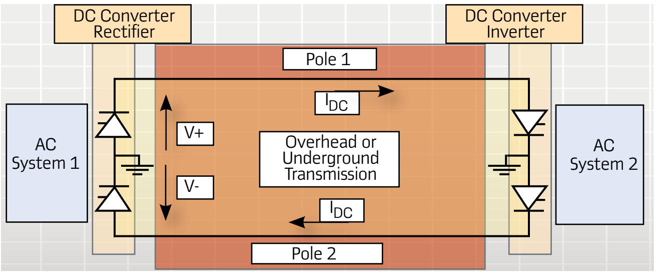
HVdc systems do not contribute a significant amount of current to faults on the AC system. This can be a benefit of integrating HVdc into AC systems with high fault current capabilities; the HVdc system will not cause a significant increase in the total fault duty. As described previously, a LCC system could contribute no current as a result of a commutation failure. If the voltage is high enough for correct commutation, the HVdc converter will appear as an ideal current source supplying a short circuit current level equal to the power order and the current will not increase significantly.

A VSC system operates differently and the response customized based upon the system need and the current rating of the IGBTs used in the converter. Typically, a VSC system is limited to 1.1 to 1.25 per unit current output for short circuit conditions. The control loops for the converters have the ability to regulate the AC current within a fraction of a cycle to protect the IGBTs from destructive current levels. In addition, the VSC control logic is typically designed so that the converter will only output balanced or positive-sequence current for all fault types.

> The response of VSC systems to AC system faults and dynamic conditions is much different than conventional AC system sources, such as AC generators.

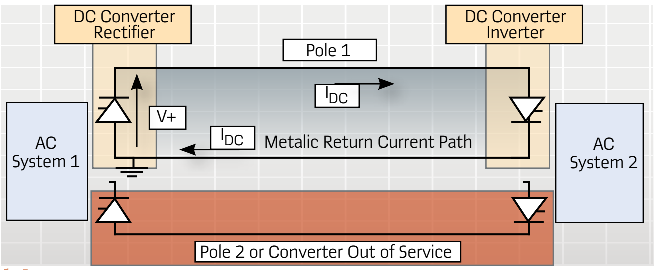
Conclusion: HVdc transmission has seen explosive growth around the world in the last 15 years, with many new installations. Earlier systems installed over the past 60 years are seeing refurbishment because of demonstrated high-availability and the value the HVdc system adds too the reliable operation of the AC power system.

10 Bipole HVdc system



11 Monopole HVdc System

a) Metallic Return



b) Earth Return