Principles of HVDC Transmission

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PRINCIPLES OF HVDC TRANSMISSION

The question that is frequently discussed is: “Why does anyone want to use D.C. transmission?” One reply is that electric losses are lower, but this is not true. Amount of losses is determined by the rating and size of chosen conductors. Both D.C. and A.C. conductors, either as transmission circuits or submarine cables can generate lower power losses but at increased cost since the bigger cross-sectional conductors will typically lead to lower power losses but will unfortunately cost more.

When power converters are utilized for D.C. electrical transmission in preference to A.C. electrical transmission, it is commonly impacted by one of the causes:

- An overhead D.C. line with associated overhead line towers can be made as less pricey per unit of length than the same A.C. transmission line made to transfer the equivalent amount of electric power. Nevertheless the D.C. converter stations at transmission line terminal ends are more expensive than the stations at terminals of an A.C. transmission line. Therefore there is a breakeven length above which the overall price of D.C. electrical transmission is lower than its A.C. electrical transmission option. The D.C. electrical transmission line can have a lower visual impact than the same A.C. transmission line, producing lower environmental effect. There are additional environmental advantages to a D.C. electrical transmission line through the electric and magnetic fields being D.C. instead of A.C.

- If transmission is achieved by underground cable, the breakeven length is lower than overhead electrical transmission. It is not feasible to look at A.C. cable installations over 50 km but D.C. cable transmission installations are in operation whose length is in the hundreds of kilometres. Lengths of 600 km or higher have been regarded as practical.

- Certain A.C. electric power networks are not synched to adjacent electrical systems although physical lengths between them is insignificant. This happens in

Japan where half the state is a 60 Hz system and the other is a 50 Hz network. It is not possible to link the two subsystems together by direct A.C. installations in order to transfer electric energy between them. Nevertheless, if a D.C. converter station is placed in each subsystem with a D.C. connection between them, it is feasible to transmit the needed power flow although the A.C. networks so connected stay asynchronous.

ARRANGEMENTS

The inherent component of an HVDC power converter station is the valve or valve arm. If it is made from one or more diodes connected in series it is known as non-controllable or controllable if it is made from one or more thyristors connected in series. Graphical symbols for valves and bridges that are set by IEC are shown in Figure 1. The typical bridge or converter link is known as a double-way connection consisting of six valves or valve arms that are linked as presented in Figure 2.

Electric power running between the HVDC valve group and the A.C. network is three phase. When electric power runs into the D.C. valve group from the A.C. network then it is conceived a rectifier. If power runs from the D.C. valve group into the A.C. network, it is an inverter. Each valve comprises of many thyristors linked in series in a form of thyristor modules.

Electric circuit system characterization for the six pulse valve group arrangement is illustrated in Figure 2. The six pulse valve group was typical when the valves were mercury arc.

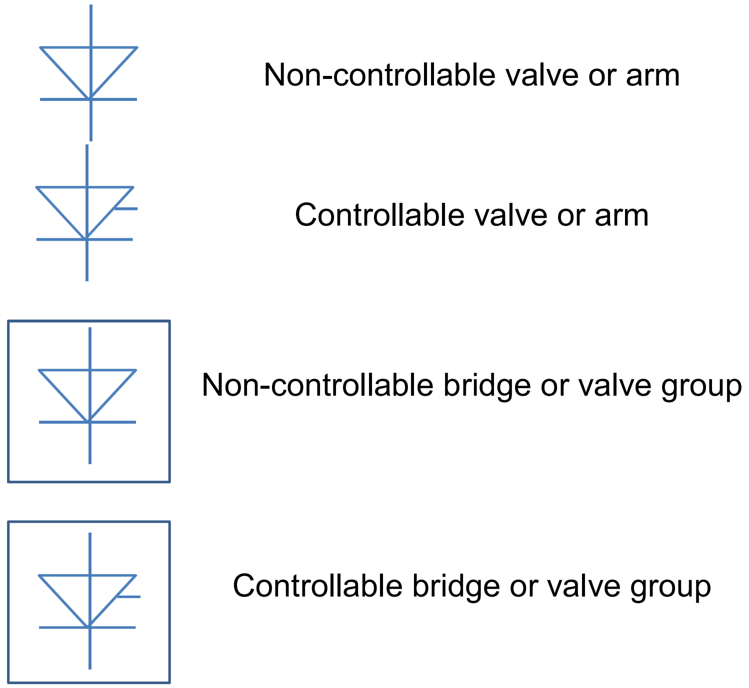


Figure 1. Typical graphical symbols for valves and bridges

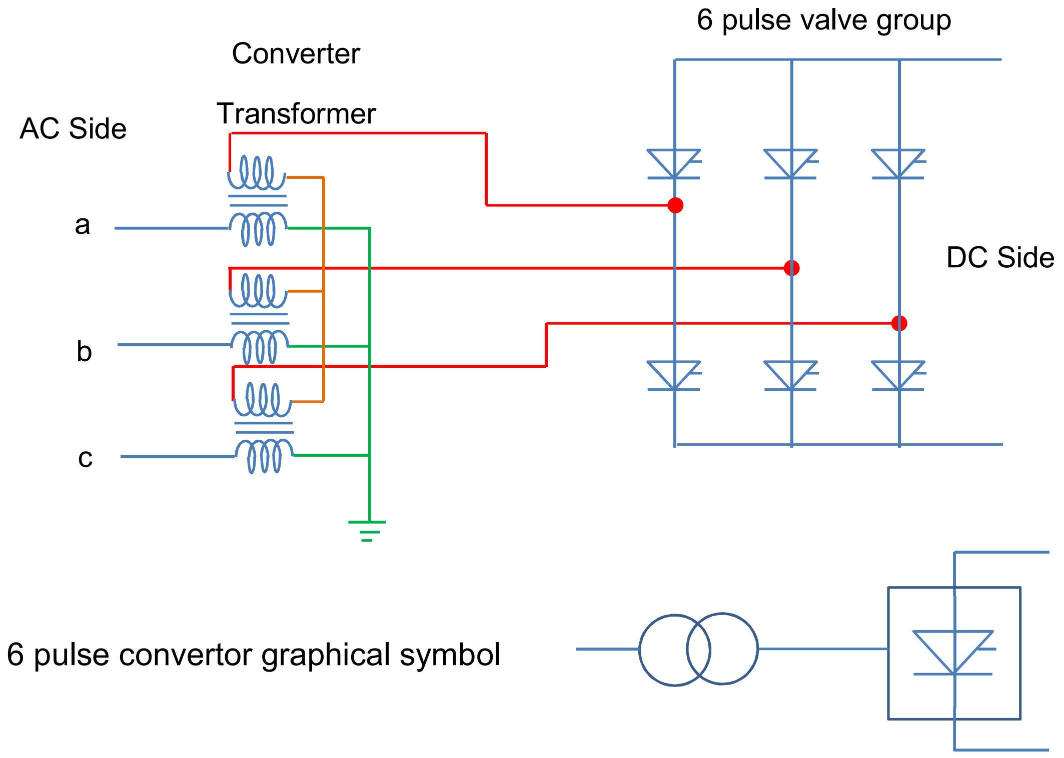
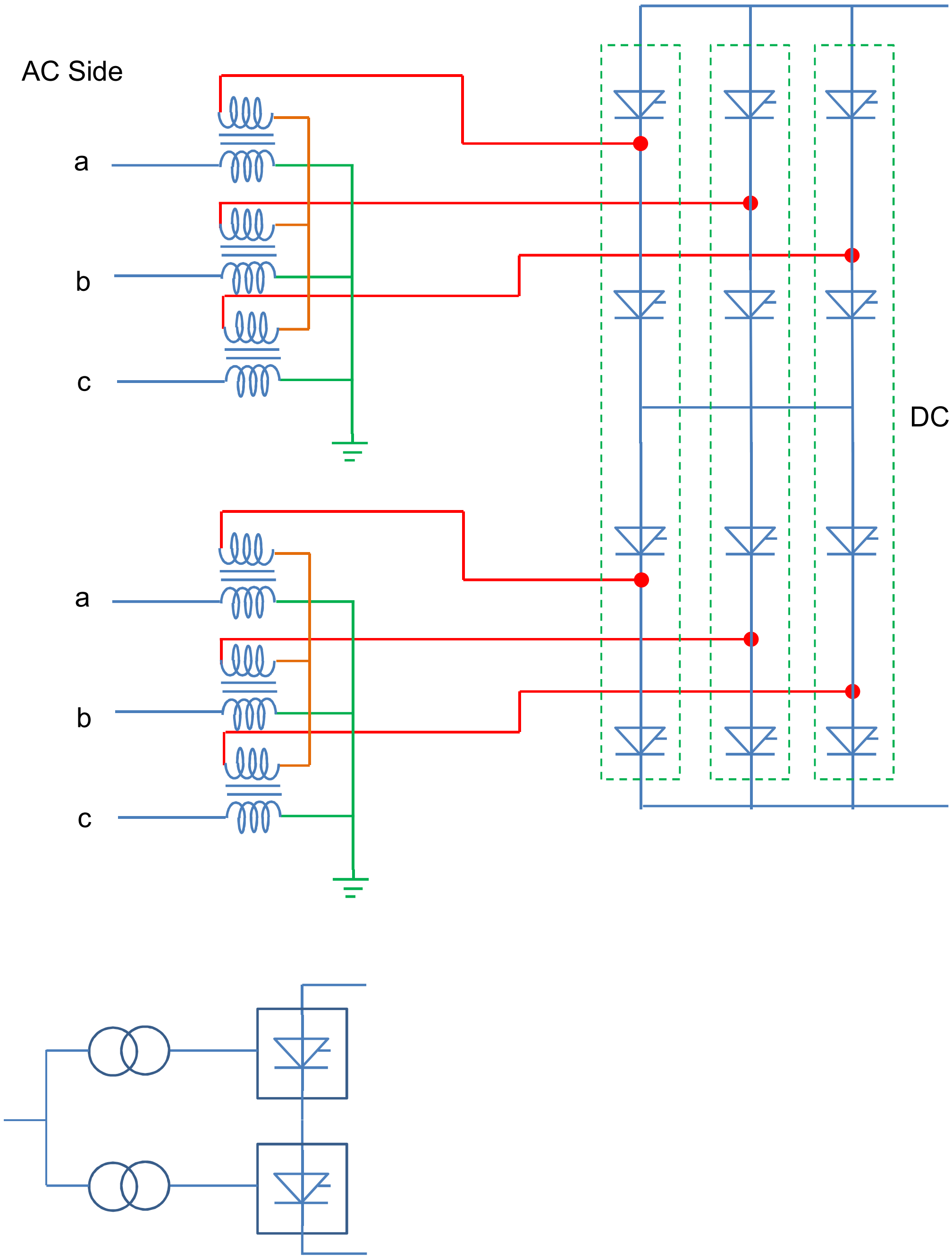


Figure 2. Electric circuit arrangement of the elemental six pulse valve group with converter transformer in star-star arrangement

TWELVE PULSE VALVE ARRANGEMENT

Almost all HVDC power converters that use thyristor valves are set up in a converter bridge of twelve pulse arrangement. The utilization of two three phase converter transformers with one D.C. side winding as an ungrounded star connection and the other a delta configuration is demonstrated in Figure 3. Accordingly, the A.C. voltages put on to each six pulse valve arrangement that make up the twelve pulse valve arrangement have a phase shift of 30 degrees that is used to offset the A.C. side 5th and 7th harmonic currents and D.C. side 6th harmonic voltage, hence ensuing in a substantial sparing in harmonic filters. Outline around each of the three arrangements of four valves in a single vertical stack is also presented in Figure 3. These are cognized as “quadrivalves” and are gathered as one valve arrangement by putting four valves in series. Since the voltage rating of thyristors is few kV, a 500 kV quadrivalve may consist of hundreds of individual thyristors arranged in series groups of valve or thyristor modules. A quadrivalve for a high voltage converter is pretty high and may hang freely from the ceiling of the valve hall, particularly in locations sensitive to earthquakes.



12 Pulse converter unit graphical symbol

Figure 3. The twelve pulse valve group arrangement with two converter transformers

THYRISTOR MODULE

A thyristor or valve module is that element of a valve in a mechanical fabrication of series linked thyristors and their immediate auxiliaries letting in heat sinks cooled by air, water or glycol, damping electrical circuits and valve firing electronics. A thyristor element is commonly exchangeable for servicing needs and comprises of electric parts as illustrated in Figure 4.

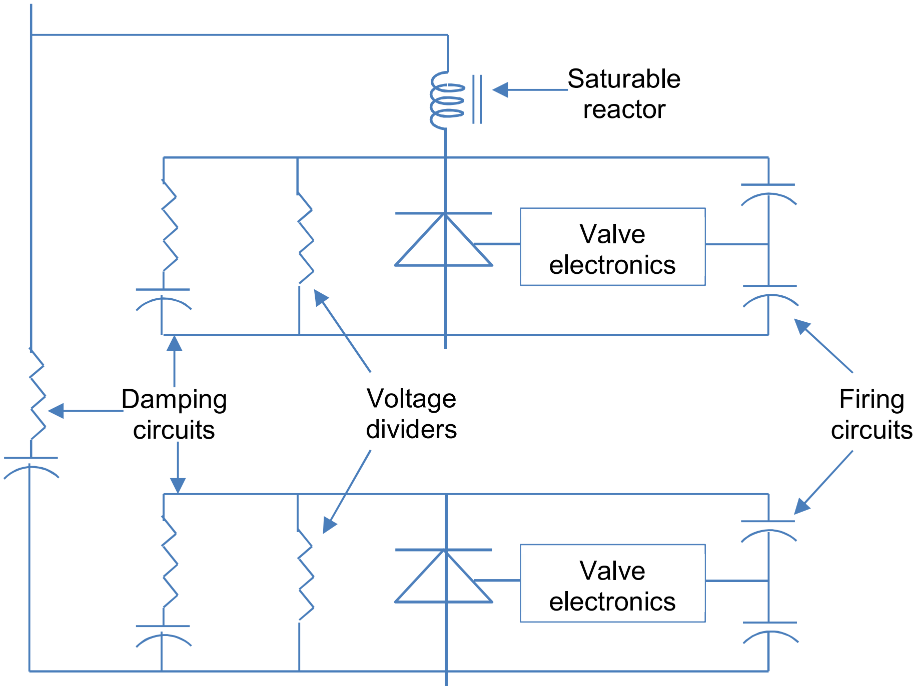


Figure 4. Elements of the thyristor modules that form a valve or quadrivalve

SUBSTATION ARRANGEMENT

The most important part of a D.C. substation is the thyristor converter that is typically placed inside a valve building. Valves placed outdoors have been also used. Electrical parts needed for a D.C. substation are presented in Figure 5. In this instance, two poles are shown that is the typical scenario and is known as the “bipole” arrangement. Several D.C. cable installations only have single pole or “monopole” arrangement and may either utilize the ground as a return path when allowed or utilize an additional cable to avert earth currents.

Basic elements in a D.C. substation are also converter transformers as can be seen in Figure 5. Their task is to convert the A.C. system voltage to which the D.C. network is linked so that the accurate D.C. voltage is gained by the converter bridges. For higher sized D.C. substations, converter transformers for 12 pulse service are typically made up of single phase elements. That is an affordable way to give spare elements for improved reliability.

The secondary side of the converter transformers are linked to the converter bridges. The converter transformer is placed in the switchyard, and in the case converter bridges are placed in the valve building, the link needs to be made through its wall. This is achieved in either of two different methods. This can be done with phase isolated bus in which the bus conductors are placed within oil or SF6 insulated bus ducts or using the wall bushings. When used at D.C. voltages at 400 kV or higher, wall bushings need significant design and attention to avert external or internal insulation failure.

Harmonic filters are needed on the A.C. side and typically on the D.C. side. The A.C. side current harmonics produced by 6 pulse converters are 6n +/- 1 and 12n +/- 1 for 12 pulse converters where n presents all positive integers. A.C. filters are commonly tuned to 11th, 13th, 23rd and 25th harmonics for 12 pulse converters. Tuning to the 5th and 7th harmonics is needed in the case converters can be set up into 6 pulse service. A.C. side harmonic filters can be turned with circuit breakers or circuit switches to meet reactive power needs since these filters produce reactive power at fundamental frequency. A parallel resonance is commonly made between the capacitance of the A.C. filters and the inductive impedance of the A.C. installation. For the special scenario where such a resonance is slightly damped and tuned to a frequency between the 2nd and 4th harmonic, then a low order harmonic filter at the 2nd or 3rd harmonic may be needed, even for 12 pulse converter service.

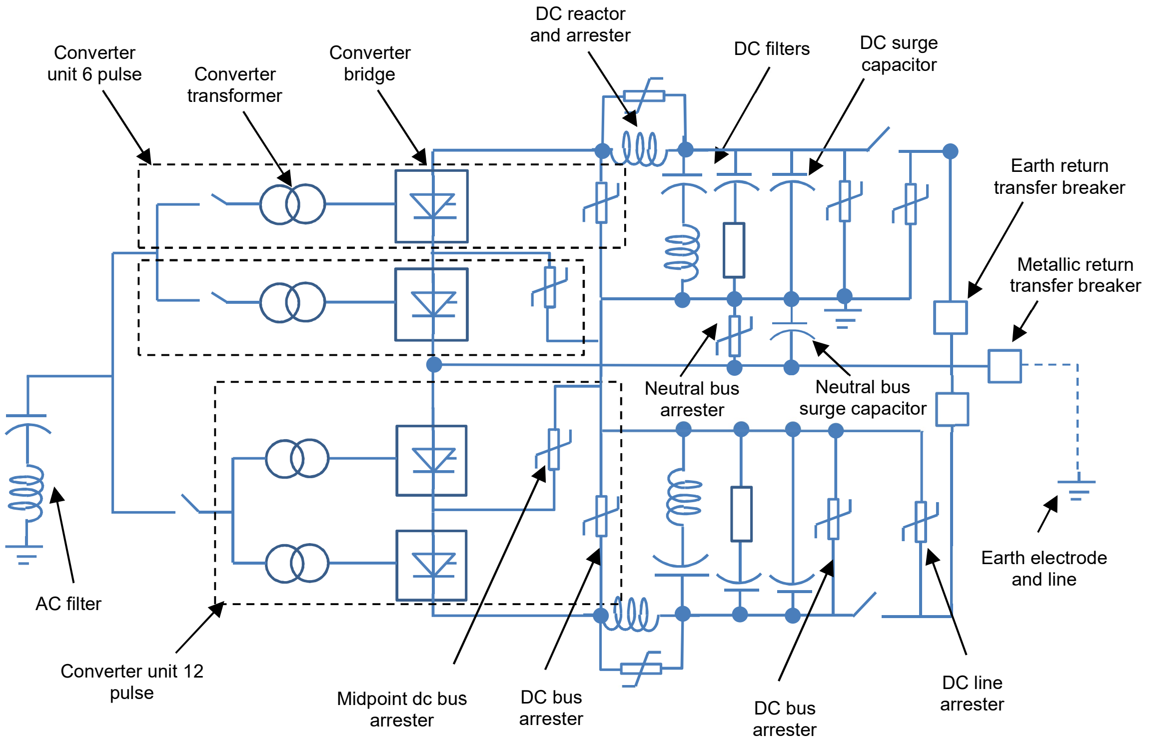


Figure 5. Typical HVDC substation

Typical D.C. side voltage harmonics produced by a 6 pulse converter are 6n and when produced by a 12 pulse converter, 12n order. D.C. side filters decrease harmonic current transfer on D.C. transmission circuits to understate coupling and interference to adjacent voice frequency communication networks. Where there is no D.C. line such as in the back-to-back arrangement, D.C. side filters may not be needed.

D.C. reactors are typically part of each pole of a converter station. They help the D.C. filters in filtering harmonic currents and smooth the D.C. side current so that a discontinuous current operation is not achieved at low load current service. Since variation rate of D.C. side current is fixed by the D.C. reactor, the commutation procedure of the D.C. converter is made more robust.

Surge arresters placed across each valve in the converter bridge, across each converter bridge and in the D.C. and A.C. switchyard are coordinated to save the devices from all voltage spikes regardless of their origin. They may be utilized in non-typical usages such as filter protection. Advanced HVDC substations utilize metal-oxide surge arresters and their size and selection is made with careful insulation coordination calculations.

USAGE OF HVDC CONVERTERS

The first usage for HVDC converters was to give point to point electrical power connections between asynchronous A.C. networks. There are other usages that can be met by HVDC converter transmission that include:

1. Connections between asynchronous power systems. Several continental power systems are made of asynchronous transmission networks such as the East, West, Texas and Quebec networks in North America.

2. Transfer power from remote generation. Where electrical production has been made at far away sites of available power, HVDC transmission has been practical way to transfer the power to load centers. Gas powered thermal generation can be placed near to load centers and may delay development of isolated power sources in the near term.

3. Import power into congested load centres. In locations where it is difficult or impossible to form new production to meet load increase or replace inefficient production, underground D.C. cable power transfer is a feasible way to import electricity.

4. Enhancing the transfer capacity of existing A.C. transmission lines by converting to D.C. transmission. New transmission lines may be impossible to construct. Existing A.C. transmission lines can drastically increase the power transfer capacities if upgraded to or overbuilt with D.C. transmission.

5. Power flow control. A.C. transmission networks do not easily adapt required power flow control. Power marketers and system operators may need the power flow control that is given by HVDC transmission technology.

6. Stabilization of electric transmission systems. Some widely used A.C. transmission

system networks function at stability limits well below the thermal capacity of their transmission conductors. HVDC power transmission is an option to consider enhancing efficiency of network conductors along with the different power electronic controllers that can be used on A.C. transmission.

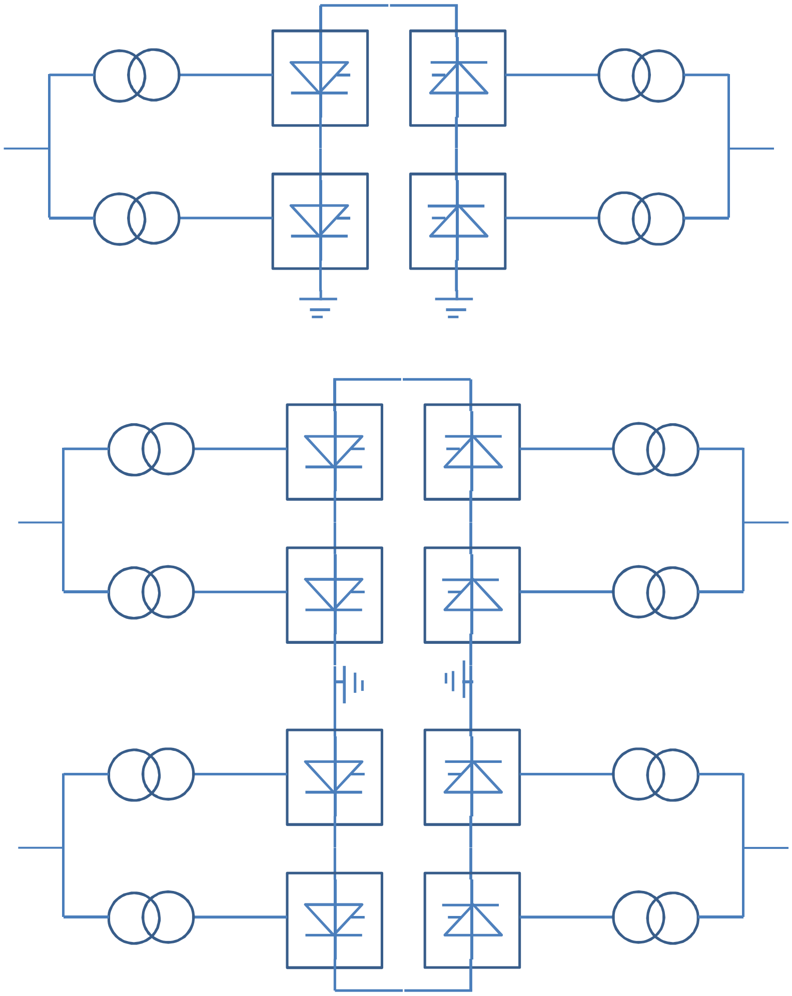


Figure 6. Monopolar and bipolar connection of HVDC converter bridges (a) Monopolar configuration (b) Bipolar configuration

HVDC CONVERTER ARRANGEMENTS

HVDC converter bridges and lines or cables can be organized into various arrangements for effective usage. Converter bridges may be organized either monopolar or bipolar as shown in 12 pulse configuration in Figure 6. Different ways

HVDC transmission is utilized are presented in simplified form in Figure 7 and take into account:

1. Back-to-Back. There are specific utilizations where the two A.C. networks to be connected are physically in the same location. Transmission circuits or cables are not needed between the converter bridges in this arrangement and the connection may be monopolar or bipolar. Back-to-back D.C. connections are utilized for connections between electrical system networks of different frequencies (50 and 60 Hz). They are also utilized as connections between adjacent asynchronous systems.

2. Transmission between two substations. When it is feasible to transfer power through D.C. transmission or cables from one location to another, a two-terminal or point-to-point HVDC transmission link can be utilized. In other words, D.C. power from a D.C. rectifier terminal is devoted to one other terminal servicing as an inverter. This is common for most HVDC transmission systems.

3. Multi-terminal HVDC transmission system. When three or more HVDC substations are separated with interconnecting transmission lines, the HVDC transmission system is multi-terminal. If all substations are operating at the same voltage then the system is parallel multi-terminal D.C. If one or more converter bridges are linked in series in one or both poles, then the system is series multi-terminal D.C. Parallel multi-terminal D.C. transmission has been used when the substation capacity surpasses 10% of the total rectifier substation capacity. It is anticipated a series multi-terminal substation would be used when its capacity is small (less than 10%) in comparison to the total rectifier substation capacity. Combining parallel and series links of converter bridges is a hybrid multi-terminal network. Multi-terminal D.C. networks are challenging to financially justify since of the cost of the additional substations.

4. Unit connection. When D.C. transmission is used at the point of power generation, it is possible to link the converter transformer of the rectifier directly to the generator terminals so the produced power feeds into the D.C. transmission network. This might be used with hydro and wind turbine production so that maximum efficiency of the

turbine can be reached with speed control. Regardless of the turbine speed, the energy is provided through the inverter terminal to the A.C. receiving network at its base frequency of 50 or 60 Hz.

5. Diode rectifier. In certain usages where D.C. power transmission is in one direction, the valves in the rectifier converter bridges can be made from diodes instead of thyristors. Power flow control is reached at the inverter, and in the situations where the unit connection is utilized, A.C. voltage control by the generator field exciter could be used to govern D.C. power. This link may need high speed A.C. circuit breakers between the electric generator and the rectifier converter bridges to save the diodes from over-currents resulting from a sustained D.C. transmission line short circuit.

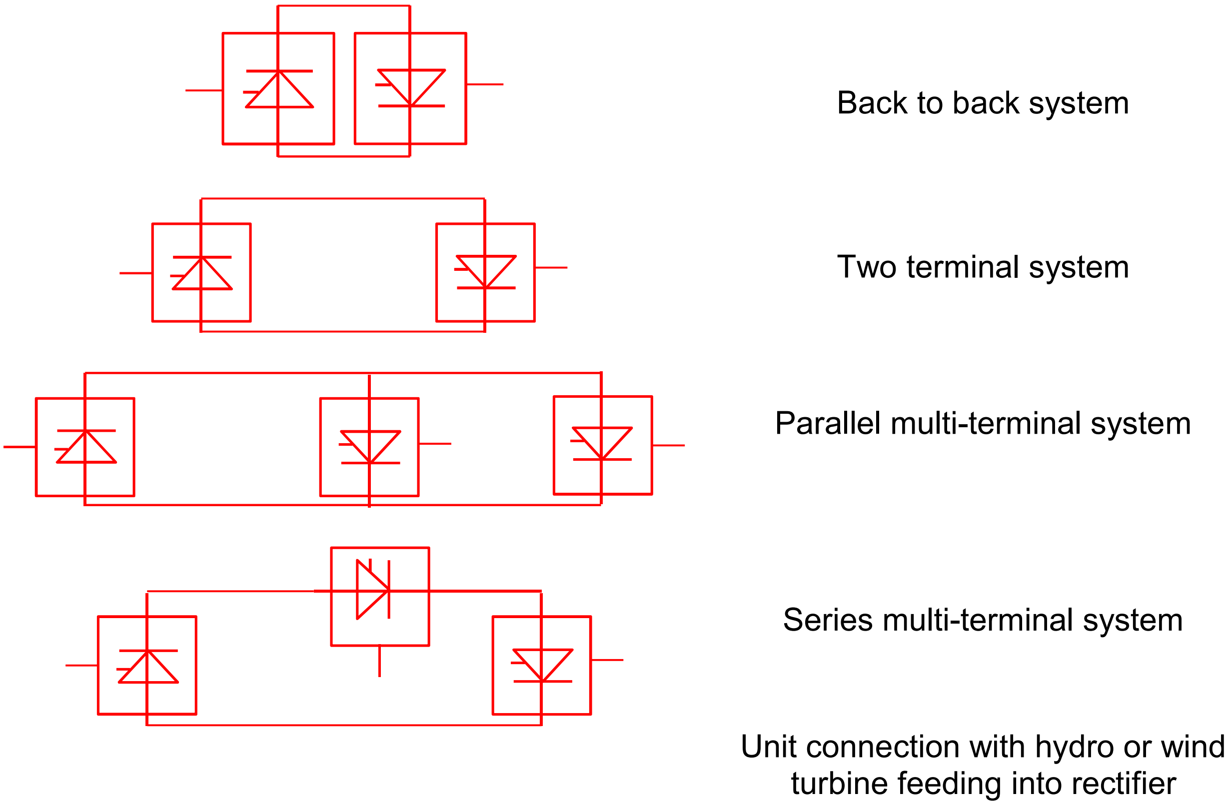


Figure 7. HVDC converter bridge arrangements

FINANCIAL FACTORS

Transmission line prices cannot be easily determined. Differences depend on the price of use of the land, the width of the needed corridor, labor construction prices and the terrain that needs to be crossed. A general rule of thumb may be used in that the price of a D.C. transmission line is 80% to 100% of the price of an A.C. transmission line whose nominal line voltage is equal to the rated pole-to-ground voltage of the D.C. transmission line. The price benefit of D.C. transmission for traversing long distances is that it may be sized at twice the power flow capacity of an A.C. line of the same voltage.

When power must be transferred by underground or undersea cables, A.C. cable network becomes impractical due to their capacitive charging current if longer than a critical distance which for undersea usages is less than 50 km. For lengths longer than this critical distance with today’s technology needs D.C. cables. The selection is unique for each system, and financial factors will dominate.

ENVIRONMENTAL FACTORS

The environmental impacts from HVDC transmission network can be qualified by field and corona processes. The electric field develops from both the electrical charge on the conductors and for a HVDC overhead line, from charges on air ions and aerosols surrounding the conductor. These increase D.C. electric fields due to the ion current density going through the air from or to the conductors as well as due to the ion density in the air. A D.C. magnetic field is generated by D.C. current flowing through the electrical conductors. Air ions generated by HVDC transmission network make clouds which drift away from the line when blown by the wind. The corona effects may generate low levels of radio interference, audible noise and ozone production.

FIELD AND CORONA IMPACTS

The field and corona impacts of transmission lines mainly privilege D.C. networks over A.C. networks. The important conditions are:

1. For a specific energy transfer requiring extra high voltage, the D.C. transmission will have a smaller tower than the same A.C. tower transferring the equivalent level of energy. This can also lead to smaller corridor width for the D.C. transmission line.

2. The steady and direct magnetic field of a D.C. transmission near or at the edge of the transmission corridor will be about the same in magnitude as the earth's occurring magnetic field. Due to this, it seems improbable that this small contribution by HVDC transmission to the geomagnetic field would be a reason for concern.

3. The static and steady electric field from D.C. transmission lines at the levels experienced below transmission lines or at the edge of the corridor have no familiar adverse impacts. There is no methodology to explain how a static electric field at the levels generated by D.C. lines could impact human health. The electric field level below a HVDC line is similar to naturally occurring static field which exists below thunder clouds. Electric fields generated by A.C. lines have been under severe scrutiny than fields produced by D.C. lines.

4. The ion and corona impacts of D.C. lines lead to a small contribution of ozone generation to greater naturally occurring concentrations. Exacting long measurements are needed to discover such concentrations. While solar radiation impacts the generation of ozone even in the rural areas, thereby keeping its level, any additive contribution from a D.C. transmission source is subject to breakdown, leading to a recommencement of background levels downwind from the transmission line. Researches of ozone for indoor terms show that in well mixed air, the half-life of ozone is 1.5 minutes to 7.9 minutes. Gains in temperature and humidity enhance the rate of decay.

5. If ground return is utilized with monopolar service, the resulting D.C. magnetic field can induce error in magnetic indications taken in the locality of the D.C. transmission. This effect is derogated by allowing for a conductor or cable return path (known as metallic return) in closeness to the main conductor or cable for magnetic field cancellation. Another issue with uninterrupted ground current is that some of the return current may flow in metallic elements such as pipelines. When pipelines or other metallic grounded elements are in the locality of a D.C. transmission network, metallic return may be required.

D.C. CONVERTER SERVICE

The six pulse converter bridge shown in Figure 2 is the basic converter element of HVDC transmission and is utilized for rectification where electric power goes from the A.C. side to the D.C. side and inversion where the power flow is from the D.C. side to the A.C. side. Thyristor valves function as switches which switch on and transfer current when fired on receiving a gate pulse and are forward biased. A thyristor valve will transfer current in one direction and once it transfers, will only switch off when it is reverse biased and the current decreases to zero. This procedure is known as line commutation.

An important feature of the thyristor valve is that once it is transferring, current decreases to zero when it is reverse biased and the gate pulse is removed. The design of the thyristor valve and converter bridge must insure such situation is averted for useful inverter service.

CONVERTER BRIDGE ANGLES

Figure 8 presents different electrical angles that define the service of converter bridges. These angles are measured on the three phase valve side voltages and are founded upon steady state without harmonics and with idealized three phase commutation voltage. They are applicable to both inverters and rectifiers.

Delay angle α, is the time presented as electrical angular measure from the zero crossing of the idealized sinusoidal changing voltage to the starting point 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 higher than 90°, it is an inverter. This angle is sometimes denoted as the firing angle.

Advance angle β, is the time presented in electrical angular measure from the starting instant of forward current conduction to the next zero crossing of the perfect sinusoidal commutating voltage. The angle of advance β can be expressed by using degrees to the angle of delay a by:

$$\beta = 180.0 - \alpha \qquad (1)$$

Overlap angle μ, is the existence of commutation between two converter valve arms presented as an electrical angular measure.

Extinction angle γ, is the time presented as an electrical angular quantity from the end of current conduction to the next zero crossing of the perfect sinusoidal commutating voltage. Excitation angle γ is impacted by the angle of advance β and the overlap angle γ and is calculated with the following formula:

$$\gamma = \beta - \mu \qquad (2)$$

STEADY STATE D.C. CONVERTER BRIDGE FORMULAS

It is beneficial to present the commutation reactance of a six pulse converter bridge in per-unit of the converter transformer size SN as shown below:

$$SN = \sqrt{2} U_{VN} I_{dN} \qquad (3)$$

where I_{dN} is the nominal direct current and U_{VN} is the nominal line-to-line voltage on the valve or secondary side of the converter transformer. Typically, the D.C. converter bridge power size is obtained from its nominal D.C. current I_{dN} and nominal D.C. voltage U_{dN}. The valve and converter bridge arrangement is very dependent upon the commutation reactance X_C and so accordingly its measure is found out. In modern HVDC converter bridges it is typically in the range $0.1<X_C<0.15$ in per unit where 1.0 per unit is $\frac{U_{VN}^2}{S_N}$ Ω.

A fairly good estimate for the power factor of a converter bridge at the A.C. commutating bus is presented with Equation (4). It is important to note that the delay angle α is typically known or calculated. For instance, the typical steady state range of delay angle for a rectifier can be 10° < α < 18° and the lowest normal operating power factor will be when α= 18°:

$$Power\ factor = \cos\theta = \cos\alpha - 0.5X_c\frac{I_d}{I_{dN}} \qquad (4)$$

and for a typical inverter:

$$Power\ facto \qquad \cos\theta = \cos\gamma - 0.5X_c\frac{I_d}{I_{dN}} \qquad (5)$$

where I_d is the D.C. load current and I_{dN} is nominal D.C. current and θ is the power factor angle. For the typical inverter, the extinction angle is founded in the converter bridge arrangement, typically at γ= 18°. Neglecting the power losses in the converter bridge, the power going through the bridge P_d can be expressed as:

$$P_d = I_d U_d \qquad (6)$$

where Id is the servicing direct current through the converter bridge and U_d is the service direct voltage across the converter bridge. If the power factor angle θ is calculated from Equation (4) or (5) and output power of the converter bridge from Equation (6), the reactive power Q_L needed by the converter bridge at the A.C. commutating voltage bus at either the rectifier or inverter can be expressed as:

$$Q_L = P_d \tan\theta \qquad (7)$$

It may be that the nominal line-to-line voltage on the valve or secondary side of the converter transformer U_{VN} is unknown. It is practical to calculate what it should be in the case power factor $\cos\theta$ from Equation (4) or (5) is known at the converter bridge size. In that case, practical estimate of U_{VN} can be calculated as:

$$U_{VN} = \frac{U_{dN}}{1.35\cos} \qquad (8)$$

Once U_{VN} is established, it is feasible to calculate the converter transformer size suing Equation (3).

It may be required to calculate the overlap angle μ. At the rectifier side, Equation (10) can be used when delay angle α, per-unit commutating reactance X_C and D.C. load current Id are previously established:

$$\cos(\alpha + \mu) = \cos\alpha - \frac{X_c I_d}{I_{dN}} \qquad (10)$$

Likewise at the inverter, the extinction angle γ is typically established for steady state operation using:

$$\cos(\gamma + \mu) = \cos\gamma - \frac{X_c I_d}{I_{dN}} \qquad (11)$$

The delay angle α at the inverter may not be previously established but once extinction angle γ and overlap angle μ have been calculated, then following expression can be used:

$$\alpha = 180° - (\gamma + \mu) \qquad (12)$$

It is also feasible to calculate the nominal turn-ratio of the converter transformer as soon as the rated secondary (D.C. valve side) voltage U_{VN} is determined and in the case the primary side rated line-to-line A.C. bus voltage U_{LN} is also determined. Starting from the line-to-line voltages, the nominal turn ratio of the converter transformer TR_N can be calculated as:

$$TR_N = \frac{Valve\ side\ phase\ to\ phase\ rated\ voltage}{A.C.side\ phase\ to\ phase\ rated\ voltage}$$

$$= \frac{U_{VN}}{U_{LN}} \qquad (13)$$

During the functioning of a converter bridge, the converter transformer on-line tap changer will correct to maintain the delay angle α at a rectifier at its required normal functioning range. Likewise at the inverter, the on-line tap changer will correct to keep the inverter function at its required level of D.C. voltage U_d or extinction angle γ. Having knowledge of the required levels of D.C. voltage (U_d), D.C. current I_d, the nominal turns ratio TR_N of the converter transformer, the functioning level of the primary side A.C. voltage U_L, and the extinction angle γ (if an inverter) or delay angle α (if a rectifier), the per-unit turn-ratio TR of the converter transformer is determined using the formula:

$$TR = \frac{U_d + U_{dN} \frac{I_d \qquad X_c}{I_{dN}(2\cos\varphi \qquad c)}}{1.35\, TR_N U_L \cos\varphi} \tag{14}$$

where X_C is the commutating reactance for the converter bridge in per-unit and φ = α for a rectifier and φ = γ in the case of an inverter. I_{dN} is the nominal D.C. current for the converter bridge and U_{dN} is its nominal D.C. voltage.

Formulas 1 to 13 are used for the steady state and fairly precise equations that determine the state of a 6 pulse converter bridge under ideal operational circumstances. Determining transient service of a converter bridge asks for the use of a proper electromagnetic transients simulation software with the features of modelling the valves, converter transformer and the related A.C. and D.C. power networks.

SHORT CIRCUIT RATIO

The rating of the A.C. electrical network at the bus of the HVDC substation can be presented by the short circuit ratio (SCR) which is determined as the relation between the short circuit level in MVA at the HVDC substation bus at 1.0 per-unit A.C. voltage and the D.C. power in MW.

The capacitors and A.C. filters linked to the A.C. bus decrease and limit the short circuit level. The expression known as an effective short circuit ratio (ESCR) is utilized for the ratio between the short circuit level decreased by the reactive power of the shunt capacitor banks and A.C. filters linked to the A.C. bus at 1.0 per-unit voltage and the nominal D.C. power.

Lower ESCR or SCR factor entails marked interaction between the HVDC substation and the A.C. electrical network. A.C. power networks can be grouped in the next classes according to their strength:

Strong systems with high ESCR: ESCR > 3.0

Systems with low ESCR: 3.0 > ESCR > 2.0

Weak systems with very low ESCR: ESCR < 2.0

In the situation of high ESCR electrical systems, alterations in the active/reactive power from the HVDC substation cause small or moderate A.C. voltage alterations. Hence, the extra transient voltage control at the bus is not typically needed. The reactive power balance between the A.C. electrical network and the HVDC substation can be accomplished by switched reactive power components.

In the situation of low and very low ESCR electrical systems, the alterations in the A.C. electrical network or in the HVDC transmission power could cause voltage oscillations and a requirement for special control procedures. Transient reactive power control at the A.C. bus at or near the HVDC substation by power electronic reactive power controller which is typically static var compensator (SVC) or static synchronous compensator (STATCOM) may be needed. In the past, transient reactive power control was accomplished with synchronous compensators.

COMMUTATION COLAPSE

When a converter bridge is functioning as an inverter, a valve will switch off when its forward current commutates to zero and the voltage across the valve stays negative. The period of time for which the valve remains negatively biased is the extinction angle γ, the time above which the valve then turns to forward biased. Without a firing pulse, the valve will remain non-conductive or blocked, although it receives a forward bias.

All D.C. valves need removal of the internal stored charges generated during the forward conducting time before the valve can demonstrate its power to block a forward bias. The D.C. inverter hence, needs a minimum time of negative bias or minimum extinction angle γ for forward blocking to be completed. If forward blocking goes wrong and conduction is started without a firing pulse, commutation collapse happens. This also ends in sudden collapse to keep current in the succeeding converter arm as the D.C. line current goes back to the valve which was previously transferring and which has collapsed to maintain forward blocking.

Commutation collapse at a converter bridge functioning as an inverter is made by any of the following processes:

1. When the D.C. current going to the inverter increases in magnitude which causes the overlap angle μ to rise, the extinction angle γ is decreased and may reach the level where the valve is unable to keep forward blocking. Raising the inductance of the D.C. current path through the converter using the D.C. smoothing reactor and commutating reactance decreases the level of change of D.C. current. This has the biggest effect on commutation collapse.

2. In the case the magnitude of the A.C. side voltage on one or more phases decreases or is distorted making the extinction angle to be inappropriate as commutation is sought.

3. A phase angle shift in the A.C. commutating voltage can produce commutation collapse. Nevertheless, the A.C. voltage magnitude decrease and not the corresponding phase shift is the most prevailing factor finding the onset of commutation collapses for single phase failures.

4. The measure of the pre-disturbance steady state extinction angle γ also impacts the sensitivity of the inverter to commutation collapse. A value of γ = 18° is typical for majority of inverters. Rising γ to values of 25°, 30° or higher will decrease the likelihood of commutation collapse.

5. The measure of valve current before the commutation collapse also impacts the

conditions at which a commutation collapse may happen. A commutation collapse may promptly occur if the pre-disturbance current is at full load in comparison to light load current service.

Typically, the more rigid the A.C. voltage to which the inverter flows into and with an absence of A.C. system disturbances, the less possibility there will be commutation collapse.

SERIES LINE CAPACITORS WITH D.C. CONVERTER SUBSTATIONS

HVDC transmission electrical systems with long D.C. underground cables are prone to commutation collapse in the case there is a decrease in D.C. voltage U_d at the inverter. The D.C. underground cable has very large capacitance which will discharge current towards the voltage drop at the inverter. The discharge current is fixed by the D.C. voltage deduced from the A.C. voltage of the commutating bus and D.C. smoothing reactor and the commutating reactance. If the discharge current of the underground cable rises too fast, commutation collapse will happen causing total underground cable discharge. To recharge the underground cable back to its nominal operating voltage will hold recovery.

The converter bridge firing controls can be made to raise the delay angle α when an gain in D.C. current is noticed. This may be in effect until the limit of the minimum allowable extinction angle γ is achieved.

Other possibility to fix the underground cable discharge current is to control the inverter bridge with a three phase series capacitor connected in the A.C. system on either side of the converter transformer. Any discharge current from the D.C. underground cable will go into the A.C. electrical system through the functioning converter bridge and will go through the series capacitor and add charge to it. Finally, the voltage of the series capacitor will rise to counterbalance the underground cable discharge and be reflected through the converter bridge as an increment in D.C. voltage U_d. This will work as a back EMF and fix the discharge current of the underground cable, thereby annulling the commutation collapse. The suggested locations of the series capacitor are given in Figure 9. With the capacitor placed between the converter transformer and the valve arrangement, it is known as a capacitor commutated converter (CCC). With the capacitor placed on the A.C. system side of the converter transformer, it is known as a controlled series capacitor converter (CSCC). Each arrangement will enhance commutation operation of the inverter but the CSCC needs design characteristics to eradicate ferroresonance between the series capacitor and the converter transformer.

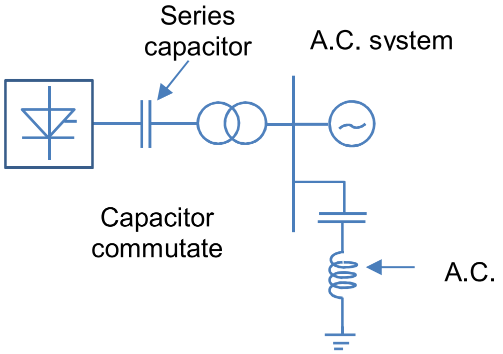


Figure 9. Arrangements for using series capacitors at HVDC substations

OPERATION AND PROTECTION

HVDC transmission electrical systems must transfer very large quantities of electric energy which can only be achieved under tightly controlled circumstances. D.C. current and voltage is exactly controlled to impact the desired power flow. Therefore, it is necessary to permanently and exactly measure system values including each converter bridge, the D.C. current, its D.C. side voltage, the delay angle α and for an inverter, its extinction angle γ.

Two terminal D.C. transmission electrical configurations are the more typical and they have in common a favoured mode of control during normal service. Under steady state circumstances, the inverter is delegated with the task of controlling the D.C. voltage. This can be done by keeping a fixed extinction angle γ which causes the D.C. voltage U_d to droop with gaining D.C. current I_d as presented in the minimum constant extinction angle γ characteristic A-B-CD in Figure 10. The weaker the A.C. electrical system at the inverter side, the steeper the droop will be.

Instead, the inverter may properly function in a D.C. voltage operating mode which is the fixed U_d characteristic B-H-E shown in Figure 10. This means that the extinction angle γ must rise above its minimum setting shown in Figure 10 as 18°.

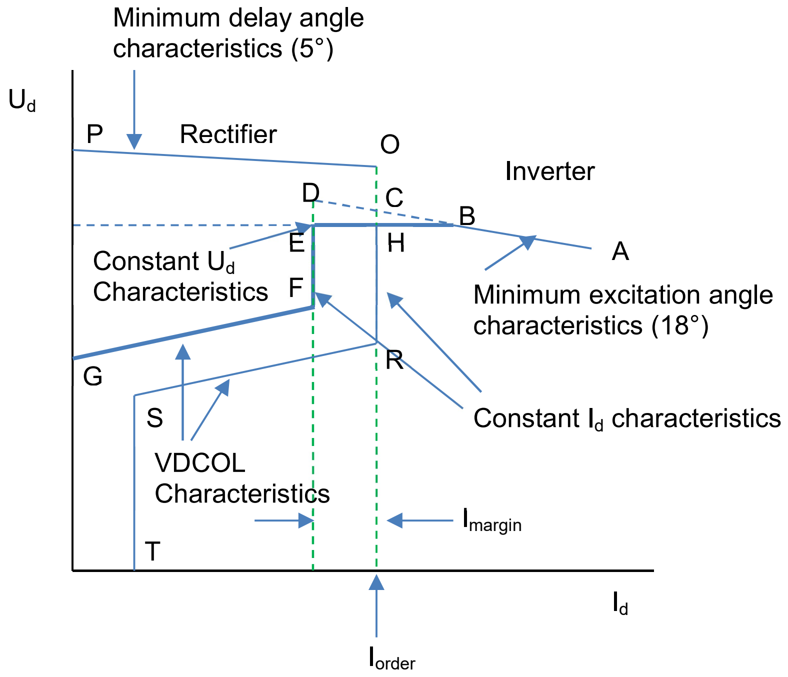


Figure 10. Steady state U_d-I_d characteristics for a two terminal HVDC electrical system

If the inverter is functioning in a minimum constant γ or fixed U_d characteristic, than the rectifier has to control the D.C. current I_d. This can be done as long as the delay angle α is not at its minimum limit (typically 5°). The steady state constant current characteristic of the rectifier is presented in Figure 10 as the vertical part Q-C-H-R. At the point at which the rectifier and inverter characteristic cross, either at points C or H, lies the operating point of the HVDC electrical system.

The operating point is achieved by action of the on-line tap changers of the converter transformers. The inverter has to establish the D.C. voltage U_d by altering its on-line tap changer to reach the needed operating level if it is in constant minimum γ control. If in constant U_d control, the on-line tap changer has to alter its tap to allow the fixed level of U_d to be reached with an extinction angle equal to or slightly greater than its minimum setting of 18°. The on-line tap changers on the converter transformers of the rectifier are maintained to keep their tap settings so that the delay angle α has a working range at a level between 10° and 15° for keeping the constant current setting I_{order} (Figure 10). If the inverter is functioning in fixed D.C. voltage control at the operating point H, and if the D.C. current order I_{order} is raised so that the operating point H goes towards and above point B, the inverter mode of control will return to fixed extinction angle γ control and function on characteristic A-B. D.C. voltage U_d will be less than the needed measure, and so the converter transformer on-line tap changer at the inverter will increase its D.C. side voltage until D.C. voltage control is resumed.

Not all HVDC transmission electrical system controls have a fixed D.C. voltage control as the one showed by the horizontal characteristic B-H-E in Figure 10. Alternatively, the constant extinction angle γ control of characteristic A-B-C-D and the tap changer will allow for the D.C. voltage control.

CURRENT MARGIN

The D.C. current order I_{order} is sent to both the rectifier and inverter. It is typical 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 shown in Figure 10. The inverter also has a current controller and it tries to control the D.C. current I_d to the value I_{order} - I_{margin} but the current controller at the rectifier typically overrides it to keep the D.C. current at I_{order}.

This variance is settled at the inverter in normal steady state service as its current controller cannot maintain the D.C. current to the needed value of I_{order} - I_{margin} and is forced out of service. The current control at the inverter starts to be active only when the current control at the rectifier finishes when its delay angle α is nailed against its minimum delay angle limit. This is promptly detected in the servicing characteristics of Figure 10 where the minimum delay angle limit at the rectifier is characteristic P-Q. If from any reason other than such as a low A.C. commutating voltage at the rectifier end, the P-Q characteristic goes below points D or E, the operating point will shift from point H to the vertical characteristic D-E-F where it is crossed by the lowered P-Q characteristic. The inverter returns to current control, fixing the D.C. current I_d to the value I_{order} - I_{margin} and the rectifier is fixing D.C. voltage as it is operating at its minimum delay angle characteristic P-Q. The controls can be made so that the transition from the rectifier fixing current to the inverter controlling current is automatic and smooth.

VOLTAGE DEPENDENT CURRENT ORDER LIMIT (VDCOL)

During disruptions where the A.C. voltage at the rectifier or inverter is lowered, it will not be useful to a weak A.C. electrical system if the HVDC transmission electrical system tries to keep full load current. A drop in A.C. voltage at either end will also end in a decreased D.C. voltage. The D.C. control characteristics presented in Figure 10 shows the D.C. current order is decreased if the D.C. voltage is decreased. This can be seen in the rectifier characteristic R-S-T and in the inverter characteristic F-G in Figure 10. The controller which decreases the maximum current order is known as a voltage dependent current order limit or VDCOL. The VDCOL control, if raised by an A.C. electrical system disruption will maintain the D.C. current I_d to the decreased limit during recovery which helps the corresponding recovery of the D.C. electrical system. Only when D.C. voltage U_d has retrieved sufficiently will the D.C. current go back to its original I_{order} level.

Figure 11 shows a schematic arrangement of how D.C. electrical transmission system controls are typically used.

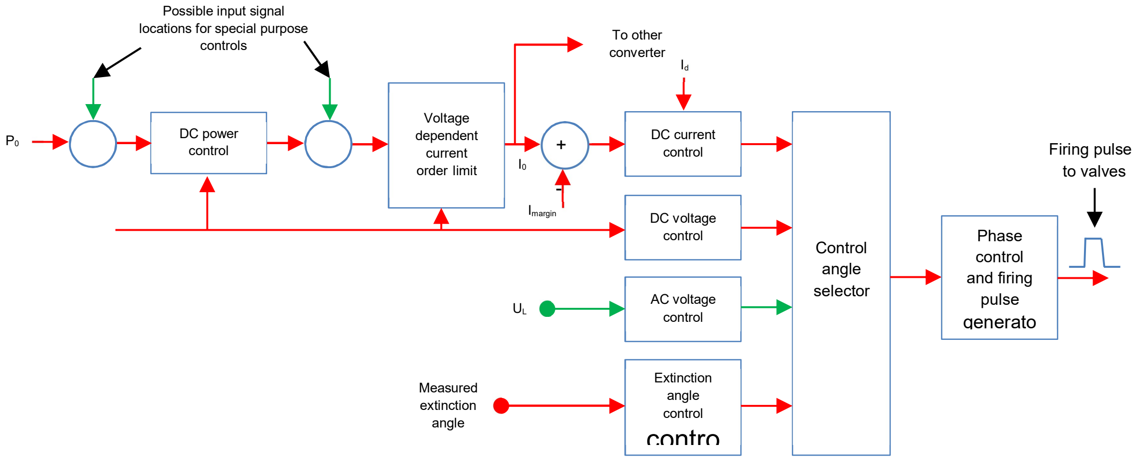


Figure 11. Typical HVDC control system arrangement

A.C. VOLTAGE CONTROL

It is suitable to rigidly keep the A.C. electrical system and commutating bus voltage to a fixed measure for best service of the HVDC electrical transmission system. This is more easily accomplished when the short circuit ratio is high. With low or very low short circuit ratio electrical systems, problems may appear following load modifications. With fast load change, there can be surplus or lack of reactive power at the A.C. commutating bus which ends in over and under-voltages. When the A.C. electrical system is weak, the modifications in converter A.C. bus voltage following a disruption may be above permissible limits. In such situations, an A.C. voltage controller is needed for the following reasons:

1. To fix transient overvoltage to permissible limits determined by substation equipment specifications and regulations.

2. To stop A.C. voltage flicker and commutation collapse due to A.C. voltage changes when load and filter switching happens.

3. To increase HVDC electrical transmission system recovery following serious A.C. system disruptions.

4. To avoid control system instability, especially when functioning in the extinction angle control mode at the inverter. The synchronous compensator has been the favoured way of A.C. voltage control as it enhances the short circuit ratio and serves as a changing reactive power source. Its weaknesses include high losses and servicing which increase to its overall price. Extra A.C. voltage controllers are available and these are:

1. Static compensators which use thyristors to fix current through inductors and switch in or out different levels of capacitors. By this means, fast control of reactive power is feasible to keep A.C. voltage within required limits. The main drawback is that it does not add to the overall short circuit ratio.

2. Converter control through delay angle control is feasible to influence the reactive power requirement of the converter bridges. This asks for that the measured A.C. voltage be utilized as a feedback signal in the D.C. controls, and delay angle α is modulated to determine the A.C. commutating bus voltage. This way of control is limited in its effectiveness, especially when there is little or no D.C. current in the converter when voltage control is needed.

3. Use of cooled metal oxide varistors along with fast mechanical switching of shunt reactors, capacitors and filters. The metal oxide varistors will defend the HVDC substation devices against the transient over-voltages, and the commutations of reactive power elements will reach the reactive power balance. Its drawback is that voltage control is not uninterrupted, reactive power control is delayed by the slowness of mechanical commutation, and short circuit ratio is not enhanced.

4. Saturated reactors have been used to determine over-voltages and reach reactive power balance. Shunt capacitors and filters are needed to keep the reactors in saturation. A.C. voltage control is reached without controls on a droop characteristic. Short circuit ratio is not enhanced.

5. Series capacitors in the form of CCC or CSCC can raise the short circuit ratio and enhance the regulation of A.C. switching bus voltage.

6. The static compensator or STATCOM uses gate turn-off thyristors in the arrangement of the voltage source converter bridge. This is the fastest reacting voltage controller available and may provide fixed capability for increased short circuit ratio.

Since each A.C. electrical system with its HVDC usage is special, the used voltage control technique is subject to study and design.

SPECIAL PURPOSE CONTROLS

There are a number of different purpose controllers which can be added to HVDC controls to take benefit of the fast response of a D.C. link and assist the operation of the A.C. electrical system. These include:

1. A.C. electrical system damping controls. An A.C. electrical system is subject to power swings due to electromechanical oscillations. A controller can be added up to tone the D.C. power order or D.C. current order to add damping. The frequency or voltage phase angle of the A.C. electrical system is evaluated at one or both ends of the D.C. link, and the controller is made to adapt the power of the D.C. link.

2. A.C. electrical system frequency control. A slow responding controller can also adapt the power of the D.C. link to assist in regulation of power system frequency. If the rectifier and inverter are in asynchronous power electrical systems, the D.C. controller can draw power from one electrical system to the other to help in frequency stabilization of each.

3. Step change power regulation. A non-continuous power regulation can be applied to take benefit of the possibility of a HVDC electrical transmission system to quickly decrease or enhance power. If A.C. electrical system protection finds out that a generator or A.C. electrical transmission line is to be opened, a signal can be sent to the D.C. controls to modify its power or current order by an amount which will compensate the loss. This possibility is helpful in assisting to keep A.C. electrical system stability and to ease the shock of a disruption over a wider area.

4. A.C. under-voltage compensation. Some parts of an electric power system are prone to A.C. voltage failure. If a HVDC electrical transmission system is in such an area, a control can be applied on sensing the A.C. voltage drop and the rate at which it is decreasing, a fast power or current order decrease of the D.C. link can be impacted. The decrease in power and reactive power can take out the under-voltage stress on the A.C. electrical system and restore its voltage to nominal value.

5. Subsynchronous oscillation damping. A steam turbine and electric generator can experience mechanical subsynchronous oscillation modes between the different turbine stages and the generator. If such a generator supplies power to the rectifier of a D.C. link, auxiliary control may be needed on the D.C. link to make sure the subsynchronous oscillation modes of concern are positively damped to fix torsional stresses on the turbine shaft.

HVDC CONVERTERS DEVELOPMENT AREAS

The thyristor as the key element of a converter bridge keeps to be enhanced so that its voltage and current rating is growing. Gate-turn-off thyristors (GTOs) and insulated gate bipole transistors (IGBTs) are needed for the voltage source converter (VSC) converter bridge arrangements. It is the VSC converter bridge which is being used in new substations. Its particular features include the possibility to independently fix real and reactive power at the connection bus to the A.C. electrical system. Reactive power can be either capacitive or inductive and can be maintained to promptly change from one to the other. A voltage source converter as in inverter does not need an active A.C. voltage source to commutate into as does the conventional line commutated converter. The VSC inverter can produce an A.C. three phase voltage and provide electricity to a load as the only source of power. It does need harmonic filtering, harmonic cancellation or pulse width modulation to give satisfactory A.C. voltage wave. Two usages are now available for the voltage source converter. The first usage is for low voltage D.C. converters used to D.C. distribution electrical systems. Other usages for a D.C. distribution electrical system may be in a D.C. feeder to remote or isolated loads, especially if underground cable is needed and for a collector arrangement of a wind farm where cable delivery and optimum and individual speed control of the wind turbines is needed for peak turbine effectiveness.

The second immediate usage for the VSC converter bridges is in back-to-back arrangement. The back-to-back VSC link is the ultimate transmission and power flow controller. It can control and easily reverse power flow, and control reactive power independently on each side. With a proper control mechanism, it can control power to increase and maintain A.C. electrical system synchronism, and function as a quick phase angle power flow regulator with 360° range of control. There is significant flexibility in the arrangement of the VSC converter bridges. Many two level converter bridges can be gathered with adequate harmonic cancellation features in order to produce satisfactory A.C. electrical system voltage waves. Another possibility is to use multilevel converter bridges to allow for harmonic cancellation. Additionally, both two level and multilevel converter bridges can use pulse width modulation to cancel low order harmonics. With pulse width modulation, high pass filters may still be needed since PWM adds to the higher order harmonics. As VSC converter bridge engineering develops for greater D.C. voltage usages, it will be feasible to eliminate converter transformers. This is feasible with the low voltage usages in use today. It is anticipated the exciting developments in power electronics will proceed to give new arrangements and usages for HVDC converters.