

Introduction to HDVC Technology



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PDHLibrary Course No 02017051
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Introduction to HVDC Technology

Electricity is produced as an alternating current (AC). It is also transferred and distributed as AC and in majority of applications it is used as AC. Nevertheless, in many situations, it is financially and technically beneficial to use direct current (DC) links. In some situations, it may be the only possible power transmission method. In situations, when two different AC systems cannot be synchronised or when the interconnection cable length is too long for stable AC transmission, DC transmission can be applied. At sending “converter station” the AC is converted to DC current, which is then transferred to a second, receiving converter station and converted back to AC. In “back-to-back” HVDC arrangements the two converter stations are placed in the same building, reducing the DC transmission length to zero. HVDC transmission installations can be classified into four broad groups and any arrangement typically involves a combination of two or more of these. The groups are:

- Transfer of bulk power where AC would be uneconomical or infeasible
- Link between electrical systems which use different frequencies, or between non-synchronised or isolated power systems which, even though they have the same nominal frequency, cannot be run reliably in synchronism.
- Introduction of power infeed without greatly increasing the short circuit level of the client's AC system.
- Improvement of AC system operation by the fast and precise control of HVDC power.

HVDC ARRANGEMENTS

MONOPOLAR HVDC CONFIGURATIONS

Monopolar HVDC configurations have either earth return or metallic return.

A Monopolar HVDC configuration with earth return contains one or more six-pulse converter units connected in series or parallel at each end, a single conductor and return through the ground or sea. This configuration is presented in Figure 1. It can be

a practical arrangement for a HVDC cable transmission and/or the first stage of a bipolar scheme. At each line end, it demands an electrode line and a earth or sea electrode built for continuous service.

A Monopolar HVDC configuration with Metallic Return typically contains one high voltage and one medium voltage conductor as presented in Figure 2. A monopolar scheme is used either as the first stage of a bipolar arrangement, avoiding earth currents. It is also applied when installation of electrode lines and earth electrodes results in an uneconomical solution due to a short distance or high value of ground resistivity.

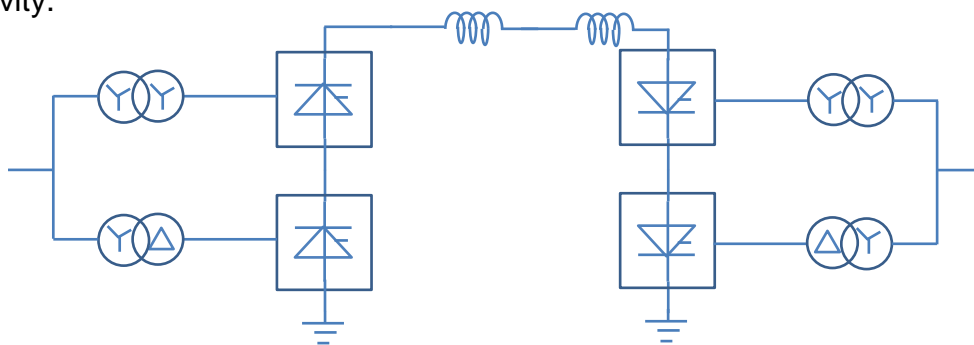


Figure 1. Monopolar HVDC arrangement with earth return

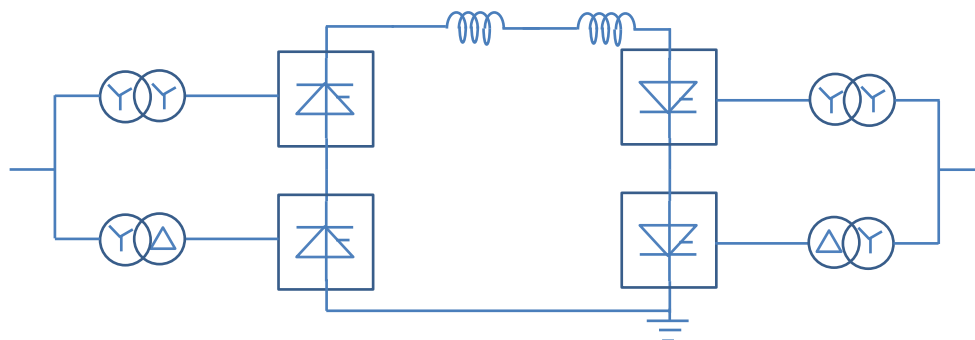


Figure 2. Monopolar HVDC arrangement with metallic return

BIPOLAR HVDC CONFIGURATIONS

A Bipolar HVDC configuration contains two poles, each of which includes one or more twelve-pulse converter units that are connected in series or parallel. Two conductors are used, one with positive and the other with negative polarity to ground for power transfer in one direction. For power transfer in the other direction, the two conductors change their polarities. A Bipole configuration is a combination of two monopolar

configurations with earth path. It is presented in Figure 3. With both poles in service, the imbalance current transfer in the earth path can be kept to a very low value.

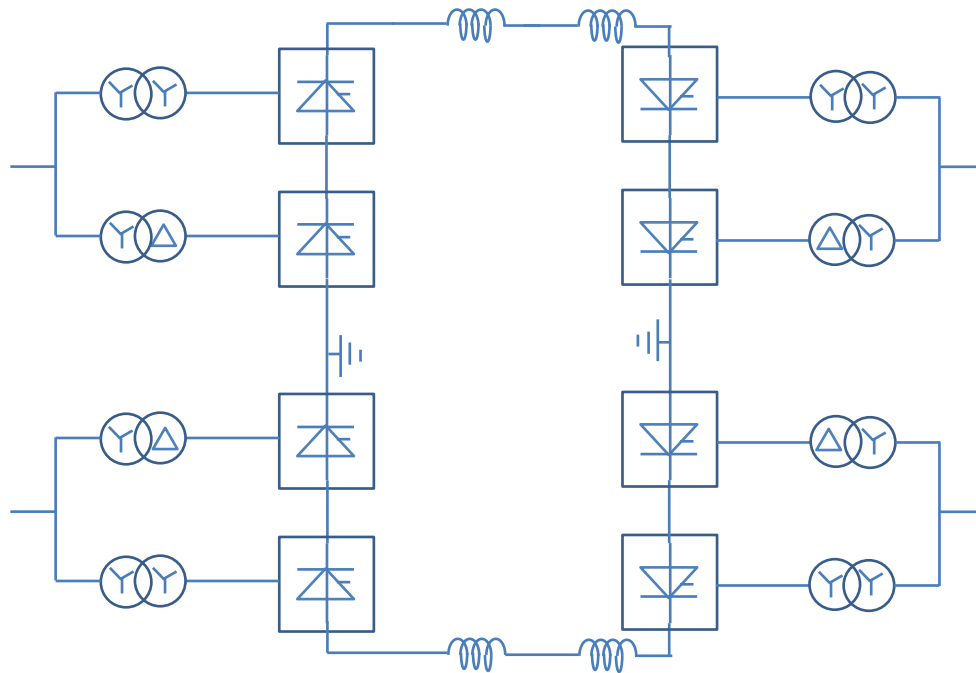


Figure 3. Bipolar HVDC configuration

This is a typical configuration with the following operational features:

- During an outage of one pole, the other could be continuously controlled with earth return.
- For a pole outage, in case long-term earth current flow is undesirable, the bipolar configuration could be ran in monopolar metallic return mode. This is only possible if adequate DC arrangements are provided, as presented in Figure 4. Current transfer to the metallic path and back without interruption demands a Metallic Return Transfer Breaker (MRTB) and other special purpose switchgear in the terminal earth path. When a short interruption of power flow is allowed, such circuit breaker is not necessary.
- During earth electrodes or electrode lines maintenance, service is possible with connection of neutrals to the earthing grid of the terminals, with the imbalance current between the two poles kept to a very low value.
- When one pole cannot be ran with full load current, the two poles of the bipolar arrangement could be controlled with different currents, as long as both earth electrodes are connected.

- In case of partial damage to DC line insulation, one or both poles could be continuously operated at decreased voltage.

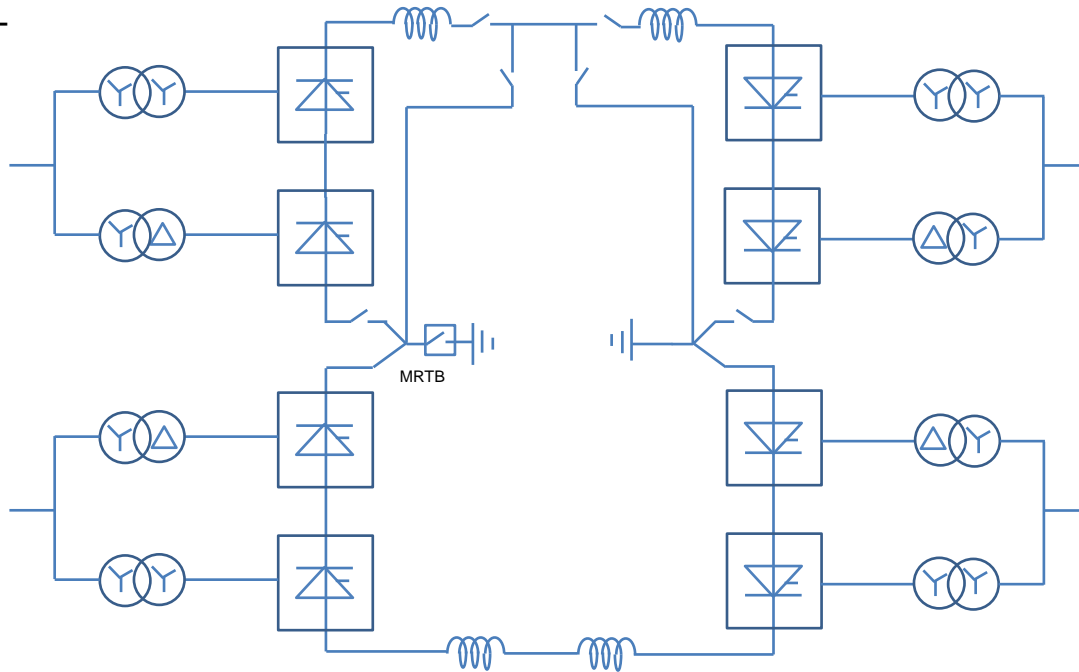


Figure 4. Bipolar configuration with monopolar metallic return for pole outage

- In place of earth return, a third conductor can be added end-to-end. This conductor transfers unbalanced currents during bipolar service and functions as the return path when a pole is out of operation.

BACK-TO-BACK HVDC CONFIGURATIONS

Back-to-back HVDC configurations are particular cases of monopolar HVDC interconnections. In these configurations, there is no DC transmission line and both converters are placed at the same site. For economic reasons each converter is typically a twelve-pulse converter unit and the valves for both converters may be placed in one valve hall. The control mechanism, cooling devices and auxiliary system may be incorporated into configurations common to the two converters. DC filters are not needed, nor are electrodes or electrode lines. The neutral connection is done within the valve hall. Back-to-back HVDC link which does not require a smoothing reactor are also developed. They do not require external DC insulation. Figure 5 presents two different back-to-back HVDC circuit configurations. Normally, for a back-to-back HVDC link, the DC voltage rating is low and the thyristor valve current rating

is high in comparison with HVDC interconnections via overhead lines or underground cables. The reason is that valve costs are voltage-dependent, as the higher the voltage the higher the number of thyristors. A low voltage tertiary winding can be installed in to the converter transformer for the AC filters and compensation. Therefore, smaller reactive power switching steps can be accomplished. Large back-to-back HVDC configurations can contain two or more independent links so that the outage of one converter unit will not cause loss of overall power capability.

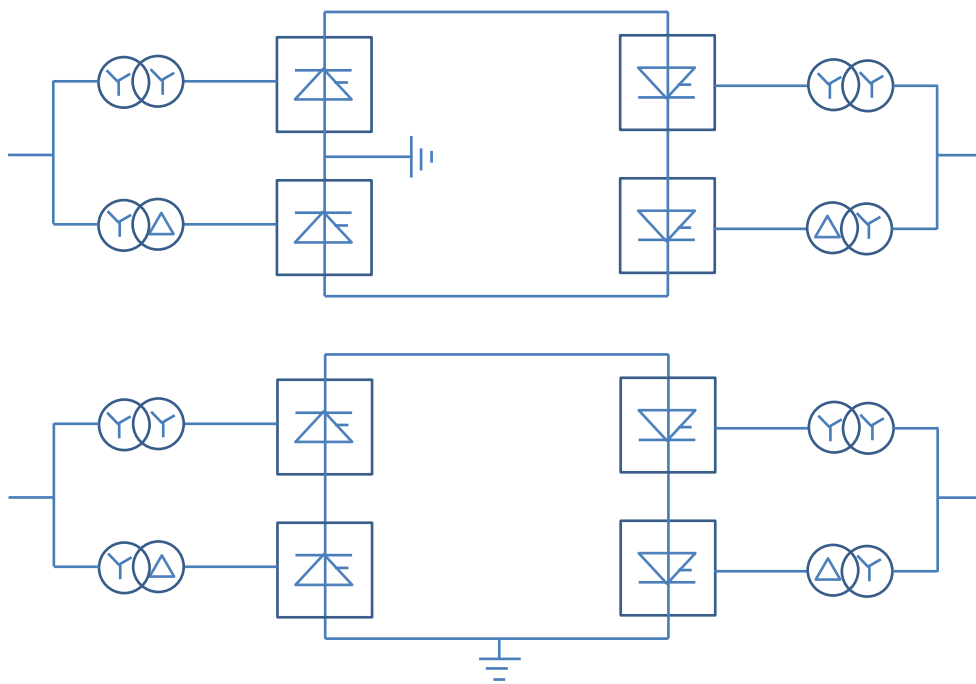


Figure 5. Back to back DC circuits

WHAT IS HVDC?

A simple HVDC interconnection scheme is presented in Figure 6. AC power is fed to a converter which works as a rectifier. Rectifier output is DC power, which is independent of the AC supply frequency and phase. The DC power is transferred through a conduction medium. It can be an overhead line, an underground cable or a short length of busbar and it is applied to the DC terminals of a second converter. The second converter is controlled as a line-commutated inverter and allows the DC power to run into the receiving AC network. Typical HVDC transmission uses line-commutated thyristor technology. Figure 7 presents a simple thyristor circuit. When a gate pulse (i_g) is applied while positive forward voltage is imposed between the anode

and cathode (V_{thy}), the thyristor will transfer current (i_L). Conduction goes on without additional gate pulses as long as current runs in the forward direction. Thyristor “turn-off” happens only when the current tries to reverse. Therefore, a thyristor converter demands an existing alternating AC voltage (V_{ac}) in order to work as an inverter. This is why the thyristor-based converter topology applied in HVDC is known as a line-commutated converter (LCC).

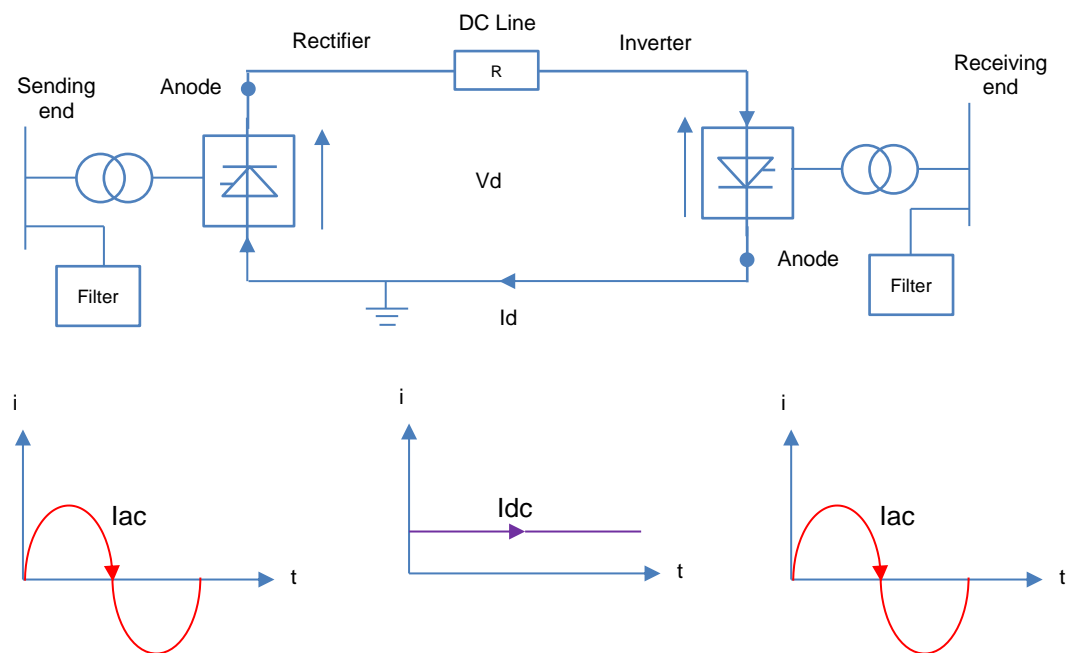


Figure 6. Essential HVDC transmission

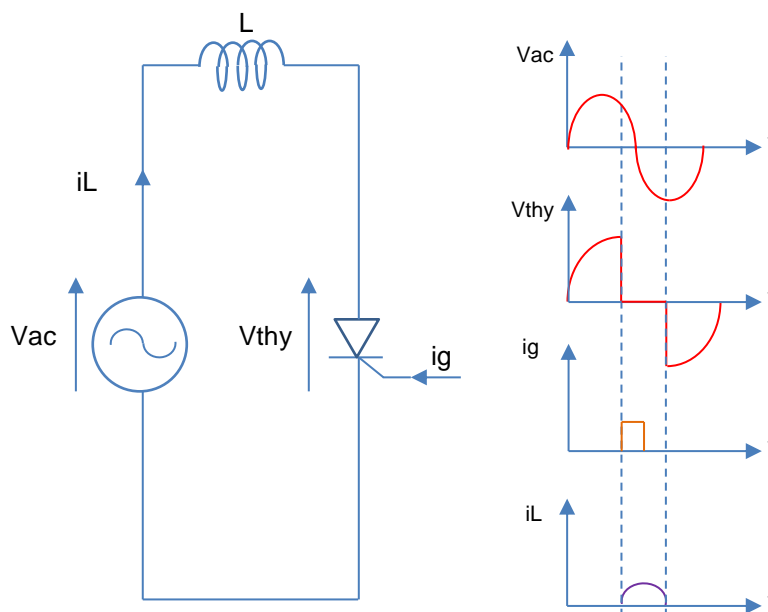


Figure 7. Thyristor gating and commutation

AC SWITCHYARD

The AC system is connected to a HVDC converter station via a “converter bus”. That is simply the AC busbar to which the converter is connected. The AC connection(s), the HVDC connection(s), connections to AC harmonic filters and other loads such as auxiliary supply transformer, extra reactive power demands, etc., can be accomplished in few ways. They are typically determined by: reliability/redundancy demands, protection and metering demands, the number of separately switchable converters and local practice in AC substation design.

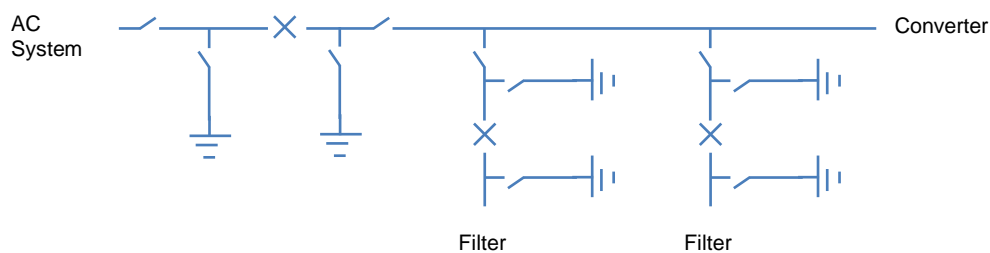


Figure 8. Single busbar

Figure 8 presents a simple, single, 3-phase busbar with one switchable connection to the AC system and the switchable AC harmonic filters which are directly connected to it. In such configuration, it is not feasible to use the AC harmonic filters for AC system reactive power support without having the converter energized. Figure 9 presents an arrangement consisting of two converters and including an extra circuit breaker dedicated to each converter. In this configuration, the AC harmonic filters can be utilized for AC reactive power support without energising the converter. Nevertheless, in common with Figure 8, a busbar fault will end in the total converter station outage. To secure some extra redundancy a double busbar configuration can be used as presented in Figure 10. In Figure 10 an AC busbar outage will end in those loads connected to that busbar being disconnected until the disconnectors can be made to re-connect the load to the remaining, “healthy” busbar. Disconnector rearrangement will usually take roughly ten seconds and in some situations such an outage may not be acceptable. Therefore the configuration presented in Figure 11 can be applied, where each load is connected via a separate circuit breaker to each busbar. This allows quick disconnection and reconnection in the case of a busbar loss (usually around 300 ms). A weakness of the configuration presented in Figure 11 is the high number of needed AC circuit breakers. In order to decrease the number of circuit

breakers, the arrangement presented in Figure 12 can be applied. In Figure 12 two loads can be separately switched between two three-phase busbars via three circuit breakers. Therefore, this configuration is typically known as a “breaker-and-a-half” configuration. Many other AC switchyard configurations exist and have been used along with existing HVDC arrangements.

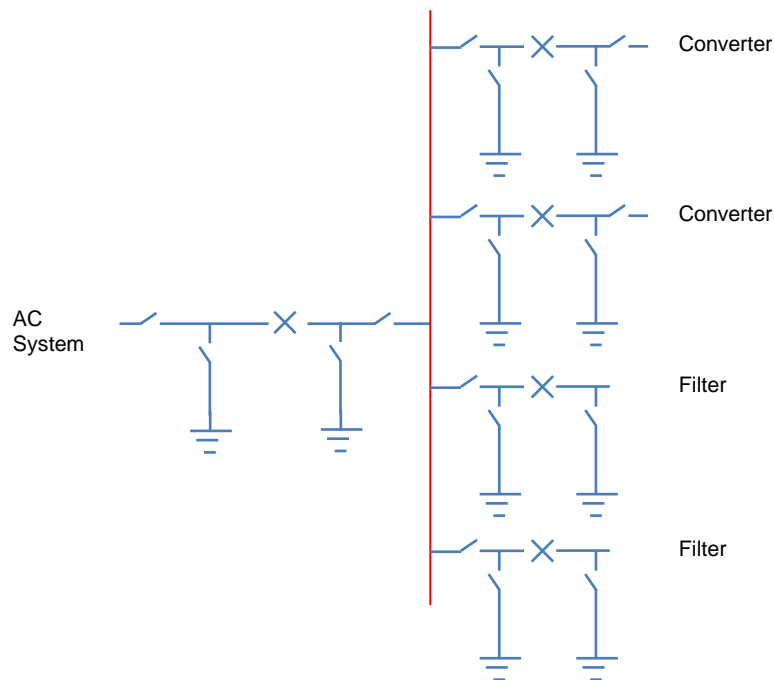


Figure 9. Single busbar with separate converter breaker configuration

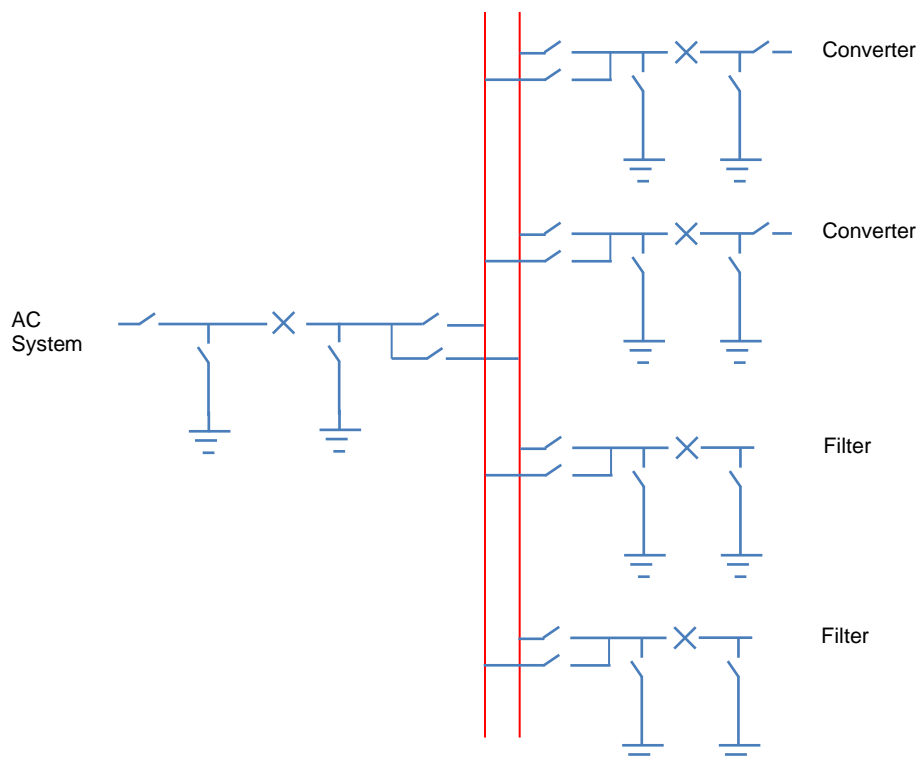


Figure 10. A double busbar configuration

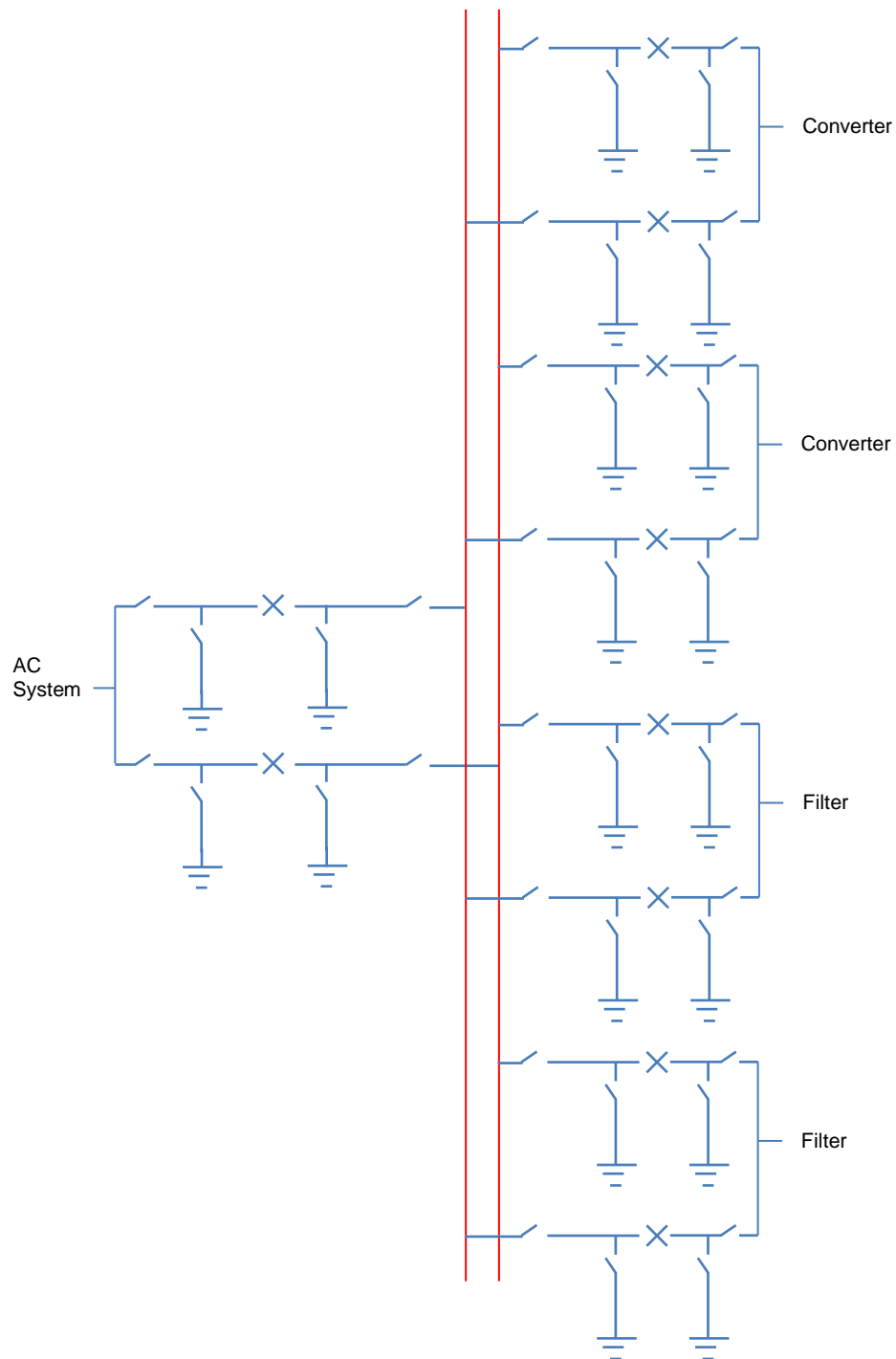


Figure 11. A double bus, double breaker configuration

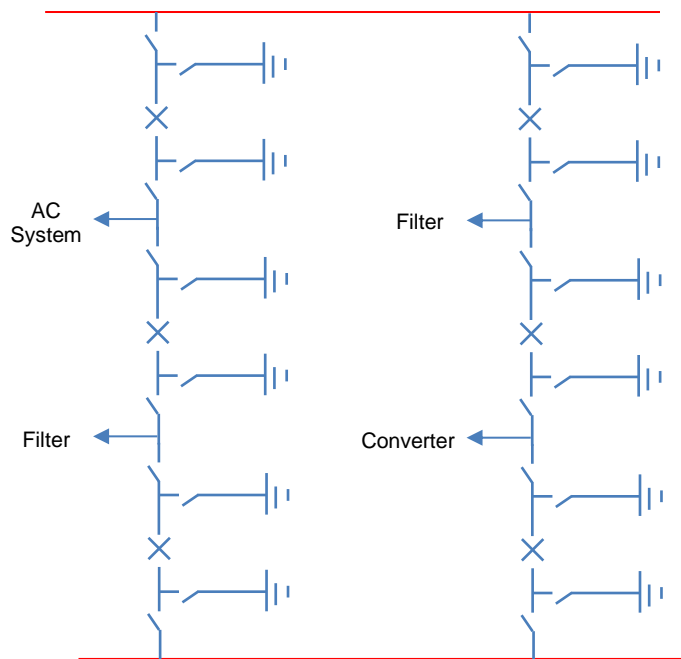


Figure 12. A breaker-and-a-half configuration

AC HARMONIC FILTERS

Converter performance results in AC current harmonics generation and the reactive power absorption. In order to fix the impact of these AC harmonic currents and the absorbed reactive power, the converter station typically includes switchable AC harmonic filters connected as shunts. They are either connected directly to the converter busbar or connected to a “filter busbar” which is connected to the converter busbar. The AC harmonic filters are automatically switched-on and off with typical AC circuit breakers when they are required to meet harmonic performance and reactive power performance limits. The AC harmonic filters are typically designed as high voltage connected capacitor bank in series with a medium voltage circuit comprising air-cored air-insulated reactors, resistors and capacitor banks. These elements are chosen to give the needed performance from the AC harmonic filter and to ensure that the filter is properly rated.

HIGH FREQUENCY HARMONIC FILTER

The converter performance will end in the generation of very high-frequency interference which will spread out into the AC system from the converter bus. While the magnitude and frequency of this interference is usually of no importance to the

safe AC system operation, there are some situations where this high-frequency interference may be unsuitable, particularly when the AC system uses Power Line Carrier (PLC) signalling.

PLC signalling is a system which transfers a communication signal as an amplitude-modulated signal, superimposed on the AC power system fundamental frequency voltage signal. This system is applied as a communication link between AC system protection devices. Nevertheless, the high frequency interference created by converter performance can overlap with the frequencies used for PLC communications (usually in the range of 40 kHz to 500 kHz). Hence, it is sometimes required to include a High Frequency (HF) filter (or PLC filter) in the connection between the converter bus and the converter in order to fix the interference that can spread into the AC system. As with the AC harmonic filter, the HF filter is made of a high voltage connected capacitor bank, an air-core air-insulated reactor and an additional low voltage circuit made of capacitors, reactors and resistors which are known as a tuning pack.

CONVERTER TRANSFORMER

The converter transformer is the link between the AC system and the thyristor valves. Normally, the HVDC converter transformer is exposed to a DC voltage insulation stress as well as the AC voltage stress that is normally experienced by a power transformer. These AC and DC stresses are different. The AC voltage stress is primarily in the insulating oil and determined by the geometry and permittivity of the materials. The DC stress is determined by the resistivity of the insulating materials which, change with operating conditions. Also, it is important that the converter transformer be thermally made to consider both the fundamental frequency load and the AC harmonic currents that will run from the converter through the converter transformer to the AC harmonic filters. Normally, the converter transformer is designed as ground star-line winding and a floating-star and delta secondary windings. Typically, there is normally an on-load tap changer on the line winding.

CONVERTER

The converter allows the transformation from AC to DC or DC to AC as needed. The fundamental building block of the converter is the six-pulse bridge. Nevertheless, majority of the HVDC converters are arranged as twelve-pulse bridges. The twelve-pulse bridge is made of 12 “valves” each of which may have many series-connected thyristors in order to reach the DC rating of the HVDC arrangement. For a HVDC power transmission configuration, the valves associated with each twelve-pulse bridge are typically contained within a purpose built building known as a “valve hall”. For back-to-back configurations, where both the sending and receiving end of the HVDC link are installed on the same location, it is common for the valves associated with both link ends to be installed within the same valve hall.

DC SMOOTHING REACTOR

For a HVDC transmission configuration, the DC smoothing reactor gives a number of functions but essentially it is used to:

- decrease the DC current ripple on the overhead transmission line or underground cable
- decrease the maximum potential fault current that could run from the DC transmission circuit into a converter fault
- change the DC side resonances of the configuration to frequencies that are not multiples of the fundamental AC frequency
- protect the thyristor valve from fast front transients generated on the DC transmission line (e.g. a lightning strike)

The DC smoothing reactor is typically a big air-cored air-insulated reactor and is installed at the HVDC converter high voltage terminal for configurations rated at, or below, 500 kVdc. Above 500 kV, the DC smoothing reactor is typically split between the high voltage and neutral terminals.

DC FILTER

Converter services results in voltage harmonics being created at the converter DC terminals. There are sinusoidal AC harmonic components superimposed on the DC terminal voltage. This AC voltage harmonic component will end in AC harmonic current

transfer in the DC circuit. Also, the field created by this AC harmonic current transfer can link with adjacent conductors, such as open-wire telecommunication systems, and create harmonic current transfer in these other circuits. In a back-to-back configuration, these harmonics are contained within the valve hall with proper shielding. With a cable arrangement the cable screen normally gives proper shielding. Nevertheless, with open-wire DC transmission it may be required to install DC filters to limit the amount of harmonic current running in the DC line. The DC filter is physically similar to an AC filter in that it is installed at the high voltage potential via a capacitor bank. Other capacitors along with reactors and resistors are then installed at the high voltage capacitor bank in order to give the desired tuning and damping.

DC SWITCHGEAR

Switchgear on the converter DC side is normally limited to disconnectors and ground switches for scheme reconfiguration and safe maintenance operation. Fault events interruption is completed by the controlled action of the converter. Therefore, it does not require switchgear with current interruption capacity. Where more than one HVDC pole share a mutual transmission conductor (normally the neutral) it is beneficial to be able to commutate the DC current between transmission paths without interrupting the DC power flow. The following DC switches can be defined.

NBGS - NEUTRAL BUS GROUND SWITCH

This switch is typically open but when closed it directly connects the converter neutral to the station ground mat. Operation with this switch can typically be kept if the converter can be ran in a bipole mode with balanced currents between the poles, that is, the DC current to ground is very small. The switch can also open, commutating a small DC unbalance current out of the switch and into the DC circuit.

NBS - NEUTRAL BUS SWITCH

A NBS is in series with the neutral connection of each pole. In the case of ground fault on one pole, that pole will be blocked. Nevertheless, the pole remaining in operation will continue to supply DC current into the fault via the mutual neutral connection. The NBS is used to divert the DC current away from the blocked pole to earth.

GRTS - GROUND RETURN TRANSFER SWITCH

The connection between the HVDC conductor and the neutral point includes both a high voltage disconnecter and a GRTS and is used as part of the switching function to make the HVDC configuration as either a earth return monopole or a metallic return monopole. The disconnecter is kept open if the HV conductor is energised in order to isolate the medium voltage GRTS from the high voltage. The GRTS is closed, following the disconnecter closing in order to put the HV conductor in parallel with the ground path. The GRTS is also applied to commutate the load current from the HV conductor transferring the path to the ground (or ground return) path. Once current flow through the HV conductor is discovered as having stopped, the disconnecter can be opened, allowing the HV conductor to be re-energised at high voltage.

MRTB - METALLIC RETURN TRANSFER BREAKER

The MRTB is used together with the GRTS to commutate the DC load current between the ground (ground return) and a parallel, otherwise idle, HV conductor (metallic return). The MRTB closes in order to put the low impedance ground return path in parallel with the metallic return path. The MRTB must also be able to open, causing current flowing through the ground return to commutate into the greater impedance metallic return path.

DC TRANSDUCERS

DC installed transducers fall into two groups, those measuring the DC voltage of the configuration and those measuring the DC current. DC voltage measurement is accomplished by either a resistive DC voltage divider or an optical voltage divider. The resistive voltage divider contains a series of connected resistors and a voltage measurement can be done across a low voltage end resistor which will be proportional to the DC voltage applied across the whole resistive divider assembly. Optical voltage transducers sense the electric field strength around a busbar with the use of Pockel cells. DC current measurement for both control and protection demands an electronic processing system. Measurement can be accomplished by generating a magnetic field within a measuring head which is adequate to cancel the magnetic field around a busbar through the measuring head. The current needed to generate the magnetic

field in the measuring head is then proportional to the real current flowing through the busbar. Devices using this technique are normally known as Zero Flux Current Transducer (ZFCT). Optical current measurement uses, amongst others, the Faraday principle in which the phase of an optical signal in a fibre optic cable is impacted by the magnetic field of a busbar around which the cable is wound. By measuring the phase variation between the generated signal and the signal reflected back from the busbar, the magnitude of the current can be obtained.

STATION LAYOUT

The converter station is typically divided into two areas:

- The AC switchyard which contains the AC harmonic filters and HF filters
- The “converter island” which contains the valve hall(s), the control and services building, the converter transformers and the DC switchyard.

AC SWITCHYARD

As with any AC switchyard, the complexity and hence the needed space changes varies, dependent upon the amount of feeders and locally-switched elements that need to be interconnected. For a HVDC converter station, the AC switchyard may be part of a major grid node. Hence, there may be a multiplicity of feeders, each with its associated towers, line end reactors, step-up/down transformers, etc. Conversely, the converter station could be placed on the network periphery and hence there may be only one or two feeders alongside the converter equipment. Nevertheless, in both situations, the space filled by these AC connections will be adequate to the AC voltage level(s).

Normally, the main HVDC converter associated components installed in the AC switchyard are the AC harmonic filters. Typically, these contain ground-level installed components placed within a fenced-off compound. Compound access is only possible once the filters have been isolated and grounded. High frequency filter elements, along with surge arresters, AC circuit breakers, disconnectors and ground switches are normally installed on structures to allow walk-around access while the equipment is energized.

CONVERTER ISLAND

In modern HVDC converter stations, the thyristor valves are normally installed indoors in a purpose built enclosure known as a valve hall. This enclosure gives a clean, controlled place in which the thyristor valves can safely function without the risk of exposure to pollution or outdoor conditions.

Within the valve hall, the thyristor valves are normally suspended from the building roof with the low voltage being closest to the roof and the high voltage being at the valve lowest point. An air gap between the valve bottom and the valve hall floor gives the high voltage insulation. The valve hall has an internal metal screen covering all walls, the roof and the floor. This screen produces a Faraday cage in order to hold the electromagnetic interference created by the thyristor valve service. The integrity of this screen is normally kept by having the valve connection side converter transformer bushings protruding into the valve hall and connecting the bushing turrets to the building screen. The DC switchyard differs widely in complexity and physical organization between projects. For outdoor DC locations, the majority of the equipment (disconnectors, ground switches, transducers, etc.) is normally installed on structures to make a walk-around area with only the DC filter. Nevertheless, where sound shielding is needed around the DC reactor, this may be ground installed with the sound shielding in the form of separate walls or an enclosure, also making the safety barrier. When the DC area is indoors, it is typical to have the majority of the equipment installed at ground level in order to avoid building excessive height requirement. In such situations, access to the DC area is controlled by a fenced-off enclosure. The control and services building is also placed on the converter island.

This building typically has equipment rooms such as:

- Control room
- Auxiliary supplies distribution
- Cooling plant room
- Workshop
- Batteries
- Offices

ACOUSTIC NOISE

Consequently, there are demands resulting from local environmental rules related to the acoustic noise any substation can produce at either its boundary or at the closest property. Much of the equipment in an HVDC converter station creates acoustic noise when working and hence careful consideration is needed in terms of equipment layout in order to decrease the acoustic noise at the measurement point.

Usual acoustic noise sources within a converter station (measured as sound power (P_ω)) are:

- Converter transformer (105 dB(A) sound power)
- DC smoothing reactor (110 dB(A) sound power)
- AC harmonic filter reactor (100 dB(A) sound power)
- Valve cooling (air blast coolers) (100 dB(A) sound power)
- AC harmonic filter capacitors (80 dB(A) sound power)
- Transformer cooling (105 dB(A) sound power)

As an approximation, the acoustic noise sound pressure ($L_\omega(A)$) from any individual point source, at a distance ' χ ' from the component is computed as follows:

$$L_\omega(\chi) = P_\omega - 20x \log_{10} \chi - 8$$

Where:

$L_\omega(\chi)$ – the sound pressure at a distance χ (in meters)

P_ω – the acoustic sound power of the point source (dB(A))

χ – the distance from the point source at which the sound pressure is to be computed (in meters)

In order to reach the boundary, or nearest residence, acoustic noise limit, it may be required to install acoustic noise barriers or to modify the equipment. The barriers may be walls or enclosures.

SIX-PULSE DIODE CONVERTER BRIDGE

Six-pulse converters are essential block of HVDC systems. An example of a six-pulse converter, which uses diodes, is presented in Figure 13. Diodes conduct in the sequence 1,2,3,4,5,6, so the transitions between one diode and the next happen

alternately in the upper and lower half-bridges. Each diode conducts for 120° , in every 360° cycle, so that the consecutive conducting pairs of diodes are 1 and 2, 2 and 3, 3 and 4, 4 and 5, 5 and 6, and 6 and 1. The conducting pair is always diodes pair which have the highest instantaneous AC voltage between them. The other diode pairs are connected to an instantaneously smaller voltage and therefore are exposed to a reverse voltage across their terminals. As time goes, the relative amplitudes of the converter's three AC supply phases (valve-winding voltages) change, so in Figure 14 the voltage B-C becomes higher than the voltage A-C and valve 3 takes over the current which had been running in valve 1. This process is known as "commutation". In this idealisation, the mean direct voltage, V_d , emerges as a constant value, completely fixed by the transformer ratio, the calculation of which is presented in Figure 15. This value is known as the "No-Load DC Voltage", or V_{dio} , of the converter.

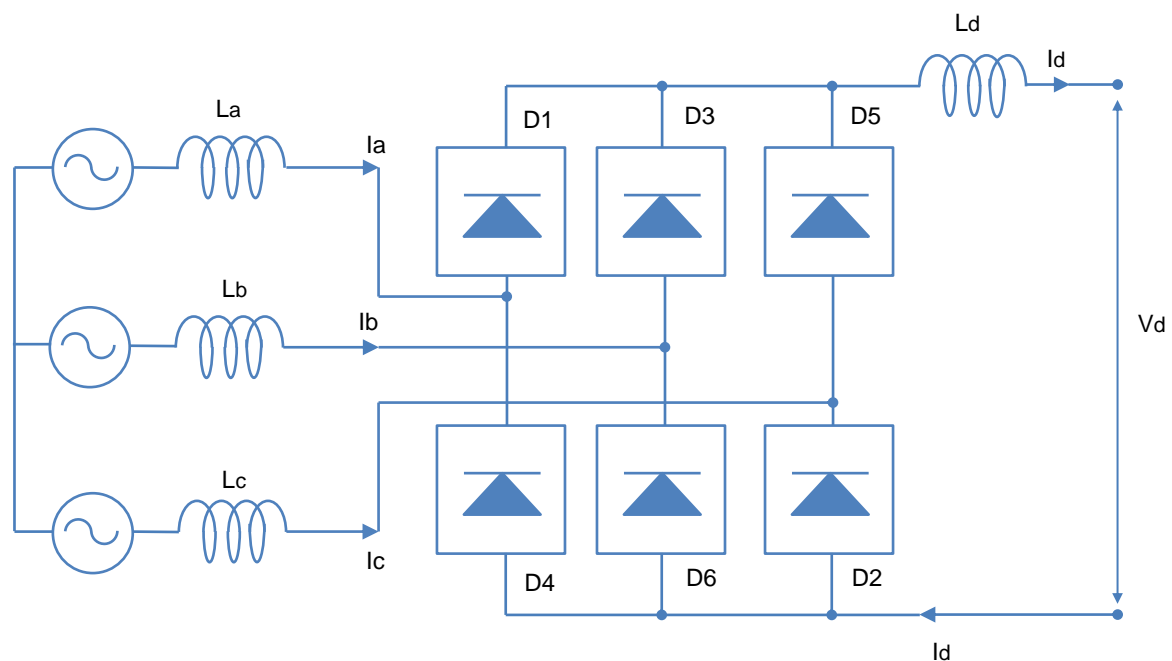


Figure 13. Six-pulse converter bridge configuration

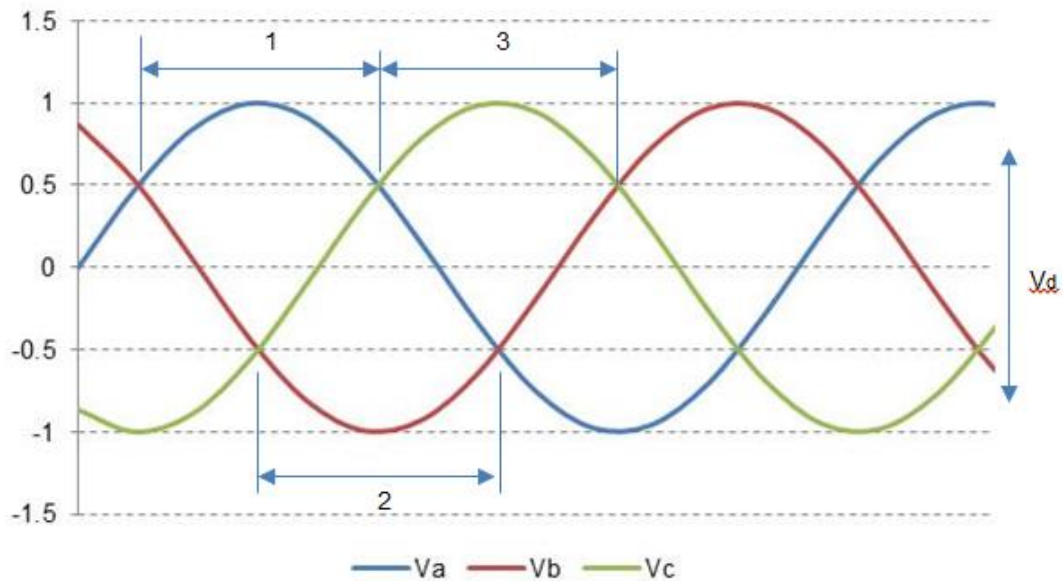
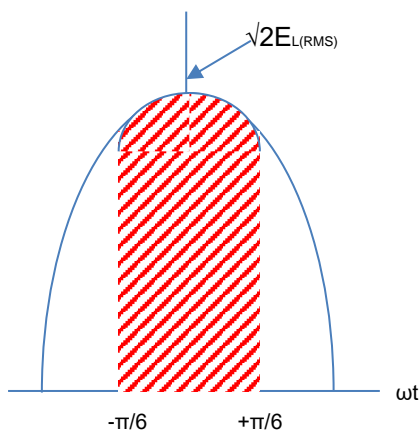


Figure 14. Current switching pattern of a six-pulse converter



$$V_{dio} = \frac{1}{\pi/3} \int_{-\pi/6}^{+\pi/6} \sqrt{2}E_L \cos \omega t d(\omega t)$$

$$V_{dio} = 3\sqrt{2}E_L [\sin \omega t]_{-\pi/6}^{+\pi/6}$$

$$V_{dio} = \frac{3\sqrt{2}}{\pi} E_{L(RMS)}$$

Figure 15. The no-load DC voltage of a six-pulse bridge

COMMUTATION

In reality, the current transfer from one diode to the next needs a finite time, since the current transfer is slowed down by the commutation reactance (consisting of converter transformer reactance, the thyristor valve and a small amount in the HF filtering circuit). This creates an "overlap" between successive conduction periods in one-half

of the six-pulse bridge. Figure 16 presents that the mean direct voltage (V_d) has been decreased in comparison to Figure 14. Figure 16 also presents the valve current waveform during the commutation process, where current falls in one valve, while the current increases in the next valve in sequence. The time needed to commutate the current from one valve to the next is known as the “overlap angle”, μ .

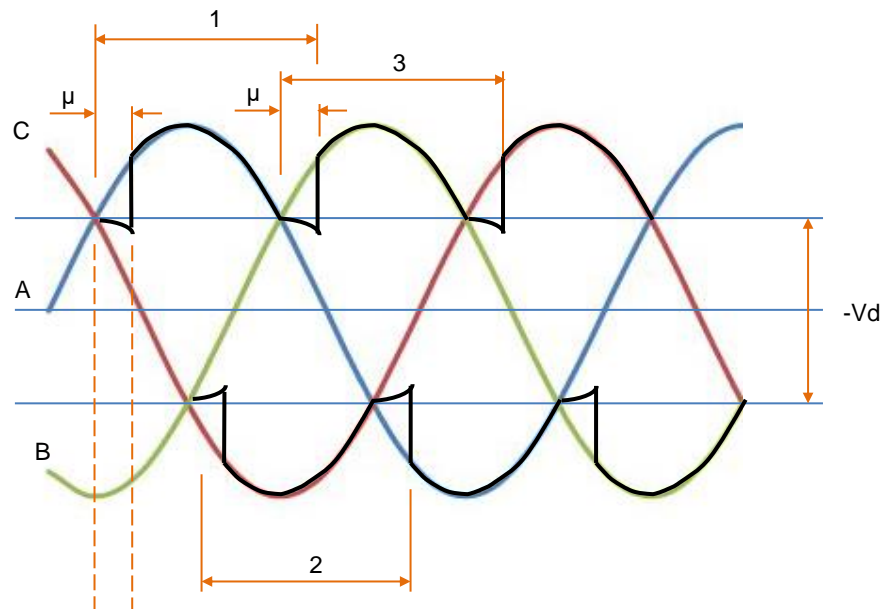


Figure 16. Commutation effect on converter operation

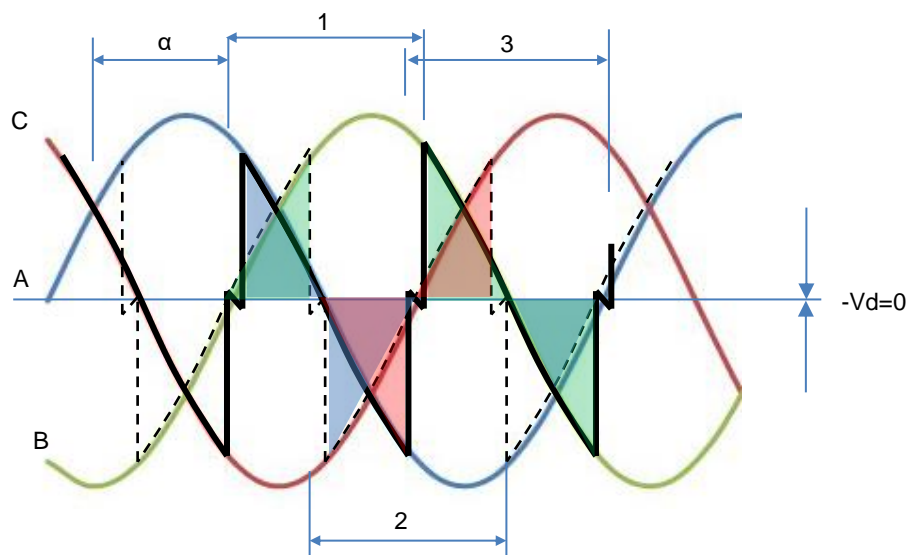


Figure 17. Effect of firing angle as it approaches 90°

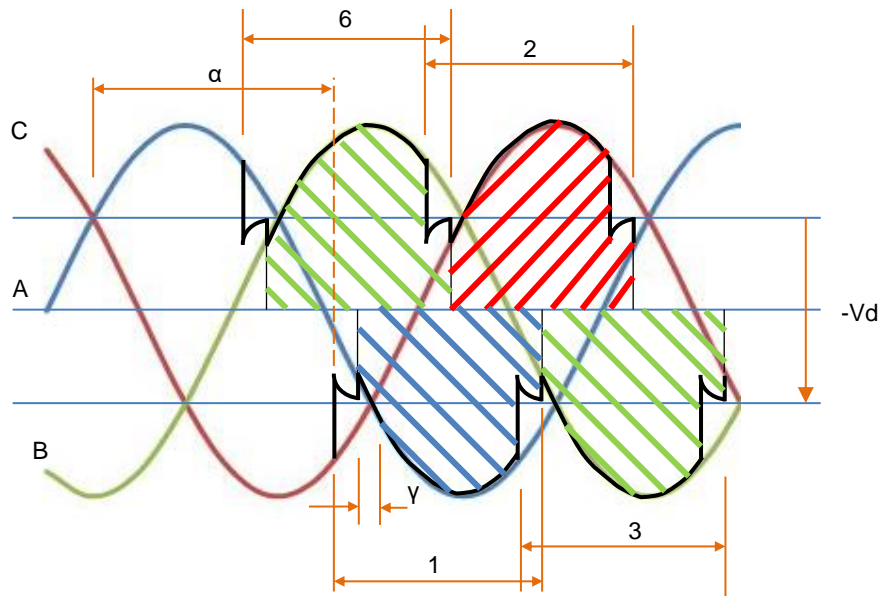


Figure 18. Effect of a firing angle of 140°

THYRISTOR CONTROLLED CONVERTER

In a thyristor converter, presented in Figure 19, it is possible to change the mean direct voltage by controlling the instant at which the thyristors are switched on. A thyristor is turned on by using a short pulse to its gate terminal and turns off when the external circuit forces its anode current to zero. In this situation, current zero is brought about by the commutation process when the next thyristor is fired. The firing delay angle α is defined as the angle between the phase voltage crossing of the valve-winding voltage and the instant when the thyristor is fired. This is presented in Figure 20. This delay angle influences when the commutation process will start and consequently sets the mean direct voltage (V_d). V_d is directly proportional to the cosine of α . For example, the bigger the delay angle, the smaller the mean direct voltage. Zero voltage is reached as α reaches 90° .

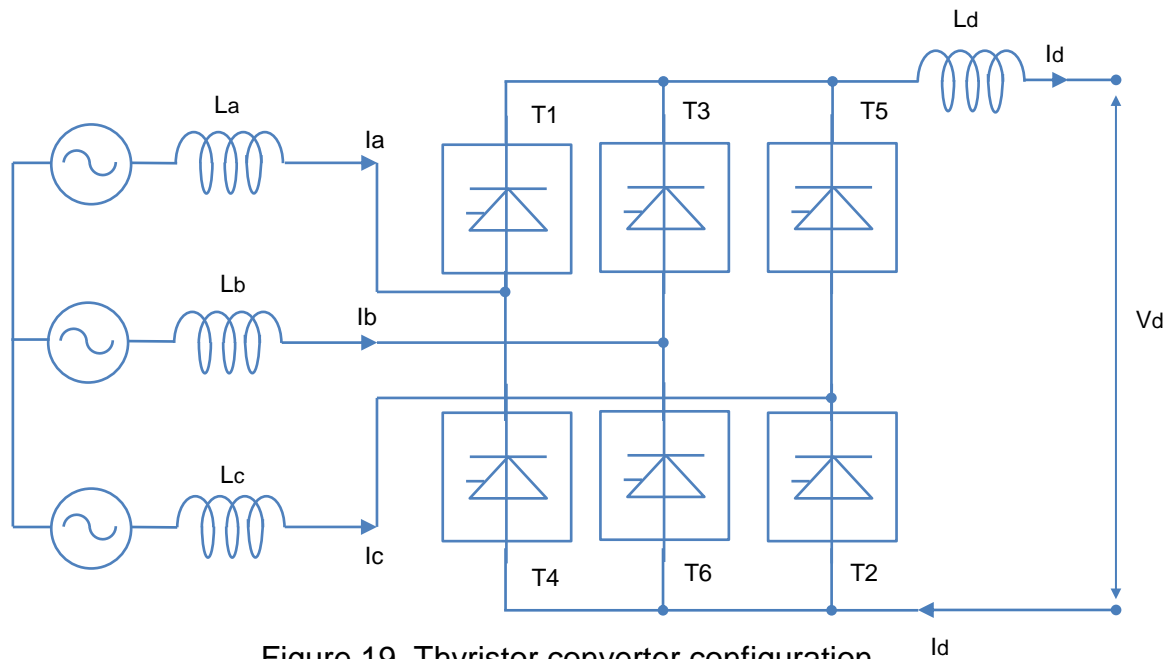


Figure 19. Thyristor converter configuration

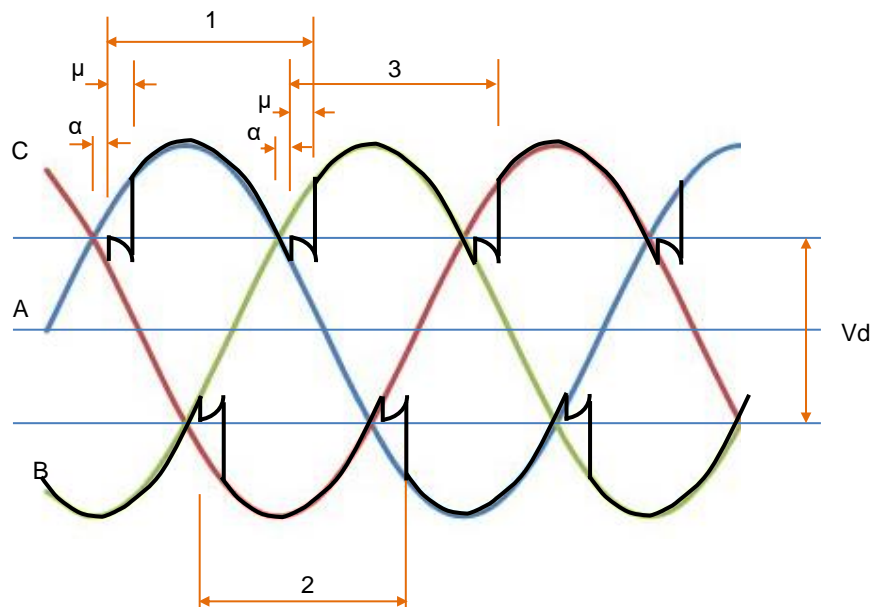


Figure 20. Effect of firing angle on converter function

THE INVERSION PROCESS

By increasing the firing angle, α , above 90° , the voltage area of the line-to-line voltage connected to the DC terminals via the conducting thyristors will be mainly negative. Therefore, the DC terminal voltage will be negative. Since, above 90° , the converter firing angle becomes big, it is more common to refer to the “extinction angle” or “gamma”, γ . This extinction angle shows the time between the end of the overlap period and the time when the phase voltage related with the outgoing valve becomes more positive/negative than that of the next valve in sequence. This is calculated as:

$$\gamma = 180^\circ - \mu - \alpha$$

It must be taken into account that the control of the output voltage of a six-pulse bridge is accomplished by the firing angle, α . The extinction angle, γ , is a representation of the available valve turn-off time following the point in time where the valve is fired.

VALVE VOLTAGE WAVEFORM

Common voltage waveforms across a valve during rectification and inversion are presented in Figure 21 and Figure 22, respectively. The “notches” in the waveforms are created when commutation starts, because commutation is a temporary phase-to-phase short circuit, created by the converter valves. This does not increase to heavy fault currents. Nevertheless at the instant the current in the valve which has just fired becomes same as the main direct current, the valve which is relinquishing current turns off, breaking the circulating current path.

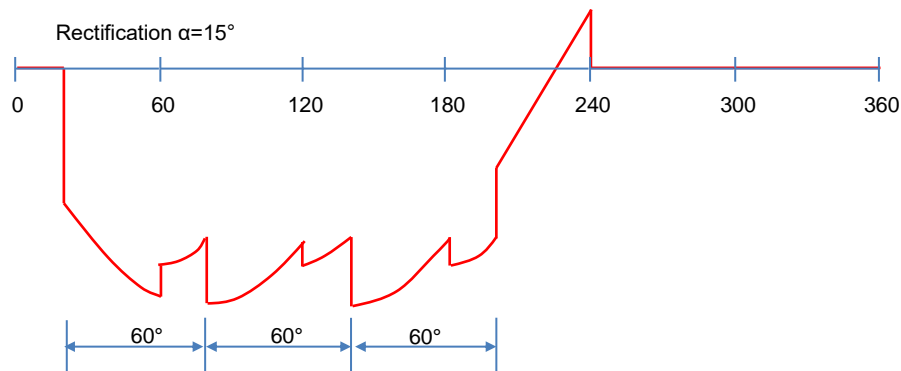


Figure 21. Rectifier valve voltage waveform (excluding commutation overshoots)

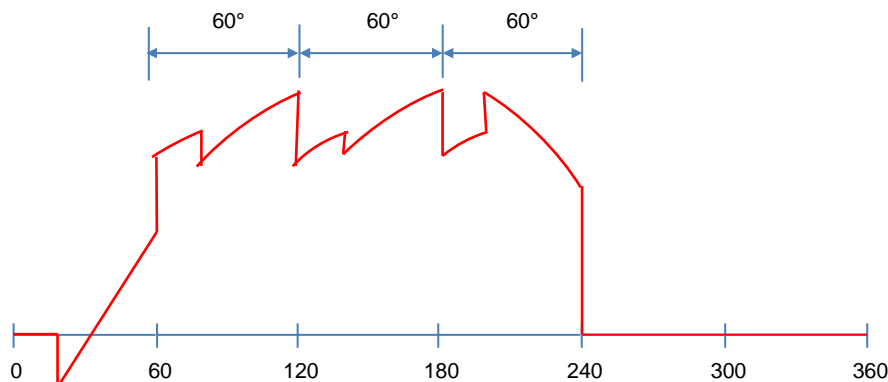


Figure 22. Inverter valve voltage waveform (excluding commutation overshoots)

TWELVE-PULSE BRIDGE RECTIFIER

Because of the high power levels related with HVDC transmission, it is important to decrease the current harmonics produced on the AC side and the voltage ripple generated on the converter DC side. This is accomplished by means of connecting two six-pulse bridge circuits in series on the DC side/parallel on the AC side to create the twelve pulse bridge arrangement (Figure 23.) Each of the bridges in Figure 23 is linked to the AC network by a single-phase three-winding transformer. One of the transformers is Y/Y (star/star) connected and the other Y/ Δ (star/delta). The Δ is on the DC side. Through this connection the bridges have a phase difference of 30° in supplying AC power. Mechanically the valves can be organized in three parallel stacks containing four valves linked in series.

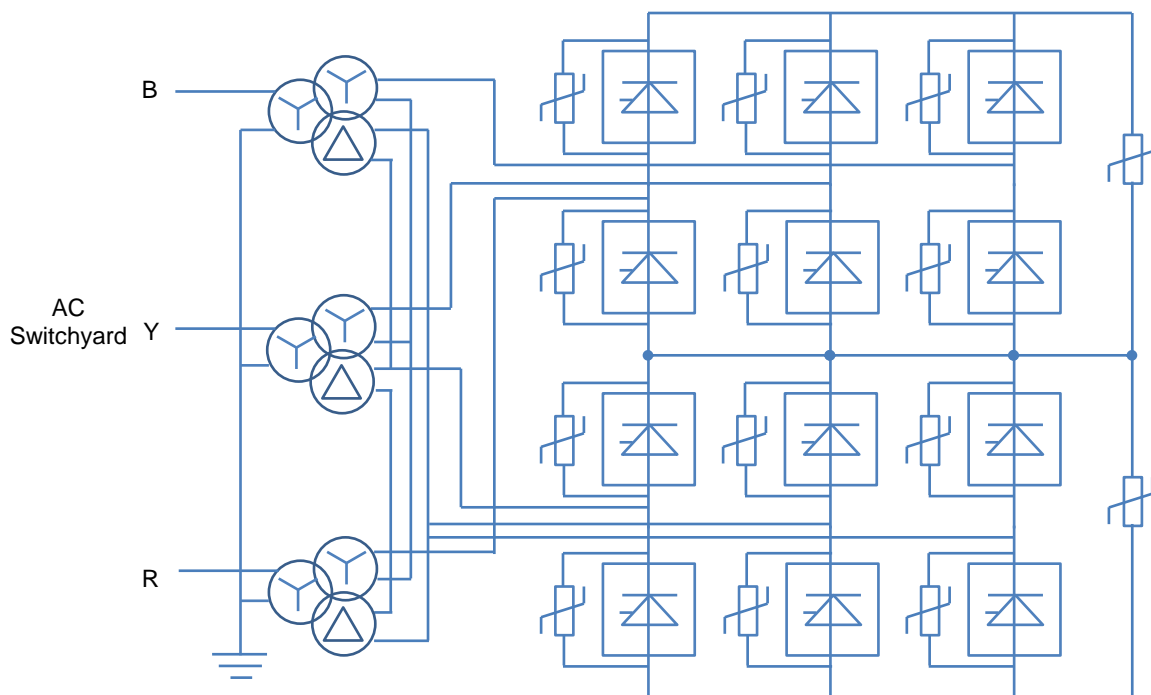


Figure 23. Twelve –pulse converter configuration

HVDC LINK CONTROL

Consider Figure 24, the voltage across the rectifier is positive with respect to both its anode terminal as well as the ground reference. Nevertheless, the inverter terminal is producing a negative voltage with respect to its anode terminal. Since it is connected in reverse parallel to the rectifier, its voltage with respect to the ground reference is also positive. Since the rectifier voltage and the inverter voltage are independently controlled, they can have different values. Therefore, there will be a voltage difference

across the resistor in the DC circuit which, as long as the rectifier voltage is higher than the inverter voltage, will cause a DC current to flow. This can be presented as:

$$I_d = \frac{V_{rectifier} - V_{inverter}}{R_d}$$

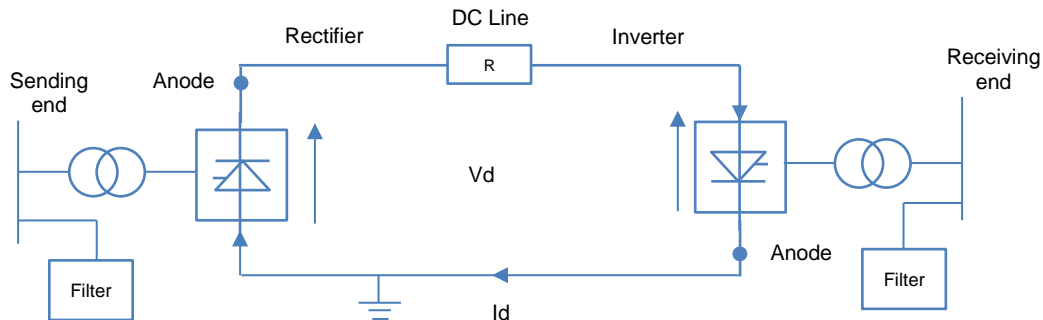


Figure 24. Inverter control arrangement

Under normal, steady-state service, the inverter control arrangement is typically organized to keep the DC voltage at a certain point on the HVDC link (known as the “compounding point”) at a set value. This target value is commonly 1.0 pu for a transmission network but for back-to-back arrangements, where the DC transmission losses can be neglected, this value can be varied to give an additional degree of reactive power control. The “compounding point” is typically at the rectifier DC terminal. Therefore, the inverter must compute this voltage based on the DC voltage at the inverter terminals, the DC current and the transmission circuit known resistance. The rectifier typically controls the DC current running in the circuit and completes this by adjusting DC voltage output to give a current flow as expressed by the above equation. There are several ways that a six-pulse converter can be controlled in a HVDC link.

For a rectifier the control possibilities are:

- Constant valve winding voltage control – With this control method, the converter transformer tap changer is used to keep the voltage applied to the AC terminals of each six-pulse bridge to a constant target value. Current control is then accomplished by change in converter operating angle.
- Constant firing angle range control – With constant valve winding voltage control, the firing angle at lower power transmission levels can be high. To decrease the range over which the firing angle can function in the steady state,

the converter transformer tap changer can be applied to change the used AC voltage to the six-pulse bridge. Therefore, it can limit the range over which the firing angle works.

For an inverter the control possibilities are:

- Fixed valve winding voltage control – This is the same as the equivalent rectifier control.
- Fixed gamma angle range control – This is similar to the rectifier “fixed firing angle range control” but reacts on the inverter extinction angle instead of the firing angle.
- Fixed extinction angle control (CEA) – With this control method, the inverter DC voltage is allowed to change in order to reach a constant extinction angle with changing DC current. The inverter converter transformer tap changer is used to adapt the used AC terminal voltage in order to keep the DC voltage to within a constant, steady-state, range.

STATIC CHARACTERISTICS

The static characteristics can be conceived as the cerebral cortex of the converter. The static characteristics determine the way in which the converter reacts to transients without involving higher control functions. The six-pulse bridge can be simplified to a battery in series with a resistor as presented in Figure 25.

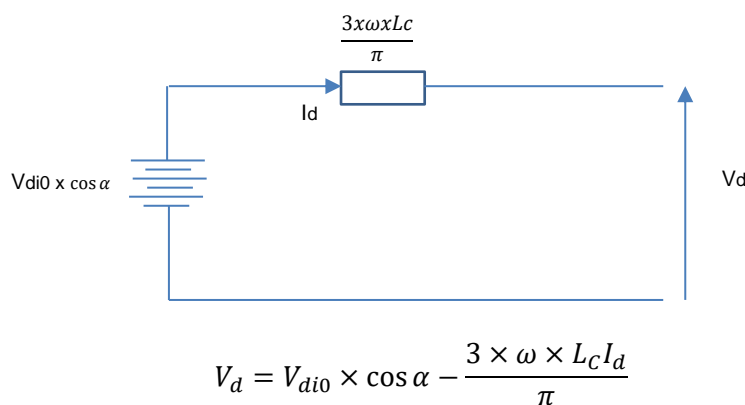


Figure 25. A basic six-pulse converter configuration

It is important to note that the resistor presented in Figure 25 is not a real resistor but is simply put in the above circuit to simulate the voltage regulation effect of the impedance of the converter bridge connection. This resistor does not have any I^2R losses. Consider the circuit presented in Figure 25. As the DC current through the converter goes to 1.0 pu, the voltage drop across the “resistor” increases, decreasing the DC terminal voltage at the circuit, as presented in Figure 26. Once at 1.0 pu DC current, the voltage can then be changed by increasing the firing angle. At a firing angle of 90° , the DC voltage is zero but the DC current, if supplied from a separate source, remains at 1.0 pu. When in inverter mode, the converter will allow a DC current to run through it is supplied by a separate DC current source. As the firing angle rises (extinction angle decreases), the converter DC terminal voltage rises up to the minimum extinction angle at which point the DC current must be decreased to accomplish additional DC terminal voltage increases, following a constant extinction angle line.

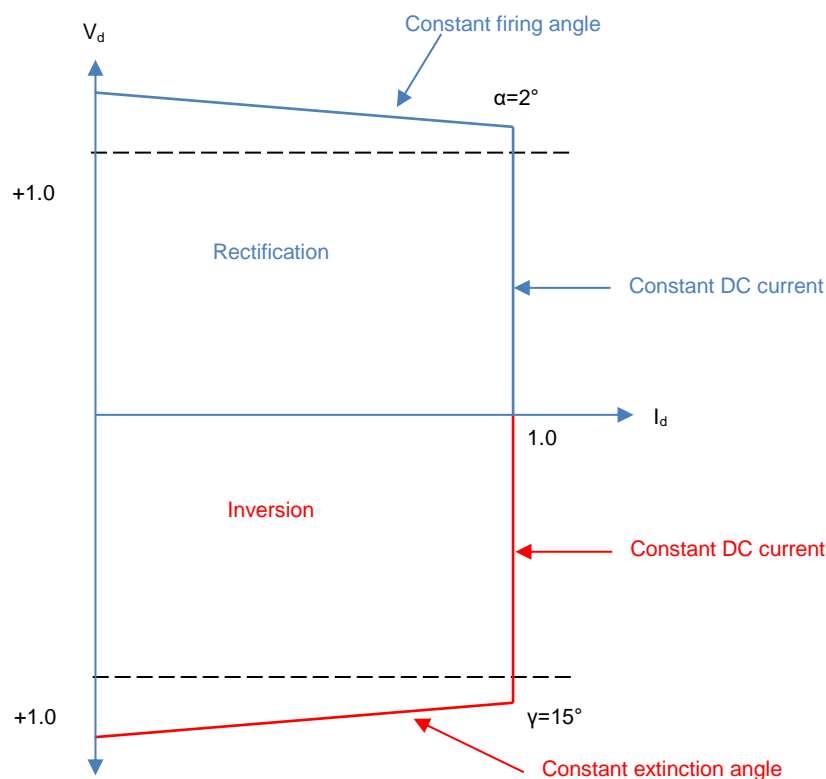


Figure 26. Converter operating profile

By vertically flipping the inverter characteristic and printing it on the same graph as the rectifier characteristic, the operating point, which is the point where the rectifier

characteristic and the inverter characteristic cross, is found. This is presented in Figure 27.

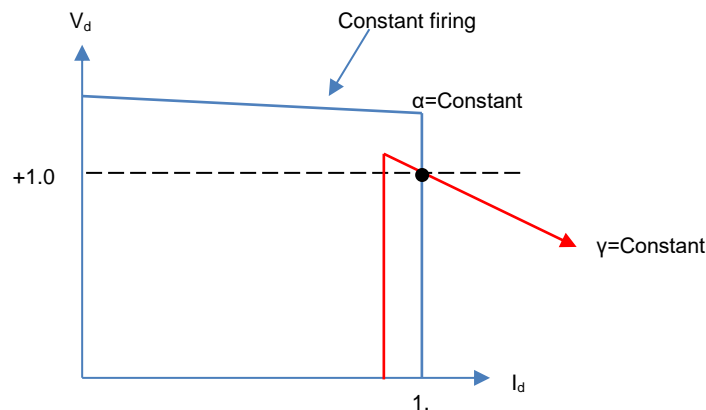


Figure 27. The basic static characteristic of an HVDC configuration

Nevertheless, with these static characteristics, as shown in Figure 28, if the AC voltage applied to the rectifier decreases then there are more crossover points between the rectifier and the inverter. Therefore, the operating point cannot be set. To resolve this, the basic converter characteristics are changed in order to control the way that the converters reacts during transient events.

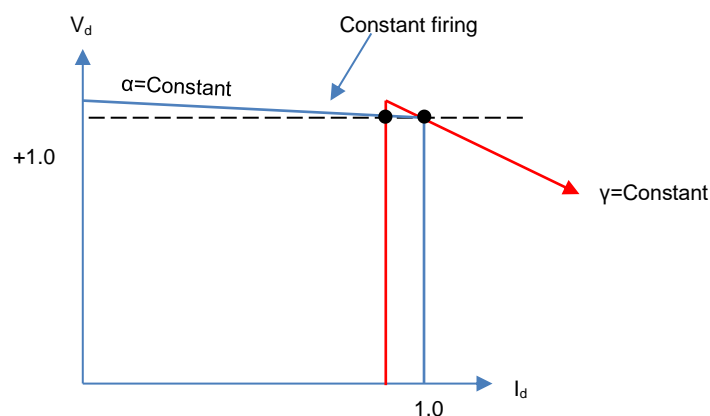


Figure 28. The basic static characteristic of an HVDC configuration with decreased rectifier AC terminal voltage

An example of a real characteristic is presented in Figure 29. Note that in Figure 29 the inverter constant current characteristic is at a lower DC current than the rectifier constant current characteristic. Under normal service, the inverter controls the DC voltage and the rectifier controls the DC current. Nevertheless, if the AC terminal voltage at the rectifier decreases such that the rectifier characteristic presented in

Figure 29 crosses the inverter constant current characteristic, then the inverter will keep the DC current at this level with the DC voltage being determined by where the rectifier characteristic crosses the inverter constant current characteristic.

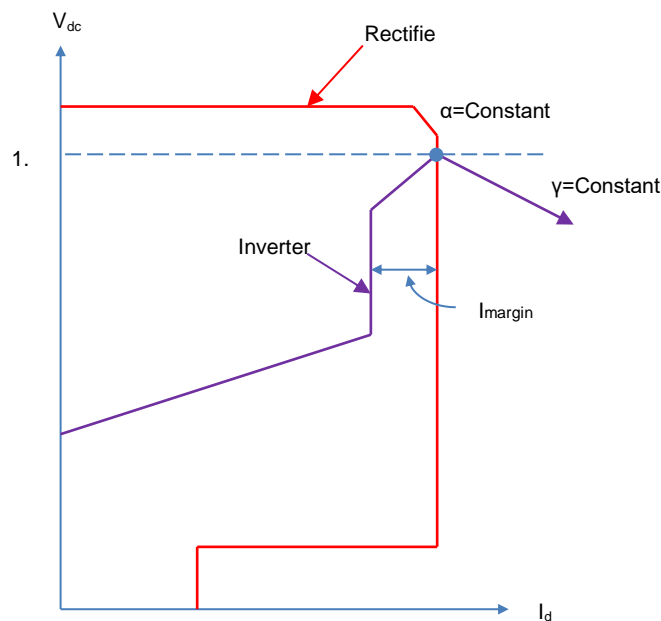


Figure 29. A real HVDC link static characteristic

The margin between the rectifier constant current characteristic and the inverter constant current characteristic is known as the “current margin”. Some dynamic characteristics can be laid over the static characteristic as presented in Figure 30. For instance, a constant real power curve can be superimposed showing the needed DC current for a given DC voltage variation to keep the rectifier DC terminal power. Another characteristic that can be laid over is one of constant reactive power. If the operating point were to be kept along the reactive power curve, then at any point the reactive power taken by the converter would remain fixed. Therefore, if there is a decrease in, for instance, the rectifier AC system, then, by following roughly constant reactive power curve, the variation in reactive power at the inverter terminal is minimized, although there is a variation in real power. Therefore, the converter bus voltage at the inverter would stay roughly constant.

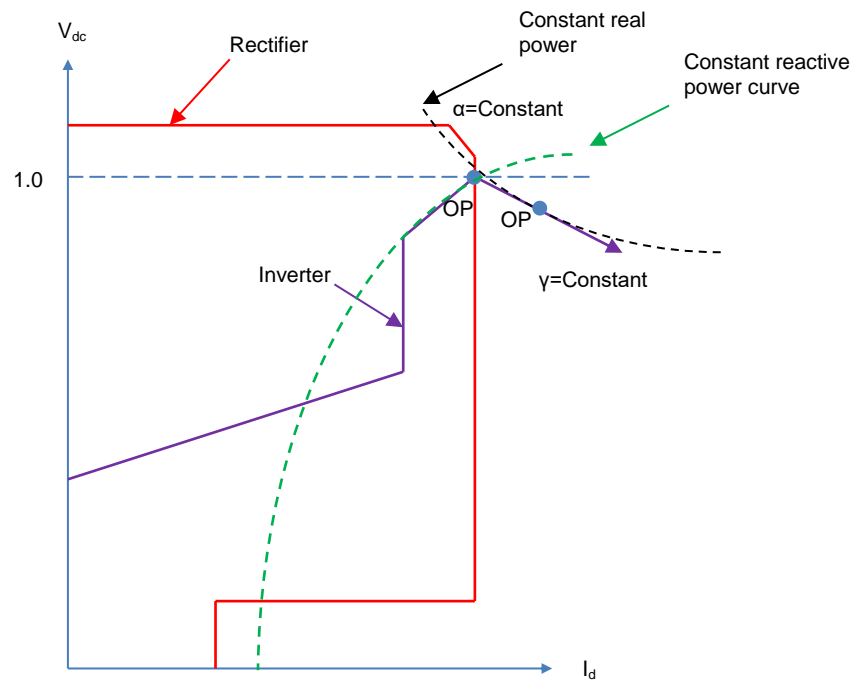


Figure 30. Constant real and reactive power characteristics laid over on the static characteristics

REACTIVE POWER IN AC SYSTEMS

Reactive power is integral part of all AC power systems. It is a quantity that is caused by the stray capacitance and inductance within all power system elements. It shifts, in phase, the current AC waveform with respect to the voltage AC waveform. Therefore, it reduces the instantaneous value of voltage multiplied by current. In order to evaluate phase shift effect, the AC power is considered as two components. The “Real” power, that is determined by in-phase voltage component and current. The “Reactive” power, that is determined by the out of-phase component of voltage and current. Reactive power can be leading in which case the current waveform is phase advanced with respect to the voltage waveform. Reactive power can also be lagging in which case the current waveform is phase delayed with respect to the voltage waveform. In HVDC configurations, it is conventional to consider leading reactive power as a “source” or “generator” of reactive power and lagging reactive power as a “load” or “absorber” reactive power. Therefore, reactive power resulting from capacitance is created and reactive power resulting from inductance and from the converter is absorbed.

An AC network is comprised of generators, VAR compensators, transmission lines and different inductive and capacitive loads. Reactive power transfer through the AC system ends in voltage change between busbars. When any extra reactive power source or load is connected to a busbar within the AC system, the change in voltage at both that busbar and interconnected busbars should still be kept within the steady-state limits. Hence, there is always a reactive power limit that can be connected to a busbar.

THE REACTIVE POWER CONVERTER LOAD

Converters are a reactive power load since they work with a delay firing angle which leads to a situation where the current lags the voltage. In addition, the converter transformer impedance (plus the small valve impedance) creates an additional current lag which is observed as the overlap angle. The converter operating overlap angle is a function of the operating current and the converter transformer leakage reactance:

$$\mu = \cos^{-1} \left[\cos(\delta) - \frac{I_d}{I_{d0}} x \chi_p \right] - \delta$$

- μ - the converter overlap angle (rad)
- I_d - converter DC operating current (pu)
- I_{d0} - rated converter DC operating current (pu)
- χ_p - converter transformer leakage reactance (pu)
- δ - converter control angle (α for rectifier operation, γ for inverter operation)

From the overlap angle and the converter firing angle, the converter operating power factor can be roughly computed as follows:

$$\cos \phi = \frac{1}{2} X [\cos(\delta) + \cos(\delta + \mu)]$$

Therefore, the reactive power absorption is roughly:

$$Q_{dc} = \tan[\cos^{-1}(\phi)] \times P_{dc}$$

Where:

- Q_{dc} - the converter reactive power absorption (pu)
- $\cos \phi$ - the converter power factor ($^{\circ}$)

P_{dc} – the converter station real power (pu)

The converter reactive power absorption at rated load can be roughly calculated as follows:

$$Q_{dc0} = \tan \left[\cos^{-1} \left(\cos \delta - \frac{\chi_p}{2} \right) \right]$$

Where:

Q_{dc0} – the converter reactive power absorption at rated DC current (pu).

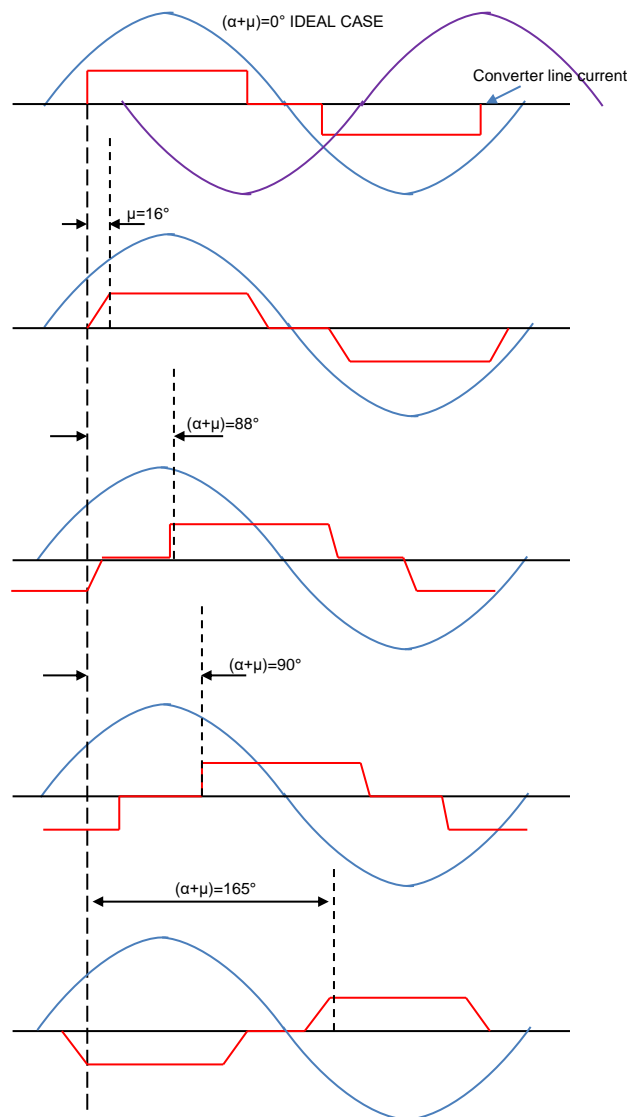


Figure 31. Lagging currents in rectifier and an inverter

REACTIVE POWER SOURCES WITHIN A CONVERTER STATION

The major sources of capacitive (positive) reactive power in a HVDC station are the AC harmonic filters. Harmonic filters have two applications: decreasing the harmonics injected into the AC system and creating reactive power. An AC filter is comprised of capacitances, inductances and resistances but at fundamental frequency the HV-installed capacitor is the main contributor to the generated reactive power.

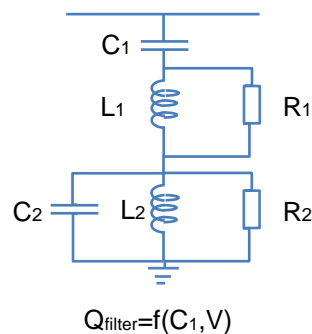


Figure 32. Typical AC harmonic filter scheme

CONTROLLING CONVERTER REACTIVE POWER

In order to meet the AC harmonic performance, each filter needs to be switched in at a certain DC power transmission level. This is known as “open-loop” control, as presented in Figure 33. These points are found from AC harmonic studies. Converter control action can be used to change the reactive power exchange with the AC system. In a HVDC arrangement, the DC power is expressed as:

$$\text{DC Power} = \text{DC Voltage} \times \text{DC Current}$$

Therefore, for a given DC power level the voltage can be decreased and the current proportionately increased at the expense of additional I^2R transmission losses. Hence, if the number of energized filters needed to meet AC harmonic filter performance exceeds the reactive power exchange limits, the converter operating conditions can be modified to increase the reactive power absorbed by the converter. This is done to accomplish the required exchange target between the converter station and the AC system. The variation in DC conditions is accomplished by decreasing the DC voltage which needs the firing delay angle to be increased and with an increase in DC current, to keep the DC power constant, the overlap angle rises. Therefore the reactive power

absorbed by the converter increases. It has to be kept in mind that as the DC side of the converter is common to the rectifier and inverter, changing the DC conditions will decrease, or increase, the reactive power load at both rectifier and inverter together. Figure 34 presents a common operating range for the DC voltage on a back-to-back HVDC converter. In Figure 34 the upper limit is determined by the minimum allowable converter operating angles while the lower limit is determined by the maximum voltage transient that can be applied to the converter resulting from the rectifier firing voltage or inverter recovery voltage.

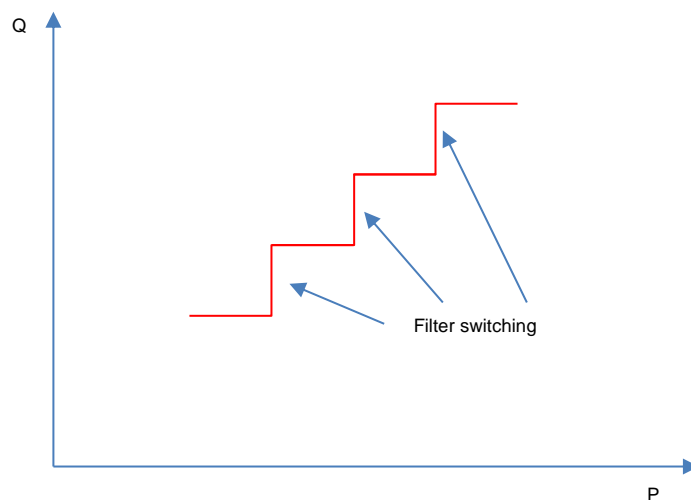


Figure 33. Filters switched with changing DC power

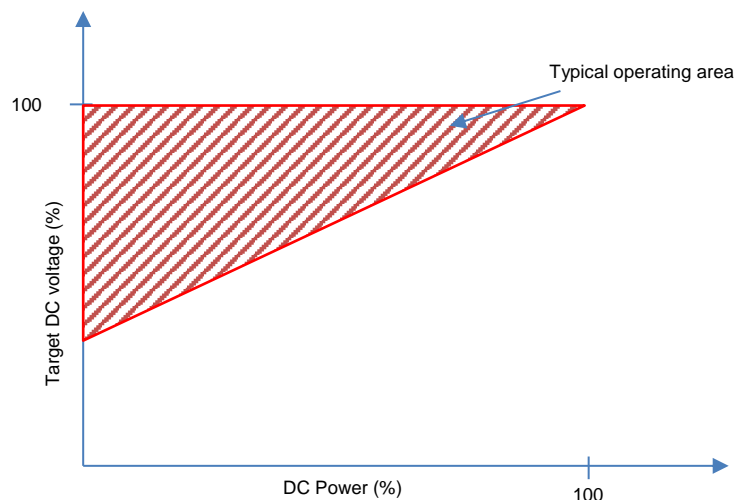


Figure 34. Common operating range of DC voltage on a back-to-back configuration

VOLTAGE STEP VARIATIONS

Another demand imposed on reactive power control is that of not surpassing a predetermined AC voltage step change as a consequence of switching a filter bank (or any reactive power element). As an estimate, the voltage step change magnitude, as a consequence of switching a filter, can be calculated from:

$$\Delta V = \frac{Q_{SWITCH}}{SCL_{min} - Q_{TOTAL}}$$

Where:

ΔV – the change in AC voltage (pu)

SCL_{min} – the minimum AC system short circuit level in which the switching operation is to take place (MVA)

Q_{SWITCH} – the reactive power step to be imposed on the AC system (MVar)

Q_{TOTAL} – the total reactive power connected to the converter bus including the reactive power to be switched (MVar)

Where the step change in AC voltage surpasses a predetermined limit, it is possible to increase the effective limit by imposing an opposite change in reactive power at the converter busbar. This opposite change can be accomplished through converter action by using a fast change to the DC voltage. As an example, consider switching in a filter onto an AC system that has a fundamental frequency var rating, which would surpass the AC voltage step change limit. By increasing the DC converter absorption at the same instant as the filter bank circuit breaker closes, the net reactive power exchanged with the AC system can be controlled and therefore AC voltage step change.

HARMONICS EFFECTS IN AC POWER SYSTEMS

Harmonics within a power system are expressed as the voltage or current modulation at an integer multiple of the fundamental frequency. Therefore on a 50 Hz system, the presence of 5th harmonic voltage means that there is an extra 250 Hz component superimposed on the voltage waveform. This component will distort the voltage waveform. Voltage waveform is presented in Figure 1. The presence of harmonics

in the power system can cause some unwanted effects on installed power system devices. The presence of harmonics can cause:

- Capacitor banks overheating
- Power electronic devices instability
- Generator overheating
- Communication systems interference

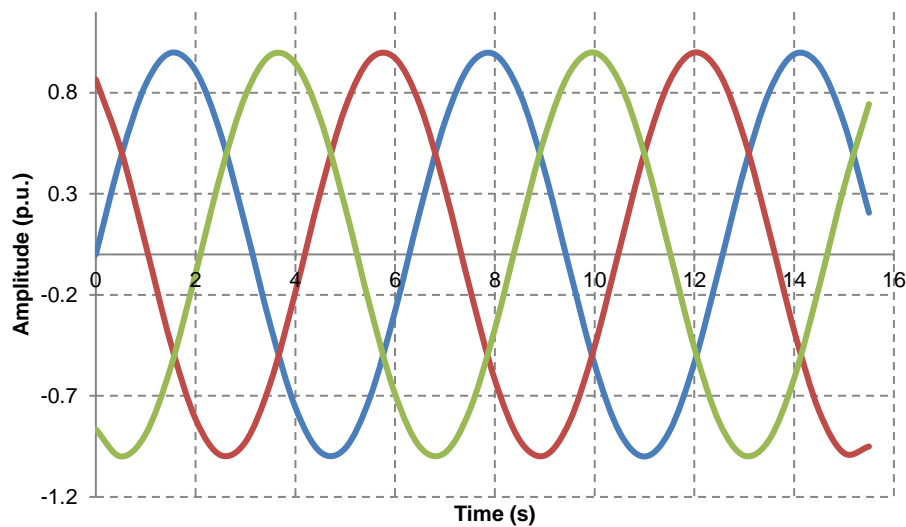


Figure 1. Three-phase fundamental frequency sine wave

AC POWER SYSTEMS HARMONICS SOURCES

All devices that contain a non-linear element and are connected to a power system can generate harmonics. This is a consequence of either their design or their operation. Examples of harmonics sources within a power system are:

- Domestic electronics (video, personal computers, television, etc.)
- Power converters (HVDC, SVC, drives)

Non-linear devices

- Voltage limiters
- Transformers
- Fluorescent lights
- PWM converters
- Rotating Machines

Typical network harmonic profile is presented in Figure 2.

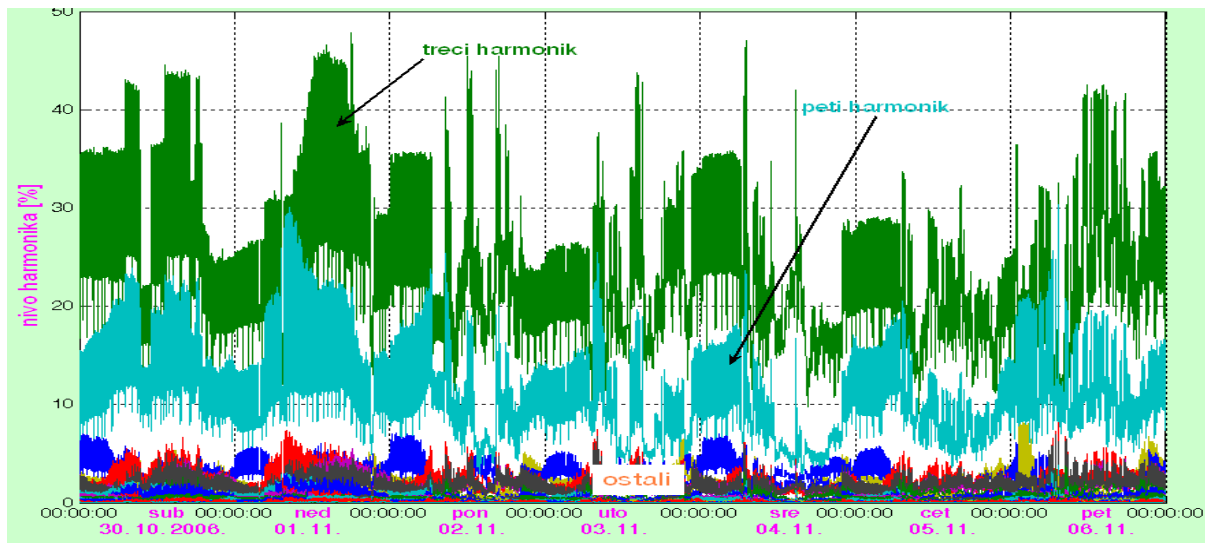
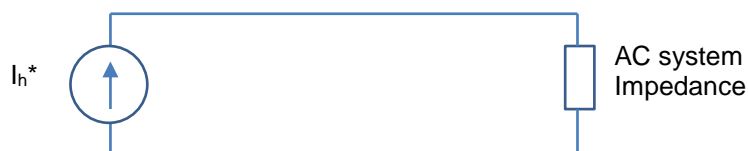


Figure 2. Harmonic profile in a typical power system

HOW CONVERTERS GENERATE HARMONICS

The AC/DC converter is a source of harmonics. This is because the converter connects the supply to the load for a controlled period of a fundamental frequency cycle. Therefore, the current taken from the supply is not sinusoidal. Looked from the AC side, a converter can be conceived as a current harmonics generator. This is shown in Figure 3. If looked from DC side, it can be conceived as voltage harmonics generator, as presented in Figure 4. The actual harmonics level produced by an AC/DC converter is a function of the duration over which a particular phase is needed to provide unidirectional current to the load. Therefore, the higher the converter “pulse number” (which means the more switching between phases within a cycle) the lower the harmonic distortion in both the AC line current and the DC terminal voltage.



* I_h – Sinusoidal current at harmonic ‘h’

Figure 3. AC/DC converter shown as AC harmonic current source on AC side

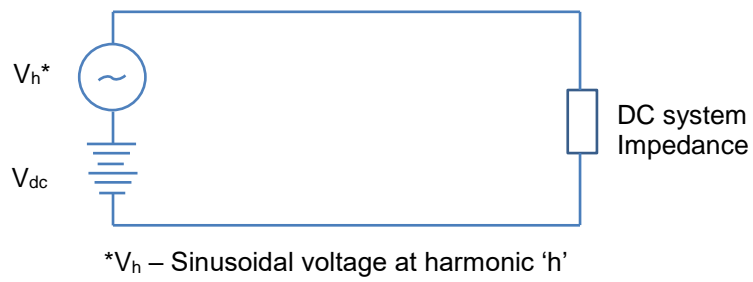


Figure 4. AC/DC converter shown as AC harmonic voltage source on DC side

PULSE NUMBER AND HARMONIC CANCELLATION

The main elements of a common HVDC converter terminal are presented in Figure 5.

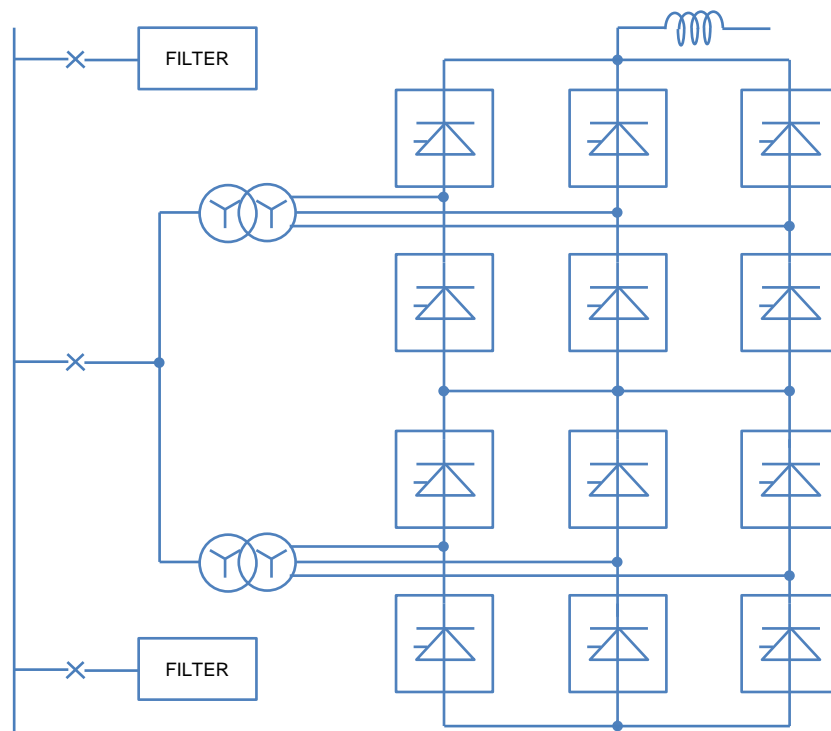


Figure 5. Common twelve-pulse converter bridge

The action of the thyristor sequential switching results in current waveforms in the transformer line side which consists of current "blocks" is presented in Figure 6.

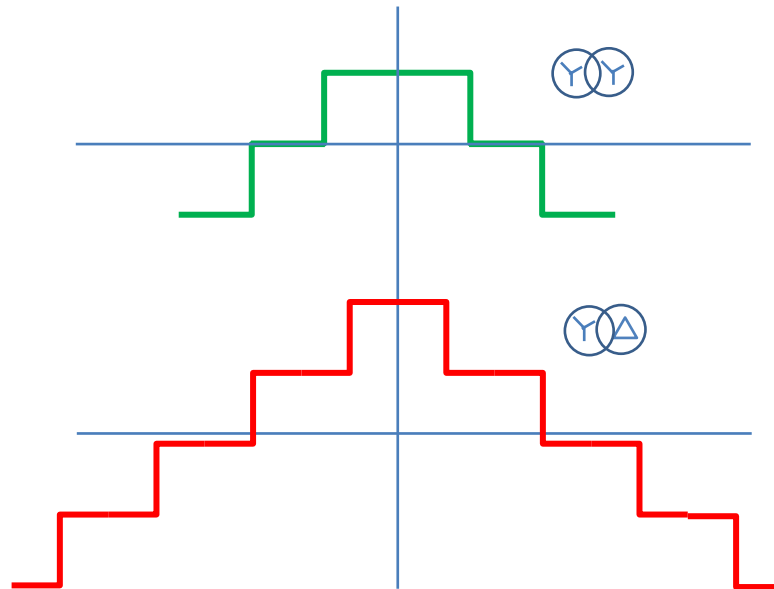


Figure 6. Idealized line winding currents in a twelve-pulse bridge

If a Fourier analysis is completed on the idealized waveforms presented in Figure 6, the next results are found:

$$I = \frac{2\sqrt{3}}{\pi} \times I_d \times \left[\cos \omega t - \frac{1}{5} \cos 5\omega t + \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t \dots \right] \dots Y/Y \quad (1)$$

$$I = \frac{2\sqrt{3}}{\pi} \times I_d \times \left[\cos \omega t + \frac{1}{5} \cos 5\omega t - \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t \dots \right] \dots Y/\Delta \quad (2)$$

It can be noted from equations (1) and (2) that each six-pulse bridge produces harmonic orders $6n \pm 1$, $n = 1, 2, 3 \dots$. There are no triplen harmonics (3rd, 6th, 9th...) and that for $n = 1, 3$, etc., the harmonics are phase shifted by 180° . The idealized magnitudes of the six-pulse harmonics are presented in Table 1. By combining two six-pulse bridges with a 30° phase shift between them, i.e. by using Y/Y and Y/Δ transformers as presented in Figure 5 and summing equations (1) and (2), a twelve-pulse bridge is found. The idealized magnitudes of the twelve-pulse harmonics are presented in Table 2.

Table 1. Idealized harmonic magnitudes in a six-pulse bridge

Fundamental	50 Hz	1
5 th	250 Hz	0.2
7 th	350 Hz	0.14
11 th	550 Hz	0.09
13 th	650 Hz	0.08
17 th	850 Hz	0.06
19 th	950 Hz	0.05
23 rd	1150 Hz	0.04
25 th	1250 Hz	0.04
n	n x 50 Hz	1/n

Table 2. Idealized harmonic magnitudes in a twelve-pulse bridge

Fundamental	50 Hz	1
5 th	250 Hz	-
7 th	350 Hz	-
11 th	550 Hz	0.09
13 th	650 Hz	0.08
17 th	850 Hz	-
19 th	950 Hz	-
23 rd	1150 Hz	0.04
25 th	1250 Hz	0.04
n	n x 50 Hz	1/n

The current waveforms presented in Figure 7 appear in the typical connection to the transformers presented in Figure 5.

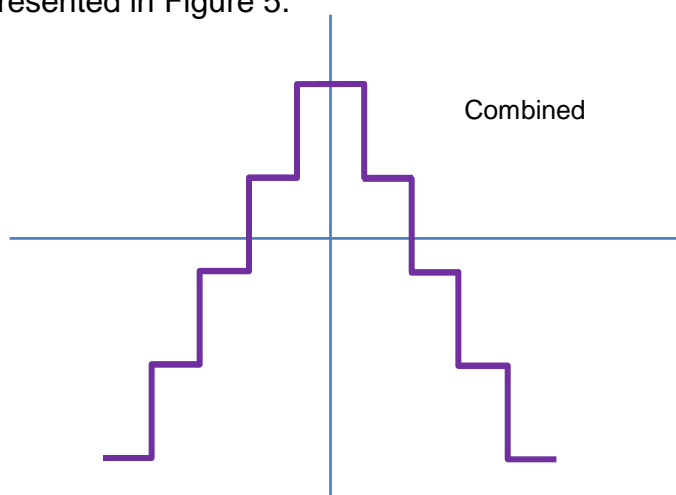


Figure 7. Idealized waveform of the AC supply current of a twelve-pulse bridge

If a Fourier analysis is completed on this idealized waveform, the following result is found:

$$I = \frac{4\sqrt{3}}{\pi} \times I_d \times \left[\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t \dots \right] \dots (3)$$

Therefore, in a twelve-pulse bridge, the harmonic orders $6n \pm 1$, $n = 1, 3, 5 \dots$ are effectively cancelled in the common supply leaving the characteristic twelve-pulse harmonics i.e. $12n \pm 1$, $n = 1, 2, 3, \dots$

The idealized waveforms presented above will be changed by the system supply reactance (predominantly the transformer reactance). Due to this commutating reactance, the harmonic current magnitudes are decreased in comparison to those relevant to pure square wave pulses. The formulas presented above are based on the assumptions that the DC current is linear, the DC reactor is infinite and the AC system voltage waveforms are sinusoidal. Because these assumptions are not applicable for real systems, more complex computations are necessary and purpose built computer programs are applied. For special needs (e.g. net harmonic contribution from two or more bridges of slightly different firing angles or reactances) both magnitude and phase (i.e. vector solutions) are needed.

DC HARMONICS

The idealized voltage across an unloaded six-pulse converter is presented in Figure 8, and the idealized voltage across a twelve-pulse converter is presented in Figure 9. The voltage is a mix of a direct voltage and harmonics. Table 3 presents the DC side harmonics generated by a six-pulse converter.

Table 3. Idealized DC voltage harmonics (RMS) at the six-pulse bridge terminals

No-load (V_{d0})	DC	1.0000
6 th	300 Hz	0.0404
12 th	600 Hz	0.0099
18 th	900 Hz	0.0044
24 th	1200 Hz	0.0025

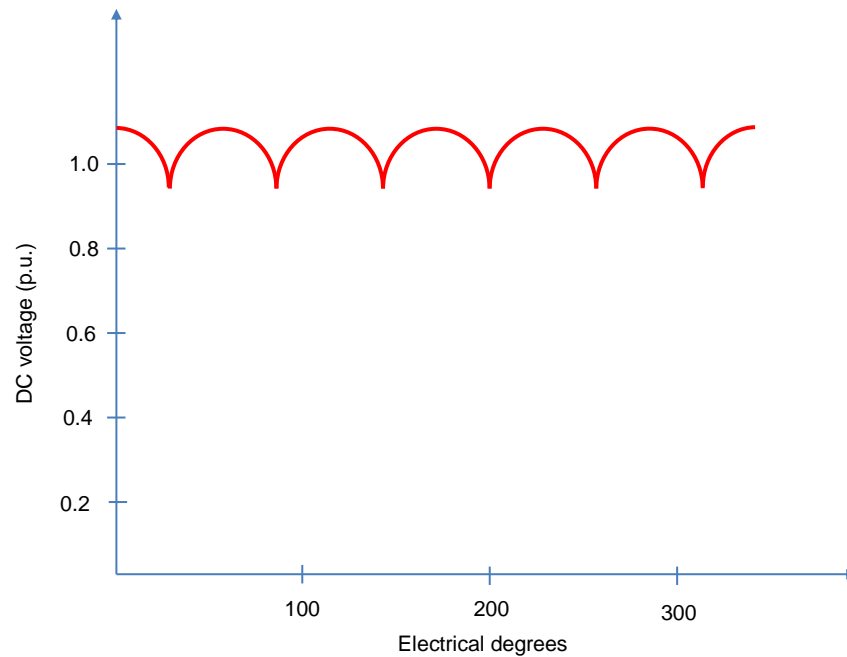


Figure 8. The idealized voltage across unloaded six-pulse bridge DC terminals

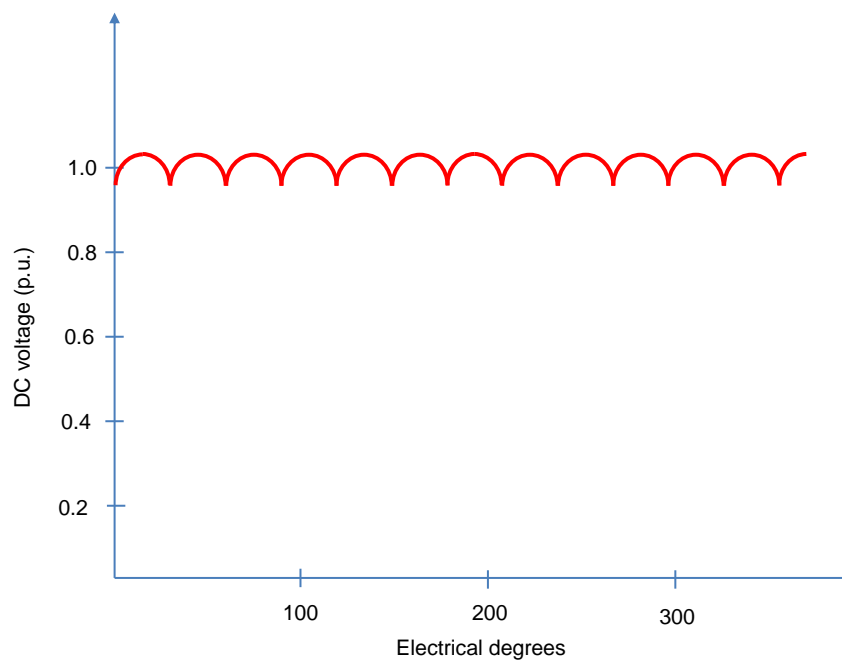


Figure 9. The idealized voltage across the unloaded twelve-pulse bridge DC terminals

CHARACTERISTIC AND NON-CHARACTERISTIC HARMONICS

The harmonic currents derived from the examination of the ideal converter are known as the converter “characteristic harmonics”. Nevertheless, a real converter can cause generation of other harmonic currents which result from non-ideal working conditions.

These harmonics are known as “non-characteristic harmonics”. Non-characteristic harmonics can be caused by several sources. An unbalance or “negative phase sequence” in the AC supply system will result in the 2nd harmonic generation on the converter DC side. A harmonic not anticipated by the $6n$ or $12n$ analysis previously described will increase 3rd harmonic current which is injected back into the AC system by the converter. Unbalance between the converter transformer leakage reactances for the Y and Δ bridges will end in a small amount of each of the classical harmonics. They should have been totally cancelled but are still present in the AC side current. Stray capacitance which is inherent in the converter transformer valve winding bushings will give a stray path within the converter for harmonic currents to flow leading to the generation of triplen harmonics (3rd, 9th and 15th) on the DC side and ± 1 of these harmonic numbers on the AC side. Moreover, insignificant control inaccuracies within the converter controller resulting in the firing instance between bridge valves not being ideally symmetrical (the error is much less than 0.1° electrical) will generate harmonics at all multiples of n on converter AC and DC side.

CROSS-MODULATION HARMONICS

In addition to the characteristic and non-characteristic harmonics which can be created by a converter, there is a third type of harmonic known as cross-modulation harmonics. These harmonics are based on the fact that in any HVDC link the DC current is never absolutely smooth. This is especially correct in the case of a back-to-back converter in which case there is little or no impedance between the two converters. In most situations, it is not practical to put sufficient inductance between the converters to make a substantial impact on the interaction between them. In most situations, the AC connection of one converter is remote, or even isolated from that of the other converter. Hence, even where the two AC systems interconnected by the DC link are typically at the same AC frequency (50 Hz or 60 Hz) the real working frequencies may be different. Therefore, AC side currents harmonic and DC side voltages created by the converters, which are a multiple of the used AC system frequency, will be at different frequencies. In the case where the two AC interconnected systems work at different AC frequencies, for example one at 50 Hz and one at 60 Hz, then the difference in the harmonics created by the converters will be higher. The actual DC converter sides are connected together and therefore the harmonic voltage distortion

introduced by one converter will be applied to the DC terminals of the other converter and vice versa. These harmonic voltage distortions will create a distortion in the circulating DC current which will cause harmonics to be made in each converter that are a multiple of the other converter's AC system frequency and not of its own. For instance, the 60 Hz converter will have AC current harmonics matching 11th and 13th harmonic at 660 Hz and 780 Hz respectively and a corresponding DC side harmonic at 720 Hz. Nevertheless, this 720 Hz distortion will result in 660 Hz and 780 Hz components in the AC current harmonics of the 50 Hz connected converter. None of these frequencies are an integer multiple of 50 Hz and non-integer harmonics are generated.

HARMONIC FILTER DESIGN AND FILTER TYPES

The HVDC converter AC side current waveform, as previously discussed, is highly non-sinusoidal, and, if allowed to run in the connected AC network, might generate unacceptable distortion levels. Hence, AC side filters are needed as part of the complete HVDC converter station in order to decrease the harmonic distortion of the AC side current and voltage to acceptably low levels. HVDC converters also use substantial reactive power, a high proportion of which must typically be locally provided within the converter station. Shunt-installed AC filters act as capacitive sources of reactive power at fundamental frequency. Typically in common HVDC configurations the AC filters are used to compensate most or all of the converter reactive consumption. Extra shunt capacitors, reactors, Static VAr Compensators (SVCs), Static Compensators (STATCOMs) or synchronous compensators may also be installed to ensure that the required reactive balance is kept within specified limits under defined working conditions. Therefore, the design of the AC filters typically has to meet these two harmonic filtering requirements and reactive power compensation, for different operational states and load levels.

FILTER CIRCUIT ARRANGEMENTS

There are different possible circuit arrangements that can be suitable for AC side filters on HVDC converter stations. This paragraph reviews these arrangements to provide background information on the benefits and disadvantages of particular filter types. Only shunt-installed filters are taken into consideration in this section. The comments

on special filter designs apply to HV- and EHV connected filters and same to MV-connected filters, e.g. tertiary installed filters.

The selection of the proper filter solution is the contractor responsibility and will vary from project to project. The configuration will be impacted by a number of factors that may be determined by the customer:

- Converter control strategy (reactive power control, voltage and overvoltage control),
- AC system conditions (supply voltage variation, negative phase sequence voltage, frequency variation, system harmonic impedance),
- Defined harmonic limits (voltage distortion, current injection, telephone interference factors),
- Switched filter size (determined by voltage step limit, self-excitation limit of nearby synchronous machines, reactive power balance etc.),
- Environmental effects (ambient temperature range),
- Loss evaluation criteria,
- Site area (limited switch bays),
- Availability and reliability requirements.

Various filter arrangements will have certain benefits and disadvantages when considering the above factors. Since, only the filter design and performance aspects are looked at, additional devices such as surge arresters, current transformers and voltage transformers are omitted. In HV and EHV applications, surge arresters are normally installed within the filters to grade the insulation levels of the equipment.

BENEFITS AND DISADVANTAGES OF COMMON FILTERS

Two main filter types are applied today:

- The tuned filter or band-pass filter. It is sharply tuned to one or several harmonic frequencies. These filters are tuned to a specific frequency, or frequencies. They are known by a relatively high q (quality) factor, i.e. they have low damping. The resistance of the filter may be connected in series with the capacitor and inductor (more often it is simply the loss of the inductor), or in parallel with the inductor, in which case the resistor has a high value. Examples

of tuned filters include single (e.g. 11th) double (e.g. 11/13th) and triple (e.g. 3/11/13th) tuned filter types.

- The damped filter or high-pass filter providing a low impedance over a broad band of frequencies. These are filters made to damp more than one harmonic. For example, a filter tuned at 24th harmonic will provide low impedance for both 23rd and 25th harmonic, and even for most of the higher harmonics. Damped filters always include a resistor in parallel with the inductor which generates a damped characteristic at frequencies above the tuning frequency. Damped filter examples include single-tuned damped high-pass (e.g. HP12) and double-frequency damped high-pass (e.g. HP 12/24). The differentiation between these two filter types may sometimes be lost depending on the selection of q -value for different filter frequencies. For a HVDC configuration with a twelve-pulse converter, the highest characteristic harmonics will be the following: 11th, 13th, 23rd, 25th, 35th, 37th, 47th, and 49th. As the level of the 11th and 13th harmonic are typically twice as high as for the rest of the harmonics, a typical practice is to install band-pass filters for the 11th and 13th harmonic and high-pass filters for the higher harmonics. Due consideration also has to be taken concerning the potential low-order resonance between the AC network and the filters and shunt banks. When a big HVDC configuration is to be installed in a weak AC system, a low-order harmonic filter (typically tuned to 3rd harmonic) may be also required.

BAND-PASS FILTER

A band-pass filter comprises LC series resonance circuit as presented in Figure 10. Figure 11 presents the impedance magnitude and phase of a band-pass filter. The benefits and the disadvantages of a single-tuned band-pass filter are as follows:

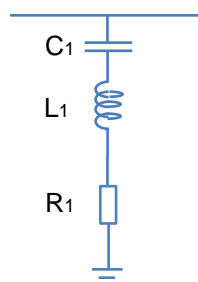


Figure 10. Single-tuned band-pass filter arrangement

Benefits:

- Simple connection with only two elements,
- Insignificant losses,
- Optimal damping for one harmonic,
- Low maintenance needs.

Disadvantages:

- Multiple filter branches may be required for various harmonics,
- May need possibility of adjusting reactors or capacitors,
- Sensitive to detuning effects.

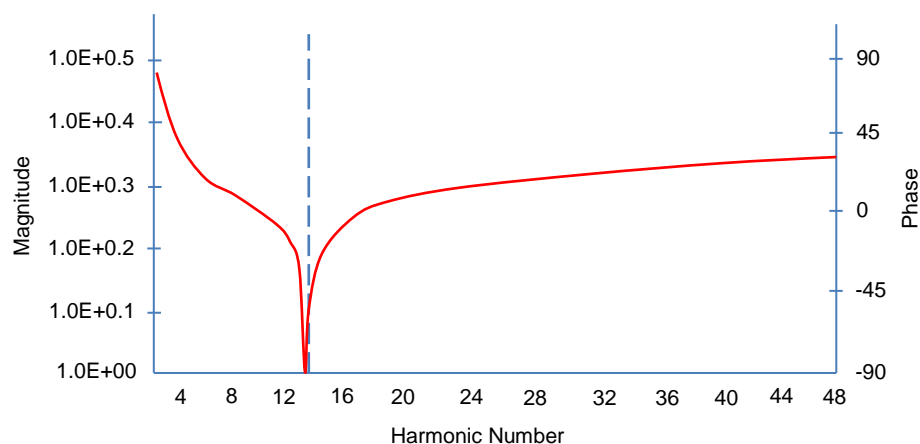


Figure 11. Single-tuned band-pass filter – impedance characteristic

DOUBLE-TUNED BAND-PASS FILTER

A double-tuned band-pass filter has the same function of two single-tuned filters. Its arrangement is presented in Figure 12, and its impedance plot in Figure 13. The benefits and the disadvantages of a double-tuned band-pass filter are as follows:

Benefits:

- Optimal damping for two harmonics,
- Only one HV capacitor and reactor required to filter two harmonics,
- Lower loss than for two single tuned branches,
- Fewer branch types, facilitating filter redundancy,
- Mitigates minimum filter size problem for a low magnitude harmonic.

Disadvantages:

- Sensitive to detuning effects,
- Complex connection, with 4 or 5 C-L-R elements,
- May need option of adjusting reactors or capacitors,
- Needs two arresters to control insulation levels.

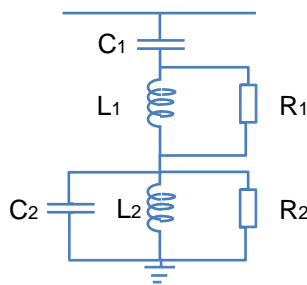


Figure 12. Double-tuned
band-pass filter
arrangement

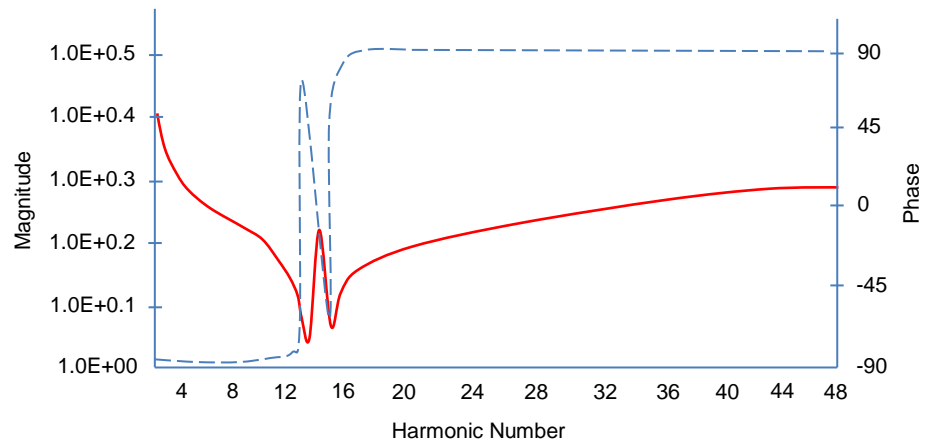


Figure 13. Double-tuned band-pass filter – impedance characteristic

TRIPLE-TUNED BAND-PASS FILTER

This filter type is electrically same to three parallel-connected tuned filters, but is implemented as a single combined filter. Figure 14 presents the circuit configuration and Figure 15 the impedance/frequency response for a common triple-tuned filter. The application of triple-tuned filters could enhance the operational requirements for reactive power control. This would be of particular interest at low-load conditions if a 3rd harmonic filter is required in the circuit from the beginning. For each of the above configurations, sensitivity to detuning has been distinguished as a disadvantage. Nevertheless, with the installation of resistors (and therefore additional losses) to make the filter configuration damped, this detuning can be avoided.

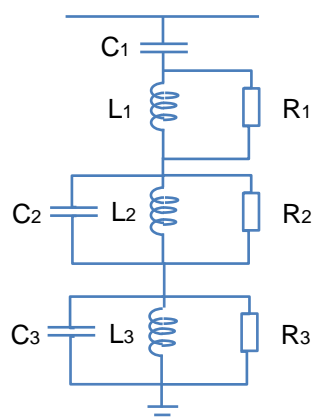


Figure 14. Triple-tuned band-pass filter configuration

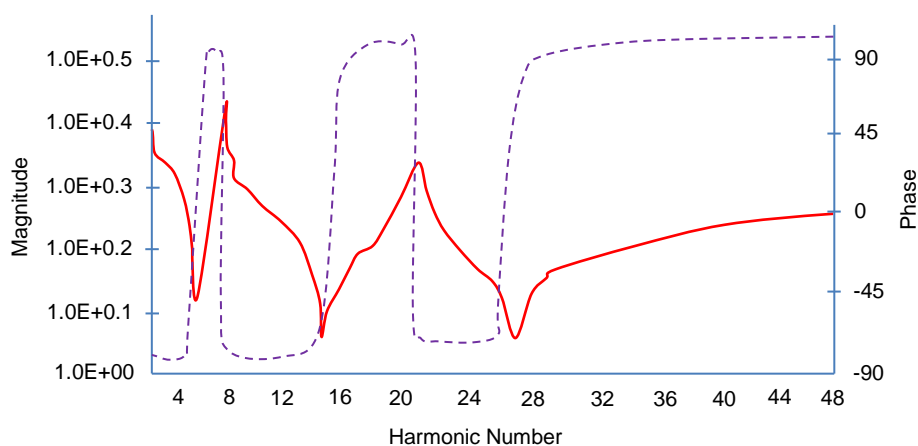


Figure 15. Triple-tuned band pass filter tuned to 3rd, 11th and 24th harmonic – impedance characteristic

AC HARMONIC PERFORMANCE AND RATING COMPUTATIONS

The basis of harmonic distortion and filter performance computations can be presented with reference to Figure 16.

I_n	-	converter harmonic current
I_{sn}	-	harmonic currents entering the supply system
I_{fn}	-	filter harmonic currents
Z_{sn}	-	AC system harmonic impedance
Z_{fn}	-	Filter harmonic impedance

The current and voltage distortion can be determined from the following equations:

$$I_{sn} = \frac{Z_{fn}}{Z_{fn} + Z_{sn}} \times I_n \quad (4)$$

$$V_n = \frac{Z_{fn} \times Z_{sn}}{Z_{fn} + Z_{sn}} \times I_n \quad (5)$$

In order to compute harmonic performance and design the filters (i.e. Z_{fn}), it is mandatory that comprehensive data is available on the harmonic currents produced by the HVDC converter (I_n) and the supply system harmonic impedance (Z_{sn}).

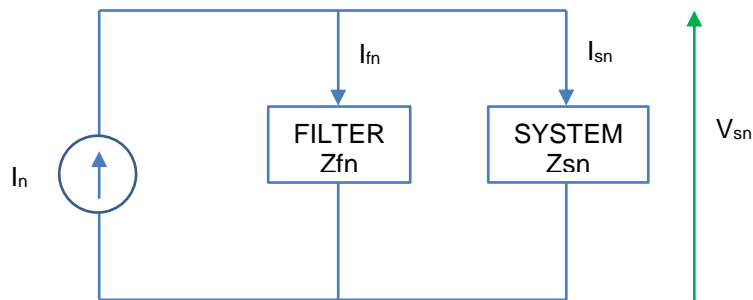


Figure 16. Circuit for AC filter performance assessment

SUPPLY SYSTEM HARMONIC IMPEDANCE

In order to precisely evaluate voltage and current distortion, it is vital that the supply system impedance is known at each harmonic of interest. Nevertheless, a lack of knowledge of the system harmonic impedance could lead to an uneconomic filter configuration, or a filter that will not adequately attenuate harmonics. There are few modeling methods of the system impedance:

IMPEDANCE CIRCLE METHOD

In a supply system with substantial shunt capacitance, the system impedance can be either inductive ($R + jX_L$) or capacitive ($R - jX_C$) at the Point of Common Coupling (PCC) at harmonic frequencies. Therefore, resonances will happen when the inductive (X_L) and capacitive ($-X_C$) components are same and only the resistance component (R) remains. Figure 17 presents a common impedance locus of a supply system as the frequency varies from 50 Hz to about 255 Hz.

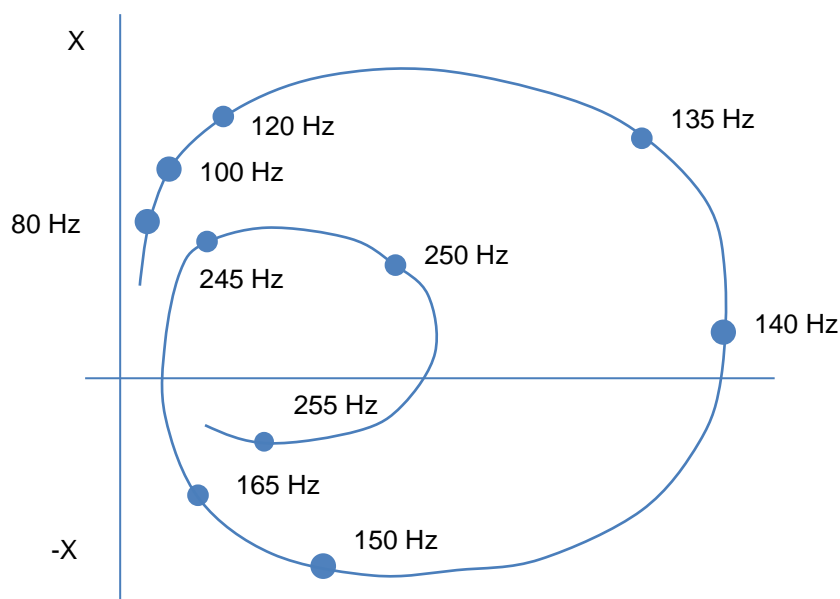


Figure 17. Common supply network impedance diagram

In this case, the system seems inductive at 100 Hz, but capacitive at 150 Hz with a resonance around 140 Hz. Additional resonances happen below 245 Hz and above 250 Hz. The system impedance can quickly vary for small frequency changes. The above locus applies to only one system arrangement, with different generation, load or line outage conditions, further impedance loci would happen. In order to make sure that the system harmonic impedance (Z_{sn}) used in filter design computations is applicable to all present and future system arrangements, a circle is typically drawn which encloses all of the computed loci. An example of such a circle is presented in Figure 18. When conducting filter design studies, the system impedance is taken to be any value within the circle which ends in the highest harmonic distortion (i.e. V_{sn} or I_{sn}). Computer maximization procedures are applied to search for the impedance area at each harmonic. In order to reflect the system impedance reality, limitations to the search area are typically specified. Limit lines of angles Φ_1 , Φ_2 (commonly 75° - 85°) are applied, and minimum values of R may be defined. This process is safe as it inherently caters to system changes and future needs. Nevertheless, it is also pessimistic as each harmonic, especially at low orders, which will only change within a limited range, and not within a large circle. The application of this approach may end in an over-designed and expensive filter.

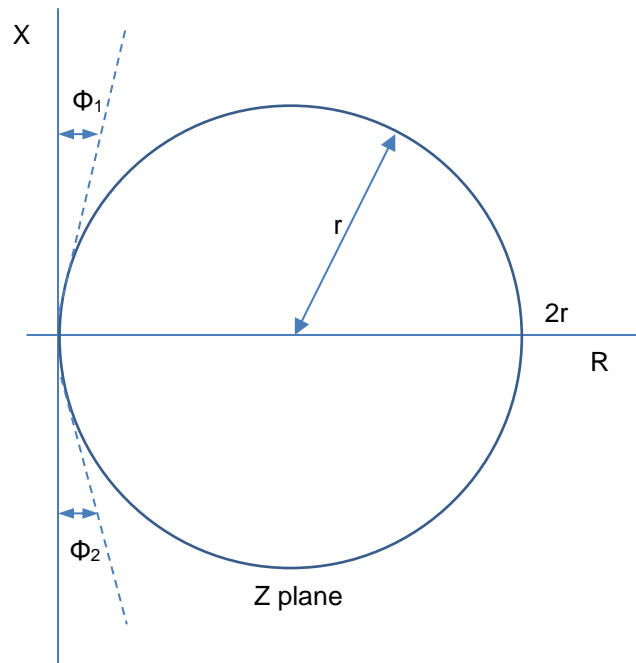


Figure 18. AC network impedance

POLYGON METHOD

At each harmonic, the system will have an impedance discrete value corresponding to various arrangements. Hence, at each harmonic the system impedance can be determined by a polygon which covers all of the computed discrete harmonics. Such a polygon is presented in Figure 19. The computer maximization process searches each defined polygon at each harmonic to compute the highest harmonic distortion (V_{sn} or I_{sn}). This method provides a realistic evaluation of the system impedances, and avoids any problems of filter overdesign.

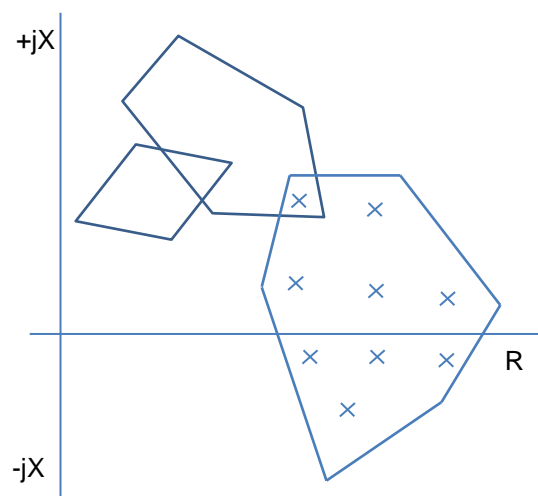


Figure 19. Impedance polygon

DC HARMONIC PERFORMANCE AND RATING COMPUTATIONS

The DC side harmonic performance of a HVDC configuration is somehow easier to compute than that of the AC side. Comparison of Figure 16 to Figure 20 indicates that the basic circuit assessment is similar. Nevertheless, unlike the AC system, which can exist in many different states (that is, different arrangements of transmission lines, loads, generation, etc.) the DC system is a determined system with several possible variations in configuration.

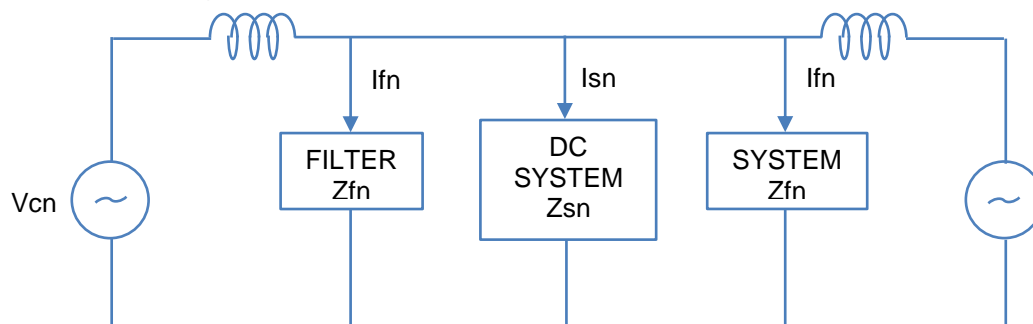


Figure 20. Circuit assessment for DC filter performance

Figure 21 presents a sample frequency versus impedance plot for an overhead transmission line. The normal performance evaluation method of an overhead DC transmission line is based on induced current, that is, the current that would run in a conductor parallel to the DC line.

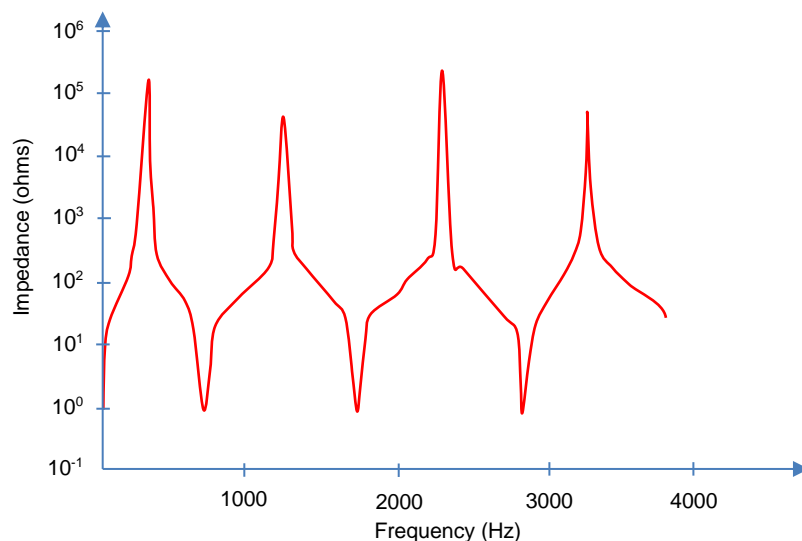


Figure 21. Common HVDC line impedance characteristic

The higher the ground impedance, the greater the induced currents in a parallel line, as this parallel line will present a viable current return path. Conversely, in locations where the ground impedance is low, the current induced in a parallel line will be insignificant. Hence, the arrangement and rating of the DC side filter is influenced by the ground conditions related with the DC line. When working in balanced bipolar mode, the harmonic currents will run through the DC lines in such a way that at any point along the line, the instantaneous harmonic currents in one pole's DC conductor will be same and opposite to that in the other. Hence, the currents induced in a parallel conductor will be decreased. Therefore, the worst-case DC harmonic operation and the case which defines the DC filter rating, is monopole operation.

Crucial consideration in the DC filter design, as opposed to an AC filter, is the main capacitor bank as, on the DC side, this will be subject to the used DC voltage. Therefore, the sharing of the DC voltage as well as the AC voltage must be controlled. This means that the resistive voltage distribution has to be controlled in DC capacitors (Figure 22). For this reason it is typical for DC filter capacitor banks to be made as one single tall bank as opposed to any form of split bank where the split banks would have post insulators between the capacitor racks and disturb the voltage distribution due to leakage currents across them.

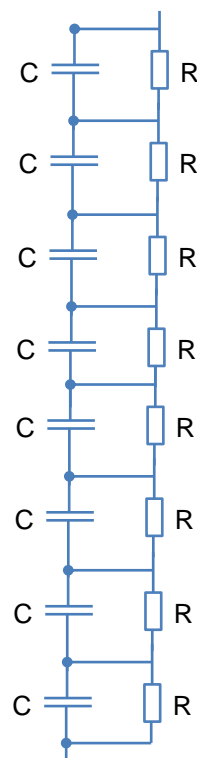


Figure 22. DC filter capacitor

CONTROL FACILITIES GIVEN BY HVDC CONFIGURATIONS

The fundamental control parameter of a HVDC converter is the DC current which flows between the rectifier and inverter assuming that the DC voltage is kept at a constant value (which is commonly true for DC power transmission configurations but not always correct for back-to back arrangements). Nevertheless, the HVDC controller can adjust the DC current flow in response to other parameters that are set by operator providing an extremely flexible and quick part of a power system's transmission infrastructure. Common control options provided or available as an extra feature are presented below.

POWER CONTROL

The power transmitted between the sending and receiving end of the HVDC link is controlled to meet an operator-set value at the point in the circuit where the DC power is defined, known as the compounding point. Commonly the compounding point is at the rectifier DC terminal but it can also be at the inverter DC terminal, the mid-point of the DC transmission conductors, the inverter AC terminal or the rectifier AC terminal. If the power requirement is varied then the power order will ramp to the new power transfer level at a rate of change (known as the "ramp rate") pre-determined by the operator. Commonly, the maximum power limit is determined by an overload controller which is continuously computing the thermal capacity of the converter station devices.

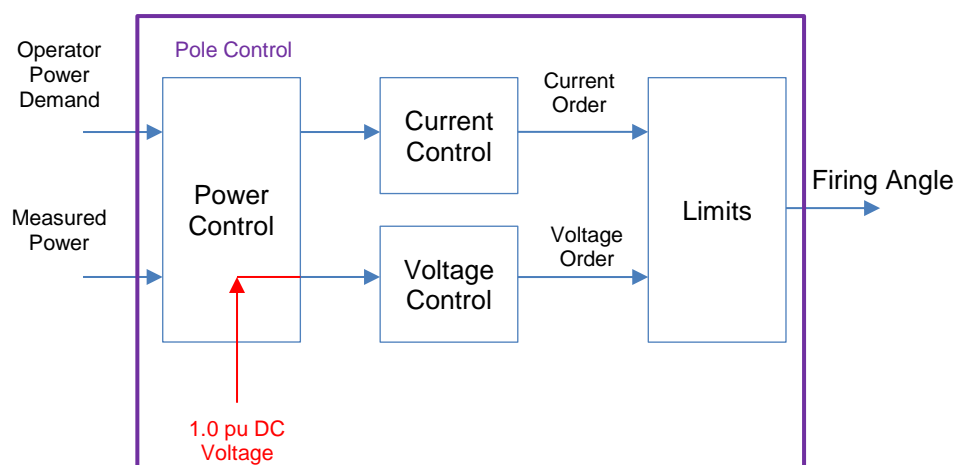


Figure 23. HVDC configuration power control

HVDC CONFIGURATION FREQUENCY CONTROL

A HVDC configuration can control the AC system frequency by automatically correcting the power being delivered into that AC system in order to balance the load with the supply. The quick HVDC power control decreases the under-frequency or over-frequency which can result from a varying load in a small power system such as an island load. Frequency control can also be used as limits to the power control function. For instance, the sending end can be arranged so that it will continue to provide power via the HVDC link to the receiving end as so long as the sending end AC system frequency is above some predetermined value. In this way the sending end can be protected from a serious system disturbance as a consequence of a disturbance in the receiving end AC system. The controllability of a HVDC configuration is crucial and is sometimes referred to as providing a “firewall”. With a power system consisting of “islands” of AC interconnected with DC, this HVDC “firewall” property will reduce the risk of cascading black-outs across multiple interconnected AC systems. Other frequency limits can be set, for example the receiving end AC system could have an upper frequency limit to automatically stop additional increases in the power being delivered by the HVDC configuration. Equally, the receiving AC system can have a lower frequency limit which, if reached, automatically increases the power being delivered into the receiving AC system. However, this can typically be overridden by the sending end minimum frequency limit described above, that is, the sending end system will help out the receiving end AC system as much as possible without risking a cascade failure.

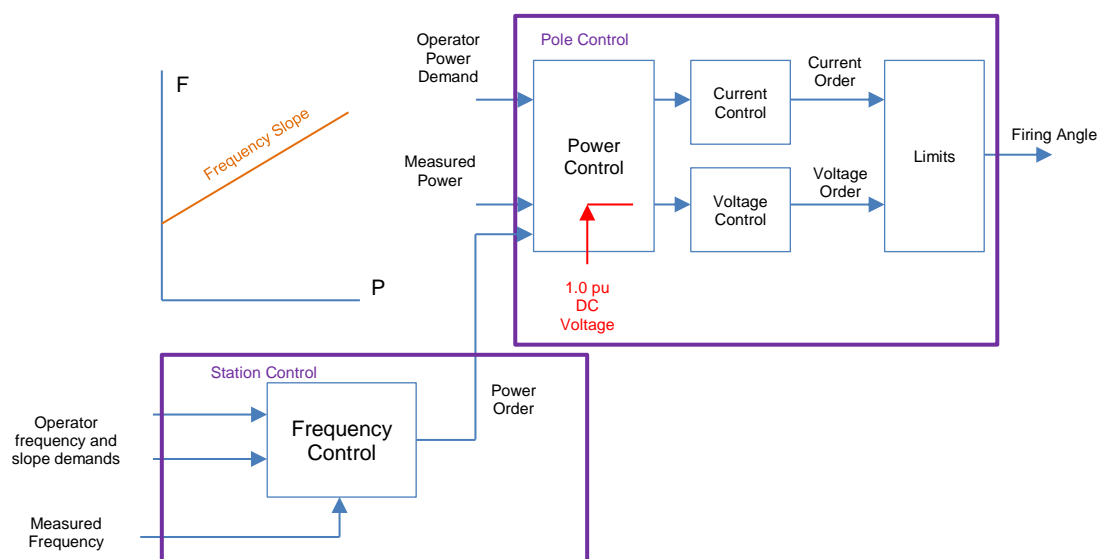


Figure 24. HVDC configuration frequency control

HVDC CONFIGURATION POWER MODULATION CONTROL

The power being transmitted through a HVDC link can be automatically modulated to give damping to low-frequency power oscillations within either, or both, interconnected AC systems. This is decided by system studies during the project design phase.

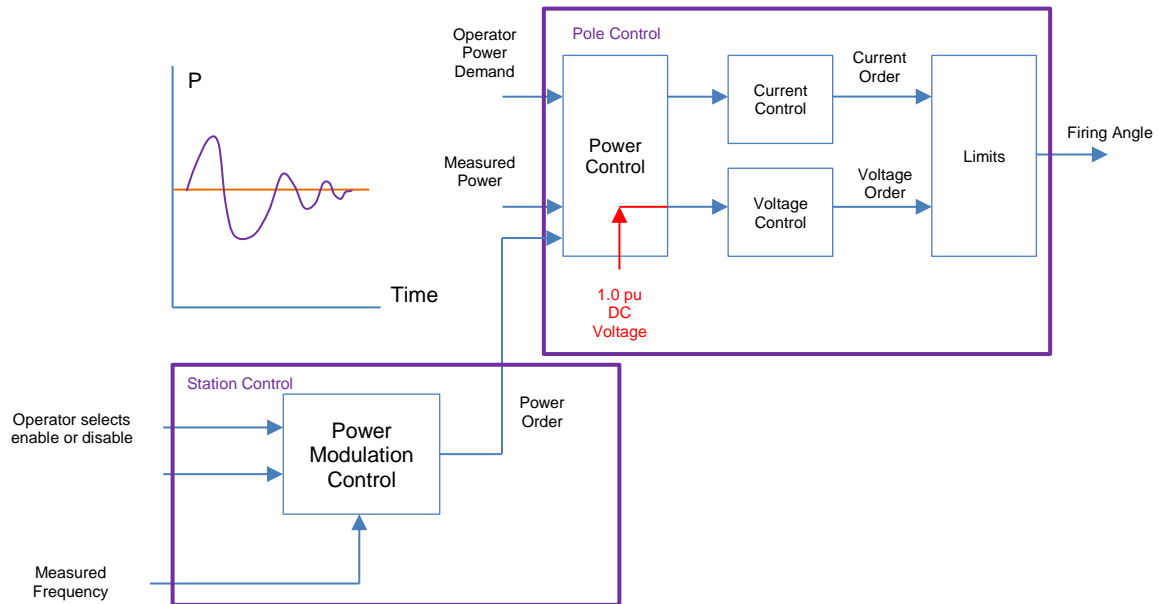


Figure 25. Typical HVDC configuration power modulation control

RUNBACK/POWER DEMAND OVERRIDE (PDO)

In response to certain situations, such as outage of an AC line, outage of an AC generator or outage of a big load, the HVDC interconnection can be made to respond in a pre-defined sequence. For example, if the line outage may end in instability within the AC system, the HVDC interconnection can be set to decrease the power transfer at a pre-defined ramp rate to a safe value as suggested by contract studies. In the same way, the generator outage can be pre-programmed to automatically increase the power transfer through the HVDC interconnection.

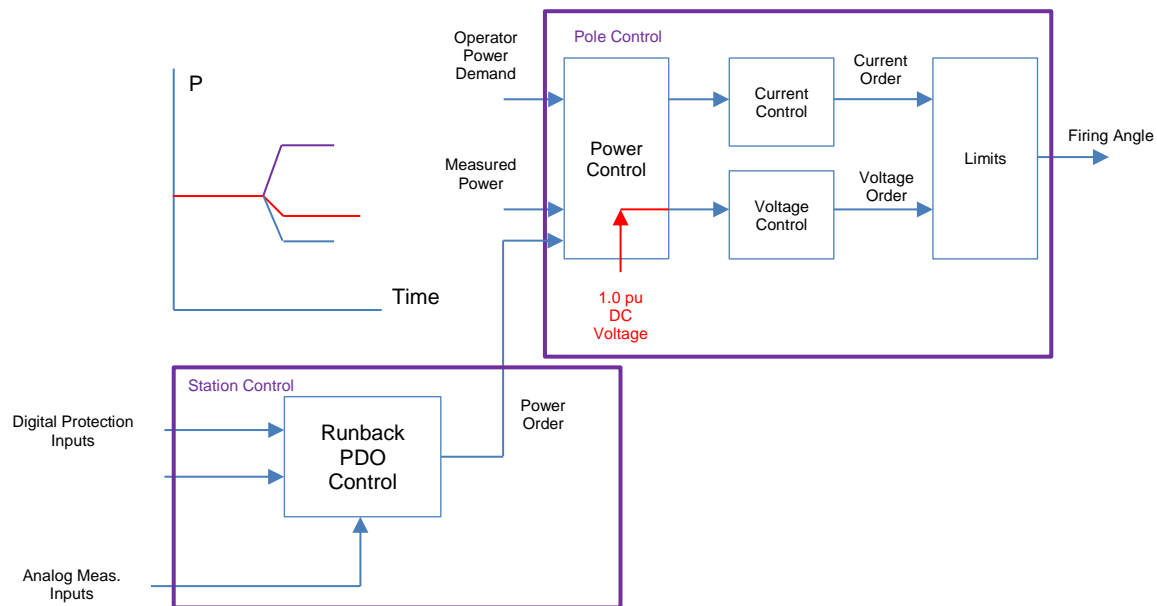


Figure 26. Runback/power demand override (PDO)

DC PROTECTION

A detailed description of the protections applied to HVDC station is beyond this course. Nevertheless, it is worth pointing that within a HVDC converter station the protection types used fall into two groups:

- Conventional (AC) substation protection
- DC protection

AC connected devices such as converter transformers and AC harmonic filter elements, along with feeders and busbars, are protected using typical AC protection relays. The converter, along with the DC circuit, is protected using hardware and software that is specifically designed. Common DC protections include:

- AC > DC
- DC Differential
- AC Overcurrent
- DC > AC
- DC Overcurrent
- AC Overvoltage
- AC Undervoltage
- Asymmetry

- Abnormal firing angle
- DC Undervoltage
- Low DC current

HVDC THYRISTOR VALVES

The term “valve” originates from the HVDC early days, when mercury-arc valves were used for this function. Mercury-arc valves worked in a completely different way (being basically vacuum tubes, therefore the name “valve”) but fundamentally completed the same job as a modern thyristor valve. When thyristors were brought in, the name “valve” was kept. The thyristor valve is the fundamental element of the modern HVDC converter. The real thyristor valve contains many series-connected thyristors in order to give the necessary blocking voltage capability. Thyristors used for HVDC valves are amongst the largest semiconductors of any type. These elements are expensive and there may be many thousand such components in a HVDC station. Also, they are rather delicate and need many additional elements to control and protect them. Even though it is the most evident component of a thyristor valve, the thyristors account for a surprisingly low percentage of the overall valve cost.

Modern thyristor valves are rather typical. The majority of the design work is completed during the product development phase. Therefore, applying the valves to a particular project is a relatively straightforward process. At its simplest, the work needed for a particular project may just involve adjusting the number of series-connected thyristors according to the voltage rating demands imposed by the overall system design. HVDC valves are almost never used as separate units. Almost always, few valves are combined together into a “Multiple Valve Unit”, or MVU. The MVU may either be directly installed on the floor or suspended from the ceiling. For insulation economy, the valve design is usually arranged so that the lower-voltage valves (typically those related with the delta connected six-pulse bridge) are used as part of the insulation on which the higher-voltage valves (typically those related with the star-connected bridge) are installed. Therefore, the low voltage end is the end at which the valve is attached to the floor or ceiling. The valves are commonly piled vertically into “quadrivalve” structures. Three quadrivalves are needed at each end of each pole.

Figure 27 presents a typical suspended MVU. Special attention has been paid to possible fire initiation processes within the modern thyristor valve. All elements are sufficiently rated, both thermally (to minimize the risk of overheating) and electrically (all other elements in parallel with the thyristor are defined with voltage ratings in excess of those of the best thyristor which could be encountered). The damping capacitors are of oil-free construction. Therefore, the potential spread of a fire throughout the valve can be almost dismissed by the applied materials and components.

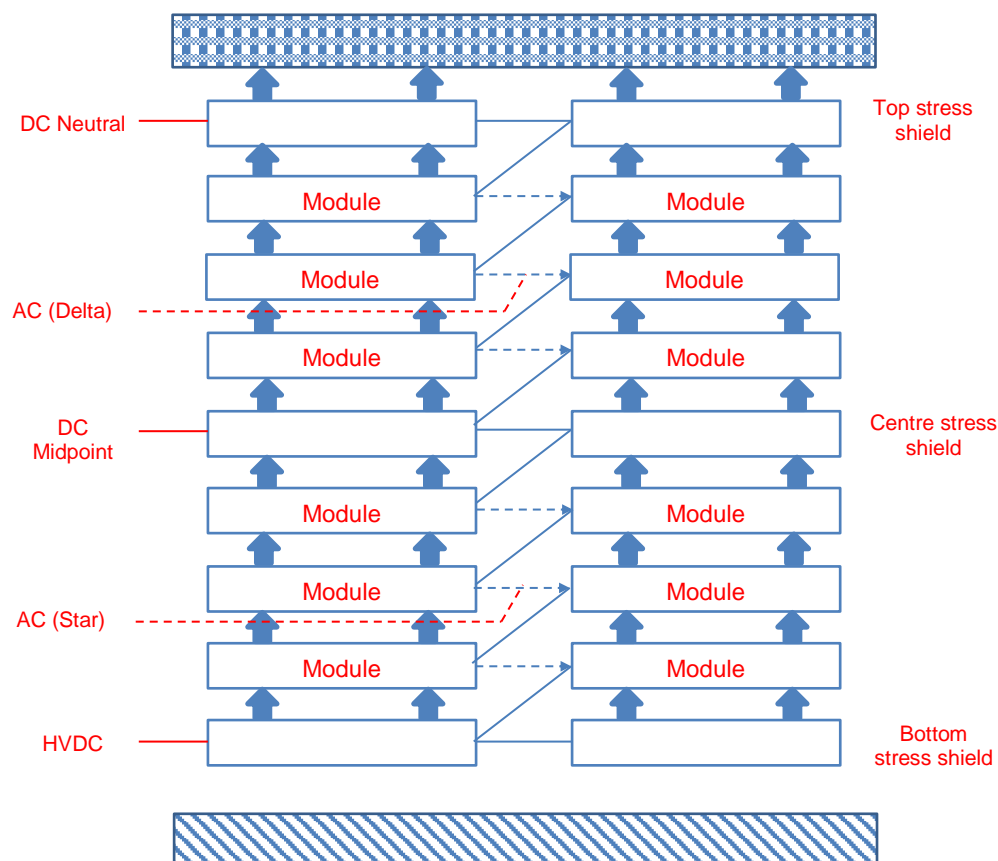


Figure 27. Common suspended MVU for HVDC

THYRISTOR VALVE COOLING CIRCUIT

In order to effectively extract the losses from the thyristors and other elements, and accomplish adequately low temperature increase in these elements, it is vital to provide some form of forced cooling circuit. Modern thyristor valves use liquid cooling by pure deionized water. It is safe with high voltage equipment as long as the water is ultra-pure, with no ionic contaminants. Deionizing devices ensure that the conductivity of the water is at a very low value. Water cooling is always provided for the thyristors

and damping resistors, and typically also for the di/dt reactor and DC grading resistor. The water coolant is transferred in parallel to every thyristor level in the valve via insulating plastic pipes, and the waste heat is rejected to outdoor-mounted coolers. The water cooling circuit design is vital engineering task in order to ensure that the system has proper flow rates in all important areas and avoids excessively high flow rates that could cause erosion, or low flow rates that lead to accumulation of gas pockets. Although the water conductivity in a HVDC valve is typically extremely low, it is never zero, and therefore, its potential for causing undesired electrochemical effects has been recognized. Ultrapure deionized water can have a very low conductivity, less than $0.1 \mu\text{S/cm}$. Nevertheless, no matter how advanced the deionization devices, it is not feasible to decrease the conductivity completely to zero, because water always dissociates into H^+ and OH^- ions, to level controlled mainly by temperature. As a consequence, any water pipe crossing two points at different electrical potentials will inevitably transfer a small leakage current. When the used voltage is only AC, the consequences of this are not especially serious, but when the used voltage has a DC component, certain electrochemical reactions inevitably happen at the anode and cathode electrodes. Aluminum, which is commonly used as a heat sink material because of its great thermal conductivity, is very vulnerable to corrosion in the case that leakage currents flowing in the water are allowed to impinge directly on the aluminum. In order to stop damage to the aluminum, it is necessary to make sure that the leakage currents flowing in the water do not flow directly from water to aluminum but instead pass via inert electrode material. In this way the vulnerable aluminum is protected from damage. This process is presented in Figure 28.

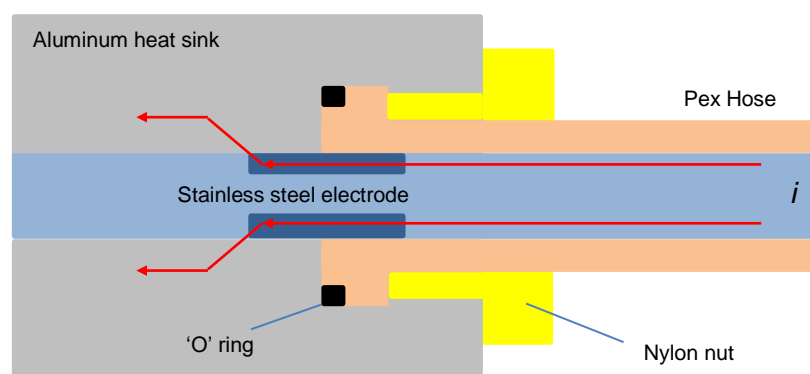


Figure 28. The protective electrode system applied in water cooled HVDC valves

HVDC CONVERTER TRANSFORMERS AND THEIR ARRANGEMENTS

The converter transformer works as the HVDC converter and the AC system interface and gives few functions including:

- Providing the precise voltage to the converters
- Providing galvanic isolation between the AC and DC systems
- Providing fault-limiting impedance
- Limiting effects of steady state AC voltage change on converter operating conditions (tap changer)
- Providing the 30° phase shift needed for twelve-pulse service via star and delta windings

AC transformer insulation is made to withstand AC voltage stresses. These voltage stresses are defined by the shape and insulation material permittivity that is used within the transformer. It is typically concentrated in the insulating oil. Nevertheless, converter transformers are exposed to AC voltage stress and DC voltage stress. DC voltage stress distribution is mainly determined by the resistivity of the insulating materials and therefore more stress is concentrated in the winding insulation than in the insulating oil. This resistivity changes due to few factors including the material temperature and the length of time the voltage stress is applied. This is why the internationally applied testing demands ask that the DC voltage stress be used for a period of time in order to ensure that a steady-state voltage stress distribution is accomplished. The converter transformer is the biggest plant item to be transferred to site for an HVDC project. Therefore, transport restrictions such as weight or height, if the transformer has to go over or under a bridge for example, can have a major impact on the selected converter transformer configuration. Figure 29 presents the typically recognized transformer arrangements in HVDC configurations.

Lowest cost can typically be accomplished by minimizing the number of components the converter transformer is broken down into. Therefore, the lowest cost is commonly a 3-phase, 3-winding transformer. Nevertheless, due to shipping limits, such a transformer may not be practical so another arrangement should be taken into account. Where a spare converter transformer is deemed necessary, based on an availability analysis of the arrangement, then it is more cost-effective to use a 1-phase,

3-winding transformer configuration, as one spare unit can replace any of the in-service units, whilst 2-winding arrangements need two spare units to be provided.

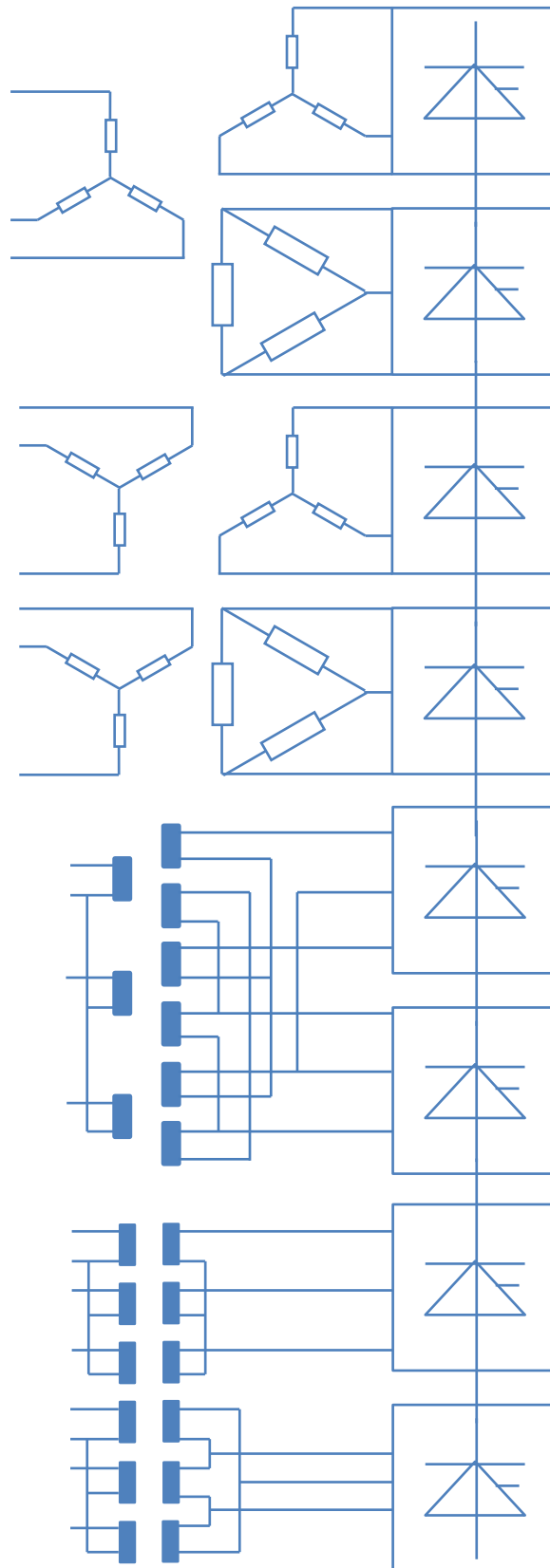


Figure 29. Common converter transformer configurations

Significant consideration in the converter transformer design is the selection of the leakage reactance as this will establish the major part of the converter's commutating reactance. The leakage reactance must mainly ensure that the maximum fault current that the thyristor valve can withstand is not surpassed. Nevertheless, beyond this limit, the choice of leakage reactance must be a balance of conflicting design issues, the most significant of which can be summarized as follows:

Lower impedance provides:

- Higher fault current
- Lower regulation drop
- Lower weight
- Taller core

Higher impedance provides:

- Lower fault current
- Higher regulation drop
- Higher weight
- Shorter core

Commonly the optimum leakage reactance will be in the range 0.12 pu to 0.22 pu.

HVDC CONVERTER RELIABILITY AND AVAILABILITY

Reliability and availability evaluation is the accepted way of assessing the HVDC converter scheme performance. CIGRE gathers reliability and availability of existing HVDC configurations from around the world and publishes a bi-annual report showing what performance is accomplished for those arrangements that give data for the report.

Reliability

Reliability is a measure of the HVDC link capability to transfer power above some minimum set value at any point in time under normal working conditions. Reliability is typically presented as the number of times in one year the configuration is incapable

of transferring power above a minimum set value. This inability to transfer above a defined power level is termed Forced Outage Rate (F.O.R.).

Availability

“Availability” is not commercially important. For instance, if the configuration is unavailable during times of zero loading, the unavailability of the configuration will have no impact. Therefore, for HVDC configurations, the term is used to represent “energy availability”. Energy availability is the HVDC configuration ability to transfer power up to the rated power. Therefore, a converter configuration which can transfer 1.0 pu power for 100% of the time would have an energy availability of 100%. Any HVDC configuration outage, for example, the outage of one pole in a bipole, will affect the energy availability, decreasing the figure to less than 100%.

CONVERTER STATION POWER LOSSES

Significant commercial consideration of any power interconnection is the electrical losses within the connection, that is, the power amount lost in the process of transferring the power from one location to another. Power losses within a line commutated converter arrangement are cautiously considered during the design phase in order to make sure that the relationship between capital equipment cost and the effective cost of losses can be optimized. In computing the losses effective cost, the purchaser must consider the duration of the financial plan for the HVDC link, the expected cost of electricity during this period and the anticipated interest rate during this period. By taking these figures, the net present value of the losses can be computed, that is, a figure which presents a cost to the owner of using the devices within the network. The loss assessment is typically assessed by multiplying a cost/kW figure by the HVDC supplier’s produced losses. Figures of 4,000 USD/kW to 5,000 USD/kW are typical. Figure 30 presents the common split between equipment within a HVDC transmission configuration whilst Figure 31 presents the split between devices for a back-to-back HVDC configuration.

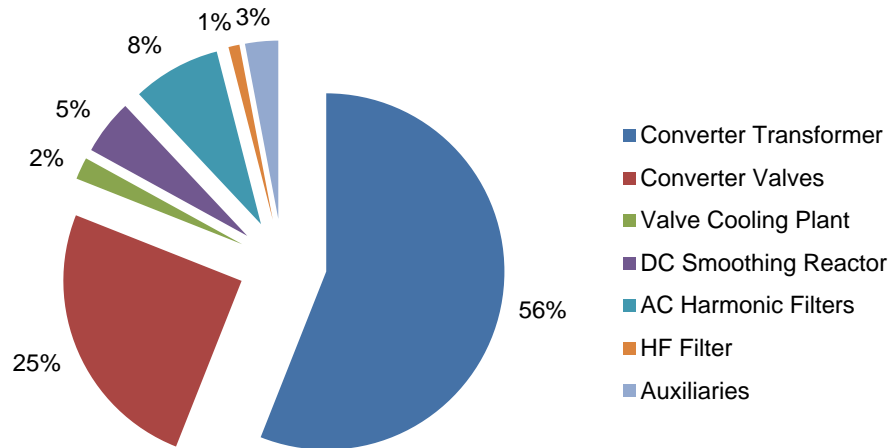


Figure 30. Common split of losses within an HVDC transmission configuration

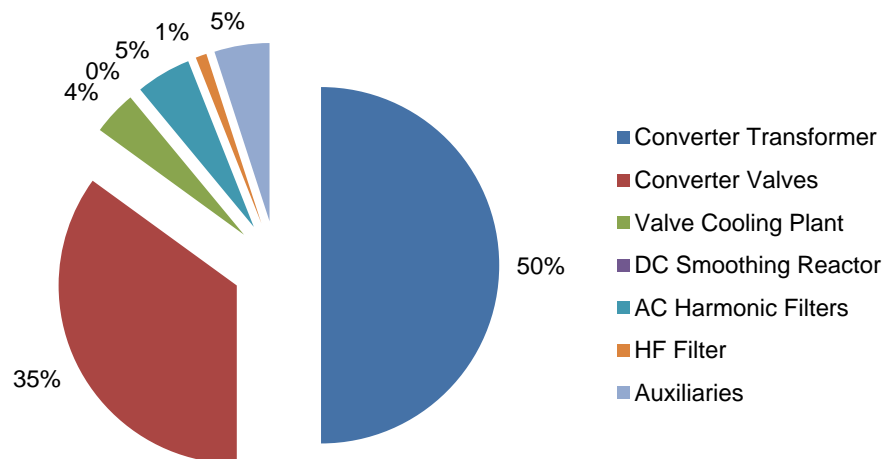


Figure 31. Common split of losses within a back-to-back HVDC configuration

Introduction to HDVC Technology - Quiz

Updated: 11/3/2017

1. A monopolar HVDC configuration with earth return contains _____.
(A) one or more six-pulse converter units
(B) single conductor and return through the ground or sea
(C) All of the above
(D) None of the above
2. In the case of _____ there is no DC transmission line and both converters are placed at the same site.
(A) Monopolar HVDC configuration
(B) Back-to-back HVDC configurations
(C) Bipolar HVDC configuration
(D) Bipolar configuration with monopolar metallic return
3. For a _____, the DC voltage rating is low and the thyristor valve current rating is high in comparison with HVDC interconnections via overhead lines or underground cables.
(A) Monopolar HVDC configuration
(B) Bipolar HVDC configuration
(C) Bipolar configuration with monopolar metallic return
(D) Back-to-back HVDC configurations
4. A bipolar HVDC configuration contains two poles, each of which includes one or more twelve-pulse converter units that are connected _____.
(A) In series
(B) In parallel
(C) All of the above
(D) None of the above

5. Rectifier output is DC power, which is not independent of the AC supply frequency and phase.
(A) True
(B) False
6. Converter transformer is designed as _____.
(A) Ground star-line winding and a floating-star
(B) Delta secondary windings
(C) All of the above
(D) None of the above
7. Typical HVDC transmission uses line-commutated thyristor technology.
(A) True
(B) False
8. Operation with _____ can typically be kept if the converter can be ran in a bipole mode with balanced currents between the poles, that is, the DC current to ground is very small.
(A) Neutral bus switch
(B) Neutral bus ground switch
(C) Ground return transfer switch
(D) Metallic return transfer breaker
9. DC voltage measurement is accomplished by _____.
(A) Resistive DC voltage divider
(B) Optical voltage divider
(C) All of the above
(D) None of the above

10. The _____ is used together with the ground return transfer switch to commutate the DC load current between the ground and a parallel, HV conductor.
- (A) Neutral bus switch
 - (B) Neutral bus ground switch
 - (C) Metallic return transfer breaker
 - (D) Ground return transfer switch
11. With constant valve winding voltage control, the firing angle at lower power transmission levels can be high.
- (A) True
 - (B) False
12. Under normal service, the inverter controls the _____.
- (A) DC voltage
 - (B) DC current
 - (C) Active power
 - (D) Reactive power
13. Under normal service, the rectifier controls the _____.
- (A) DC voltage
 - (B) DC current
 - (C) Active power
 - (D) Reactive power
14. Converters are a _____ since they work with a delay firing angle.
- (A) Active power load
 - (B) Reactive power load
 - (C) Reactive power generator
 - (D) Active power generator

15. Harmonic filters are used for _____.
(A) Decreasing the harmonics injected into the AC system
(B) Creating reactive power
(C) All of the above
(D) None of the above
16. Great majority of HVDC converters with thyristor valves are assembled in a converter bridge of _____ configuration.
(A) Three
(B) Nine
(C) Six
(D) Twelve
17. HVDC transmission system can rapidly reduce or increase power by implementing step change power adjustment.
(A) True
(B) False
18. In the case of a _____ once the partial damage to DC line insulation happens, one or both poles could be continuously operated at decreased voltage.
(A) Monopolar HVDC configuration
(B) Back-to-back HVDC configurations
(C) Bipolar HVDC configuration
(D) Bipolar configuration with monopolar metallic return
19. High frequency interference generated by converter performance can overlap with the frequencies in the range of _____ that are used for PLC communications.
(A) 50 kHz to 200 kHz
(B) 20 kHz to 100 kHz
(C) 10 kHz to 50 kHz
(D) 40 kHz to 500 kHz

20. In the case of a six-pulse diode converter bridge, the conducting pair is always diodes pair which have the _____.
(A) Lowest instantaneous AC voltage
(B) Highest instantaneous AC voltage
(C) Highest instantaneous DC voltage
(D) Lowest instantaneous DC voltage
21. Power harmonic generation is a consequence of _____.
(A) Equipment design
(B) Equipment operation
(C) All of the above
(D) None of the above
22. The actual harmonics level generated by an AC/DC converter is a function of the duration over which a particular phase is needed to provide _____.
(A) Unidirectional current to the load
(B) Directional current to the load
(C) Balanced voltage to the load
(D) Unbalanced voltage to the load
23. The higher the converter “pulse number” the lower the harmonic distortion in the _____.
(A) AC line current
(B) DC terminal voltage
(C) All of the above
(D) None of the above
24. Twelve-pulse bridge is made by combining two six-pulse bridges with a _____ phase shift between them.
(A) 90°
(B) 60°
(C) 45°
(D) 30°

25. Six-pulse bridge generates harmonic orders_____.
- (A) $6n \pm 1$, $n = 1, 2, 3$
 - (B) $3n \pm 1$, $n = 1, 2, 3$
 - (C) $12n \pm 1$, $n = 1, 2, 3$
 - (D) $9n \pm 1$, $n = 1, 2, 3$
26. Twelve-pulse bridge generates harmonic orders_____.
- (A) $6n \pm 1$, $n = 1, 2, 3$
 - (B) $3n \pm 1$, $n = 1, 2, 3$
 - (C) $12n \pm 1$, $n = 1, 2, 3$
 - (D) $9n \pm 1$, $n = 1, 2, 3$
27. The idealized waveforms are changed by the system supply reactance due to which the harmonic current magnitudes are _____ in comparison to those relevant to pure square wave pulses.
- (A) Increased
 - (B) Decreased
 - (C) Kept constant
 - (D) Oscillating
28. The harmonic currents derived from the examination of the ideal converter are known as _____.
- (A) Characteristic harmonics
 - (B) Non-characteristic harmonics
 - (C) Cross-modulation harmonics
 - (D) Even harmonics
29. Non-characteristic harmonics can be caused by _____.
- (A) An unbalance or “negative phase sequence” in the AC supply system
 - (B) Unbalance between the converter transformer leakage reactances
 - (C) All of the above
 - (D) None of the above

30. _____ are based on the fact that in any HVDC link the DC current is never absolutely smooth.
- (A) Characteristic harmonics
 - (B) Non-characteristic harmonics
 - (C) Even harmonics
 - (D) Cross-modulation harmonics
31. _____ are especially dominant in the case there is little or no impedance between the two converters.
- (A) Characteristic harmonics
 - (B) Cross-modulation harmonics
 - (C) Non-characteristic harmonics
 - (D) Even harmonics
32. Main filter types include _____.
- (A) Tuned filter or band-pass filter
 - (B) Damped filter or high-pass filter
 - (C) All of the above
 - (D) None of the above
33. _____ are filters made to damp more than one harmonic.
- (A) Damped filter or high-pass filter
 - (B) Tuned filter or band-pass filter
 - (C) Double-tuned band-pass filter
 - (D) Triple-tuned band-pass filter
34. The higher the ground impedance, the greater the induced currents in a parallel line, as this parallel line will present a viable current return path.
- (A) True
 - (B) False

35. DC filter capacitor banks are made as _____.
(A) Split bank
(B) One single tall bank
(C) All of the above
(D) None of the above
36. Power transfer compounding point is usually set at _____.
(A) Inverter DC terminal
(B) Mid-point of the DC transmission conductors
(C) All of the above
(D) None of the above
37. The power being transmitted through a HVDC link can be automatically modulated to give damping to _____ power oscillations within either, or both, interconnected AC systems.
(A) Low-frequency
(B) High-frequency
(C) All of the above
(D) None of the above
38. For insulation economy, the valve design is usually arranged so that the _____ valves are used as part of the insulation.
(E) Higher-voltage
(F) Lower-voltage
(G) All of the above
(H) None of the above
39. The converter transformer provides _____.
(A) 30° phase shift needed for twelve-pulse service via star and delta windings
(B) fault-limiting impedance
(C) All of the above
(D) None of the above

40. Converter transformer optimal leakage reactance is in the range of_____.

- (A) 0. 2 pu to 0.3 pu
- (B) 0.1 pu to 0.3 pu
- (C) 0.05 pu to 0.1 pu
- (D) 0.12 pu to 0.22 pu