J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HVDC POWER CONVERTERS

Electric power transmission was originally developed with direct current. The availability of transformers and the development and improvement of induction motors at the beginning of the twentieth century led to greater appeal and use of ac transmission. Through research and development in Sweden at Allmana Svenska Electriska Aktiebolaget (*ASEA*), an improved multielectrode grid-controlled mercury arc valve for high power and voltages was developed in 1929. Experimental plants were set up in the 1930s in Sweden and the USA to investigate the use of mercury arc valves in conversion processes for transmission and frequency changing.

Then dc transmission became practical when long distances were to be covered or where cables were required. The increase in the need for electricity after the Second World War stimulated research, particularly in Sweden and in Russia. In 1950, a 116 km experimental transmission line at 200 kV was commissioned from Moscow to Kasira. The first commercial HVDC line built in 1954 was a 98 km submarine cable with earth return between the island of Gotland and the Swedish mainland.

Thyristors were applied to dc transmission in the late 1960s, and solid-state valves became a reality. In 1969, a contract for the Eel River dc link in Canada with awarded as the first application of solid-state valves for HVDC transmission. Today, the highest functional dc voltage for dc transmission is ±600 kV for the 785 km transmission line of the Itaipu scheme in Brazil. Dc transmission is now an integral part of electricity delivery in many countries throughout the world.

Why Use DC Transmission?

The question is often asked, “Why use dc transmission?” One response is that losses are lower, but this is not strictly correct. The level of losses is designed into a transmission system and is regulated by the size of the conductor selected. Dc and ac conductors, as overhead transmission lines or submarine cables, can have lower losses but at higher expense because the larger cross-sectional area generally results in lower losses but costs more.

When converters are used for dc transmission in preference to ac transmission, it is generally by economic choice driven by one of the following reasons:

(1) An overhead dc transmission line with its towers can be designed to cost less per unit of length than an equivalent ac line designed to transmit the same level of electric power. However the dc converter stations at each end are more costly than the terminating stations of an ac line, and so there is a breakeven distance above which the total cost of dc transmission is less than its ac transmission alternative. The dc transmission line can have a lower visual profile than an equivalent ac line and so contributes to a lower environmental impact. Other environmental advantages to a dc transmission line are dc instead of ac electric and magnetic fields.

(2) If transmission is by submarine or underground cable, the breakeven distance is much less than overhead transmission. It is not practical to consider ac cable systems exceeding 50 km, but dc cable transmission

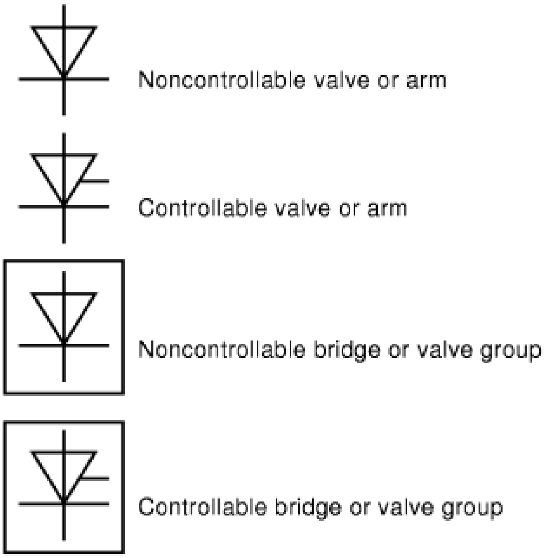


Fig. 1. Standard graphical symbols for valves and bridges.

systems in service are as long as hundreds of kilometers. Distances of 600 km or greater have been considered feasible.

(3) Some ac electric power systems are not synchronized with neighboring networks even though the physical distances between them are quite small. This occurs in Japan where part of the country has a 60 Hz network and the other part has a 50 Hz system. It is physically impossible to connect the two together by direct ac methods to exchange electric power between them. However, if a dc converter station is located in each system with an interconnecting dc link, it is possible to transfer the required power even though the ac systems so connected remain asynchronous.

Configurations

The integral part of an HVDC power converter is the valve or valve arm. It is noncontrollable if constructed from one or more power diodes in series and controllable if constructed from one or more thyristors in series. Figure 1 depicts the International Electrotechnical Commission (IEC) graphical symbols for valves and bridges (1). The standard bridge or converter connection is defined as a two-way connection comprising six valves or valve arms which are connected as illustrated in Fig. 2. Electric power flowing between the HVDC valve group and the ac system is three-phase. When electric power flows into dc valve group from the ac system, then it is considered a rectifier. If power flows from the dc valve group into the ac system, it is an inverter. Each valve consists of many series-connected thyristors in thyristor modules. Figure 2 depicts the electric circuit network for the six-pulse valve group. The six-pulse valve group was usual when valves were mercury arc.

Twelve-Pulse Valve Group. Nearly all HVDC power converters with thyristor valves are assembled in a converter bridge of twelve-pulse configuration. Figure 3 illustrates the use of two three-phase converter transformers with one dc side winding, one as an ungrounded star connection and the other a delta configuration. Consequently the ac voltages applied to each six-pulse valve group of the twelve-pulse valve group have a phase difference of 30° which is utilized to cancel the ac side fifth and seventh harmonic currents and, the dc side sixth harmonic voltage, thus resulting in a significant saving in harmonic filters. Figure 3 also shows

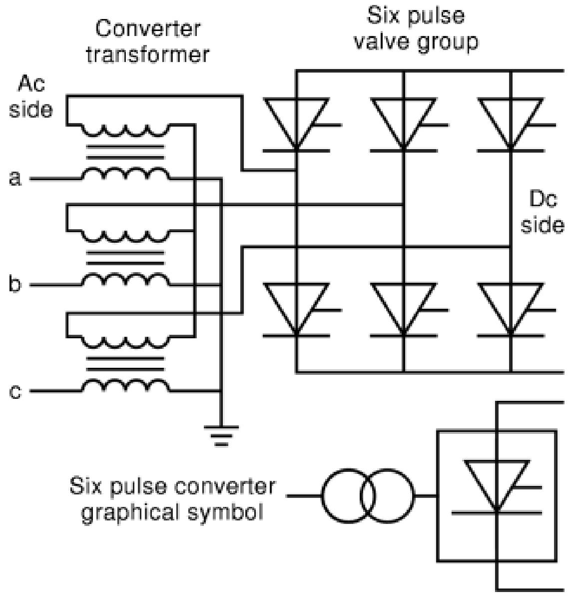


Fig. 2. Electric circuit configuration of the basic six-pulse valve group with its converter transformer in star–star connection.

the outline around each of the three groups of four valves in a single vertical stack. Known as "quadrivalves," they are assembled as one valve structure by stacking four valves in series. Because the voltage rating of thyristors is several kilovolts, a 500 kV quadrivalve may have hundreds of individual thyristors connected in series groups of valve or thyristor modules. A quadrivalve for a high-voltage converter is mechanically quite tall and may be suspended from the ceiling of the valve hall, especially in locations susceptible to earthquakes.

Thyristor Module. A thyristor or valve module is part of a valve in a mechanical assembly of series-connected thyristors and their immediate auxiliaries, including heat sinks cooled by air, water or glycol, damping circuits, and valve firing electronics. A thyristor module is usually interchangeable for maintenance and consists of electric components, as shown in Fig. 4.

Substation Configuration. The central equipment of a dc substation (2) consists of the thyristor converters which are usually housed inside a valve hall. Outdoor valves have been used as in the Cahora Bassa dc transmission line between Mozambique and South Africa. Figure 5 is a schematic of the electrical equipment required for a dc substation. In this example, two poles are represented, which is usual and it is known as the "bipole" configuration. Some dc cable systems have only one pole or "monopole" configuration and may either use the ground as a return path, when permitted, or use an additional cable to avoid Earth currents.

From Fig. 5, the essential equipment in a dc substation, in addition to the valve groups, includes the converter transformers. They transform the ac system voltage to which the dc system is connected so that the correct dc voltage is derived by the converter bridges. For higher rated dc substations, converter transformers for 12-pulse operation are usually comprised of single-phase units which is cost effective in providing spare units for increased reliability.

The secondary or dc side windings of the converter transformers are connected to the converter bridges. The converter transformer is located in the switchyard. If the converter bridges are located in the valve hall, the connection has to be made through its wall in either of two ways, first, with phase-isolated busbars whose bus conductors are housed within insulated bus ducts containing oil or SF6 as the insulating medium or, secondly,

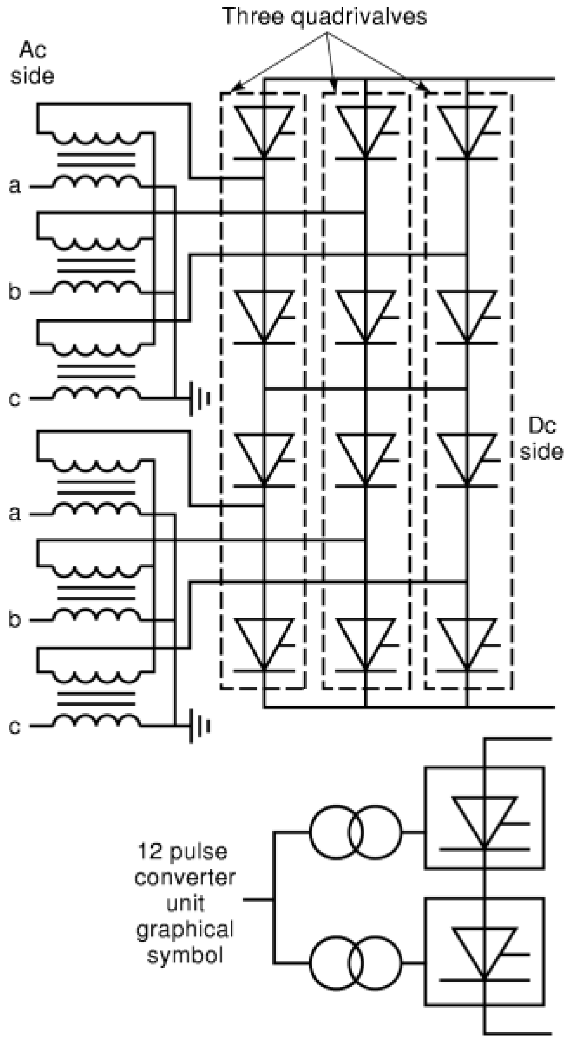


Fig. 3. The twelve-pulse valve group configuration with two converter transformers, one in star–star connection and the other in star–delta connection.

with wall bushings. When applied at dc voltages of 400 kV or greater, wall bushings require considerable design and care to avoid external or internal insulation breakdown.

Harmonic filters are required on the ac side and usually on the dc side. The characteristic ac side current harmonics generated by six-pulse converters are $6n \pm 1$ and $12n \pm 1$ for 12-pulse converters where n equals all positive integers. Ac filters are typically tuned to the 11th, 13th, 23rd, and 25th harmonics for 12-pulse converters. Tuning to the fifth and seventh harmonics is required if six-pulse converters are permitted. Ac side harmonic filters may be switched with circuit breakers or circuit switchers to accommodate reactive power requirement strategies because these filters generate reactive power at fundamental frequency. A parallel resonance is naturally created between the capacitance of the ac filters and the inductive impedance of the ac system. For the special case where such a resonance is lightly damped and tuned to a frequency between

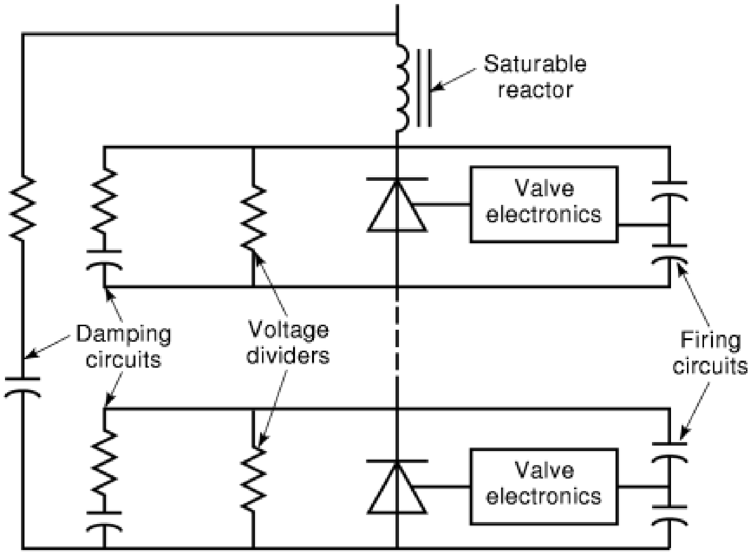


Fig. 4. Components of the thyristor modules which make up a valve or quadrivalve.

the second and fourth harmonics, then a low-order harmonic filter at the second or third harmonic may be required, even for 12-pulse converter operation.

Characteristic dc side voltage harmonics generated by a six-pulse converter are of the order of 6n and when generated by a 12-pulse converter, are of the order of 12n. Dc side filters reduce harmonic current flow on dc transmission lines to minimize coupling and interference with adjacent voice frequency communication circuits. Where there is no dc line, such as in the back-to-back configuration, dc side filters may not be required.

Dc reactors are usually included in each pole of a converter station. They assist the dc filters in filtering harmonic currents and smooth the dc side current so that a discontinuous current mode is not reached at low load current operation. Because the rate of change of dc side current is limited by the dc reactor, the commutative process of the dc converter is more robust.

Surge arresters across each valve in the converter bridge, across each converter bridge, and in the dc and ac switchyards are coordinated to protect the equipment from all overvoltages regardless of their source. They may be used in nonstandard applications, such as filter protection. Modern HVDC substations use metal oxide arresters whose rating and selection are made with careful insulation coordination design.

Applications of HVDC Converter Bridges

The first application for HVDC converters was to provide point-to-point electrical power interconnections between asynchronous ac power networks. The other applications which can be met by HVDC converter transmission include the following:

(1) Interconnections between asynchronous systems. Some continental electric power systems consist of asynchronous networks, such as the East, West, Texas, and Quebec networks in North America, and island loads, such as the Island of Gotland in the Baltic Sea, make good use of HVDC interconnections.

(2) Delivering energy from remote energy sources. Where generation has been developed at remote sites of available energy, HVDC transmission has been economical for bringing the electricity to load centers. Gas-

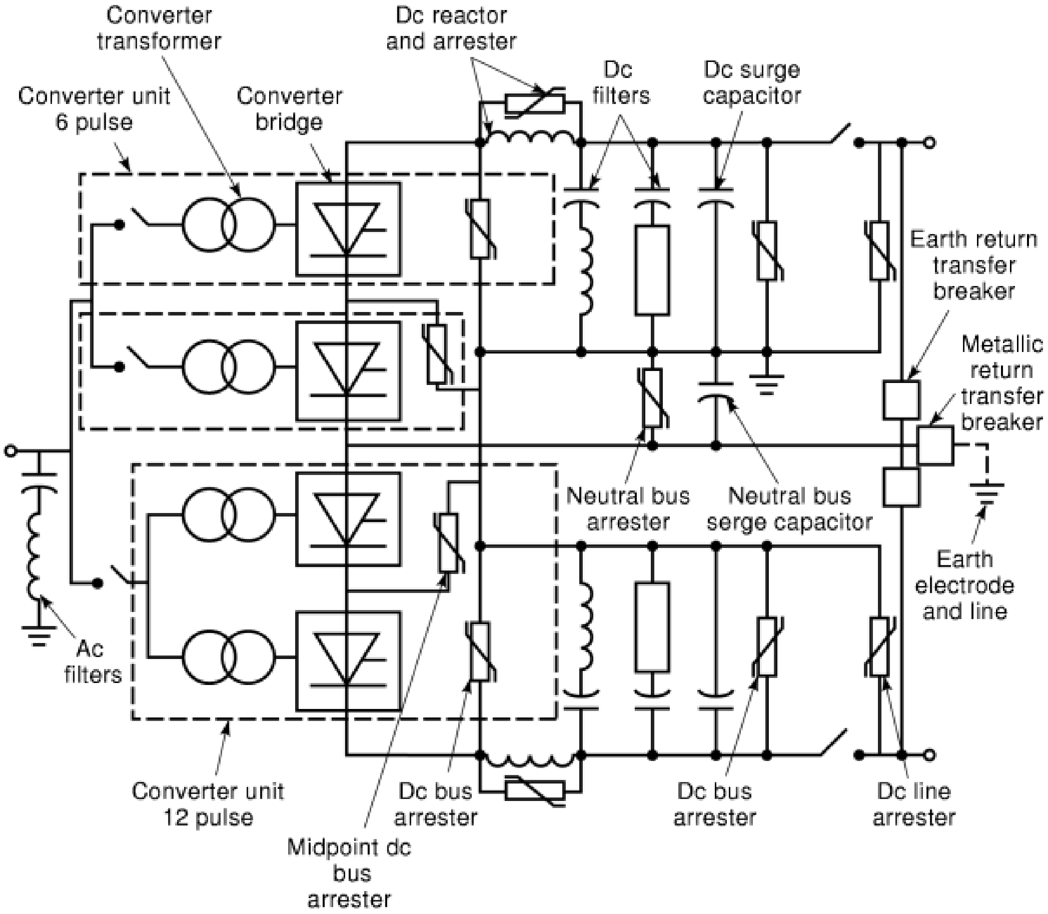


Fig. 5. Example of an HVDC substation.

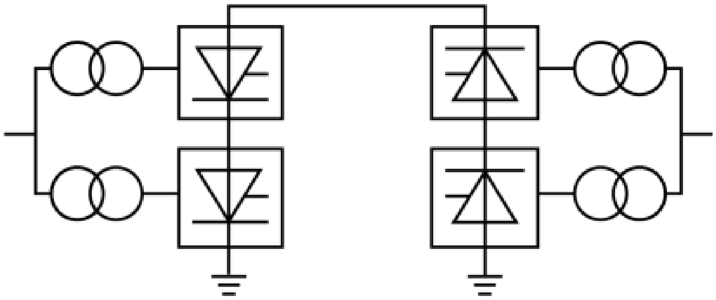
fired thermal generation can be located close to load centers and may delay development of isolated energy sources in the near term.

(3) Importing electric energy into congested load areas. In areas where new generation is impossible to put in service to meet load growth or replace inefficient or decommissioned plants, underground dc cable transmission is a viable means of importing electricity.

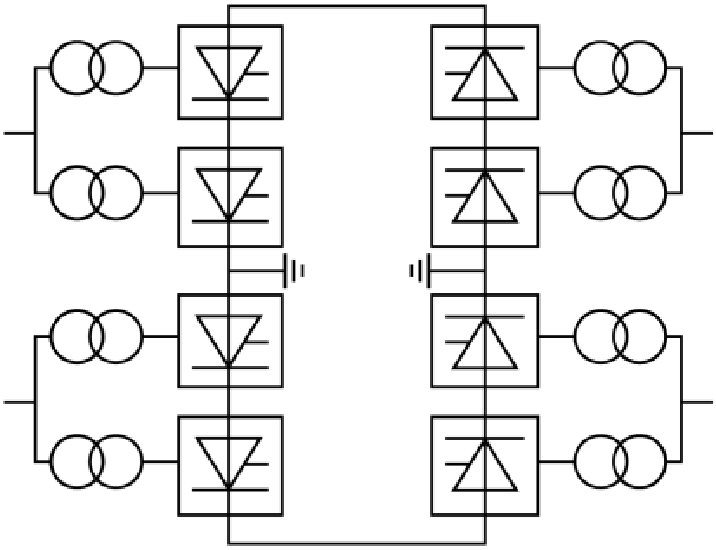
(4) Increasing the capacity of existing ac transmission by conversion to dc transmission. New transmission rights-of-way may be impossible to obtain. Existing overhead ac transmission lines upgraded to or overbuilt with dc transmission can substantially increase the power transfer capability on the existing right-of-way.

(5) Power flow control. AC networks do not easily accommodate desired power-flow control. Power marketers and system operators may require the power-flow control capability provided by HVDC transmission.

(6) Stabilization of electric power networks. Some widespread ac power system networks operate at stability limits well below the thermal capacity of their transmission conductors. HVDC transmission is an option to increase utilization of network conductors along with the various electronic power controllers which can be applied to ac transmission.



Monopolar configuration



Bipolar configuration

Fig. 6. Monopolar and bipolar connection of HVDC converter bridges.

HVDC Converter Arrangements. HVDC converter bridges and lines or cables can be arranged in a number of effective configurations. Converter bridges may be arranged either as monopolar or bipolar, as shown in the 12-pulse arrangement in Fig. 6. Various ways of using HVDC transmission are shown in simplified form in Fig. 7 and include the following:

(1) Back-to-back. There are some applications where the two ac systems to be interconnected are in the same physical location or substation. No transmission line or cable is required between the converter bridges in this case and the connection may be monopolar or bipolar. Back-to-back dc links are used in Japan for interconnections between power system networks of different frequencies (50 and 60 Hz). They are also used as interconnections between adjacent asynchronous networks.

(2) Transmission between two substations. When it is economical to transfer electric power through dc transmission or cables from one geographical location to another, two-terminal or point-to-point HVDC transmission is used. In other words, dc power from a dc rectifier terminal is dedicated to one other terminal operating as an inverter. This is typical of most HVDC transmission systems

Table 1. Four Representative HVDC Systems for Substation Cost Analysis

System No.	Dc Voltage (kV)	Capacity (MW)	Ac Voltage (kV)
1	±250	500	230
2	±350	1000	345
3	±500	3000	500
4	Back-to-back	200	230

(3) Multiterminal HVDC transmission system. When three or more HVDC substations are geographically separated and have interconnecting transmission lines or cables, the HVDC transmission system is multiterminal. If all substations are connected to the same voltage, then the system is parallel multiterminal dc. If one or more converter bridges are added in series in one or both poles, then the system is series multiterminal dc. Parallel multiterminal dc transmission has been applied when the capacity of any substation exceeds 10% of the total rectifier substation capacity. It is expected that a series multiterminal substation would be applied when its capacity is small (less than 10%) compared to the total rectifier substation capacity. A combination of parallel and series connections of converter bridges is a hybrid multiterminal system. Multiterminal dc systems are more difficult to justify economically because of the cost of the additional substations.

(4) Unit connection. When dc transmission is applied right at the point of generation, it is possible to connect the converter transformer of the rectifier directly to the generator terminals so that the generated power feeds into the dc transmission lines. This might be applied with hydro and wind turbine generators so that the turbine's maximum efficiency is achieved with speed control. Regardless of the turbine speed, the power is delivered through the inverter terminal to the ac receiving system at its fundamental frequency of 50 or 60 Hz.

(5) Diode rectifier. It has been proposed that in some applications where dc power transmission is only in one direction, the valves in the rectifier converter bridges can be constructed from diodes instead of thyristors. Power-flow control would be achieved at the inverter, and where the unit connection is used, ac voltage control by the generator field exciter could be applied to regulate dc power. This connection may require high-speed ac circuit breakers between the generator and the rectifier converter bridges to protect the diodes from overcurrents resulting from a sustained dc transmission line short circuit.

Economic Considerations. A study for Oak Ridge National Laboratory (3) surveyed three suppliers of HVDC equipment for quotations of turnkey costs to supply two bipolar substations for four representative systems. Each substation requires one dc electrode and interfaces to an ac system with a short circuit capacity four times the rating of the HVDC system. The four representative systems are summarized in Table 1. Table 2 provides a major component breakdown based on avarage values derived from the responses of the suppliers. The turnkey costs are in 1995/96 US dollars and are only for one terminal, assuming that both terminals are provided by the same supplier. The back-to-back dc link cost is for the complete installation.

Transmission line costs cannot be so readily defined. Variations depend on the cost of land use, the width of the right-of-way required, labor rates for construction, and the difficulty of the terrain to be crossed. A simple guideline is that the cost of dc transmission line is 80% to 100% of the cost of an ac line whose rated line voltage is the same as the rated pole-to-ground voltage of the dc line. The cost advantage of dc transmission for traversing long distances is that it may be rated at twice the power-flow capacity of an ac line of the same voltage.

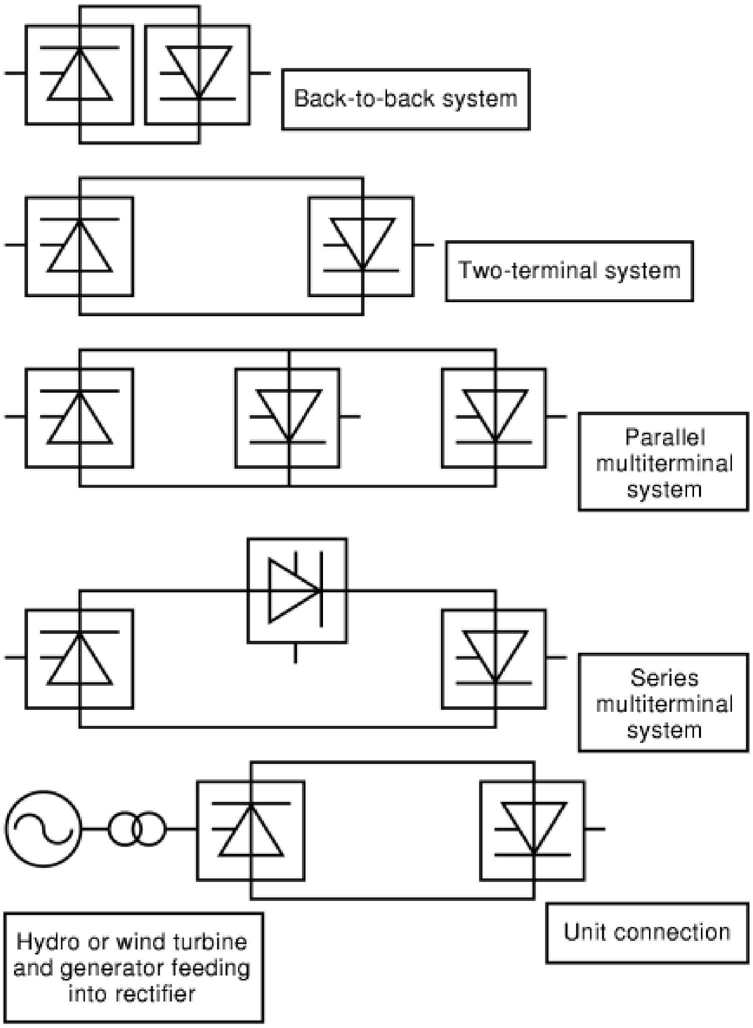


Fig. 7. HVDC converter bridge arrangements.

When electricity must be transmitted by underground or undersea cables, ac cables become impractical because of their capacitive charging current if they are longer than a critical length which is less than 50 km for undersea applications. For distances longer than this critical length, dc cables are required. The choice is system-specific, and economic considerations prevail.

Environmental Considerations

The electrical environmental effects from HVDC transmission lines can be characterized by field, ion, and corona effects (4,5). The electric field arises from both the electrical charge on the conductors and from charges on air ions and aerosols surrounding the conductor in a HVDC overhead transmission line. These give rise to dc electric fields due to the ion current density flowing through the air from or to the conductors and due to the

Table 2. Average Breakdown of HVDC Turnkey Costs from Three HVDC Suppliers

Item	Project Component	Back-to-Back 200 MW	±250 kV 500 MW	±350 kV 1000 MW	±500 kV 3000 MW
1	Converter valves	19.0%	21.0%	21.3%	21.7%
2	Conv. transformers	22.7%	21.3%	21.7%	22.0%
3	DC switchyard	3.0%	6.0%	6.0%	6.0%
4	AC switchyard	10.7%	9.7%	9.7%	9.3%
5	Control, protection, and communication	8.7%	8.0%	8.0%	7.7%
6	Civil works	13.0%	13.7%	13.7%	13.7%
7	Auxiliary power	2.0%	2.3%	2.3%	2.3%
8	Project admin.	21.0%	18.0%	17.3%	17.3%
Total estimated cost $MUS		43.3	145.0	213.7	451.7
Cost–$/kW/station		217	145	107	75

ion density in the air. A static magnetic field is produced by dc current flowing through the conductors. Air ions produced by HVDC lines form clouds which drift away from the line when blown by the wind and may come in contact with humans, animals, and plants outside the transmission line's right-of-way or corridor. The corona effects may produce low levels of radio interference, audible noise, and ozone.

Field and Corona Effects. The field and corona effects of transmission lines largely favor dc over ac transmission. The significant considerations are as follows:

(1) For a given power transfer requiring extra high voltage transmission, the dc transmission line has a tower profile smaller than the equivalent ac tower carrying the same level of power. This can also lead to a narrower right-of-way for dc transmission.

(2) The steady and direct magnetic field of a dc transmission line near or at the edge of the transmission right-of-way has about the magnitude as the earth's naturally occurring magnetic field. For this reason alone, it seems unlikely that this small contribution by HVDC transmission lines to the background geomagnetic field is a basis for concern.

(3) The static and steady electric field from dc transmission at the levels experienced beneath lines or at the edge of the right-of-way have no known adverse biological effects. There is no theory or mechanism to explain how a static electric field at the levels produced by dc transmission lines could affect human health. The electric field level beneath a HVDC transmission line has a magnitude similar to the naturally occurring static field which exists beneath thunder clouds. Electric fields from ac transmission lines have undergone more intense scrutiny than fields generated by dc transmission lines.

(4) The ion and corona effects of dc transmission lines contribute a low level of ozone production to higher naturally occurring background concentrations. Exacting long-term measurements are required to detect such concentrations. The measurements taken at cross-sections across the Nelson River dc lines in Canada failed to distinguish background from downwind levels (4). Although solar radiation influences the production of ozone even in a rural environment, thereby maintaining its level, any incremental contribution from a dc line is subject to breakdown, leading to a resumption of background levels downwind from the line. Investigations of ozone in indoor conditions indicate that in well-mixed air, the half-life of ozone is 1.5 min to 7.9 min. Increases in temperature and humidity increase the rate of decay (4).

(5) If ground return is used with monopolar operation, the resulting dc magnetic field can cause error in magnetic compass readings in the vicinity of the dc line or cable. This impact is minimized by providing a conductor or cable return path (known as a metallic return) close to the main conductor or cable to cancel the magnetic field. Another concern with continuous ground current is that some of the return current may flow in metallic structures, such as pipelines, and intensify corrosion if cathodic protection is not provided. When pipelines or other continuous metallic grounded structures are in the vicinity of a dc link, a metallic return may be necessary.

DC Converter Operation

The six-pulse converter bridge of Fig. 2, the basic converter unit of HVDC transmission, is used equally well for rectification when electric power flows from the ac to the dc side and for inversion when the power flow is from the dc to the ac side. Thyristor valves operate as switches which turn on and conduct current, when fired on receiving a gate pulse, and are forward-biased. A thyristor valve conducts current in one direction and, once it conducts, turns off only when it is reverse-biased and the current falls to zero. This process is known as line commutation and is discussed in more detail below.

An important property of the thyristor valve is that once its conducting current falls to zero, when it is reverse-biased and the gate pulse is removed, too rapid an increase in the magnitude of the forward-biased voltage causes the thyristor to turn on inadvertently and conduct. The design of the thyristor valve and converter bridge must ensure that such a condition is avoided in useful inverter operation.

Commutation. Rectification or inversion for HVDC converters is accomplished through a process known as line or natural commutation. The valves act as switches so that the ac voltage is sequentially switched to provide always a dc voltage. With line commutation the ac voltage at both the rectifier and inverter must be provided by the ac networks at each end and should be three-phase and relatively free of harmonics, as depicted in Fig. 8. As each valve switches on, it begins to conduct current while the current begins to fall to zero in the next valve to turn off. Commutation is the process of transferring current between any two converter valves, and both valves carry current simultaneously during the process.

Consider the rectification process. Each valve switches on when it receives a firing pulse to its gate and its forward-bias voltage becomes more positive than the forward-bias voltage of the conducting valve. The current flow through a conducting valve does not change instantaneously as it commutates to another valve because the transfer is through transformer windings. The leakage reactance of the transformer windings is also the commutative reactance so long as the ac filters are located on the primary or ac side of the converter transformer. The commutative reactance at the rectifier and inverter is shown as an equivalent reactance X_{C} in Fig. 8. The sum of all of the valve currents transferred to the dc side and through the dc reactor is the direct current, and it is relatively flat because of the inductance of the dc reactor and converter transformer.

At the inverter, the three-phase ac voltage supplied by the ac system provides the forward- and reverse-bias conditions of each valve in the converter bridge to allow commutation of current between valves, as in the rectifier. The inverter valve can only turn on and conduct when the positive direct voltage from the dc line is greater than the back negative voltage derived from the ac commutative voltage of the ac system at the inverter.

Because of the line-commutative, valve-switching process, a nonsinusoidal current is taken from the ac system at the rectifier (I_{vr} in Fig. 8) and is delivered to the ac system at the inverter (I_{vi} in Fig. 8). Both I_{vr} and I_{vi} lag the alternating voltage. This nonsinusoidal current waveform consists of the fundamental frequency ac component plus higher harmonics taken from and injected into each ac system. The ac filters divert the harmonics from entering the ac system by offering a low impedance bypass path that allows the commutative voltage to be relatively harmonic-free (U_{Lr} and U_{Li} in Fig. 8).

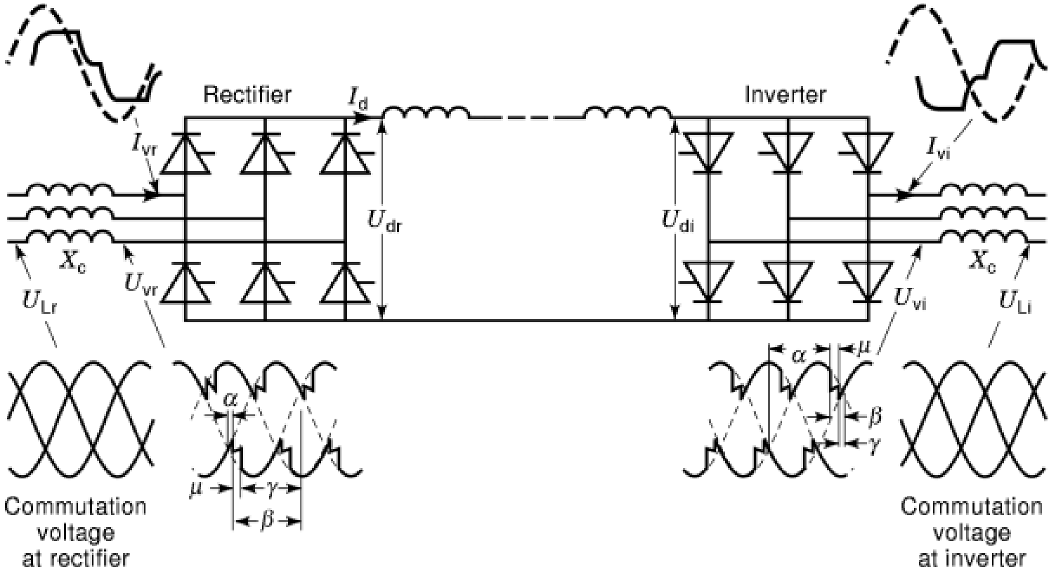


Fig. 8. Voltage and current waveshapes associated with dc converter bridges.

Reversal of power flow in a line-commutated dc link is not possible by reversing the direction of the direct current. The valves allow conduction only in one direction. Power flow can be reversed only in line-commutated dc converter bridges by changing the polarity of the direct voltage. The dual operation of the converter bridge as either a rectifier or inverter is achieved through firing control of the grid pulses.

Converter Bridge Angles. Figure 8 shows the various electrical angles which define the operation of converter bridges. These angles are measured on the three-phase, valve-side voltages and are based on steady-state conditions with a harmonic-free and idealized three-phase commutative voltage. They apply to both inverters and rectifiers.

Delay Angle α. The time expressed in electrical angular measure from the zero crossing of the idealized sinusoidal commutating voltage to the starting instant of forward-current conduction. This angle is controlled by the gate firing pulse and if less than 90°, the converter bridge is a rectifier, and if greater than 90°, it is an inverter. This angle is often referred to as the firing angle.

Advance Angle β. The time expressed in electrical angular measure from the starting instant of forward-current conduction to the next zero crossing of the idealized sinusoidal commutating voltage. The angle of advance β is related in degrees to the angle of delay α by

$$\beta = 180.0 - \alpha \tag{1}$$

Overlap Angle μ. The duration of commutation between two converter valve arms expressed in electrical angular measure.

Extinction Angle γ. The time expressed in electrical angular measure from the end of current conduction to the next zero crossing of the idealized sinusoidal commutating voltage. γ depends on the angle of advance β and the angle of overlap μ and is determined by the relationship

$$\gamma = \beta - \mu \tag{2}$$

Steady-State dc Converter Bridge Equations. It is useful to express the commutative reactance of a six-pulse converter bridge per unit of the converter transformer rating S_N as follows:

$$S_N = \sqrt{2} U_{VN} I_{dN} \tag{3}$$

where I_{dN} is the rated direct current and U_{VN} is the rated phase-to-phase voltage on the valve or secondary side of the converter transformer. Usually the dc converter bridge power rating is known from its rated dc current I_{dN} and rated dc voltage U_{dN}. The valve and converter bridge design are very dependent on the commutative reactance X_C, and so consequently its value is established and known. In modern HVDC converter bridges it is usually in the range $0.1 < X_C < 0.15$ per unit where 1.0 per unit is $(U_{VN})^2/S_N$ Ω.

A reasonably good approximation for the power factor of a converter bridge at the ac commutating bus is given by the following expression for a rectifier. Note that the delay angle α is usually known or determined. For example, the normal steady-state range of the delay angle for a rectifier may be $10° < \alpha < 18°$, and the lowest normal operating power factor occurs when $\alpha = 18°$:

$$\text{Power factor} = \cos\theta = \cos\alpha - 0.5 X_C (I_d / I_{dN}) \tag{4}$$

and for an inverter,

$$\text{Power factor} = \cos\theta = \cos\gamma - 0.5 X_C (I_d / I_{dN}) \tag{5}$$

where I_d is the dc load current, I_{dN} is the rated dc current, and θ is the power factor angle. For the inverter, the normal rated extinction angle is established in the converter bridge design, usually at $\gamma = 18°$. Ignoring the losses in the converter bridge, the power flowing through the bridge P_d is given by

$$P_d = I_d U_d \tag{6}$$

where I_d is the operating direct current through the converter bridge and U_d is the operating direct voltage across the converter bridge. Having calculated the power factor angle θ from Eq. (4) or (5) and the throughput power of the converter bridge from Eq. (6), the reactive power Q_L demanded by the converter bridge at the ac commutating voltage busbar at either the rectifier or inverter is given by

$$Q_L = P_d \tan\theta \tag{7}$$

It may be that the rated phase-to-phase voltage U_{VN} on the valve or secondary side of the converter transformer is not known. It is possible to compute what it should be if the power factor cos θ from Eq. (4) or (5) is known at the converter bridge rating. Then a good estimate of U_{VN} is given by

$$U_{VN} = U_{dN} / (1.35 \cos\theta) \tag{8}$$

Once U_{VN} is known, it is possible to find the converter transformer rating from Eq. (3).

It may be necessary to determine the overlap angle μ. At the rectifier, the following approximate expression can be applied when the delay angle α per unit of commutating reactance X_C and the dc load current I_d are known:

$$\cos(\alpha + \mu) = \cos\alpha - X_C I_d / I_{dN} \tag{9}$$

Similarly at the inverter, the extinction angle γ is usually known for steady-state operation so that

$$\cos(\gamma + \mu) = \cos \gamma - X_C I_d / I_{dN} \qquad (10)$$

The delay angle α at the inverter may not be inherently known, but once the extinction angle γ and the overlap angle μ have been determined, then

$$\alpha = 180^\circ - (\gamma + \mu) \qquad (11)$$

It is also possible to determine the nominal turns ratio of the converter transformer once the rated secondary (dc valve side) voltage U_{VN} is known and if the primary side rated phase-to-phase ac bus voltage U_{LN} is also known. Based on phase-to-phase voltages, the nominal turns ratio of the converter transformer TR_N is given by

$$\begin{aligned} TR_N &= \frac{\text{Valve side phase-to-phase rated voltage}}{\text{ac side phase-to-phase rated voltage}} \\ &= U_{VN}/U_{LN} \end{aligned} \qquad (12)$$

During the operation of a converter bridge, the converter transformer on-line tap changer adjusts to keep the delay angle α at a rectifier in its desired normal operating range. Similarly at the inverter, the on-line tap changer adjusts to maintain the inverter operation at its desired level of dc voltage U_d or extinction angle γ. Knowing the desired levels of dc voltage (U_d), the dc current I_d, the nominal turns ratio TR_N of the converter transformer, the operating level of the primary side ac voltage U_L, and the extinction angle γ (if an inverter) or delay angle α (if a rectifier), the per unit turns ratio TR of the converter transformer is found from the expression

$$TR = \frac{U_d + U_{dN} \dfrac{I_d}{I_{dN}} \dfrac{X_C}{(2\cos(\varphi) - X_C)}}{1.35 TR_N U_L \cos \varphi} \qquad (13)$$

where X_C is the commutating reactance for the converter bridge per unit, $\phi = \alpha$ for a rectifier, and $\phi = \gamma$ if an inverter. I_{dN} is the rated dc current for the converter bridge and U_{dN} is its rated dc voltage.

Equations 1 to 13 are the steady-state and reasonably accurate expressions that define the state of a six-pulse converter bridge under ideal conditions. More exacting expressions can be found in Refs. (6,7,8,9,10,11) and can be used if the network data are known with sufficient accuracy to justify precise mathematical formulation. Defining the performance and operation of a converter bridge under dynamic or transient conditions requires a suitable electromagnetic transients simulation program with capability of modeling the valves, converter transformer, the control system which produces the firing pulses to the valves, and the associated ac and dc networks.

Short Circuit Ratio. The strength of an ac network at the bus of a HVDC substation can be expressed by the short circuit ratio (*SCR*), defined as the relationship between the short circuit level in MVA at the HVDC substation bus at 1.0 per unit ac voltage and dc power in MW.

The capacitors and ac filters connected to the ac bus reduce the short circuit level. The effective short circuit ratio (*ESCR*) is the ratio between the short circuit level reduced by the reactive power of the shunt capacitor banks and ac filters connected to the ac bus at 1.0 per unit voltage and the rated dc power.

A lower ESCR or SCR means more pronounced interaction between the HVDC substation and the ac network (9,10). Ac networks can be classified in the following categories according to strength:

strong systems with a high ESCR: ESCR > 3.0
systems with a low ESCR: $3.0 >$ ESCR > 2.0
weak systems with a very low ESCR: ESCR < 2.0

In high ESCR systems, changes in the active/reactive power from the HVDC substation lead to small or moderate ac voltage changes. Therefore the additional transient voltage control at the busbar is not normally required. The reactive power balance between the ac network and the HVDC substation is achieved by switched reactive-power elements.

In low and very low ESCR systems, the changes in the ac network or in the HVDC transmission power could lead to voltage oscillations and a need for special control strategies. Dynamic reactive-power control at the ac bus at or near the HVDC substation by some form of electronic reactive-power controller, such as a static var, compensator (*SVC*) or static synchronous compensator (*STATCOM*), may be necessary (12). In earlier times, dynamic reactive-power control was achieved with synchronous compensators.

Commutation Failure. When a converter bridge operates as an inverter, as represented at the receiving end of the dc link in Fig. 8, a valve turns off when its forward current commutates to zero and the voltage across the valve remains negative. The period for which the valve stays negatively biased is the extinction angle γ, the duration beyond which the valve then becomes forward-biased. Without a firing pulse, the valve ideally stays nonconductive or blocked, even though it experiences a forward bias.

All dc valves require removing the internally stored charges produced during the forward-conducting period (defined by period $\alpha + \mu$ at the inverter in Fig. 8) before the valve can successfully block a forward bias. Therefore the dc inverter requires a minimum period of negative bias or minimum extinction angle γ for successful forward blocking. If forward blocking fails and conduction is initiated without a firing pulse, commutation failure occurs. This also results in an immediate failure to maintain current in the succeeding converter arm as the dc line current returns to the valve which was previously conducting and has failed to sustain forward blocking (13).

Commutation failure at a converter bridge operating as an inverter is caused by any of the following conditions:

(1) When the dc current entering the inverter experiences an increase in magnitude which causes the overlap angle μ to increase, the extinction angle γ is reduced and may reach the point where the valve cannot maintain forward blocking. Increasing the inductance of the dc current path through the converter by the dc smoothing reactor and commutating reactance reduces the rate of change of dc current. This has the greatest effect on commutation failure onset.

(2) When the magnitude of the ac side voltage in one or more phases reduces or is distorted causing an inadequate extinction angle as commutation is attempted.

(3) A phase angle shift in the ac commutating voltage can cause commutation failure. However, the magnitude of ac voltage reduction and not the corresponding phase shift is the most dominant factor determining the onset of commutation failures for single-phase faults.

(4) The value of the predisturbance steady-state extinction angle γ also affects the sensitivity of the inverter to commutation failure. A value of $\gamma = 18^\circ$ is usual for most inverters. Increasing γ to values of 25°, 30°, or higher reduces the possibility of commutation failure (at the expense of increasing the reactive-power demand of the inverter).

(5) The value of valve current before commutation failure also affects the conditions at which a commutation failure may occur. A commutation failure may more readily happen if the predisturbance current is at full load compared to light load current operation.

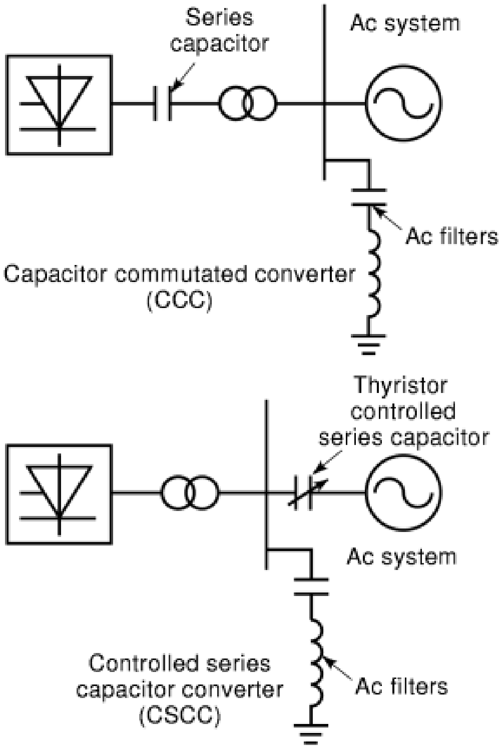


Fig. 9. Configurations for applying series capacitors at HVDC substations.

In general, the more rigid the ac voltage into which the inverter feeds and with an absence of ac system disturbances, the less the likelihood of commutation failures.

Series Capacitors with dc Converter Substations. HVDC transmission systems with long dc cables are prone to commutation failure when there is a drop in dc voltage U_d at the inverter. The dc cable has a very large capacitance which discharges current toward the voltage drop at the inverter. The discharge current is limited by the dc voltage derived from the ac voltage of the commutating bus, from the dc smoothing reactor, and from the commutating reactance. If the discharge current of the cable increases too quickly, commutation failure occurs causing a complete discharge of the cable. Recharging the cable to its normal operating voltage delays recovery.

The converter bridge firing controls can be designed to increase the delay angle α when an increase in dc current is detected. This may be effective until the limit of the minimum allowable extinction angle γ is reached.

Another way to limit the cable discharge current is to operate the inverter bridge with a three-phase series capacitor in the ac system on either side of the converter transformer. Any discharge current from the dc cable passes into the ac system through the normally functioning converter bridge and in doing so, passes through the series capacitor and adds charge to it. As a consequence, the voltage of the series capacitor increases to oppose the cable discharge and is reflected through the converter bridge as an increase in dc voltage U_d. This acts as a back emf and limits the discharge current of the cable, thereby avoiding commutation failure.

The proposed locations of the series capacitor are shown in Fig. 9 in single-line diagram form (14,15). When the capacitor is between the converter transformer and the valve group, it is known as a capacitor commutated converter (*CCC*). When the capacitor is on the ac side of the converter transformer, it is known as

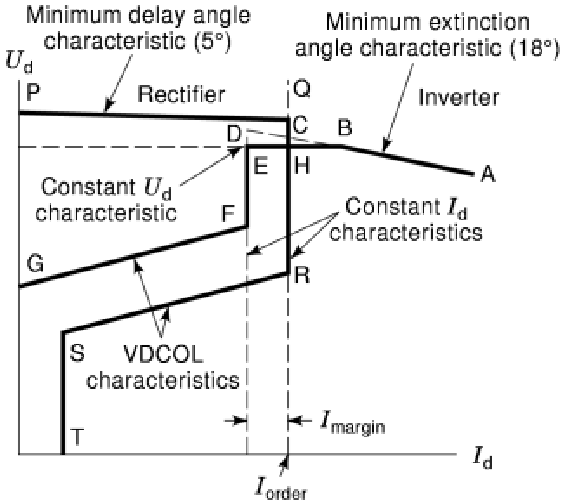


Fig. 10. Steady-state U_d–I_d characteristics for a two-terminal HVDC system.

a controlled series capacitor converter (*CSCC*). Each configuration improves the commutative performance of the inverter, but the CSCC requires design features to eliminate ferroresonance between the series capacitor and the converter transformer if it occurs.

Control and Protection

HVDC transmission systems must transport very large amounts of electric power which is accomplished only under tightly controlled conditions. Dc current and voltage are precisely controlled to effect the desired power transfer. Therefore it is necessary to measure system quantities continuously and precisely. These quantities at each converter bridge include the dc current, its dc side voltage, the delay angle α, and for an inverter, its extinction angle γ.

Two-terminal dc transmission systems are more usual, and they have in common a preferred mode of control during normal operation. Under steady-state conditions, the inverter is assigned the task of controlling the dc voltage. It may do this by maintaining a constant extinction angle γ which causes the dc voltage U_d to droop with increasing dc current I_d, as shown in the minimum constant extinction angle γ characteristic A-B-C-D in Fig. 10. The weaker the ac system at the inverter, the steeper the droop.

Alternatively, the inverter may normally operate in a dc voltage-controlling mode which is the constant U_d characteristic B-H-E in Fig. 10. This means that the extinction angle γ must increase beyond its minimum setting, depicted in Fig. 10 as 18°.

If the inverter operates at a minimum constant γ or constant U_d characteristic, then the rectifier must control the dc current I_d. It can do this so long as the delay angle α is not at its minimum limit (usually 5°). The steady-state constant current characteristic of the rectifier is shown in Fig. 10 as the vertical section Q-C-H-R. The operating point of the HDVC system is where the rectifier and inverter characteristic intersect, either at points C or H.

The operating point is reached by the action of the on-line tap changers of the converter transformers. The inverter must establish the dc voltage U_d by adjusting its on-line tap changer to achieve the desired operating level if it is in constant minimum γ control. If in constant U_d control, the on-line tap changer must adjust its tap to achieve the controlled level of U_d with an extinction angle equal to or slightly larger than its minimum setting of 18° in this case.

The on-line tap changers on the converter transformers of the rectifier are controlled to adjust their tap settings so that the delay angle α has a working range between approximately 10° and 15° to maintain the constant current setting I_order (see Fig. 10). If the inverter is operating in constant dc voltage control at the operating point H and if the dc current order I_order is increased so that the operating point H moves toward and beyond point B, the inverter mode of control reverts to constant extinction angle γ control and operates on characteristic A-B. Dc voltage U_d is less than the desired value, and so the converter transformer on-line tap changer at the inverter boosts its dc side voltage until dc voltage control is resumed.

Not all HVDC transmission controls have a constant dc voltage control, such as depicted by the horizontal characteristic B-H-E in Fig. 10. Instead, the constant extinction angle γ control of characteristic A-B-C-D and the tap changer provide the dc voltage control.

Current Margin. The dc current order I_order is sent to both the rectifier and inverter. It is usual to subtract a small value of current order from the I_order sent to the inverter. This is known as the current margin I_margin and is depicted in Fig. 10. The inverter also has a current controller, and it attempts to control the dc current I_d to the value $I_\mathrm{order} - I_\mathrm{margin}$, but the current controller at the rectifier normally overrides it to maintain the dc current at I_order. This discrepancy is resolved at the inverter in normal steady-state operation as its current controller cannot keep the dc current at the desired value of $I_\mathrm{order} - I_\mathrm{margin}$ and is forced out of action. The current control at the inverter becomes active only when the current control at the rectifier ceases because its delay angle α is pegged against its minimum delay angle limit. This is readily observed in the operating characteristics of Fig. 10 where the minimum delay angle limit at the rectifier is characteristic P-Q. If for some reason or other, such as a low ac commutating voltage at the rectifier end, the P-Q characteristic falls below points D or E, the operating point shifts from point H to somewhere on the vertical characteristic D-E-F where it is intersected by the lowered P-Q characteristic. The inverter reverts to current control, controls the dc current I_d at the value $I_\mathrm{order} - I_\mathrm{margin}$, and the rectifier effectively controls dc voltage as long as it is operating at its minimum delay angle characteristic P-Q. The controls can be designed so that the transition from controlling the current by the rectifier to controlling the current by the inverter is automatic and smooth.

Voltage-Dependent Current-Order Limit (*VDCOL*). During disturbances when the ac voltage at the rectifier or inverter is depressed, it is not helpful to a weak ac system if the HVDC transmission system attempts to maintain full-load current. A sag in ac voltage at either end also results in a reduced dc voltage. The dc control characteristics shown in Fig. 10 indicate that the dc current order is reduced if the dc voltage is lowered. This can be observed in the rectifier characteristic R-S-T and in the inverter characteristic F-G in Fig. 10. The controller which reduces the maximum current order is known as a voltage-dependent current order limit or *VDCOL* (sometimes called a *VDCL*). If invoked by an ac system disturbance, the VDCOL control keeps the dc current I_d to the lowered limit during recovery which aids the corresponding recovery of the dc system. Only when the dc voltage U_d has recovered sufficiently does the dc current return to its original I_order level.

Figure 11 is a schematic diagram showing how dc transmission system controls are usually implemented.

Ac Voltage Control. It is desirable to maintain the ac system and commutating bus voltage rigidly at a constant value for best operation of an HVDC transmission system. This is more easily achieved when the short circuit ratio is high. With low or very low short circuit ratio systems, difficulties may arise following load changes. With fast load variation, there can be an excess or deficiency of reactive power at the ac commutating bus which results in over- and undervoltages, respectively. When the ac system is weak, changes in converter ac bus voltage following a disturbance may be beyond permissible limits. In such cases, an ac voltage controller is required for the following reasons:

(1) To limit dynamic and transient overvoltage to within permissible limits defined by substation equipment specifications and standards.

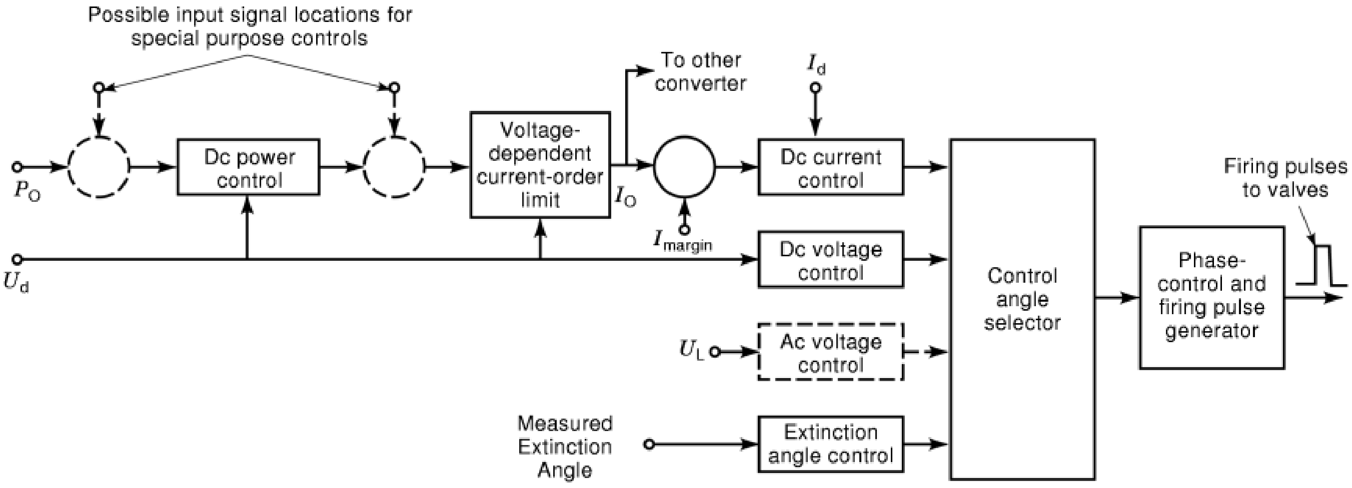


Fig. 11. HVDC control system layout.

(2) To prevent ac voltage flicker and commutation failure due to ac voltage fluctuations when load and filter switching occurs.
(3) To enhance HVDC transmission system recovery following severe ac system disturbances.
(4) To avoid control system instability, particularly when operating in the extinction angle control mode at the inverter.

The synchronous compensator has been the preferred means of ac voltage control because it increases the short circuit ratio and is a variable reactive-power source. Its disadvantages include high losses and maintenance which add to its overall cost. Other ac voltage controllers available include the following:

(1) Static compensators which utilize thyristors to control current through inductors and switch various levels of capacitors in or out. By this means, fast control of reactive power is possible to maintain ac voltage within desired limits. The main disadvantage is that it does not add to the short circuit ratio.
(2) Converter control through delay angle control is possible to regulate the reactive-power demand of converter bridges. This requires that the measured ac voltage be used as a feedback signal in the dc controls and delay angle α is transiently modulated to regulate the ac commutating bus voltage. This form of control is limited in its effectiveness, particularly when there is little or no dc current in the converter when voltage control is required.
(3) Specially cooled metal oxide varistors together with fast mechanical switching of shunt reactors, capacitors, and filters. The metal oxide varistors protect the HVDC substation equipment against transient overvoltages, and switching of reactive-power components achieves the reactive-power balance. The disadvantage of this system is that voltage control is not continuous, reactive-power control is delayed by slow mechanical switching, and the short circuit ratio is not increased.
(4) Saturated reactors to limit overvoltages and achieve reactive-power balance. Shunt capacitors and filters are required to maintain the reactors in saturation. Ac voltage control is achieved without controls on a droop characteristic. Short circuit ratio is not increased.
(5) Series capacitors in the form of CCC or CSCC to increase the short circuit ratio and improve the regulation of ac commutating bus voltage.

(6) The static synchronous compensator or STATCOM to use gate turn-off thyristors in the configuration of the voltage source converter bridge. This is the fastest responding voltage controller available and may offer limited capability for an increased short circuit ratio.

Because each ac system with its HVDC application is unique, the voltage control method applied is subject to study and design.

Special Purpose Controls. There are a number of special purpose controllers which can be added to HVDC controls to take advantage of the fast response of a dc link and help the performance of the ac system.

Ac System Damping Controls. An ac system is subject to power swings due to electromechanical oscillations. A controller can be added to modulate the dc power order or dc current order to add damping. The frequency or voltage phase angle of the ac system is measured at one or both ends of the dc link, and the controller is designed to adjust the power of the dc link accordingly.

Ac System Frequency Control. A slow responding controller can also adjust the power of the dc link to help regulate power system frequency. If the rectifier and inverter are in asynchronous power systems, the dc controller can draw power from one system to the other to assist in frequency stabilization of each.

Step Change Power Adjustment. A noncontinuous power adjustment can be implemented to take advantage of the ability of a HVDC transmission system to reduce or increase power rapidly. If ac system protection determines that a generator or ac transmission line is to be tripped, a signal can be sent to the dc controls to change its power or current order by an amount which compensates for the loss. This feature is useful in helping maintain ac system stability and easing the shock of a disturbance over a wider area.

Ac Undervoltage Compensation. Some portions of an electric power system are prone to ac voltage collapse. If a HVDC transmission system is in such an area, a control can be implemented which on detecting the ac voltage drop and the rate at which it is dropping, can effect a fast power or current order reduction of the dc link. The reduction in power and reactive power can remove the undervoltage stress on the ac system and restore its voltage to normal.

Subsynchronous Oscillation Damping. A steam turbine and electric generator can have mechanical subsynchronous oscillation modes between the various turbine stages and the generator. If such a generator feeds into the rectifier of a dc link, supplementary control may be required on the dc link to ensure that the subsynchronous oscillation modes of concern are positively damped to limit torsional stresses on the turbine shaft.

Areas for Development in HVDC Transmission

The thyristor as the key component of a converter bridge continues to be developed so that its voltage and current rating are increasing. Gate-turn-off thyristors (*GTO*s) and insulated gate bipole transistors (*IGBT*s) are required for the voltage source converter (*VSC*) converter bridge configuration. The VSC converter bridge is being applied in new developments (12). Its special properties include the ability to control real and reactive power independently at the connection bus to the ac system. Reactive power can be either capacitive or inductive and can be controlled to change quickly from one to the other.

A voltage source converter as an inverter does not require an active ac voltage source into which to commutate as does the conventional line-commutated converter. The VSC inverter can generate an ac three-phase voltage and supply electricity to a load as the only source of power. It requires harmonic filtering, harmonic cancellation, or pulse-width modulation to provide an acceptable ac voltage waveshape.

Two applications are now available for the voltage source converter. The first is for low-voltage dc converters used in dc distribution systems. The first application of a dc distribution system in 1997 was developed in Sweden (16) and is known as "HVDC Light." Other applications for a dc distribution system may be (1) in a dc feeder to remote or isolated loads, particularly if underwater or underground cable is necessary and (2) for a collector system of a wind farm where cable delivery and optimum and individual speed control of the wind turbines is desired for peak turbine efficiency.

The second immediate application for VSC converter bridges is in a back-to-back configuration. The back-to-back VSC link is the ultimate transmission and power flow controller. It can control and reverse power flow easily and control reactive power independently on each side. With a suitable control system, it can control power to enhance and preserve ac system synchronism and act as a rapid phase-angle power-flow regulator with a 360° range of control.

There is considerable flexibility in the configuration of VSC converter bridges. Many two-level converter bridges can be assembled with appropriate harmonic canceling properties to generate acceptable ac system voltage waveshapes. Another option is to use multilevel converter bridges to provide harmonic cancellation. Additionally, both two-level and multilevel converter bridges can utilize pulse-width modulation to eliminate low-order harmonics. With pulse-width modulation, high-pass filters may still be required because PWM adds to the higher order harmonics.

As VSC converter bridge technology develops for higher dc voltage applications, it will be possible to eliminate converter transformers. This is possible with the low-voltage applications in use today. It is expected that the exciting developments in power electronics will continue to provide exciting new configurations and applications for HVDC converters.

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