HVDC

for beginners and beyond

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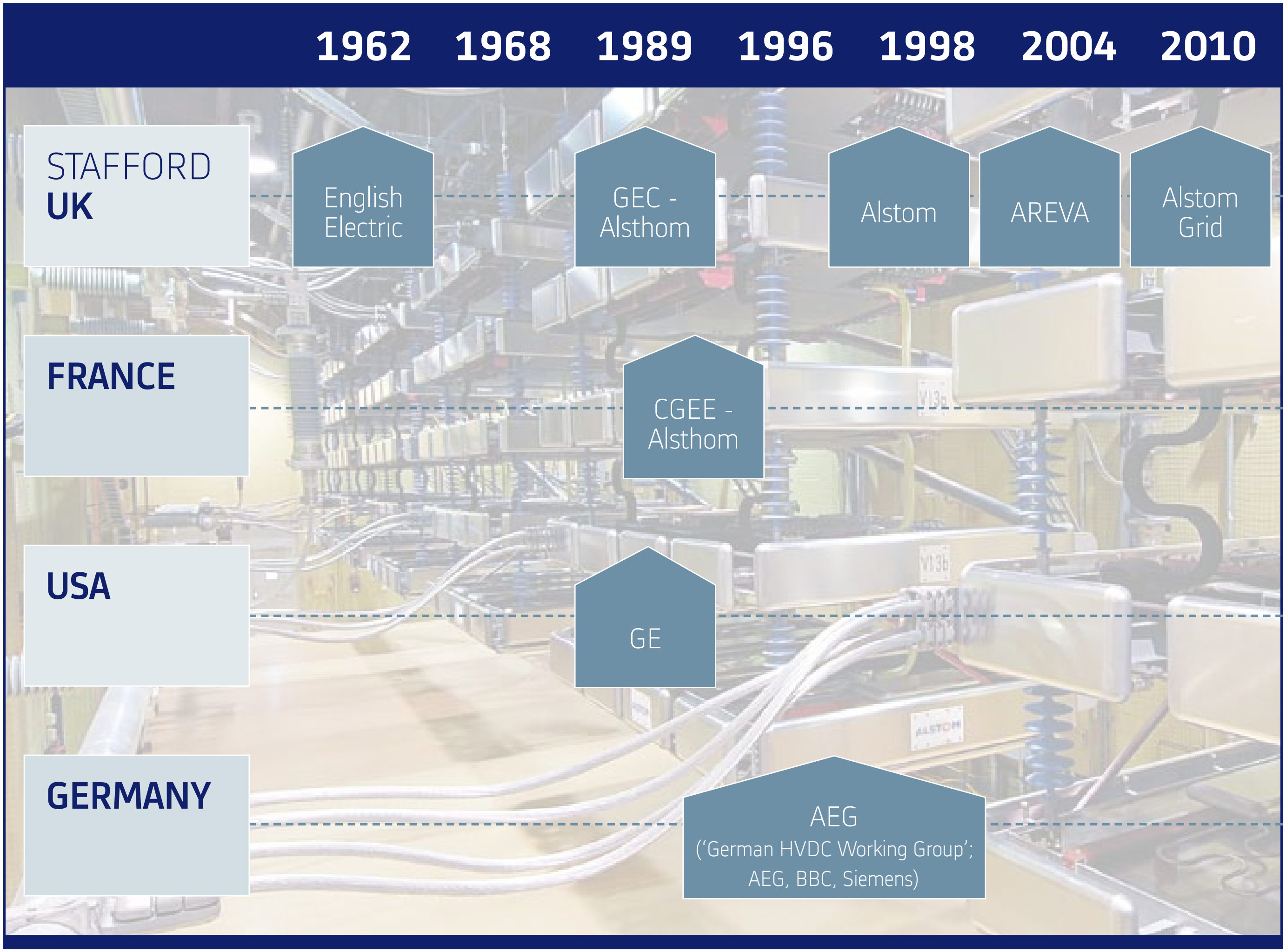


PREFACE

This booklet's contents are intended to fill a gap in the available literature between the very basic introductory material generally available from suppliers and the more academic analysis of HVDC presented in text books. This booklet is therefore aimed at those who wish to gain a better understanding of the complex systems which are now forming an integral part of power transmission in the world today, a trend which will only increase.

In recent years the technology of HVDC transmission using power transistors known as 'Voltage Source Converter' (VSC) has been introduced into the market. Whilst sharing some commonality with Line Commutated Converter (LCC) HVDC in terms of the asynchronous nature of the interconnection and the benefits it can bring to the AC system the technology differs in several ways. In order to avoid any confusion with VSC technology this booklet focuses on LCC HVDC only.

The first three chapters of the booklet provide an introductory overview of the subject of LCC HVDC, covering usage, configurations and basic operating principles. Chapter 4 contains more detailed examination of the main equipment of a HVDC converter station and chapter 5 discusses the layout of this equipment within the converter station. Chapters 6 and 7 review the operation of a HVDC converter and its control. Chapter 8 provides an introduction to 'static characteristics' and introduces the concept of superposition of AC quantities onto the characteristics.

An important design consideration of an LCC HVDC scheme relates to the reactive power loading that a HVDC converter station imposes on the network to which it is connected and this is reviewed in chapters 9 through to 13.

Chapters 14 to 22 provide an explanation of the causes, effects and mitigation methods relating to converter generated harmonics, both AC and DC.

A more detailed review of the control facilities available as standard on an LCC HVDC scheme are introduced in chapter 23, whilst chapters 24, 25 and 26 provide a more detailed technical discussion regarding HVDC converter valves, valve cooling and transformers.

As a HVDC connection will always be a significant element within any power system its performance in terms of reliability, availability and losses are important considerations and these concepts are introduced in chapters 27 and 28.

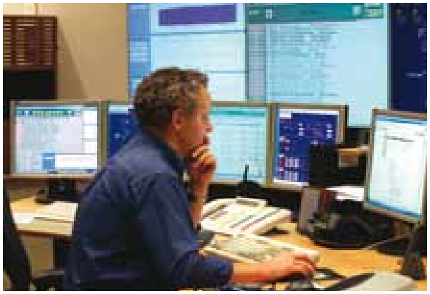
Special consideration has also been given to those in industry who may be in the position of having to prepare a specification for a HVDC converter scheme. Section 29 provides a description of the minimum studies normally performed as part of a turnkey HVDC project. Additionally, an Appendix is included at the end of this booklet which identifies the data needed for a budget quotation, that needed for tendering and the remaining data normally required during a contract.

The data used in the creation of this booklet has come from many engineers within Alstom Grid UK PES and to all of them I am grateful. Any errors are mine.

Carl Barker
Chief Engineer, Systems

CONTENTS

1 INTRODUCTION TO HVDC



Electrical power is generated as an alternating current (AC). It is also transmitted and distributed as AC and, apart from certain traction and industrial drives and processes, it is consumed as AC.

In many circumstances, however, it is economically and technically advantageous to introduce direct current (DC) links into the electrical supply system. In particular situations, it may be the only feasible method of power transmission. When two AC systems cannot be synchronised or when the distance by land or cable is too long for stable and/or economic AC transmission, DC transmission is used. At one “converter station” the AC is converted to DC, which is then transmitted to a second converter station, converted back to AC, and fed into another electrical network. In “back-to-back” HVDC schemes the two converter stations are brought under the same roof, reducing the DC transmission length to zero.

HVDC transmission applications fall into four broad categories and any scheme usually involves a combination of two or more of these. The categories are:

i) Transmission of bulk power where AC would be uneconomical, impracticable or subject to environmental restrictions.

ii) Interconnection between systems which operate at different frequencies, or between non-synchronised or isolated systems which, although they have the same nominal frequency, cannot be operated reliably in synchronism.

iii) Addition of power infeed without significantly increasing the short circuit level of the receiving AC system.

iv) Improvement of AC system performance by the fast and accurate control of HVDC power.

2 HVDC CONFIGURATIONS

2.1 Monopolar HVDC Systems

Monopolar HVDC systems have either ground return or metallic return.

A Monopolar HVDC System with Ground Return consists of one or more six-pulse converter units in series or parallel at each end, a single conductor and return through the earth or sea, as shown in Figure 2.1. It can be a cost-effective solution for a HVDC cable transmission and/or the first stage of a bipolar scheme [1]. At each end of the line, it requires an electrode line and a ground or sea electrode built for continuous operation.

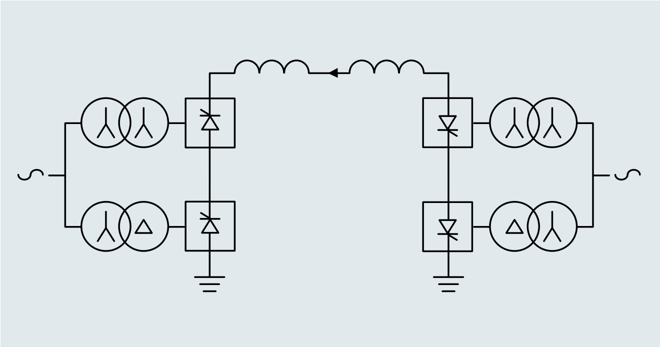


Figure 2.1: Monopolar HVDC System with Ground Return

A Monopolar HVDC System with Metallic Return usually consists of one high voltage and one medium voltage conductor as shown in Figure 2.2. A monopolar configuration is used either as the first stage of a bipolar scheme, avoiding ground currents, or when construction of electrode lines and ground electrodes results in an uneconomical solution due to a short distance or high value of earth resistivity.

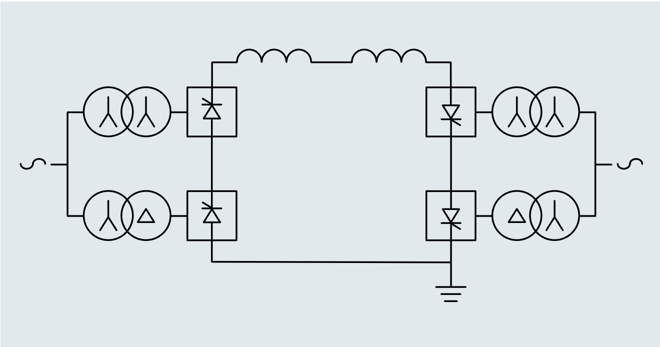


Figure 2.2: Monopolar HVDC System with Metallic Return

2.2 Bipolar HVDC Systems

A Bipolar HVDC System consists of two poles, each of which includes one or more twelve-pulse converter units, in series or parallel. There are two conductors, one with positive and the other with negative polarity to ground for power flow in one direction. For power flow in the other direction, the two conductors reverse their polarities. A Bipole system is a combination of two monopolar schemes with ground return, as shown in Figure 2.3 [2]. With both poles in operation, the imbalance current flow in the ground path can be held to a very low value.

This is a very common arrangement with the following operational capabilities:

- During an outage of one pole, the other could be operated continuously with ground return.

- For a pole outage, in case long-term ground current flow is undesirable, the bipolar system could be operated in monopolar metallic return mode, if appropriate DC arrangements are provided, as shown in Figure 2.4. Transfer of the current to the metallic path and back without interruption requires a Metallic Return Transfer Breaker (MRTB) and other special-purpose switchgear in the ground path of one terminal. When a short interruption of power flow is permitted, such a breaker is not necessary.

- During maintenance of ground electrodes or electrode lines, operation is possible with connection of neutrals to the grounding grid of the terminals, with the imbalance current between the two poles held to a very low value.

- When one pole cannot be operated with full load current, the two poles of the bipolar scheme could be operated with different currents, as long as both ground electrodes are connected.

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

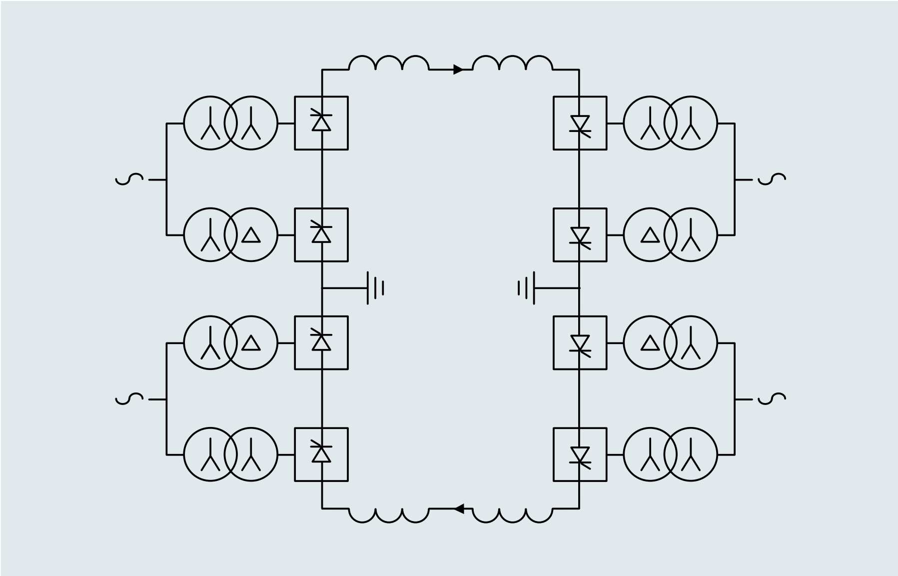


Figure 2.3: Bipolar HVDC System

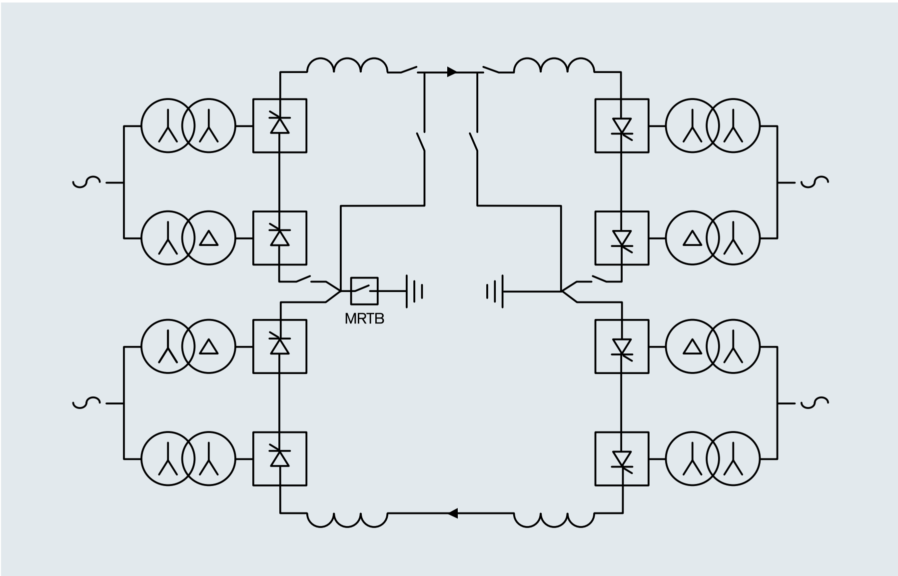


Figure 2.4: Bipolar System with Monopolar Metallic Return for Pole Outage

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

2.3 Back-to-Back HVDC Links

Back-to-back HVDC links are special cases of monopolar HVDC interconnections, where there is no DC transmission line and both converters are located at the same site. For economic reasons each converter is usually a twelve-pulse converter unit, and the valves for both converters may be located in one valve hall. The control system, cooling equipment and auxiliary system may be integrated into configurations common to the two converters. DC filters are not required, nor are electrodes or electrode lines, the neutral connection being made within the valve hall. It is important to note that Alstom Grid has developed a solution for a back-to-back HVDC link which does not require a smoothing reactor, hence, there is no external DC insulation [3]. Figure 2.5 shows two different circuit configurations used by Alstom Grid for back-to-back HVDC links.

Generally, 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 cables. The reason is that valve costs are much more voltage-dependent, as the higher the voltage the greater the number of thyristors. A low voltage tertiary winding can be built in to the converter transformer for the AC filters and compensation [4]. Smaller reactive power switching steps can thus be achieved.

A large back-to-back HVDC system can comprise two or more independent links so that the loss of one converter unit will not cause loss of full power capability.

Sasaram 500 MW Back-to-Back Converter Station

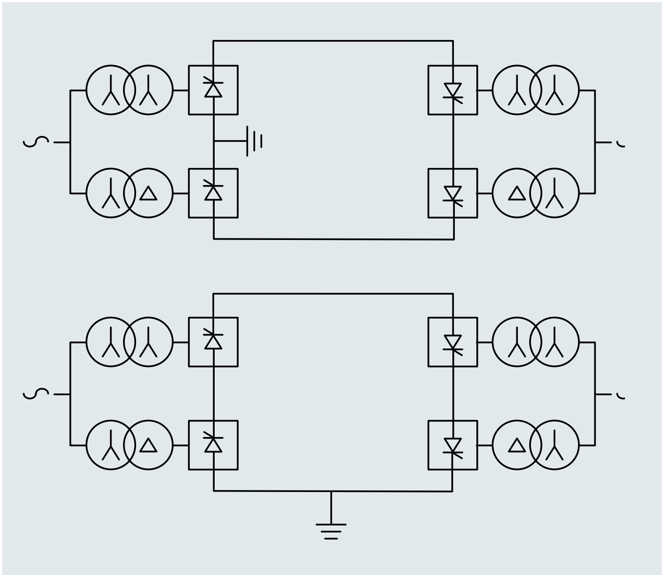


Figure 2.5: Back-to-Back DC Circuits

3 WHAT IS HVDC?

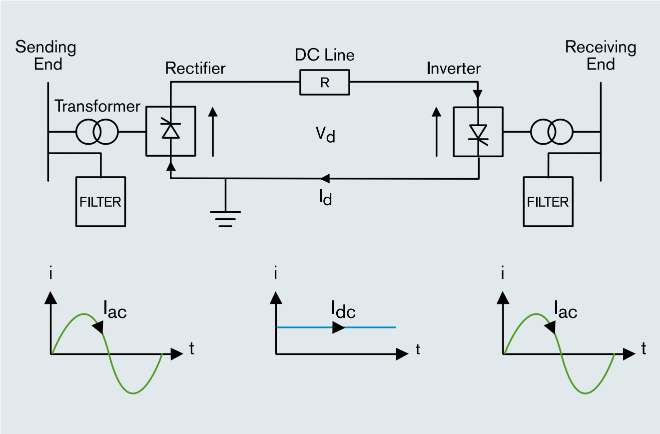


Figure 3.1: Basic HVDC Transmission

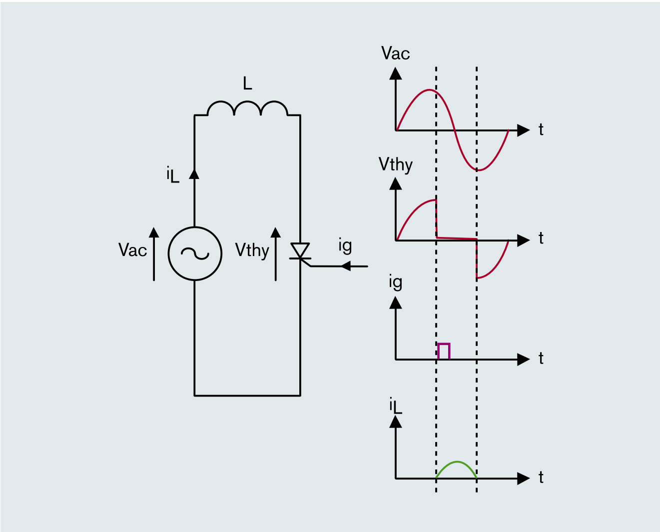


Figure 3.2: The Gating and Commutation of a Thyristor

A simple representation of a HVDC interconnection is shown in Figure 3.1. AC power is fed to a converter operating as a rectifier. The output of this rectifier is DC power, which is independent of the AC supply frequency and phase. The DC power is transmitted through a conduction medium; be it an overhead line, a cable or a short length of busbar and applied to the DC terminals of a second converter. This second converter is operated as a line-commutated inverter and allows the DC power to flow into the receiving AC network.

Conventional HVDC transmission utilises line-commutated thyristor technology. Figure 3.2 shows a simple thyristor circuit. When a gate pulse (ig) is applied while positive forward voltage is imposed between the anode and cathode (Vthy), the thyristor will conduct current (iL). Conduction continues without further gate pulses as long as current flows in the forward direction. Thyristor "turn-off" takes place only when the current tries to reverse. Hence, a thyristor converter requires an existing alternating AC voltage (Vac) in order to operate as an inverter. This is why the thyristor-based converter topology used in HVDC is known as a line-commutated converter (LCC).

H400 8.5 kV, 125 mm Thyristor valves

GCCIA HV switchyard at Al Fadhili

HV converter transformers 400 kV / 380 MVA at Al Fadhili

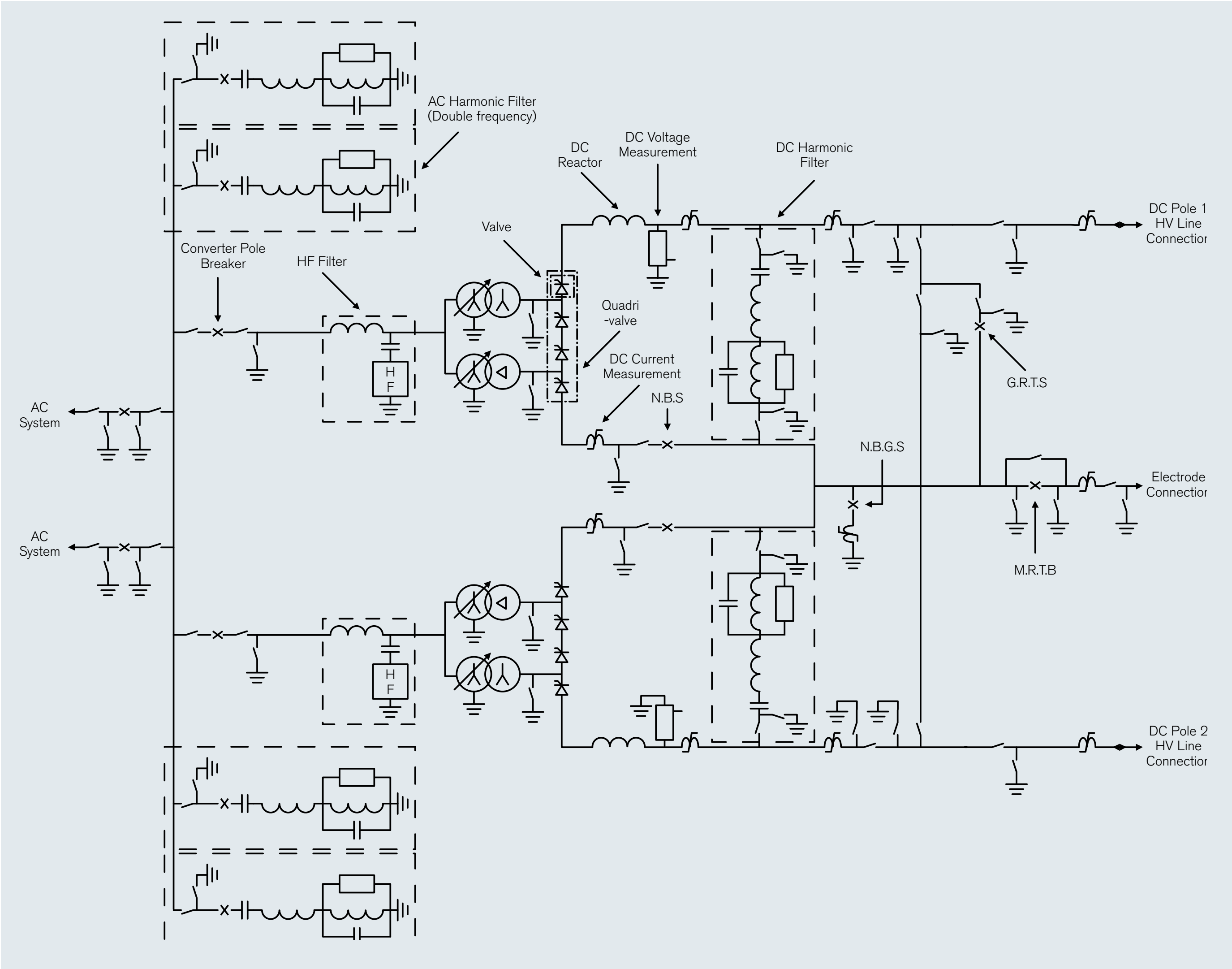


Figure 4.1: Typical SLD for a Bipole HVDC Converter

4 A LOOK AT THE SINGLE LINE DIAGRAM (SLD) OF ONE END OF A HVDC BIPOLE CONVERTER

Figure 4.1 (opposite) shows a typical SLD of one end of a bipole overhead transmission line HVDC converter station. The following discussion reviews the major components which make up the converter station.

4.1 AC Switchyard

The AC system connects to a HVDC converter station via a "converter bus", which is simply the AC busbar to which the converter is connected. The AC connection(s), the HVDC connection(s) along with connections to AC harmonic filters and other possible loads such as auxiliary supply transformer, additional reactive power equipment, etc., can be arranged in several ways normally dictated by: reliability/redundancy requirements, protection and metering requirements, the number of separately switchable converters and local practice in AC substation design. Figure 4.2 shows a selection of AC connection arrangements that can be used in HVDC converter stations starting with (a) a simple, single, 3-phase busbar with one switchable connection to the AC system and the switchable AC harmonic filters connected directly to it. In such an arrangement it is not possible to use the AC harmonic filters for reactive power support of the AC system without having the converter energised (as the AC system connection is common). Figure 4.2(b) shows a scheme comprising two converters and includes an additional circuit breaker dedicated to each converter. In this arrangement the AC harmonic filters can be used for AC reactive power support without energising the converter. However, in common with Figure 4.2(a), a busbar fault will result in the complete outage of the converter station. To provide some additional redundancy a double busbar arrangement can be used as shown in Figure 4.2(c). In Figure 4.2(c) an AC busbar outage will result in those loads connected

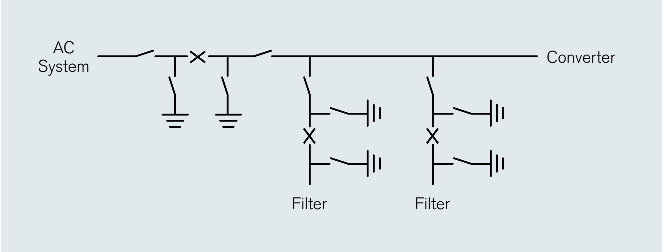


Figure 4.2 (a) Single busbar

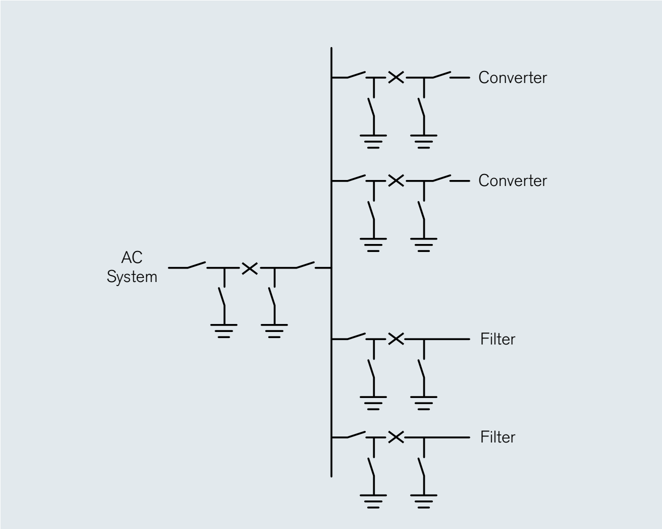


Figure 4.2 (b) Single busbar with separate converter breaker

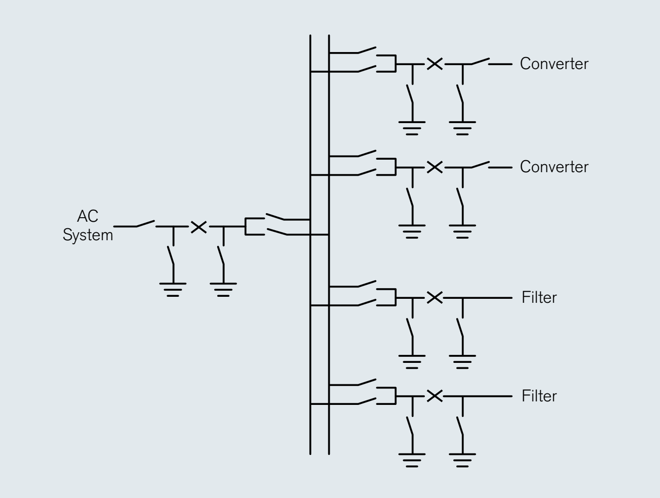


Figure 4.2 (c) A double busbar

to that busbar being disconnected until the disconnectors can be arranged to re-connect the load to the remaining, “healthy” busbar. Disconnector rearrangement will typically take in the order of ten seconds to complete and in some circumstances such an outage may not be acceptable, hence the arrangement shown in Figure 4.2(d) can be used, where each load is connected via a dedicated circuit breaker to each busbar, allowing for fast disconnection and reconnection in the event of a loss of a busbar (typically around 300 ms). A disadvantage of the arrangement shown in Figure 4.2(d) is the large number of AC circuit breakers required. In order to reduce the number of circuit breakers, the arrangement shown in Figure 4.2(e) can be used. In Figure 4.2(e) two loads can be individually switched between two three-phase busbars via three circuit breakers, hence, this configuration is commonly known as a “breaker-and-a-half” arrangement. Many other arrangements of AC switchyard configuration exist and have been used in association with existing HVDC schemes.

4.2 AC Harmonic Filters

Converter operation results in both the generation of AC current harmonics and the absorption of reactive power. In order to limit the impact of these AC harmonic currents and the absorbed reactive power, the converter station normally includes shunt connected switchable AC harmonic filters, either connected directly to the converter busbar or connected to a “filter busbar” which, in-turn, is connected to the converter busbar.

The AC harmonic filters are automatically switched-on and off with conventional AC circuit breakers when they are needed to meet harmonic performance and reactive power performance limits. The AC harmonic filters are typically composed of a high voltage connected capacitor bank in series with a medium voltage circuit comprising air-cored air-insulated reactors, resistors and capacitor banks. These components are selected to provide the required performance from the AC harmonic filter and to ensure that the filter is adequately rated.

4.3 High Frequency Filter

The converter operation will result in the generation of very high-frequency interference which will propagate out into the AC system from the converter bus. Whilst the magnitude and frequency of this interference is often of no importance to the safe operation of the AC system, there are some instances where this high-frequency interference may be undesirable, in particular when the AC system uses Power Line Carrier (PLC) signalling.

PLC signalling is a system which transmits a communication signal as an amplitude-modulated signal, superimposed on the fundamental frequency voltage signal of an AC power system. This system is used, in some power systems, as a communication system between AC system protection devices. However, the high-frequency interference generated by converter operation can overlap with the frequencies used for PLC communications (typically in the range of 40 kHz to 500 kHz). Therefore, it is sometimes necessary to include a High Frequency (HF) filter (or PLC filter) in the connection between the converter bus and the converter in order to limit the interference that can propagate into the AC system.

As with the AC harmonic filter, the HF filter comprises a high voltage connected capacitor bank, an air-core air-insulated reactor and an additional low voltage circuit composed of capacitors, reactors and resistors which are referred to as a tuning pack.

4.4 Converter Transformer

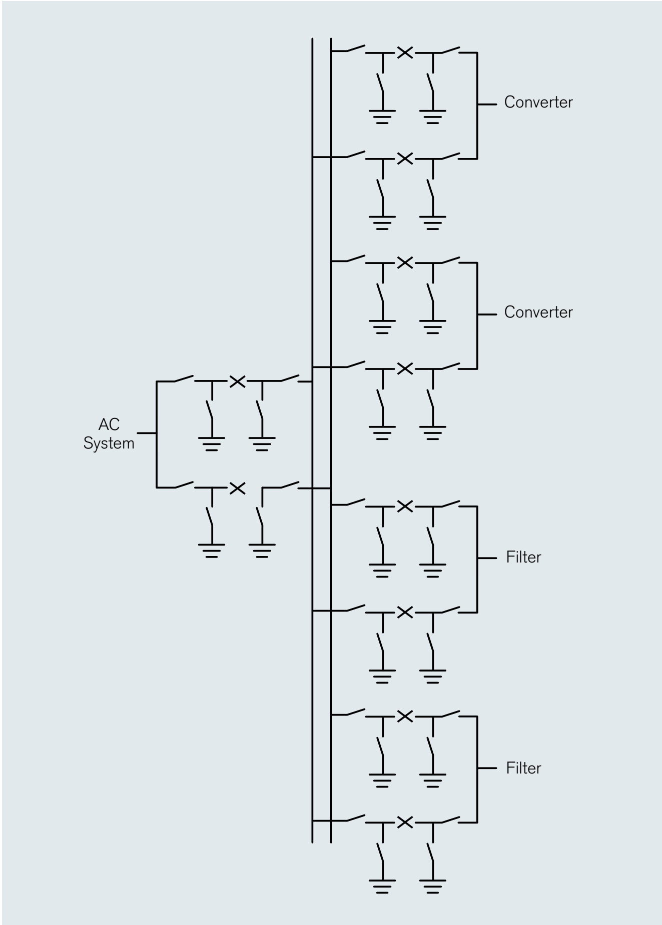


Figure 4.2 (d) A double bus, double breaker

The converter transformer is the interface between the AC system and the thyristor valves. Typically the HVDC converter transformer is subjected to a DC voltage insulation stress as well as the AC voltage stress normally experienced by a power transformer. These AC and DC stresses are fundamentally different. The AC voltage stress is predominantly in the insulating oil and defined by the geometry and permittivity of the materials, whilst the DC stress is governed by the resistivity of the insulating materials which, in turn, vary with operating conditions. In addition, it is important that the converter transformer be thermally designed to take into consideration both the fundamental frequency load and the AC harmonic currents that will flow from the converter through the converter transformer to the AC harmonic filters.

Typically, the converter transformer is arranged as an earthed star-line winding and a floating-star and delta secondary windings. There is normally an on-load tapchanger on the line winding.

4.5 Converter

The converter provides the transformation from AC to DC or DC to AC as required. The basic building block of the converter is the six-pulse bridge; however, most HVDC converters are connected as twelve-pulse bridges. The twelve-pulse bridge is composed of 12 “valves” each

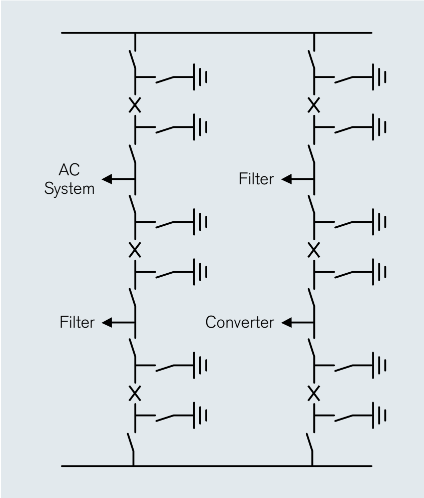


Figure 4.2 (e) A breaker-and-a-half

of which may contain many series-connected thyristors in order to achieve the DC rating of the HVDC scheme.

For a HVDC power transmission scheme, the valves associated with each twelve-pulse bridge are normally contained within a purpose built building known as a “valve hall”. For back-to-back schemes, where both the sending and receiving end of the HVDC link are located on the same site, it is typical for the valves associated with both ends of the link to be located within the same valve hall.

4.6 DC Smoothing Reactor

DC smoothing reactors are normally only required for power transmission schemes; they are not required for Alstom Grid back-to-back schemes.

For a HVDC transmission scheme, the DC smoothing reactor provides a number of functions but principally it is used to:

a) reduce the DC current ripple on the overhead transmission line or cable
b) reduce the maximum potential fault current that could flow from the DC transmission circuit into a converter fault
c) modify the DC side resonances of the scheme to frequencies that are not multiples of the fundamental AC frequency
d) protect the thyristor valve from fast front transients originating on the DC transmission line (for example a lightning strike)

The DC smoothing reactor is normally a large air-cored air-insulated reactor and is principally located at the high voltage terminal of the HVDC converter for schemes rated at, or below, 500 kVdc. Above 500 kV, the DC smoothing reactor is commonly split between the high voltage and neutral terminals.

4.7 DC Filter

Converter operation results in voltage harmonics being generated at the DC terminals of the converter, that is, there are sinusoidal AC harmonic components superimposed on the DC terminal voltage. This AC harmonic component of voltage will result in AC harmonic current flow in the DC circuit and the field generated by this AC harmonic current flow can link with adjacent conductors, such as open-wire telecommunication systems, and induce harmonic current flow in these other circuits. In a back-to-back scheme, these harmonics are contained within the valve hall with adequate shielding and, with a cable scheme, the cable screen typically provides adequate shielding. However, with open-wire DC transmission it may be necessary to provide DC filters to limit the amount of harmonic current flowing in the DC line. The DC filter is physically similar to an AC filter in that it is connected to the high voltage potential via a capacitor bank; other capacitors along with reactors and resistors are then connected to the high voltage capacitor bank in order to provide the desired tuning and damping.

4.8 DC Switchgear

Switchgear on the DC side of the converter is typically limited to disconnectors and earth switches for scheme reconfiguration and safe maintenance operation. Interruption of fault events is done by the controlled action of the converter and therefore, with the exception of the NBS, does not require switchgear with current interruption capability.

Where more than one HVDC Pole share a common transmission conductor (typically the neutral) it is advantageous to be able to commutate the DC current between transmission paths without interrupting the DC power flow. Figure 4.1 shows a typical Single Line Diagram (SLD) for a HVDC transmission scheme utilising DC side switchgear to transfer the DC current between different paths whilst on load. The following switches can be identified from Figure 4.1.

NBGS - Neutral Bus Ground Switch

This switch is normally open but when closed it solidly connects the converter neutral to the station earth mat. Operation with this switch can normally be maintained if the converter can be operated in a bipole mode with balanced currents between the poles, that is, the DC current to earth is very small. The switch is also able to 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 event of an earth fault on one pole, that pole will be blocked. However, the pole remaining in service will continue to feed DC current into the fault via the common neutral connection. The NBS is used to divert the DC current away from the blocked pole to ground.

GRTS - Ground Return Transfer Switch

The connection between the HVDC conductor and the neutral point includes both a high voltage disconnector and a GRTS and is used as part of the switching operation to configure the HVDC scheme as either a ground return monopole or a metallic return monopole. The disconnector is maintained 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 closing of the disconnector in order to put the HV conductor in parallel with the earth path. The GRTS is also used to commutate the load current from the HV conductor transferring the path to the earth (or ground return) path. Once current flow through the HV conductor is detected as having stopped, the disconnector can be opened, allowing the HV conductor to be re-energised at high voltage.

MRTB - Metallic Return Transfer Breaker

The MRTB is used in conjunction with the GRTS to commutate the DC load current between the earth (ground return) and a parallel, otherwise unused, HV conductor (metallic return).

The MRTB closes in order to put the low impedance earth return path in parallel with the metallic return path. The MRTB must also be able to open, causing current flowing through the earth return to commutate into the much higher impedance metallic return path.

4.9 DC Transducers

DC connected transducers fall into two types, those measuring the DC voltage of the scheme and those measuring the DC current.

DC voltage measurement is made by either a resistive DC voltage divider or an optical voltage divider. The resistive voltage divider comprises a series of connected resistors and a voltage measurement can be taken across a low voltage end resistor which will be proportional to the DC voltage applied across the whole resistive divider assembly. Optical voltage transducers detect the strength of the electric field around a busbar with the use of Pockel cells.

DC current measurement for both control and protection requires an electronic processing system. Measurement can be achieved by generating a magnetic field within a measuring head which is sufficient to cancel the magnetic field around a busbar through the measuring head. The current required to generate the magnetic field in the measuring head is then proportional to the actual current flowing through the busbar. Devices using this method are commonly known as Zero Flux Current Transducer (ZFCT).

Optical current measurement makes use of, amongst others, the Faraday effect in which the phase of an optical signal in a fibre optic cable is influenced by the magnetic field of a busbar around which the cable is wound. By measuring the phase change between the generated signal and the signal reflected back from the busbar, the magnitude of the current can be found.

5 STATION LAYOUT

The converter station is normally split into two areas:

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

An example of a converter station layout including the AC switchyard and the converter island is shown in Figure 5.1 with the actual site shown in Figure 5.2.

Figure 5.2: Lindome, Sweden, Converter Station; Part of the 380 MW Konti-Skan HVDC Interconnection

5.1 AC Switchyard

As with any AC switchyard, the complexity and therefore the space occupied varies, dependent upon the amount of both feeders and locally-switched elements to be interconnected. For a HVDC converter station, the AC switchyard may be part of a major node on the grid and therefore 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 located on the periphery of the network and therefore there may be only one or two feeders alongside the converter equipment. In both cases, however, the space occupied by these AC connections will be appropriate to the AC voltage level(s).

Typically, the main HVDC converter associated components located in the AC switchyard are the AC harmonic filters. These normally comprise ground-level mounted components located within a fenced-off compound. Compound access is only possible once the filters have been isolated and earthed.

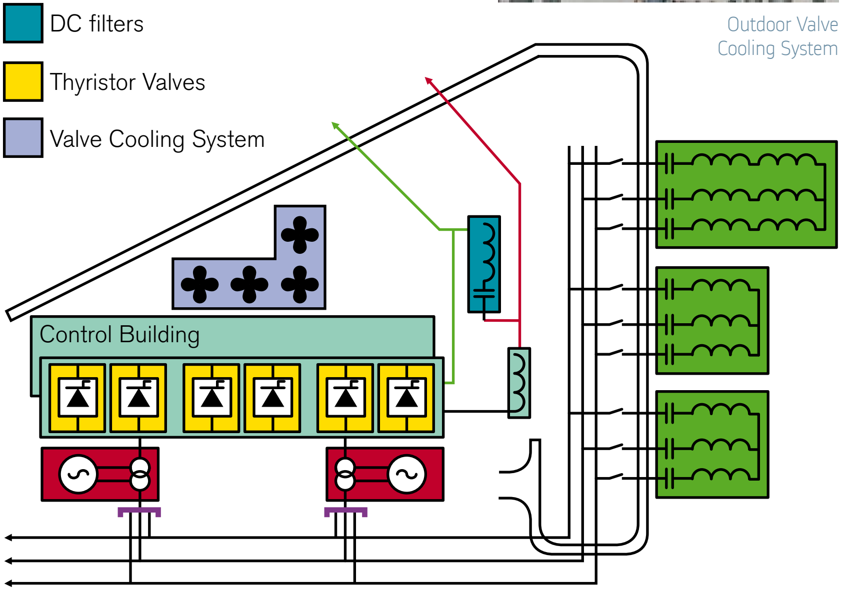
High frequency filter components, along with surge arresters, AC circuit breakers, disconnectors and earth switches are usually mounted on structures to allow walk-around access while the equipment is live.

5.2 Converter Island

In modern HVDC converter stations, the thyristor valves are almost always located indoors in a purpose built enclosure known as a valve hall. This enclosure provides a clean, controlled environment in which the thyristor valves can safely operate without the risk of exposure to pollution or outdoor conditions.

Figure 5.1: Lindome, Sweden, Converter Station Layout; Part of the 380 MW Konti-Skan HVDC Interconnection


Outdoor Valve Cooling System




H400 Thyristor Valves


Converter Transformers


Smoothing Reactor


AC Filters

Within the valve hall, the thyristor valves are typically suspended from the roof of the building with the low voltage being closest to the roof and the high voltage being at the lowest point on the valve. An air gap between the bottom of the valve and the valve hall floor provides the high voltage insulation.

The valve hall has an internal metal screen covering all walls, the roof and the floor. This screen creates a Faraday cage in order to contain the electromagnetic interference generated by the thyristor valve operation. The integrity of this screen is typically maintained 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 varies widely in complexity and physical arrangement between projects. For outdoor DC areas, the majority of the equipment (disconnectors, earth switches, transducers, etc.) is typically mounted on structures to create a walk-around area with only the DC filter, if present, ground mounted within a fenced-off area. However, where sound shielding is required around the DC reactor, this may be ground mounted with the sound shielding in the form of separate walls or an enclosure, also forming the safety barrier. When the DC area is located indoors, it is more common to have the majority of the equipment mounted at ground level in order to avoid an excessive height requirement for the building. In such circumstances, access to the whole, or parts of, the DC area is controlled by a fenced-off enclosure.

The control and services building is also located on the converter island. This building generally contains equipment rooms such as:

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

5.3 Acoustic Noise

Invariably there are requirements resulting from local environmental rules related to the acoustic noise any substation (or other industrial site) can generate at either its boundary or at the nearest property. Much of the equipment in an HVDC converter station generates acoustic noise when operating and therefore careful consideration is required in terms of equipment layout in order to minimise the acoustic noise at the point of measurement.

Typical acoustic noise sources within a converter station (measured as sound power ($P\omega$)) are:

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

$$L\omega(\chi) = P\omega - 20 \times \mathrm{Log10}\,\chi - 8$$

Where:

$L\omega(\chi)$ = the sound pressure at a distance χ (in metres).
$P\omega$ = 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 calculated (in metres).

In order to meet the boundary, or nearest residence, acoustic noise limit, it may be necessary to add acoustic noise barriers or to modify the equipment itself. The barriers may take the form of walls or enclosures.

6 HOW DOES A LINE COMMUTATED CONVERTER WORK?

6.1 Six-Pulse Diode Converter Bridge

Six-pulse converters are the building block of HVDC systems. An example of a six-pulse converter, which employs diodes, is shown in Figure 6.1. Diodes conduct in the sequence 1,2,3,4,5,6, so the transitions between one diode and the next occur alternately in the upper and lower half-bridges.

Each diode conducts for 120°, in every 360° cycle, so that the successive 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 that pair of diodes which have the largest instantaneous AC voltage between them. The other diode pairs are connected to an instantaneously smaller voltage and hence are subjected to a reverse voltage across their terminals. As time passes, the relative amplitudes of the converter's three AC supply phases (valve-winding voltages) change, so in Figure 6.2 the voltage B-C becomes greater than the voltage A-C and valve 3 takes over the current which had been flowing in valve 1. This process is known as "commutation".

In this idealisation, the mean direct voltage, Vd, emerges as a fixed value, determined entirely by the transformer ratio, the calculation of which is shown in Figure 6.3. This value is known as the "No-Load DC Voltage", or Vdio, of the converter.

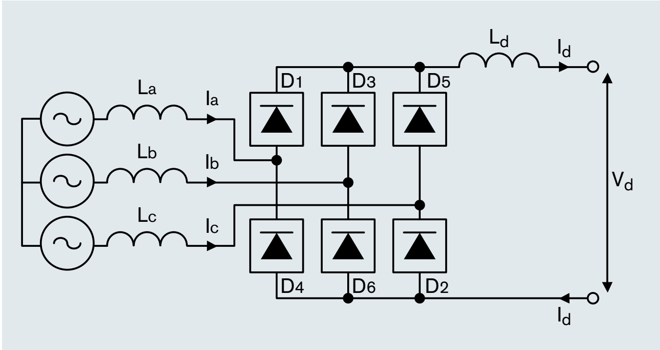


Figure 6.1: Six-Pulse Converter

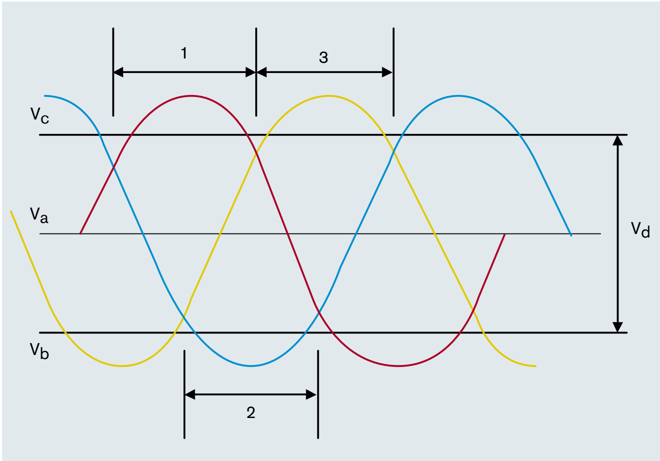


Figure 6.2: Current Switching Pattern of a Six-Pulse Converter

6.2 Commutation

In practice, the transfer of current from one diode to the next requires a finite time, since the current transfer is slowed down by the commutation reactance (made up of reactance in the converter transformer, the thyristor valve and a small amount in the HF filtering circuit). This produces an "overlap" between successive periods of conduction in one half of the six-pulse bridge. Figure 6.4 shows that the mean direct voltage (Vd) has been reduced compared to Figure 6.2. Figure 6.4 also shows the valve current waveform during the commutation process, where current falls in one valve, while the current rises in the next valve in sequence. The time taken to commutate the current from one valve to the next is called the "overlap angle", μ.

6.3 Thyristor Controlled Converter

In a thyristor converter, shown in Figure 6.5, it is possible to vary the mean direct voltage by controlling the instant at which the thyristors are turned on.

A thyristor is turned on (fired) by applying a short pulse to its gate terminal and turns off when the external circuit forces its anode current to zero. In this case, 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 illustrated in Figure 6.6. This delay angle determines when the commutation process will commence and consequently determines the mean direct voltage (V_d). V_d is proportional to the cosine of α; i.e. the greater the delay angle, the smaller the mean direct voltage. Zero voltage is reached as α approaches 90°.

6.4 The Inversion Process

By increasing the firing angle, α, beyond 90°, the voltage area of the phase-to-phase voltage connected to the DC terminals via the conducting thyristors will be predominantly negative, hence the DC terminal voltage will be negative.

As, beyond 90°, the firing angle of the converter becomes large, it is more common to refer to the "extinction angle" or "gamma", γ. This extinction angle represents the time between the end of the overlap period and the time when the phase voltage associated with the out-going valve becomes more positive/negative than that of the next

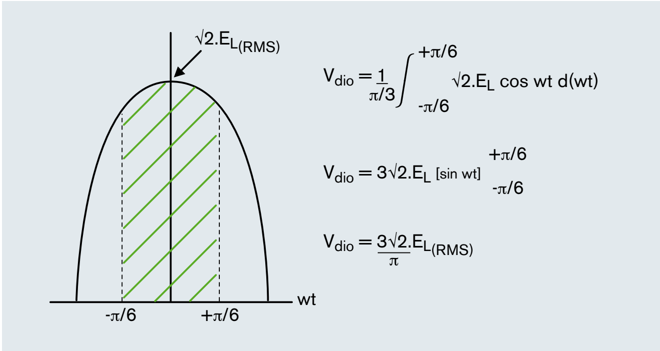


Figure 6.3: The No-Load DC Voltage of a Six-Pulse Bridge

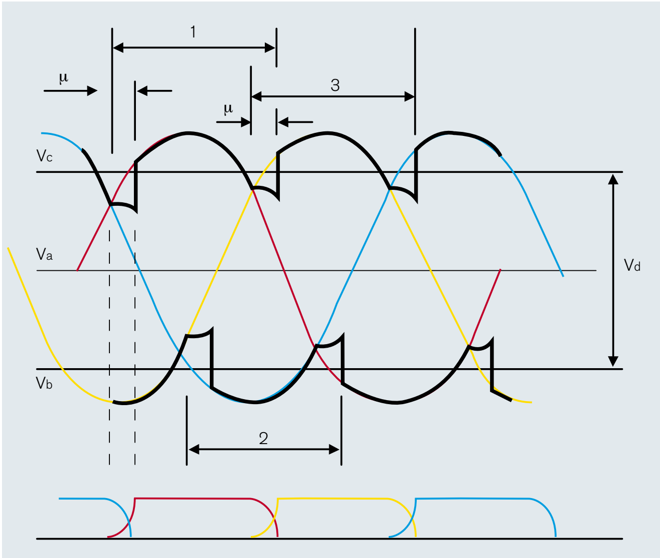


Figure 6.4: Effect of Commutation on Converter Operation

valve in sequence, and it is mathematically expressed as:

$$\gamma = 180° - \mu - \alpha$$

It must be noted that the control of the output voltage of a six-pulse bridge is only achieved by the firing angle, α. The extinction angle, γ, is a measure of the available turn-off time for the valve following the point in time where the valve is fired.

6.5 Valve Voltage Waveform

Typical voltage waveforms across a valve during rectification and inversion are shown in Figures 6.9 and 6.10 respectively. The "notches" in the waveforms are caused when commutation takes place, because commutation is actually a temporary line-to-line short circuit, imposed by the converter valves. This does not give rise to heavy fault currents however, as at the instant the current in the valve which has just fired reaches equality with the main direct current, the valve which is relinquishing current turns off, breaking the circulating current path.

6.6 Twelve-Pulse Bridge Rectifier

Because of the high power levels associated with HVDC transmission, it is important to reduce the current harmonics generated on the AC side and the voltage ripple produced on the DC side of the converter. This is achieved by means of connecting two six-pulse bridge circuits in series on the DC side/parallel on the AC side to form the twelve-pulse bridge configuration (Figure 6.11)

In Figure 6.11 each of the bridges is connected to the AC network by a single-phase three-winding transformer. One of the transformers is connected (star/star) Y/Y and the other (star/delta) Y/Δ; the Δ is on the DC side. Through this connection the bridges have a phase difference of 30° in feeding AC power. Mechanically the valves can be grouped in three parallel stacks containing four valves connected in series.

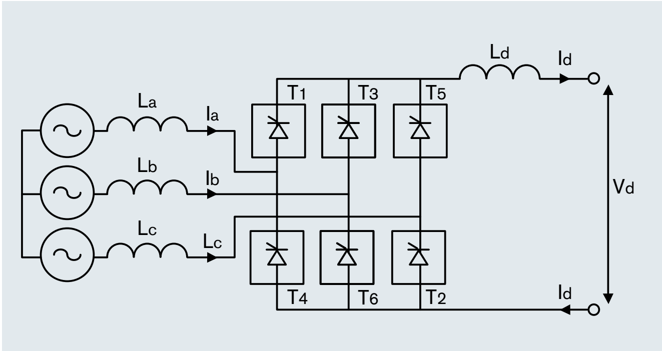


Figure 6.5: Thyristor Converter

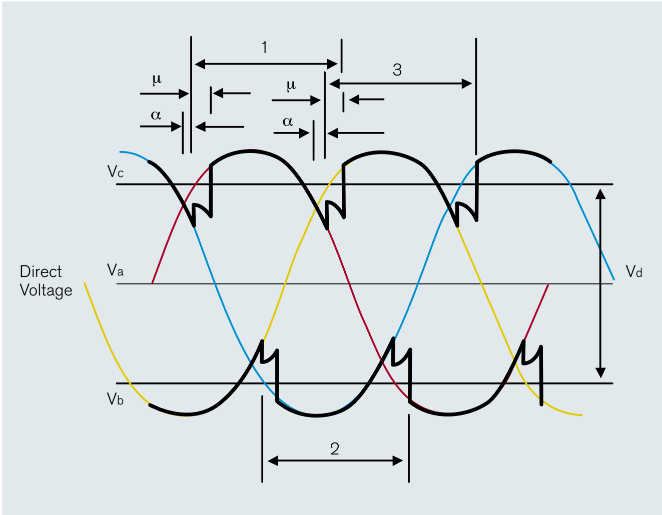


Figure 6.6: Effect of Firing Angle on Converter Operation

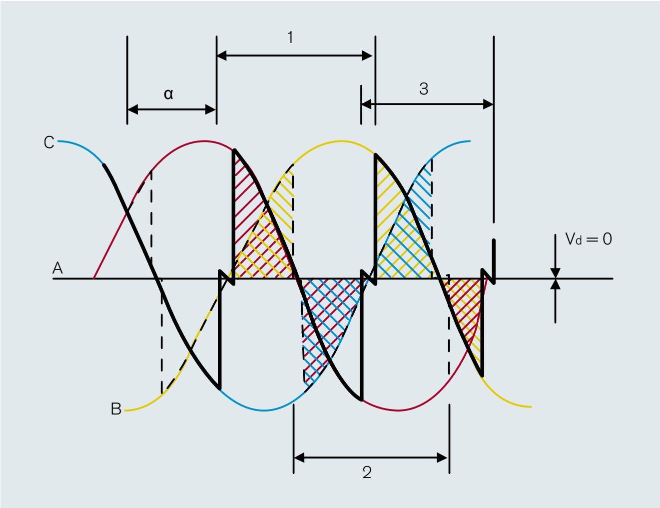


Figure 6.7: Effect of Firing Angle as it Approaches 90°

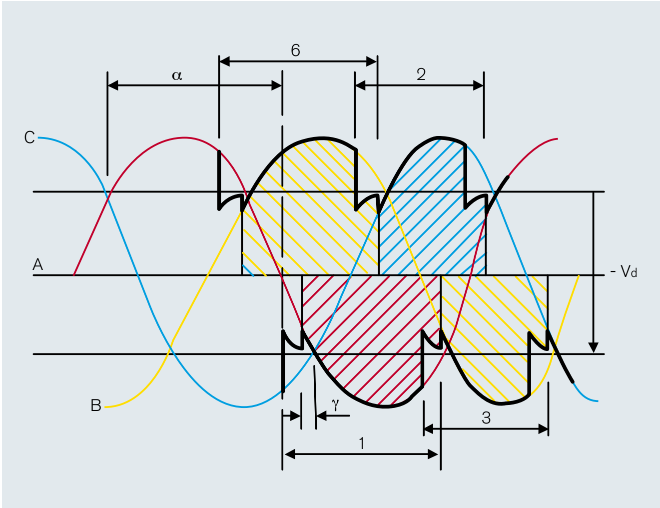


Figure 6.8: Effect of a Firing Angle of 140°

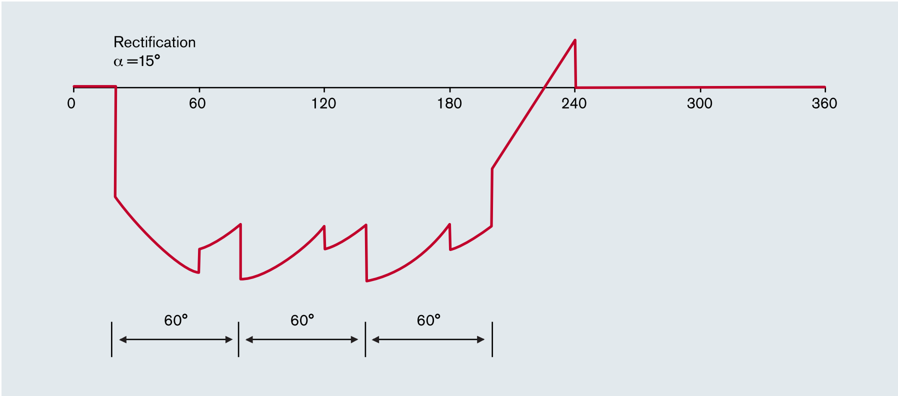


Figure 6.9: Rectifier Valve Voltage Waveform (excluding commutation overshoots)

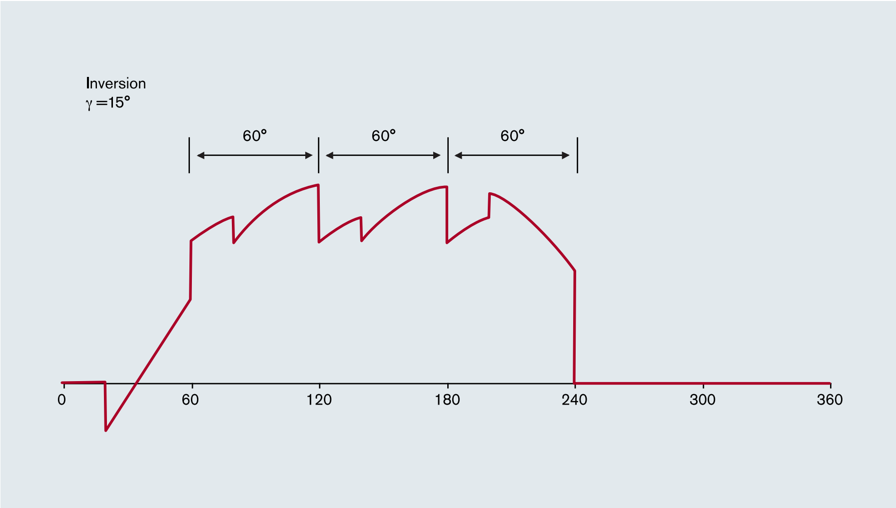


Figure 6.10: Inverter Valve Voltage Waveform
(excluding commutation overshoots)

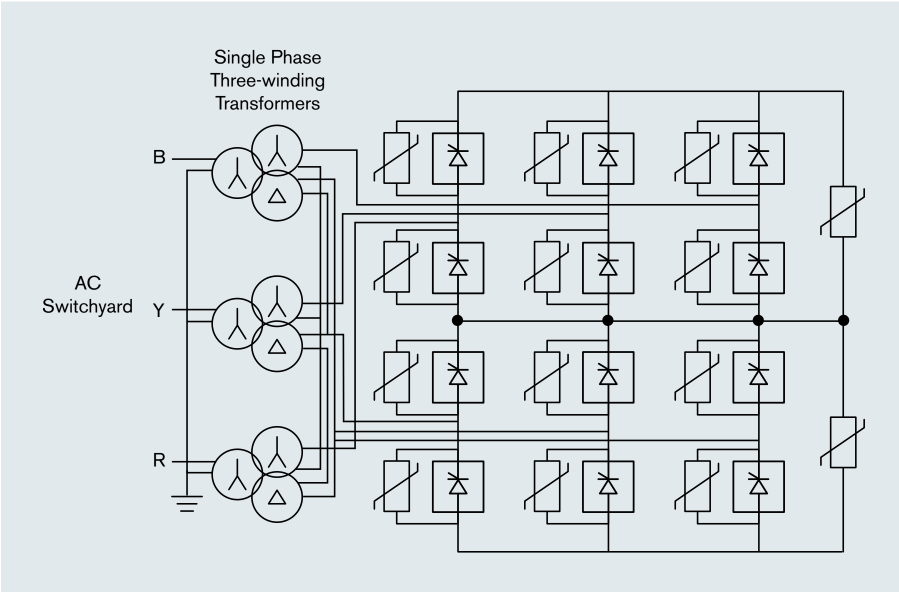


Figure 6.11: Twelve-Pulse Converter

7 CONTROL OF A HVDC LINK

Consider Figure 7.1, the voltage across the rectifier is positive with respect to both its anode terminal as well as the earth reference. The inverter terminal is, however, generating a negative voltage with respect to its anode terminal but, as it is connected in reverse parallel to the rectifier, its voltage with respect to the earth reference is also positive. As the rectifier voltage and the inverter voltage are independently controlled, they can have different values and hence there will be a voltage difference across the resistor in the DC circuit which, as long as the rectifier voltage is larger than the inverter voltage, will cause a DC current to flow. This can simply be expressed as:

$$I_d = \frac{V_{\text{Rectifier}} - V_{\text{Inverter}}}{R_d}$$

Under normal, steady-state operation, the inverter control system is normally arranged to maintain the DC voltage at a certain point on the HVDC link (known as the “compounding point”) at a target value. This target value is typically 1.0 pu for a transmission scheme but for back-to-back schemes, where the DC transmission losses can be ignored, this value can be varied to provide a further degree of reactive power control. The “compounding point” is usually at the rectifier DC terminal and hence the inverter must calculate this voltage based on the DC voltage at the inverter terminals, the DC current and the known resistance of the transmission circuit (this latter quantity being measurable by the HVDC controller if telecommunications between the rectifier and the inverter are available). The rectifier normally controls the DC current flowing in the circuit and does this by adjusting its output DC voltage to give a current flow as described by the above equation.

There are a number of ways that a six-pulse converter can be controlled in a HVDC link.

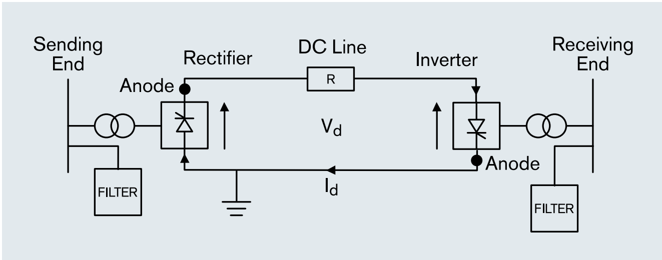


Figure 7.1: Inverter control system

For a rectifier the control options are:

- Constant valve winding voltage control – With this method of control, the converter transformer tapchanger is used to maintain the voltage applied to the AC terminals of each six-pulse bridge to a constant target value. Control of the current is then achieved by variation 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 large. To reduce the range over which the firing angle can operate in the steady state, the converter transformer tapchanger can be used to vary the applied AC voltage to the six-pulse bridge and hence limit the range over which the firing angle operates.

For an inverter the control options are:

- Constant valve winding voltage control – This is the same as the equivalent rectifier control.
- Constant gamma angle range control – This is similar to the rectifier “constant firing angle range control” but acts on the inverter extinction angle instead of the firing angle.
- Constant extinction angle control (CEA) – With this method of control, the inverter DC voltage is allowed to vary in order to achieve a constant extinction angle with varying DC current. The inverter converter transformer tapchanger is used to adjust the applied AC terminal voltage in order to maintain the DC voltage to within a fixed, steady-state, range.

8 STATIC CHARACTERISTICS

The static characteristics can be considered as the cerebral cortex of the converter as, in the same way as if you touch something hot with your hand you move it quickly away, without the involvement of higher brain functions, the static characteristics describe the way in which the converter responds to transients without involving higher control functions.

The six-pulse bridge introduced in Section 4 can be simplified to a battery in series with a resistor as shown in Figure 8.1. Note that the resistor shown in Figure 8.1 is not an actual resistor but is simply included in the above circuit to simulate the voltage regulation effect of the impedance of the converter bridge connection. This resistor does not have any associated I^2R losses.

Consider the circuit shown in Figure 8.1. As the DC current through the converter increases up to 1.0 pu, the voltage drop across the "resistor" increases, reducing the voltage at the DC terminal of the circuit as shown in Figure 8.2. Once at 1.0 pu DC current, the voltage can then be varied 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 flow through it supplied by a separate DC current source. As the firing angle increases (extinction angle decreases), the converter DC terminal voltage increases up to the minimum extinction angle at which point the DC current must be reduced to achieve further increases in DC terminal voltage, following a constant extinction angle line.

By vertically flipping the inverter characteristic and plotting 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 as shown in Figure 8.3.

However, with these static characteristics, as can be seen in Figure 8.4, if the AC voltage applied to the rectifier falls then there are

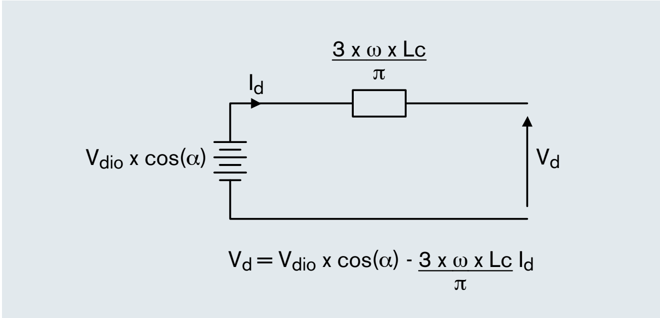


Figure 8.1: A Basic Six-Pulse Converter Model

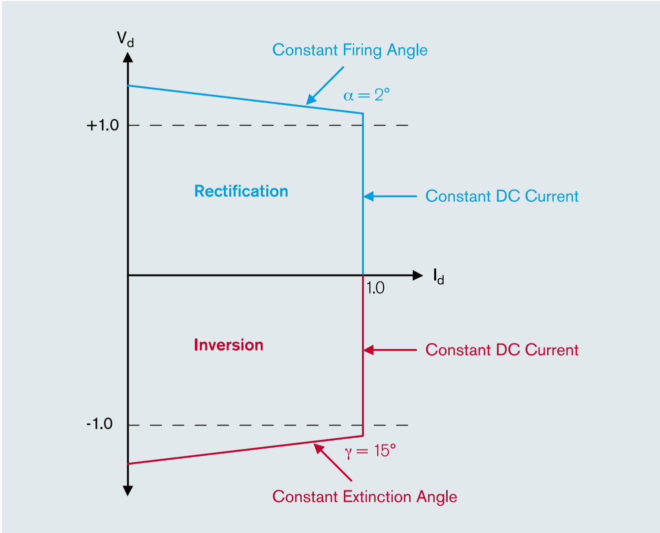


Figure 8.2: Converter Operating Profile

multiple crossover points between the rectifier and the inverter. Hence, the operating point cannot be determined. To overcome this, the basic converter characteristics are modified in order to control the way that the converters respond during transient events. An example of a practical characteristic is shown in Figure 8.5. Note that in Figure 8.5 the constant current characteristic of the inverter is at a lower DC current than the constant current characteristic of the rectifier. Under normal operation, the inverter controls the DC voltage and the rectifier controls the DC current. However, if the AC terminal voltage at the rectifier falls such that the rectifier characteristic shown in Figure 8.5 crosses the inverter constant current characteristic, then the inverter will maintain the DC current at this level with the DC voltage being dictated by where the rectifier characteristic crosses the inverter constant current 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 superimposed on the static characteristic as shown in Figure 8.6. For example, a curve of constant real power can be superimposed indicating the required DC current for a given change in DC voltage to maintain the rectifier DC terminal power. Another characteristic that can be superimposed is one of constant reactive power. If the operating point were to be maintained along the reactive power curve, then at any point the reactive power absorbed by the converter would remain constant. Consequently, if there is a reduction in, for example, the rectifier AC system, then, by following an approximately constant reactive power curve, the change in reactive power at the inverter terminal is minimised, even though there is a change in real power. Consequently, the converter bus voltage at the inverter would remain approximately constant.

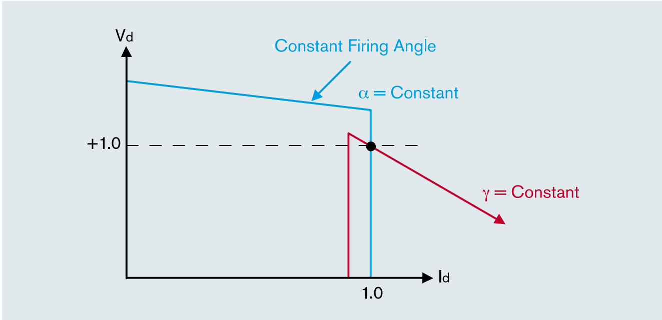


Figure 8.3: The Basic Static Characteristic of an HVDC Link

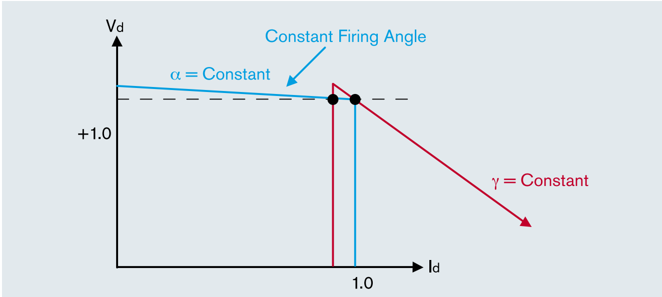


Figure 8.4: The Basic Static Characteristic of an HVDC Link with Reduced Rectifier AC Terminal Voltage

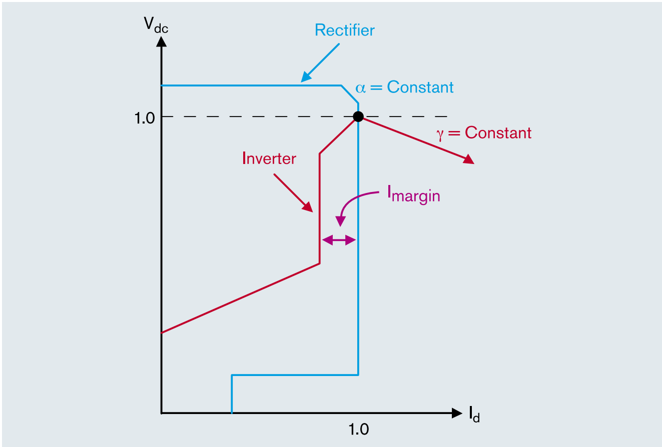


Figure 8.5: A Practical HVDC Link Static Characteristic

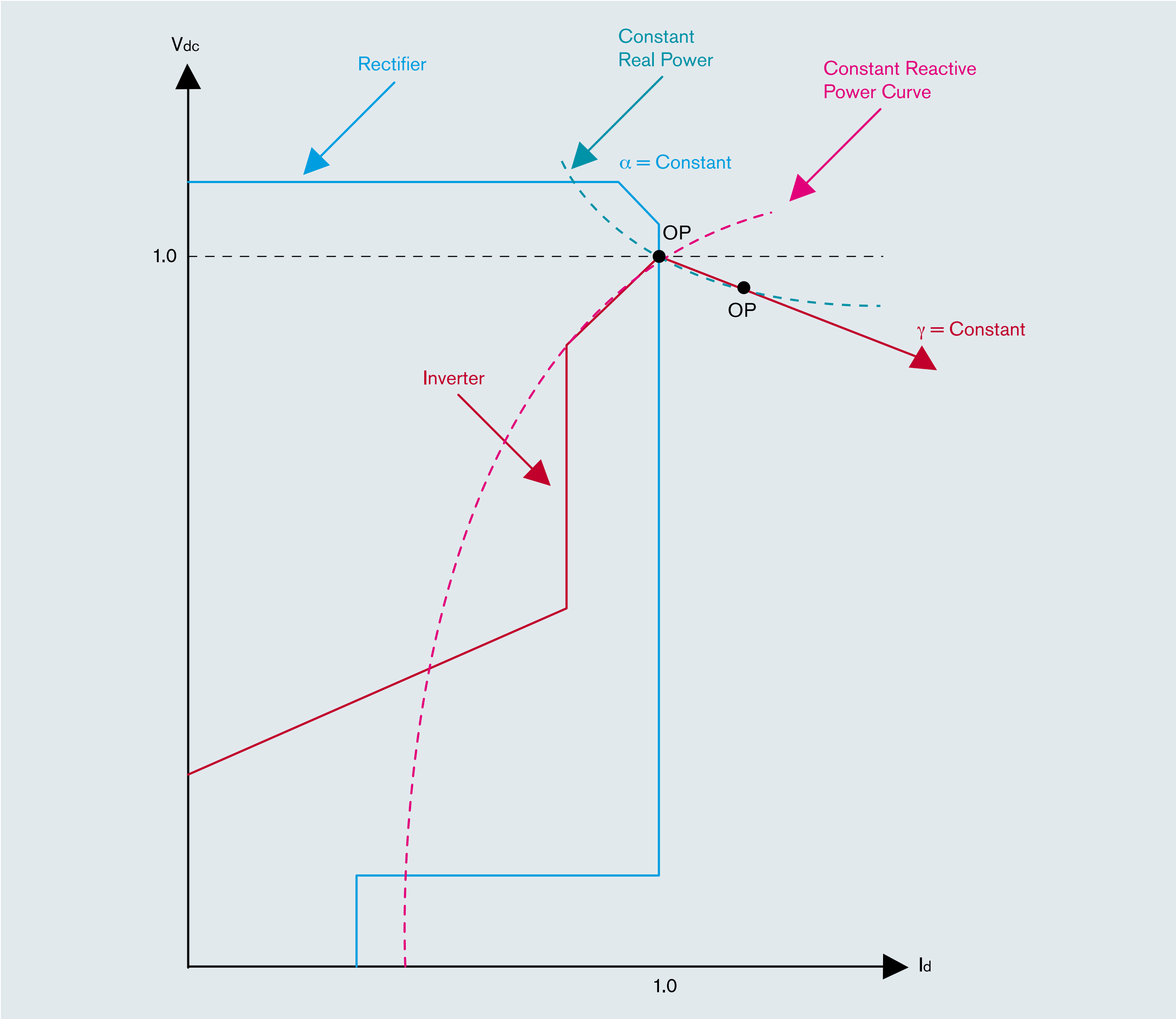


Figure 8.6: Constant Real and Reactive Power Characteristics Superimposed on the Static Characteristics

9 REACTIVE POWER IN AC SYSTEMS

Reactive power is inherent within all AC power systems. It is a quantity that results from the stray capacitance and inductance within all elements of the power system. Its effect is to shift, in phase, the current AC waveform with respect to the voltage AC waveform hence reducing the instantaneous value of voltage multiplied by current. In order to assess the effect of this phase shift, the AC power is considered as two components; the “Real” power which results from the in-phase component of voltage and current and the out-of-phase component of voltage and current which is referred to as “Reactive” power.

Reactive power can either be leading, that is the current waveform is phase advanced with respect to the voltage waveform, or lagging, that is the current waveform is phase delayed with respect to the voltage waveform. In HVDC systems, 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. Hence, reactive power resulting from capacitance is generated and reactive power resulting from inductance and from the converter is absorbed.

An AC network is composed of generators, VAr compensators, transmission lines and various inductive and capacitive loads. Reactive power flow through the AC system results in voltage variation between busbars. When any additional reactive power source or load is connected to a busbar within the AC system, the variation in voltage at both that busbar and interconnected busbars should still be maintained within the steady-state limits. Therefore, there is always a limit to the reactive power that can be connected to a busbar.

10 THE REACTIVE POWER LOAD OF A CONVERTER

Converters are a reactive power load as they operate 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) introduces an additional lag in the current 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:

$$\mu = \cos^{-1}\left[\cos(\delta) - \frac{Id}{Id_o} \times \chi_p\right] - \delta$$

μ = the converter overlap angle (rad),
Id = converter DC operating current (pu),
Id_o = rated converter DC operating current (pu),
χ_p = converter transformer leakage reactance (pu),
δ = converter control angle,
= alpha (α) for rectifier operation (rad),
= gamma (γ) for inverter operation (rad).

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

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

Hence the reactive power absorption is approximately:

$$Qdc = \tan[\cos^{-1}(\phi)] \times Pdc$$

Where:
Qdc = the reactive power absorption of the converter (pu),
$\cos\phi$ = the power factor of the converter (°),
Pdc = the real power of the converter station (pu).

The reactive power absorption of a converter at rated load can be approximated as follows:

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

Where:
Qdc_0 = the reactive power absorption of the converter at rated DC current (pu).

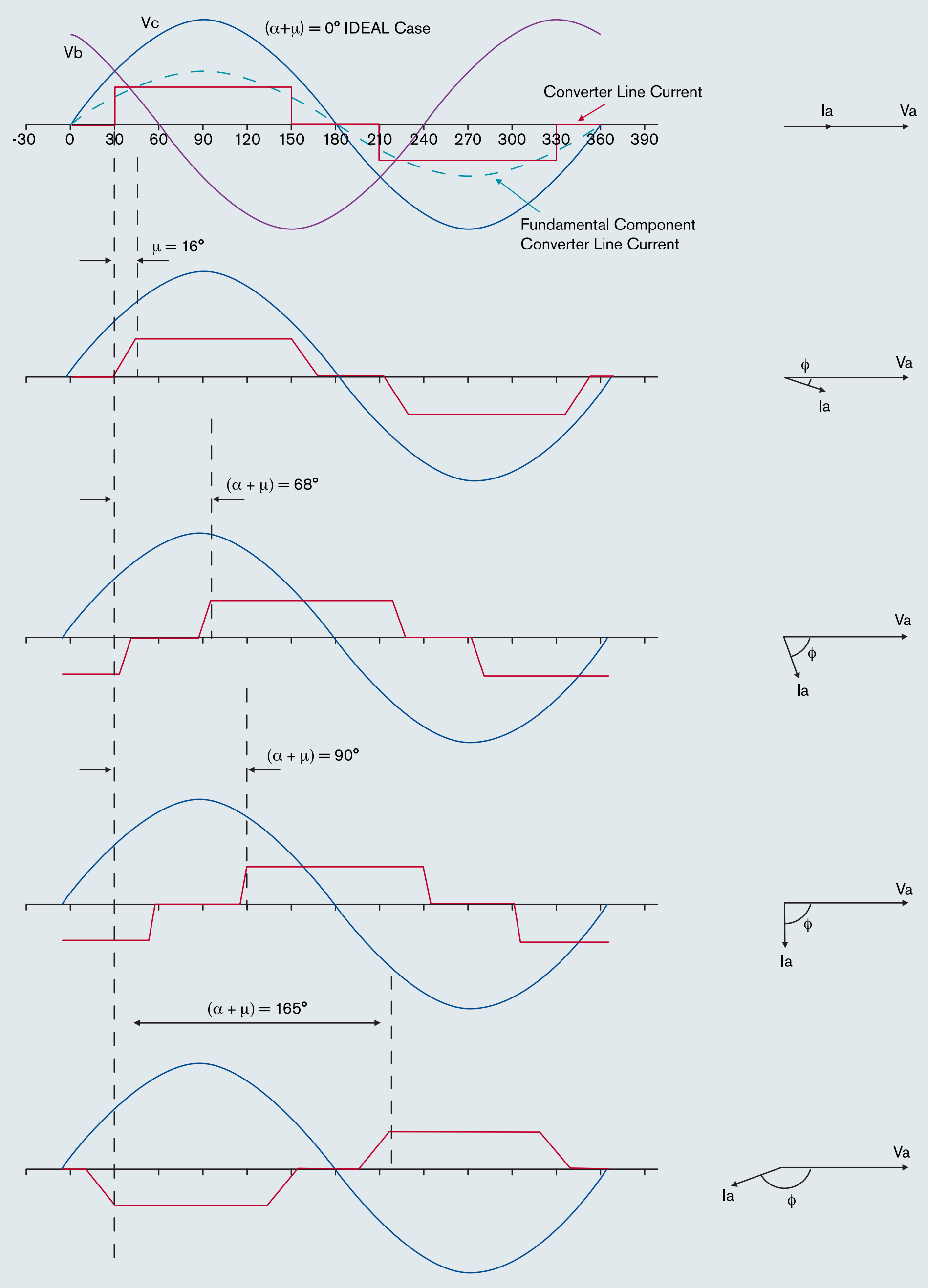


Figure 10.1: Lagging Currents in a Rectifier and an Inverter

11 REACTIVE POWER SOURCES WITHIN A CONVERTER STATION

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

Lindome AC Filters

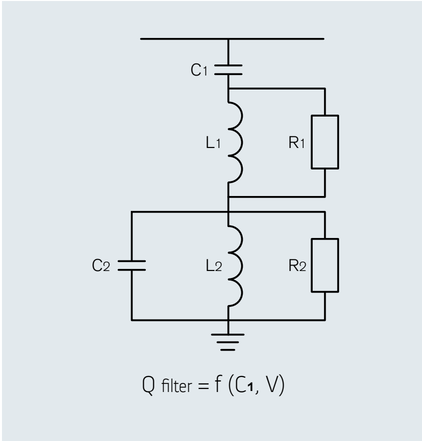


Figure 11.1: The Single Line Diagram of a typical AC Harmonic Filter

12 CONTROLLING CONVERTER REACTIVE POWER

In order to meet the AC harmonic performance, each filter has to be switched in at a certain DC power transmission level. This is known as “open-loop” control, as shown in Figure 12.1. These points are determined from AC harmonic studies.

Control action on the converter can be used to modify the reactive power exchange with the AC system. In a HVDC scheme, the DC power is defined as:

DC Power = DC Voltage x DC Current

Hence, for a given DC power level the voltage can be reduced and the current proportionately increased at the expense of additional I^2R transmission losses. Therefore, if the number of filters energised to meet AC harmonic filter performance exceeds the reactive power exchange limits, the converter operating conditions can be changed to increase the reactive power absorbed by the converter in order to achieve the desired exchange target between the converter station and the AC system.

The change in DC conditions is achieved by lowering the DC voltage which requires the firing delay angle to be increased and with an increase in DC current, to maintain the DC power constant, the overlap angle increases, hence the reactive power absorbed by the converter increases. It must be noted that, as the DC side of the converter is common to the rectifier and inverter, changing the DC conditions will reduce, or increase, the reactive power load at both rectifier and inverter together. Figure 12.2 shows a typical operating range for the DC voltage on a back-to-back HVDC converter.

In Figure 12.2 the upper limit is defined by the minimum allowable operating angles of the converter whilst the lower limit is defined by the maximum voltage transient that can be applied to the converter resulting from the firing voltage of a rectifier or recovery voltage of an inverter.

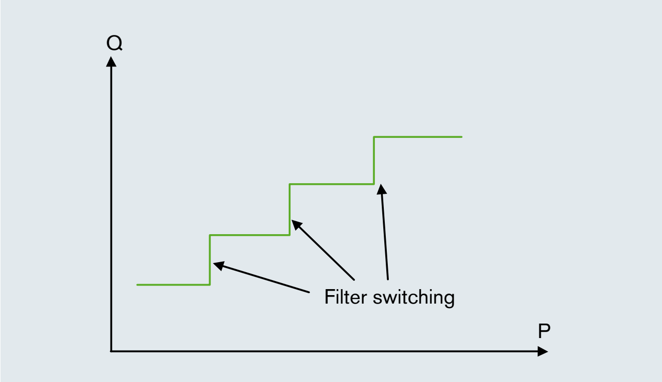


Figure 12.1: Filters Switched with Changing DC Power

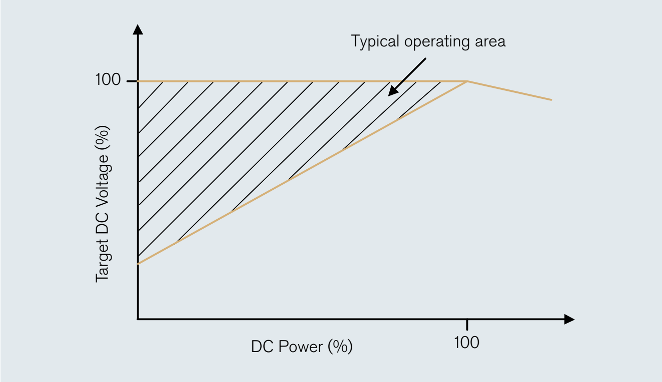


Figure 12.2: Typical Operating Range of DC Voltage on a Back-to-Back Scheme

13 VOLTAGE STEP CHANGES

Another requirement imposed on reactive power control is that of not exceeding a specified AC voltage step change as a consequence of switching a filter bank (or any reactive power element). As an approximation, the magnitude of a voltage step change, as a consequence of switching a filter, can be approximated as:

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

Where:

ΔV = the change in AC voltage (p.u.)

SCL_{min} = the minimum Short Circuit Level of the AC system 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 exceeds a defined 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 achieved through converter action by applying a fast change to the DC voltage whilst maintaining the DC power as discussed in Section 12 above. As an example, consider switching in a filter onto an AC system that has a fundamental frequency VAr rating, which would exceed 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 hence the step change in AC voltage.

14 EFFECTS OF HARMONICS IN AC POWER SYSTEMS

Harmonics within a power system are defined as the modulation of the voltage or current at an integer multiple of the fundamental frequency. Hence, for example, on a 50 Hz system, the presence of 5th harmonic voltage means that there is an additional 250 Hz component added to the voltage waveform which will distort the voltage waveform as shown in Figure 14.1.

The presence of harmonics in the power system can result in some undesirable effects on connected power system equipment, for example, the presence of harmonics can result in:

- Overheating of capacitor banks
- Overheating of generators
- Instability of power electronic devices
- Interference with communication systems

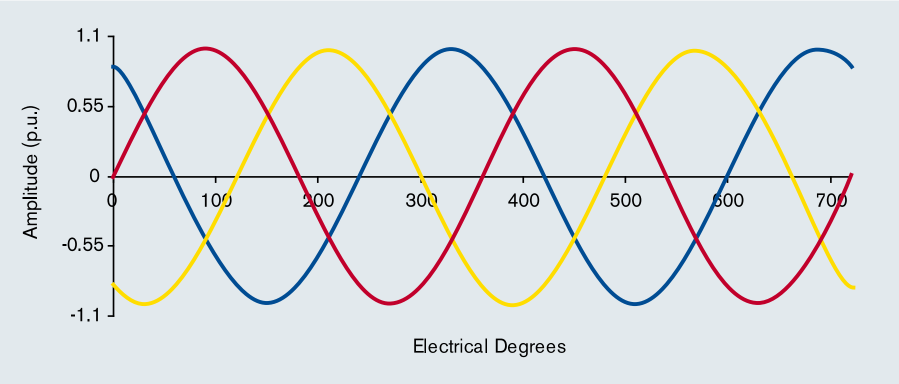


Figure 14.1 (a): Three-Phase fundamental frequency sine wave

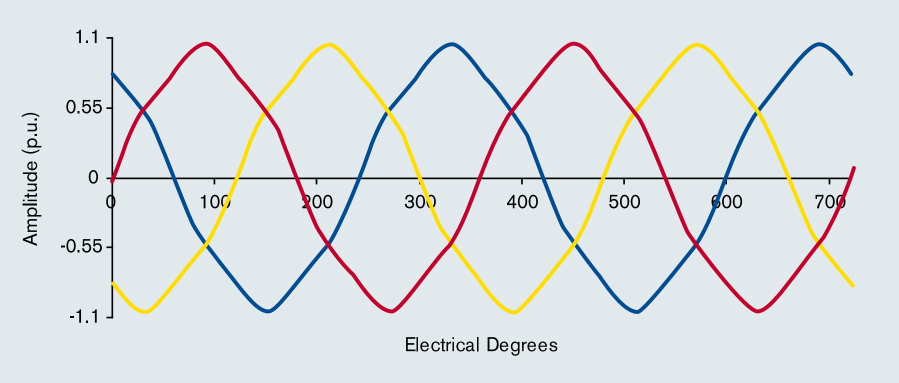


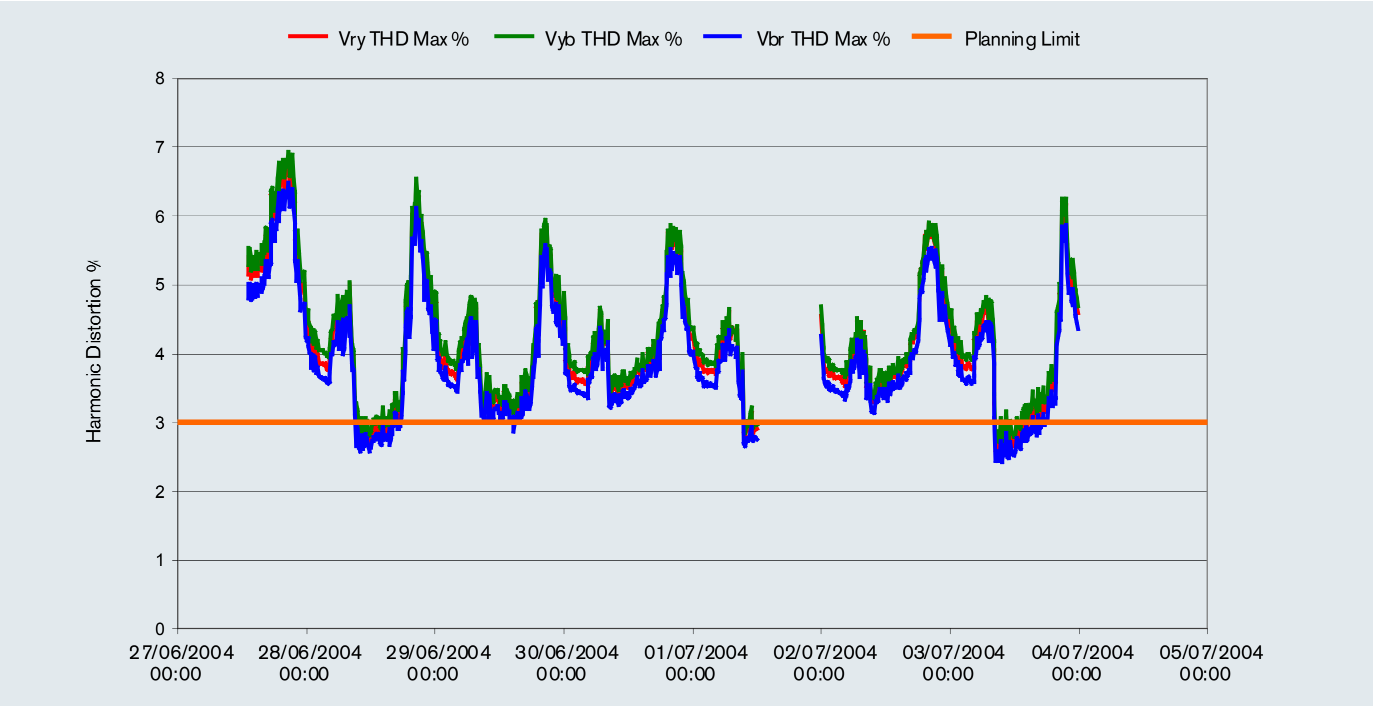
Figure 14.1 (b): Example of 5% 5th Harmonic Distortion on a Three-Phase AC Waveform

15 SOURCES OF HARMONICS IN AC POWER SYSTEMS

All equipment that includes a non-linear element and is connected to a power system can result in the generation of harmonics as a consequence of either its design or its operation. Examples of harmonics sources within a Power System are:

- Power converters (HVDC, SVC, drives)
- Domestic electronics (television, video, personal computers, etc.)
- Non-linear devices
  - Transformers
  - Voltage limiters
- Fluorescent lights
- Rotating Machines
- PWM converters

Figure 15.1: An example of excessive background harmonic distortion on an 11 kV network



16 HOW CONVERTERS CAUSE HARMONICS

The AC/DC converter is a source of harmonics. This is because the converter only connects the supply to the load for a controlled period of a fundamental frequency cycle and hence the current drawn from the supply is not sinusoidal. Seen from the AC side, a converter can be considered as a generator of current harmonics (Figure 16.1), and from the DC side a generator of voltage harmonics (Figure 16.2). The actual level of harmonics generated by an AC/DC converter is a function of the duration over which a particular phase is required to provide unidirectional current to the load. Hence, the higher the "pulse number" of the converter, 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.

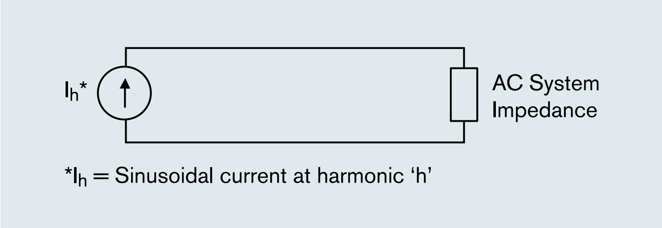


Figure 16.1: AC/DC converter represented as AC harmonic current source on AC side

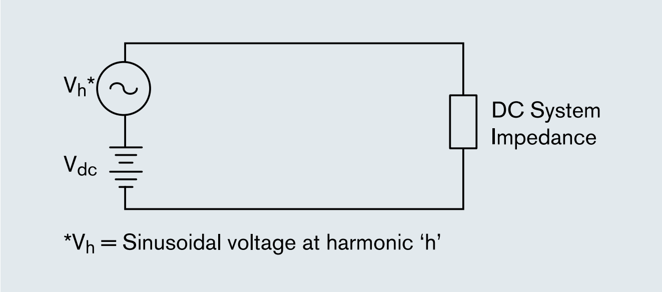


Figure 16.2: AC/DC converter represented as AC harmonic voltage source on DC side

17 PULSE NUMBER AND HARMONIC CANCELLATION

The main components of a typical HVDC converter terminal are shown in Figure 17.1. The action of the thyristor sequential switching results in current waveforms in the line side of the transformer which consists of ”blocks” of current as shown in Figure 17.2.

If a Fourier analysis is performed on the idealised waveforms shown in Figure 17.2, the following results are obtained:

1)
Y/Y

$$I = \frac{2 \times \sqrt{3}}{\pi} \times I_d \times \left[\cos \omega t - \frac{1}{5} \cos 5\,\omega t + \frac{1}{7} \cos 7\,\omega t - \frac{1}{11} \cos 11\,\omega t + \frac{1}{13} \cos 13\,\omega t \ldots \right]$$

2)
Y/Δ

$$I = \frac{2 \times \sqrt{3}}{\pi} \times I_d \times \left[\cos \omega t + \frac{1}{5} \cos 5\,\omega t - \frac{1}{7} \cos 7\,\omega t - \frac{1}{11} \cos 11\,\omega t + \frac{1}{13} \cos 13\,\omega t \ldots \right]$$

It can be seen from equations (1) and (2) that each six-pulse bridge generates harmonic orders $6n \pm 1$, $n = 1, 2, 3 \ldots$, there are no triplen harmonics (3rd, 6th, 9th...) present and that for $n = 1, 3$, etc., the harmonics are phase shifted by 180°. The idealised magnitudes of the six-pulse harmonics are shown in Table 17.

By combining two six-pulse bridges with a 30° phase shift between them, i.e. by using Y/Y and Y/Δ transformers as shown in Figure 17.1 and summating equations (1) and (2), a twelve-pulse bridge is obtained. The idealised magnitudes of the twelve-pulse harmonics are shown in Table 17.2.

The current waveforms shown in Figure 17.3 appear in the common connection to the transformers shown in Figure 17.1.

If a Fourier analysis is performed on this idealised waveform, the following result is obtained:

3)

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

Thus, in a twelve-pulse bridge, the harmonic orders $6n \pm 1$, $n = 1, 3, 5$ ... are effectively cancelled in the common supply leaving only the characteristic twelve-pulse harmonics

i.e. $12n \pm 1$, $n = 1, 2, 3$, ...

The idealised waveforms shown above will, in reality, be modified by the reactance of the supply system (mainly the transformer reactance). Due to this commutating reactance, the harmonic current magnitudes are reduced compared to those applicable to pure square wave pulses.

The equations given above are based on the assumptions that, firstly, the DC current is linear, that is, the DC reactor is infinite and, secondly, the AC system voltage waveforms are sinusoidal. Because both of these assumptions are not valid for practical systems, more complex calculations are necessary and purpose built computer programs are used.

The usual published formulae and graphs for these currents give magnitudes only. For special purposes (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 required.

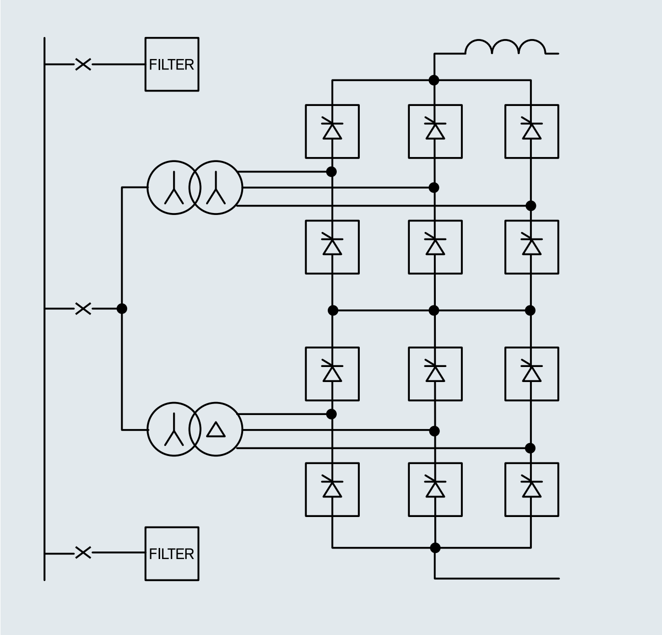


Figure 17.1: A typical twelve-pulse converter bridge

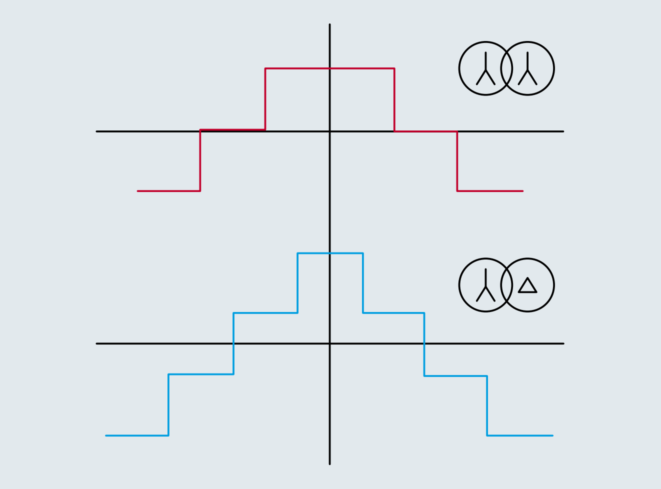


Figure 17.2: Idealized line winding currents in a Twelve-Pulse Bridge

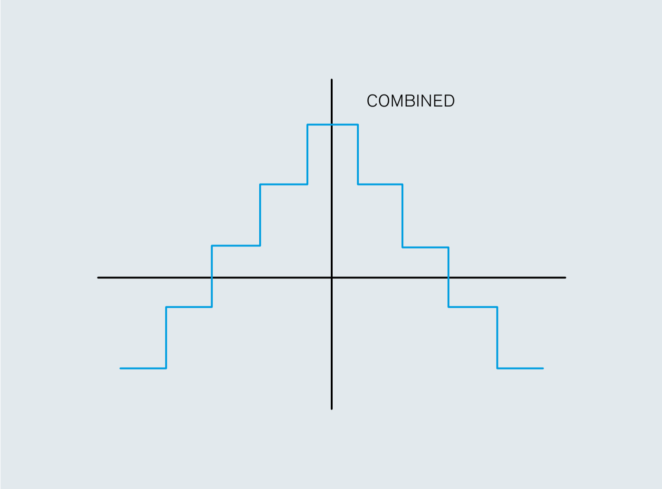


Figure 17.3: Idealized Waveform of the AC Supply Current of a Twelve-Pulse Bridge

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

Table 17.1: Idealized Harmonic Magnitudes in a Six-Pulse Bridge

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

Table 17.2: Idealized Harmonic Magnitudes in a Twelve-Pulse Bridge

18 DC HARMONICS

The idealised voltage across an unloaded six-pulse converter is shown in Figure 18.1, and the idealised voltage across a twelve-pulse converter is shown in Figure 18.2. The voltage is a mix of a direct voltage and harmonics. Table 18.1 shows the harmonics on the DC side produced by a six-pulse converter.

No-Load DC (Vd0)	**(DC)**	**1.0000**
6th	(300 Hz)	0.0404
12th	(600 Hz)	0.0099
18th	(900 Hz)	0.0044
24th	(1200 Hz)	0.0025

Table 18.1: Idealized DC Voltage Harmonics (RMS) at the Terminals of a Six-Pulse Bridge

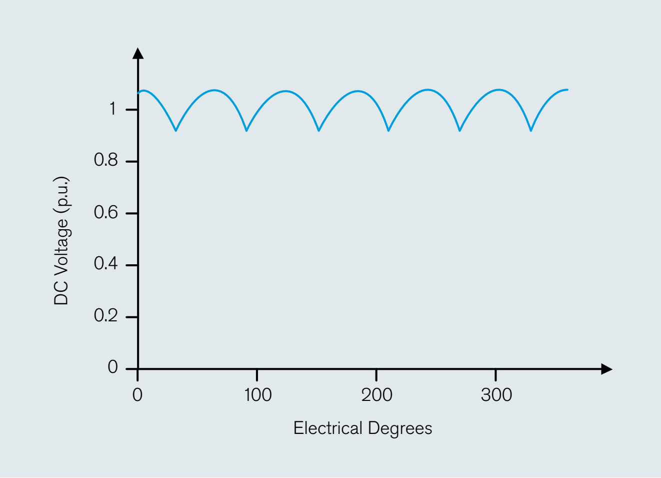


Figure 18.1: The Idealized Voltage Across the DC Terminals of a Six-Pulse Bridge at no-load

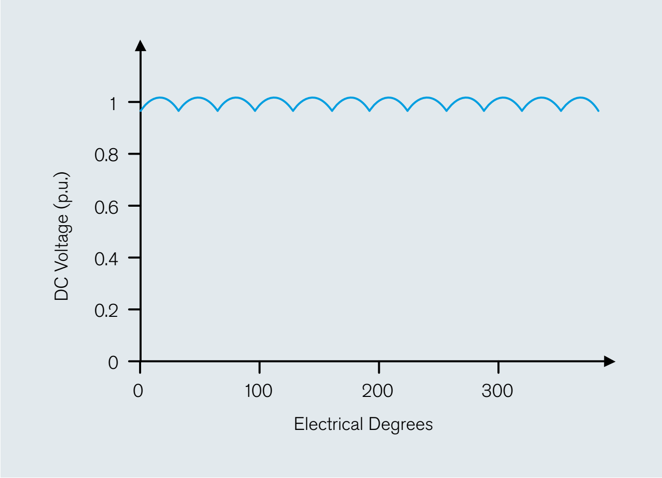


Figure 18.2: The idealized voltage across the DC Terminals of a Twelve-Pulse Bridge at no-load

19 CHARACTERISTIC AND NON-CHARACTERISTIC HARMONICS

The harmonic currents derived from the examination of the ideal converter, as described in Section 17, are known as the "characteristic harmonics" of a converter. However, a practical converter can cause other harmonic currents to be generated which result from non-ideal operating conditions. These harmonics are referred to as "non-characteristic harmonics". Non-characteristic harmonics can result from several sources; unbalance or "negative phase sequence" in the supply AC system will result in the generation of 2nd harmonic voltage on the DC side by the converter; a harmonic not predicted by the 6n or 12n analysis described previously will give rise to 3rd harmonic current being injected back into the AC system by the converter. Unbalance between the converter transformer leakage reactances for the Y and Δ bridges will result in a small amount of each of the classical harmonics – which should have been completely cancelled – still being present in the AC side current. Stray capacitance which is inherent in, for example, the converter transformer valve winding bushings will provide a stray path within the converter for harmonic currents to flow leading to the generation of triplen harmonics such as, 3rd, 9th and 15th on the DC side and ±1 of these harmonic numbers on the AC side. Also, minor control inaccuracies within the converter controller resulting in the firing instance between valves of a bridge not being perfectly symmetrical (the error is much less than 0.1° electrical) will cause the generation of harmonics at all multiples of n on both the AC and DC side of the converter.

19.1 Cross-Modulation Harmonics

In addition to the characteristic and non-characteristic harmonics which can be generated by a converter, there is a third type of harmonic referred to as cross-modulation harmonics. These harmonics result from the fact that in any HVDC link the DC current is never perfectly smooth. This is particularly true in the case of a back-to-back converter where there is little or no impedance between the two converters and, in most cases, it is impractical to install sufficient inductance between the converters to make a significant impact on the interaction between them.

In most cases, the AC connection of one converter is remote, or even isolated from that of the other converter. Therefore, even where the two AC systems interconnected by the DC link are nominally at the same AC frequency (50 Hz or 60 Hz), the actual operating frequencies may be slightly different and hence the harmonic AC side currents and DC side voltages generated by the converters, which are a multiple of the applied AC system frequency, will be at different frequencies. In the case where the two AC interconnected systems operate at different AC frequencies, for example one at 50 Hz and one at 60 Hz, then the difference in the harmonics generated by the converters will be larger. The actual DC sides of the converters are connected together and hence the harmonic voltage distortion caused by one converter will be applied to the DC terminals of the other converter and vice versa. These harmonic voltage distortions will cause a distortion in the circulating DC current which will cause harmonics to be generated in each converter that are a multiple of the other converter's AC system frequency and not of its own. For example, the 60 Hz converter will have AC current harmonics corresponding to 11th and 13th harmonic at 660 Hz and 780 Hz respectively and a corresponding DC side harmonic at 720 Hz. However, this 720 Hz distortion will result in 660 Hz and 780 Hz components in the AC current harmonics of the 50 Hz connected converter. Neither of these frequencies are an integer multiple of 50 Hz and, as a consequence, non-integer harmonics are produced.

20 HARMONIC FILTER DESIGN, TYPES OF FILTERS

The AC side current waveform of a HVDC converter, as already discussed previously, is highly non-sinusoidal, and, if allowed to flow in the connected AC network, might produce unacceptable levels of distortion. AC side filters are therefore required as part of the total HVDC converter station in order to reduce the harmonic distortion of the AC side current and voltage to acceptably low levels.

HVDC converters also consume substantial reactive power, a large proportion of which must normally be supplied locally within the converter station. Shunt-connected AC filters appear as capacitive sources of reactive power at fundamental frequency, and normally in conventional HVDC schemes the AC filters are used to compensate most or all of the reactive consumption of the converter. Additional shunt capacitors and reactors and occasionally Static VAr Compensators (SVCs), Static Compensators. (STATCOMs) or synchronous compensators, may also be used to ensure that the desired reactive balance is maintained within specified limits under defined operational conditions.

The design of the AC filters, therefore, normally has to satisfy these two requirements of harmonic filtering and reactive power compensation, for various operational states and load levels.

20.1 Filter Circuit Configurations

There are various possible circuit configurations that can prove suitable for AC side filters on HVDC converter stations. This section reviews these designs to give background information on the advantages and disadvantages of particular filter types.

Only shunt-connected filters are considered in this section. The comments on particular filter designs apply to HV- and EHV-connected filters and equally to MV-connected filters, e.g. tertiary-connected filters.

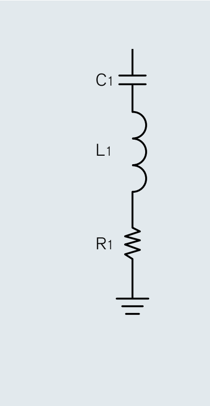


Figure 20.1: Single-Tuned Band-Pass Filter Circuit

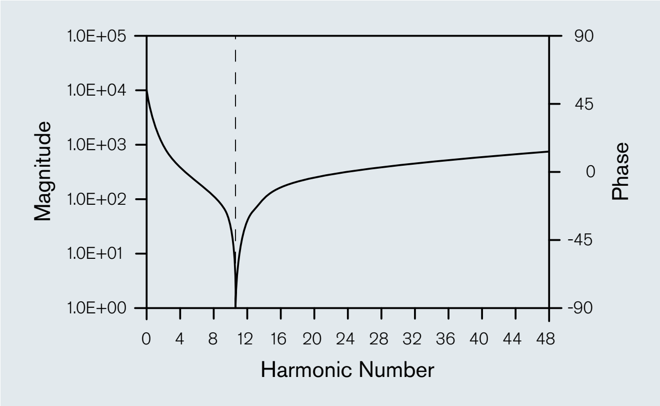


Figure 20.2: Single-Tuned Band-Pass Filter - Impedance Characteristic

The choice of the optimum filter solution is the responsibility of the contractor and will differ from project to project. The design will be influenced by a number of factors that may be specified by the customer:

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

Different filter configurations will possess certain advantages and disadvantages when considering the above factors. As only the filter design and performance aspects are considered, additional equipment such as surge arresters, current transformers and voltage transformers are omitted from the circuits shown. In HV and EHV applications, surge arresters are normally used within the filters to grade the insulation levels of the equipment.

20.2 Advantages and Disadvantages of Typical Filters

Two main filter types are used today:

- The tuned filter or band-pass filter which is sharply tuned to one or several harmonic frequencies.

These are filters tuned to a specific frequency, or frequencies. They are characterised by a relatively high q (quality) factor, i.e. they have low damping. The resistance of the filter may be 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 is of high value. Examples of tuned filters include single (e.g. 11th) double (e.g. 11/13th) and triple (e.g. 3/11/13th) tuned types

- The damped filter or high-pass filter offering a low impedance over a broad band of frequencies.

These are filters designed to damp more than one harmonic, for example a filter tuned at 24th harmonic will give 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 produces a damped characteristic at frequencies above the tuning frequency. Examples of damped filters include single-tuned damped high-pass (e.g. HP12) and double-frequency damped high-pass (e.g. HP 12/24).

The distinction between these two filter types may sometimes be almost lost depending on the choice of q-value for different filter frequencies.

For a HVDC scheme with a twelve-pulse converter, the largest 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 generally twice as high as for the rest of the harmonics, a common practice is to provide 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 possible low-order resonance between the AC network and the filters and shunt banks. When a big HVDC scheme is to be installed in a weak AC system, a low-order harmonic filter (most often tuned to 3rd harmonic) may be also needed.

20.3 Band-Pass Filter

A band-pass filter consists of an LC series resonance circuit as shown in Figure 20.1. Figure 20.2 shows the impedance magnitude and phase of a band-pass filter.

The advantages and the disadvantages of a single-tuned band-pass filter are as follows:

Advantages:

- Simple connection with only two components,
- Optimum damping for one harmonic,
- Low losses,
- Low maintenance requirements.

Disadvantages:

- Multiple filter branches may be needed for different harmonics,
- Sensitive to detuning effects,
- May require possibility of adjusting reactors or capacitors.

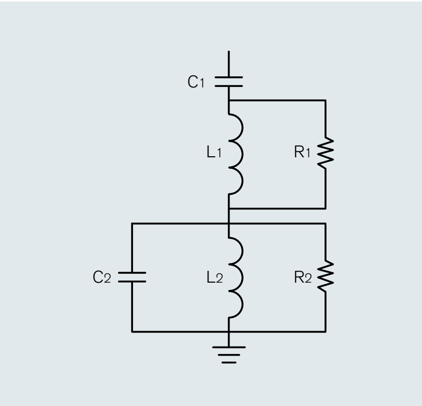


Figure 20.3: Double-Tuned Band-Pass Filter - circuit

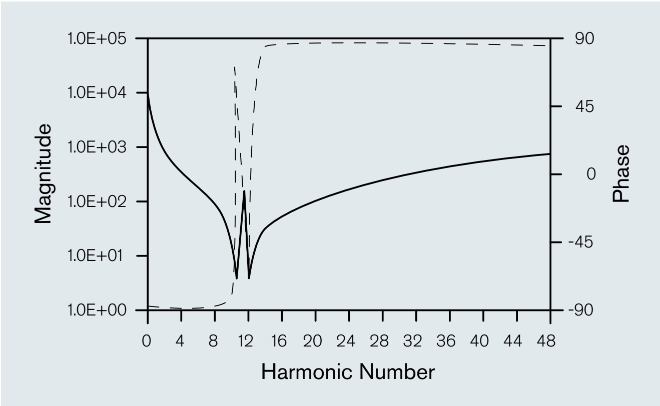


Figure 20.4: Double-Tuned Band-Pass Filter - Impedance Characteristic

20.4 Double-Tuned Band-Pass Filter

A double-tuned band-pass filter has the equivalent function of two single-tuned filters. Its configuration is shown in Figure 20.3, and its impedance plot in Figure 20.4.

The advantages and the disadvantages of a double-tuned band-pass filter are as follows:

Advantages:

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

Disadvantages:

- Sensitive to detuning effects,
- May require possibility of adjusting reactors or capacitors,
- Complex interconnection, with 4 or 5 C-L-R components,
- Requires two arresters to control insulation levels.

20.5 Triple-tuned band-pass filter

This type of filter is electrically equivalent to three parallel-connected tuned filters, but is implemented as a single combined filter. Figure 20.5 shows the circuit arrangement and Figure 20.6 the impedance/frequency response for a typical triple-tuned filter.

The use of triple-tuned filters could improve the operational requirements for reactive power control. This would be of particular importance at low-load conditions if a 3rd harmonic filter is needed in the circuit from the beginning. As they are similar in nature to double-tuned filters, their merits and drawbacks are as described in section 20.2 above.

For each of the above arrangements, sensitivity to detuning has been identified as a disadvantage. However, with the addition of resistors (and hence additional losses) to make the filter arrangement damped as discussed in section 20.2, this detuning can be mitigated.

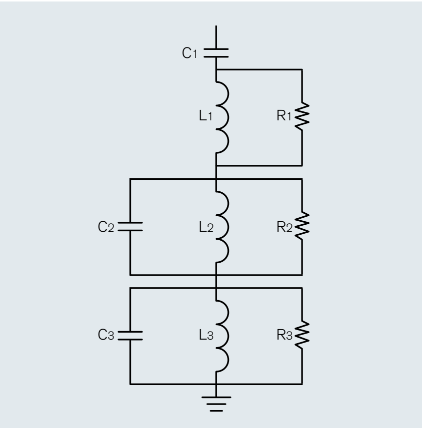


Figure 20.5: Triple-Tuned Band-Pass Filter - Circuit

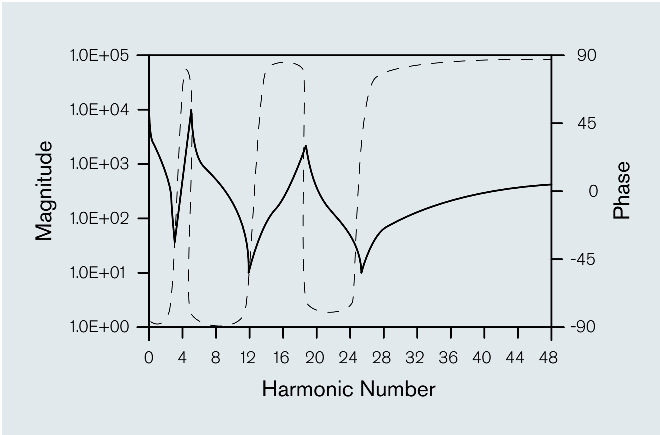


Figure 20.6: Triple-Tuned Band-Pass Filter Tuned to 3rd, 11th and 24th Harmonic - Impedance Characteristic

21 AC HARMONIC PERFORMANCE AND RATING CALCULATIONS

The basis of harmonic distortion and filter performance calculations can be explained with reference to Figure 21.1.

I_n = harmonic currents from the converter
I_{fn} = harmonic currents in the filter
I_{sn} = harmonic currents entering the supply system
Z_{fn} = harmonic impedance of the filter
Z_{sn} = harmonic impedance of the AC system

The current and voltage distortion can be calculated from the following expressions:

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

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

In order to calculate harmonic performance and design the filters (i.e. Z_{fn}), it is essential that detailed information be available on the harmonic currents generated by the HVDC converter (I_n) and the harmonic impedance of the supply system (Z_{sn}).

21.1 Harmonic Impedance of the Supply System

In order to accurately assess voltage and current distortion, it is essential that the impedance of the supply system be known at each harmonic of interest. This is a topic that is often poorly defined or understood. However, a lack of knowledge of the system harmonic impedance could lead to an uneconomic filter design, or a filter that will not adequately attenuate harmonics.

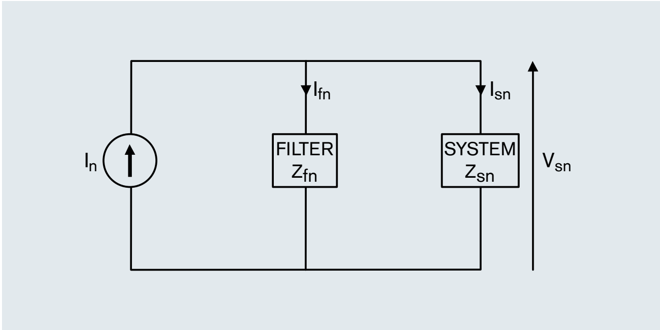


Figure 21.1: Circuit Analysis for AC Filter Performance Evaluation

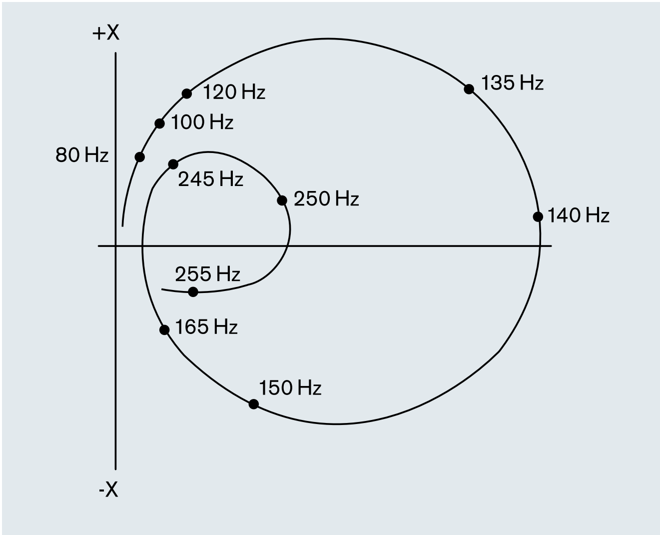


Figure 21.2: Typical Supply Network Impedance Diagram

There are several methods of modelling the system impedance:

21.2 Impedance Circle Method

In a supply system with significant shunt capacitance, the impedance of the system can appear either inductive ($R + jX_L$) or capacitive ($R - jX_C$) at the Point of Common Coupling (pcc) at harmonic frequencies. Inevitably, resonances will occur when the inductive (X_L) and capacitive ($-X_C$) components are equal and only the resistance component (R) remains. Figure 21.2 shows a typical impedance locus of a supply system as the frequency changes from 50 Hz to about 255 Hz.

In this example, the system appears inductive at 100 Hz, but capacitive at 150 Hz with a resonance close to 140 Hz. Further resonances occur below 245 Hz and above 250 Hz. The system impedance can change very rapidly for small changes in frequency.

The above locus applies to only one system configuration; with different generation, load or line outage conditions, further impedance loci would occur. In order to ensure that the system harmonic impedance (Z_{sn}) used in filter design calculations is applicable to all present and future system configurations, a circle is normally drawn which encloses all of the calculated loci. An example of such a circle is shown in Figure 21.3.

When performing filter design studies, the system impedance is taken to be any value within the circle which results in the largest harmonic distortion (i.e. V_{sn} or I_{sn}). Computer maximisation routines are used to search for the impedance area at each harmonic. In order to reflect the practical reality of system impedance, limitations to the search area are normally specified. Limit lines of angles ϕ_1, ϕ_2 (typically 75° - 85°) are commonly used, and minimum values of R may be specified.

This method is safe as it inherently caters to system changes and future requirements. However, it is also pessimistic as each harmonic, particularly at low orders, which will only vary within a limited range, and not within a large circle. The use of this approach may result in an over-designed and expensive filter.

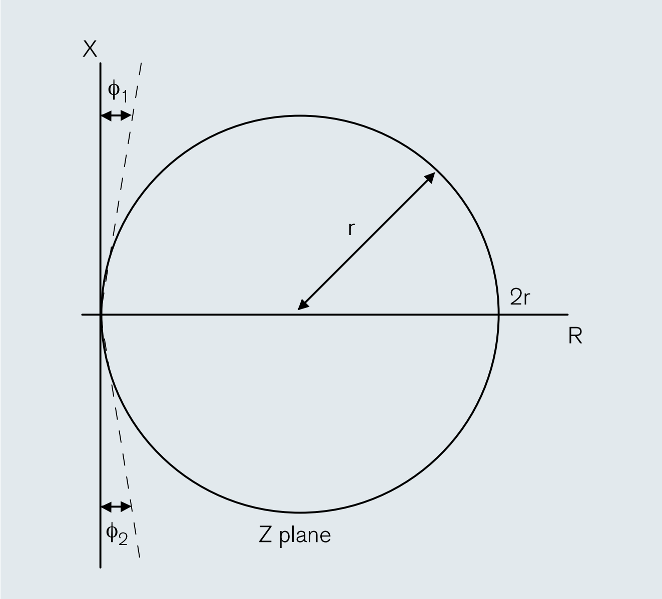


Figure 21.3: AC Network Impedance

21.3 Polygon Method

At each harmonic, the system will have a discrete value of impedance corresponding to different configurations. Therefore at each harmonic the system impedance can be defined by a polygon which encompasses all of the calculated discrete harmonics. Such a polygon is shown in Figure 21.4.

The computer maximisation routine searches each defined polygon at each harmonic to calculate the largest harmonic distortion (Vsn or Isn).

This method gives a realistic assessment of the system impedances, and avoids any problems of over-designing the filter.

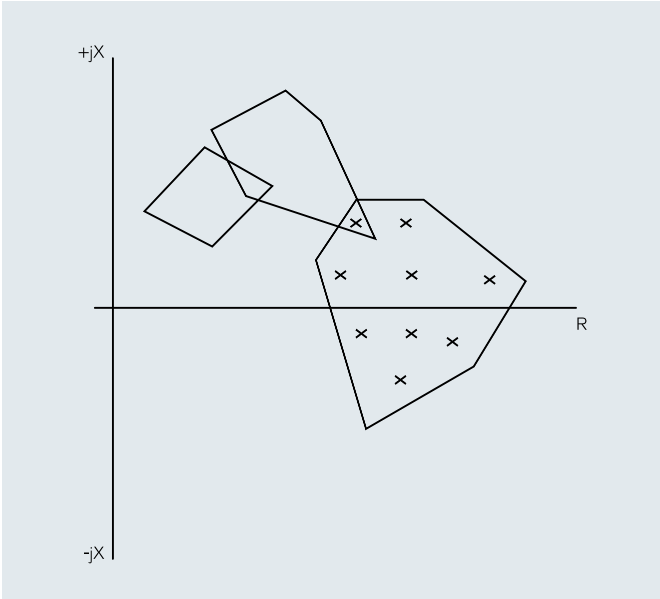


Figure 21.4: Impedance Polygon

22 DC HARMONIC PERFORMANCE AND RATING CALCULATIONS

The DC side harmonic performance of a HVDC scheme is, in some respects, simpler to calculate than that of the AC side. Comparison of Figure 21.1 to Figure 22.1 shows that the basic analysis circuit is similar. However, unlike the AC system, which can exist in many different states (that is, different configurations of transmission lines, loads, generation, etc) the DC system is a defined system with few possible changes in configuration. Figure 22.2 shows a sample frequency versus impedance plot for an overhead transmission line.

The normal performance assessment method of an overhead DC transmission line is based on induced current, that is, the current that would flow in a conductor parallel to the DC line. The higher the earth impedance, the higher the induced currents in a parallel line, as this parallel line will present a viable current return path. Conversely, in areas where the earth impedance is low, the current induced in a parallel line will be low. The design and rating of the DC side filter is, therefore, influenced by the earth conditions associated with the DC line.

When operating in balanced bipole mode, the harmonic currents will flow 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 equal and opposite to that in the other (assuming that both poles are operating identically, that is, at the same DC voltage, DC current, measurement errors, tolerances, etc). Therefore, the currents induced in a parallel conductor will be reduced. Hence, typically, the worst-case DC harmonic performance and the case which defines the DC filter rating, is monopole operation.

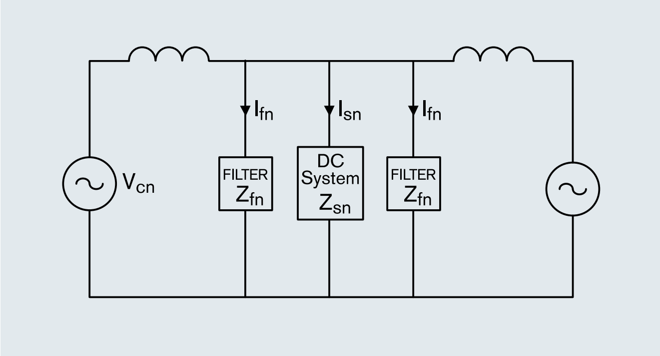


Figure 22.1: Circuit Analysis for DC Filter Performance Evaluation

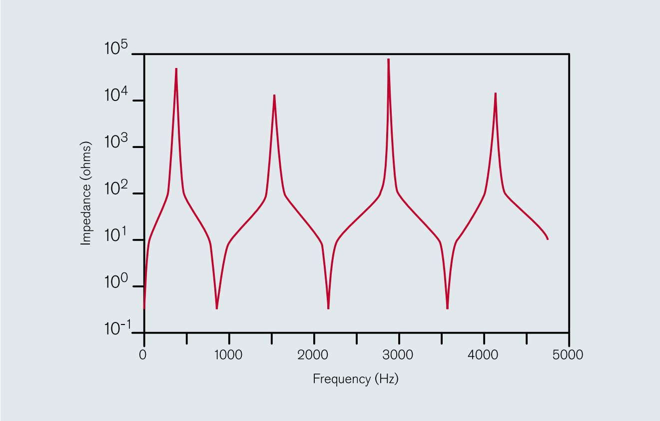


Figure 22.2: Typical HVDC Line Impedance Characteristic

An important consideration in the design of a DC filter, as opposed to an AC filter, is the main capacitor bank as, on the DC side, this will be subject to the applied DC voltage and hence the sharing of the DC voltage as well as the AC voltage must be controlled. This means that the resistive voltage distribution needs to be controlled in DC capacitors (Figure 22.3). For this reason it is common for DC filter capacitor banks to be constructed 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.

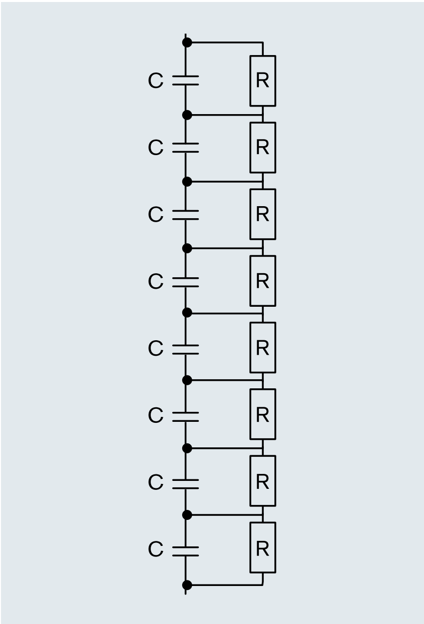


Figure 22.3: DC Filter Capacitor

23 CONTROL FACILITIES PROVIDED BY HVDC SCHEMES

The basic control parameter of a HVDC converter is the DC current which circulates between the rectifier and inverter assuming that the DC voltage is maintained at a constant value (which is typically true for DC power transmission schemes but not always true for back-to-back schemes). However, the HVDC controller can adjust the DC current flow in response to other operator-settable parameters or measured quantities providing an extremely flexible and fast part of a power system's transmission infrastructure. Typical control features provided or available as an additional feature are described below:

23.1 Power Control

The power transferred 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. Typically 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 (e.g., at the border between two countries), the inverter AC terminal or the rectifier AC terminal.

If the power demand is changed then the power order will ramp to the new power transfer level at a rate of change (known as the "ramp rate") pre-selected by the operator. Typically the maximum power limit is defined by an overload controller which is continuously calculating the thermal capability of the converter station equipment.

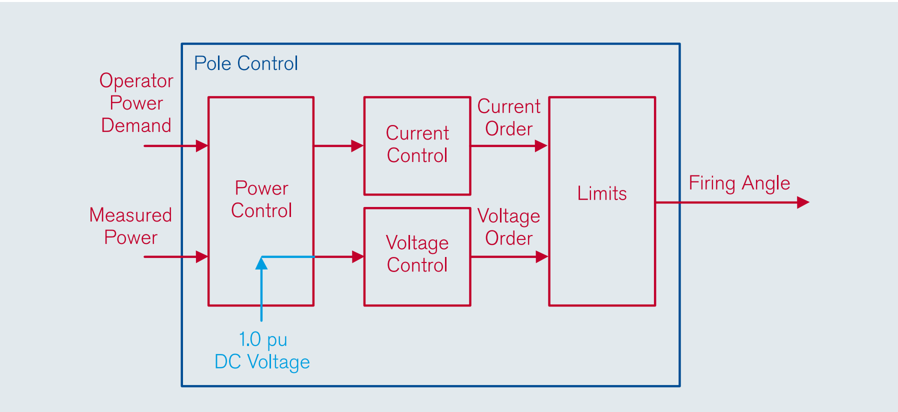


Figure 23.1: Power control

23.2 Frequency Control

A HVDC scheme can control the AC frequency of an AC system by automatically adjusting the power being delivered into that AC system in order to balance the load with the supply. The fast power control by the HVDC reduces the under-frequency or over-frequency which can result from a changing load in a small power system such as an island load.

Frequency control can also be applied as limits to the power control function. For example, the sending end can be arranged so that it will continue to supply power via the HVDC link to the receiving end as so long as the sending end AC system frequency is above some threshold value. In this way the sending end can be protected from a severe system disturbance as a consequence of a disturbance in the receiving end AC system. The controllability of a HVDC scheme is very important and is sometimes referred to as providing a “firewall”. With a power system consisting of “islands” of AC interconnected with DC, this “firewall” property of HVDC will mitigate the risk of cascading black-outs across multiple interconnected AC systems [5].

Other frequency limits can be applied, for example the receiving end AC system could have an upper frequency limit to automatically stop further increases in the power being delivered by the HVDC scheme. 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, though this can normally 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.

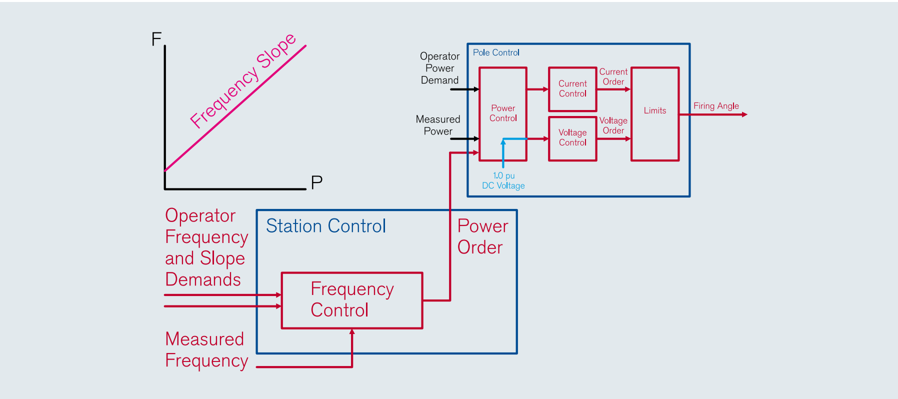


Figure 23.2: Frequency control

23.3 Power Modulation Control

The power being transferred through a HVDC link can be automatically modulated to provide damping to low-frequency power oscillations within either, or both, interconnected AC systems as determined by studies during the design phase of the HVDC scheme.

23.4 Runback/Power Demand Override (PDO)

In response to certain events, such as loss of an AC transmission line, loss of an AC generator or loss of a major load, the HVDC interconnection can be programmed to respond in a pre-defined manner. For example, if the loss of a line may result in instability within the AC system, the HVDC interconnection can be pre-programmed to reduce the power transfer at a pre-determined ramp rate to a safe value as established by contract studies. Equally, the loss of a generator can be pre-programmed to automatically increase the power flow through the HVDC interconnection.

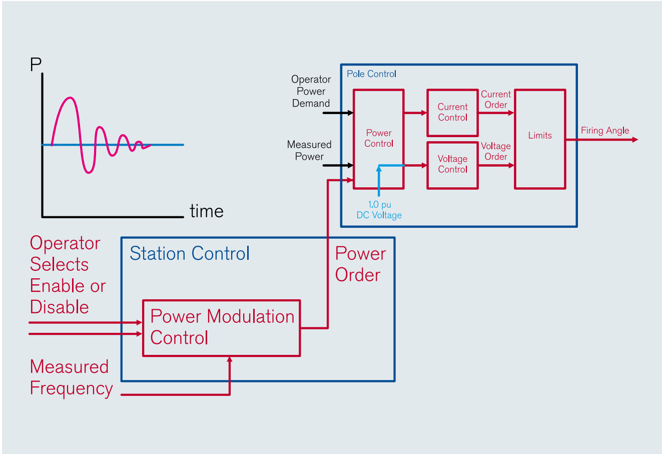


Figure 23.3: Power Modulation Control

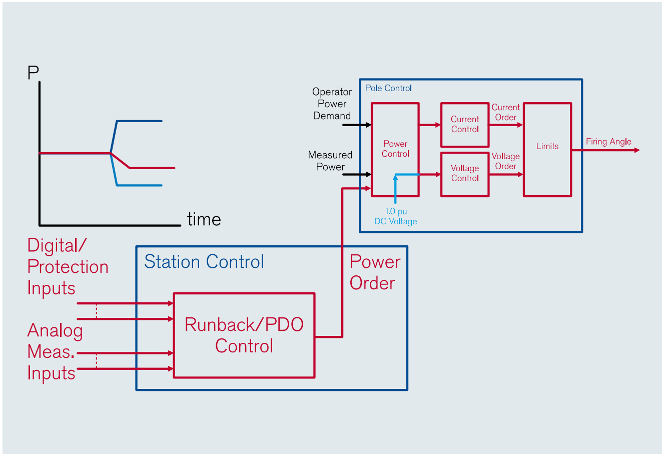


Figure 23.4: Runback/Power Demand Override (PDO)

23.5 DC Protection

A detailed description of the protections used within a HVDC station is beyond the scope of this document. However, it is worth noting that within a HVDC converter station the types of protection utilised fall into two categories:

- Conventional (AC) substation protection
- DC protection

AC connected equipment such as converter transformers and AC harmonic filter components, along with feeders and busbars, are protected using conventional AC protection relays. The converter, along with the DC circuit, is protected using hardware and software specifically purpose designed by Alstom Grid. Typical DC specific protections include:

- AC > DC
- AC Overcurrent
- DC Differential
- DC Overcurrent
- DC > AC
- AC Overvoltage
- Asymmetry
- AC Undervoltage
- Abnormal firing angle
- Low DC current
- DC Undervoltage

24 HVDC THYRISTOR VALVES

The term “valve” derives from the early days of HVDC, when mercury-arc valves were used for this function. Mercury-arc valves operated in a totally different way (being essentially vacuum tubes, hence the name “valve”) but did essentially the same job as a modern thyristor valve. Figure 24.1 shows the mercury arc valves supplied by Alstom Grid (then English Electric) for the Nelson River Bipole 1 HVDC project in Canada; these valves had the highest rating of any mercury-arc valves ever made.

When thyristors were introduced, the name “valve” was retained.

The thyristor valve is the basic component of the modern HVDC converter, whose operation is discussed in section 6.3. However, a real thyristor valve comprises many series-connected thyristors in order to provide the necessary blocking voltage capability.

Thyristors used for HVDC valves are amongst the largest semiconductors of any type produced for any industry. Figure 24.2 shows an 8.5 kV thyristor with an active silicon diameter of 115 mm (which starts life as a silicon ingot of 125 mm diameter, hence such thyristors are often referred to as “125 mm” thyristors).

Such components are expensive and there may be many thousand such components in a HVDC station. Moreover, they are quite delicate and require a great many additional components to control and protect them. In fact, although it is the most obvious component of a thyristor valve, the thyristors account for a surprisingly low percentage of the total valve cost.

Figure 24.1: Mercury-Arc Valves on the Nelson River Bipole 1 HVDC Project

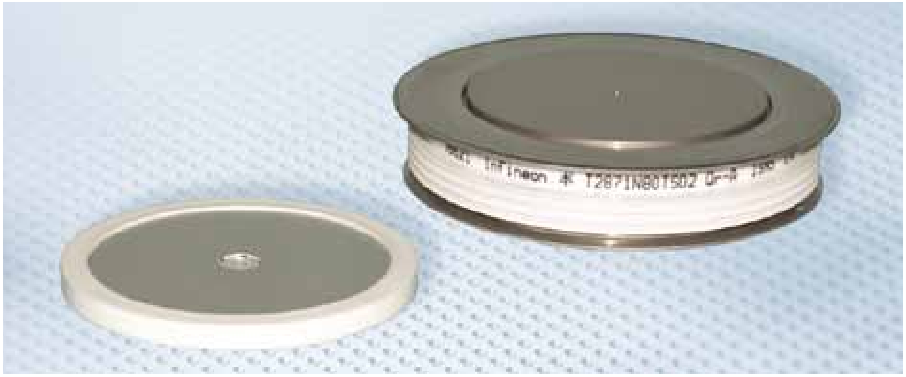


Figure 24.2: Modern 8.5 kV 125 mm Thyristor: Alloyed Silicon Slice (Left) and Complete Capsule (Right)

Modern thyristor valves are relatively standardised, that is to say that the bulk of the real design work is carried out during the product development phase, hence, applying the valves to a particular project is a relatively straightforward matter. At its simplest, the work involved for a particular project may just involve adapting the number of series-connected thyristors according to the voltage rating requirements imposed by the overall system design.

HVDC valves are almost never installed as individual units. Nearly always, several valves are combined together into a “Multiple Valve Unit”, or MVU. The MVU may either be mounted directly on the floor or, more commonly today, suspended from the ceiling. For economy of insulation, the valve design is often arranged so that the lower-voltage valves (usually those associated with the Delta-connected six-pulse bridge) are used as part of the insulation on which the higher-voltage valves (usually those associated with the star-connected bridge) are mounted. Hence the low voltage end is the end at which the valve is attached to the floor or ceiling. The valves are typically stacked vertically into ”quadrivalve” structures, with three such quadrivalves being required at each end of each pole.

Figure 24.3 shows a typical suspended MVU.

Careful attention has been paid to possible fire initiation processes within the modern thyristor valve. All components are generously rated, both thermally (to minimise the risk of overheating) and electrically (all other components in parallel with the thyristor are specified with voltage ratings in excess of those of the best thyristor which could be encountered). The damping capacitors, for example, are of oil-free construction. Hence, the potential spread of a fire throughout the valve can be virtually dismissed by the materials and components used.

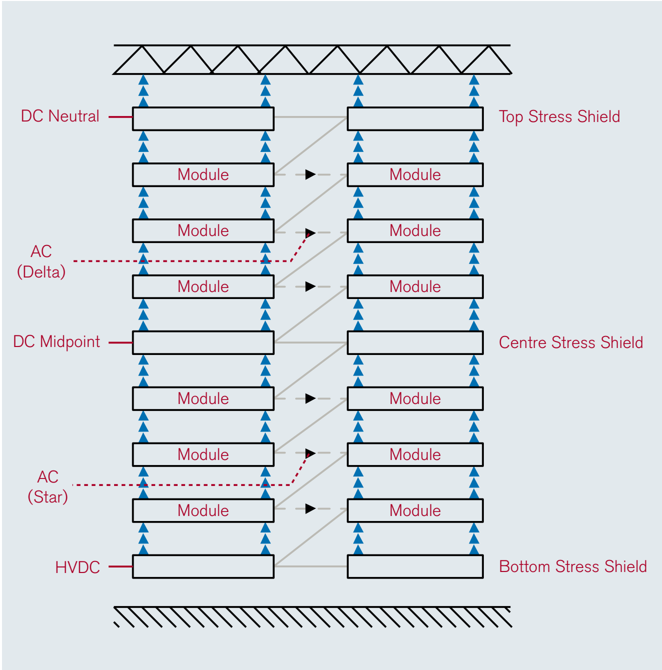


Figure 24.3: Typical suspended MVU for HVDC for a 285 kVdc Application (dimensions approx 6 m x 4 m x 8 m tall)

25 THYRISTOR VALVE COOLING CIRCUIT

In order to extract the losses efficiently from the thyristors and other components, and achieve adequately low temperature rise in these components, it is essential to provide some form of forced cooling circuit. Modern thyristor valves use liquid cooling by pure deionized water, which, when used with high voltage equipment is safe as long as the water is ultra-pure, with no ionic contaminants. Deionizing equipment ensures that the conductivity of the water is at a very low value.

Water cooling is always provided for the thyristors and damping resistors, and usually also for the di/dt reactor and DC grading resistor.

The water coolant is distributed in parallel to every thyristor level in the valve via insulating plastic pipes, and the waste heat is rejected to outdoor-mounted coolers.

The design of the water cooling circuit is an important engineering task in order to ensure that the system has adequate flow rates in all critical areas and avoids excessively high flow rates that could cause erosion, or low flow rates that lead to accumulation of gas pockets.

Even though the water conductivity in a HVDC valve is normally extremely low, it is never zero, and hence, its potential for causing undesired electrochemical effects has been widely recognised. Ultra-pure deionized water can have a very low conductivity, less than 0.1 μS/cm. However, no matter how sophisticated the deionization equipment, it is not possible to reduce the conductivity completely to zero, because water always dissociates into H^+ and OH^- ions, to an extent governed mainly by temperature. As a consequence, any water pipe spanning two points at different electrical potentials will inevitably carry a small leakage current. When the applied voltage is only AC, the consequences of this are not particularly serious, but when the applied voltage has a DC component, certain electrochemical reactions inevitably take place at the anode and cathode electrodes.

Aluminum, which is widely used as a heatsink material because of its excellent thermal conductivity, is very vulnerable to corrosion in the event that leakage currents flowing in the water are allowed to impinge directly on the aluminum. In order to prevent damage to the aluminum, it is necessary to ensure that the leakage currents flowing in the water do not flow directly from water to aluminum but instead pass via some inert electrode material. In this way (shown on Figure 25.1) the vulnerable aluminum is protected from damage.

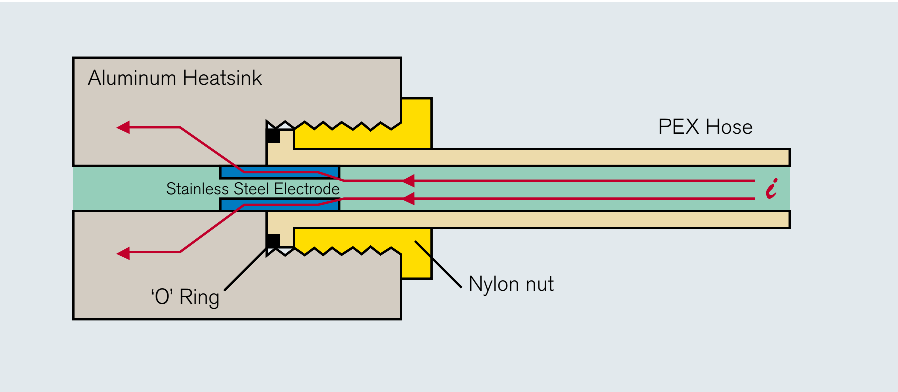


Figure 25.1: The Protective Electrode System Used in Alstom Grid's Water-Cooled HVDC Valves

Alstom Grid's first water-cooled HVDC valves have now been in service since 1989 [6] and those of the Nelson River project have been in service since 1992, see Figure 25.2. Alstom has maintained the same design principles used on those projects, up to the present day, on all its HVDC valves and most of its FACTS converters. Alstom Grid has in excess of 70,000 small-diameter (15 mm) and 8,000 larger-diameter (50-75 mm) cooling connections installed in such converters around the world. Even with such a large installed base, there have been no reported problems caused by electrochemical erosion or deposition in any of Alstom Grid's HVDC valves.

Figure 25.2: A valve hall from Valve Group VG13 of the Nelson River project in Canada, showing the large developed length used for the coolant pipework to span the distance between earth and the base of the valve stack at 330 kVdc.

Cooling plant

26 HVDC CONVERTER TRANSFORMERS AND THEIR CONFIGURATIONS

The converter transformer acts as the interface between the HVDC converter and the AC system and provides several functions including:

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

AC transformer insulation is designed to withstand AC voltage stresses. These voltage stresses are determined by the shape and permittivity of the insulation materials used within the transformer but is generally concentrated in the insulating oil. Converter transformers are, however, exposed to AC voltage stress and DC voltage stress. The distribution of the DC voltage stress is predominantly defined by the resistivity of the insulating materials and hence more stress is concentrated in the winding insulation than in the insulating oil. This resistivity varies due to several factors including the temperature of the materials and the length of time the voltage stress is applied. This is why the internationally recognised testing requirements demand that the DC voltage stress be applied for a period of time in order to ensure that a steady-state voltage stress distribution is achieved.

The converter transformer is the largest plant item to be shipped to site for an HVDC project. Hence 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 arrangement. Figure 26.2 illustrates the commonly recognised transformer arrangements in HVDC schemes.

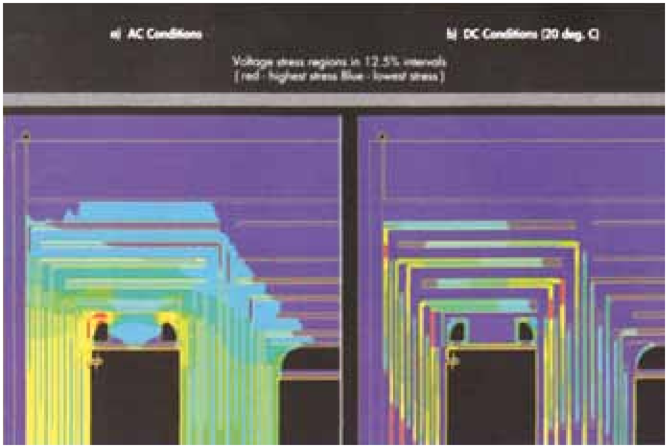


Figure 26.1: Comparison of AC and DC Voltage Stress Distribution in a Typical Converter Transformer

Lowest cost can normally be achieved by minimising the number of elements the converter transformer is broken down into, hence the lowest cost is typically a 3-phase, 3-winding transformer. However, due to shipping limits, such a transformer may not be practical so another arrangement should be considered. Where a spare converter transformer is deemed necessary, based on an availability analysis of the scheme, then it is more cost-effective to use a 1-phase, 3-winding transformer arrangement, as one spare unit can replace any of the in-service units, whilst 2-winding arrangements require two spare units to be supplied.

An important consideration in the design of a converter transformer is the selection of the leakage reactance as this will constitute the major part of the converter's commutating reactance. The leakage reactance must primarily ensure that the maximum fault current that the thyristor valve can withstand is not exceeded. However, beyond this limitation, the selection of leakage reactance must be a balance of conflicting design issues, the most important of which can be summarised as follows:

Lower impedance gives:

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

Higher impedance gives:

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

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

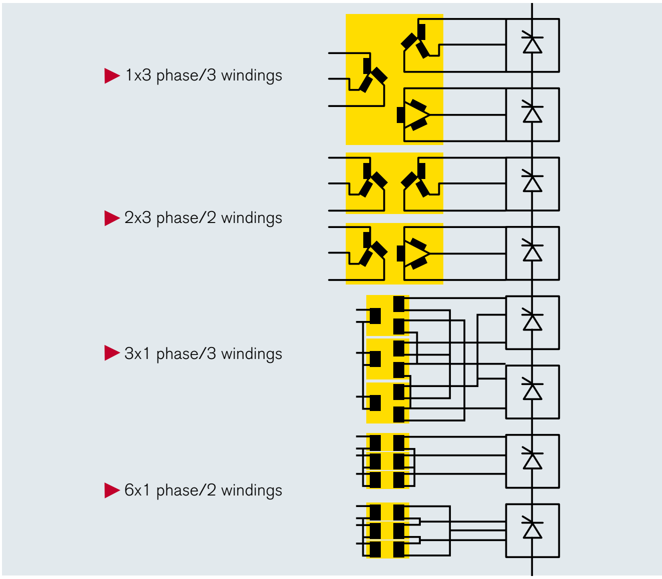
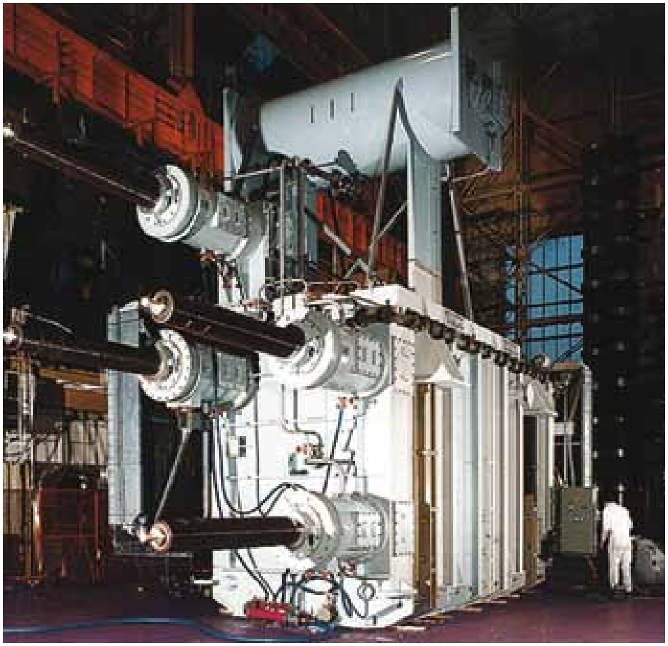


Figure 26.2: Typical Converter Transformer Arrangements



1-Phase, 3-Winding Converter transformer for the 500 MW Chandrapur Back-to-Back scheme

27 RELIABILITY AND AVAILABILITY OF AN HVDC CONVERTER

Reliability and availability assessment is the recognised way of assessing the performance of an HVDC converter scheme [7]. CIGRE collects reliability and availability of existing HVDC schemes from around the world and publishes a bi-annual report indicating what performance is being achieved for those schemes that provide data for the report.

27.1 Reliability

Reliability is a measure of the capability of the HVDC link to transmit power above some minimum defined value at any point in time under normal operating conditions. Reliability is normally expressed as the number of times in one year the scheme is incapable of transmitting power above a minimum defined value. This inability to transmit above a defined power level is termed Forced Outage Rate (F.O.R.).

27.2 Availability

"Availability" is not commercially significant, for example, if the scheme is unavailable during times of zero loading, the unavailability of the scheme will have no impact. For HVDC schemes, the term is, therefore, used to represent "energy availability". Energy availability is the ability of a HVDC scheme to transmit, at any time, power up to the rated power. Hence, a converter scheme which can transmit 1.0 pu power for 100% of the time would have an energy availability of 100%. Any outage of the HVDC scheme or, for example, the outage of one pole in a bipole, will impact the energy availability, reducing the figure to less than 100%.

28 LOSSES IN A CONVERTER STATION

An important commercial consideration of any power interconnection is the electrical losses within the connection, that is, the amount of power lost in the process of transmitting the power from one location to another. Losses within a line commutated converter scheme are carefully considered during the design phase in order to ensure that the relationship between capital equipment cost and the effective cost of losses can be optimised. In calculating the effective cost of the losses, the purchaser must consider the duration of the financial plan for the HVDC link, the expected cost of electricity during this period and the expected interest rate during this period. By taking these values, the net present value of the losses can be calculated, that is, a figure which represents a cost to the owner of using the equipment within the network. The loss evaluation is normally assessed by multiplying a cost/kW figure by the HVDC supplier's guaranteed losses. Figures of 4,000 USD/kW to 5,000 USD/kW are common today.

Figure 28.1 shows the typical split between equipment within a HVDC transmission scheme whilst Figure 28.2 shows the split between equipment for a back-to-back HVDC scheme.

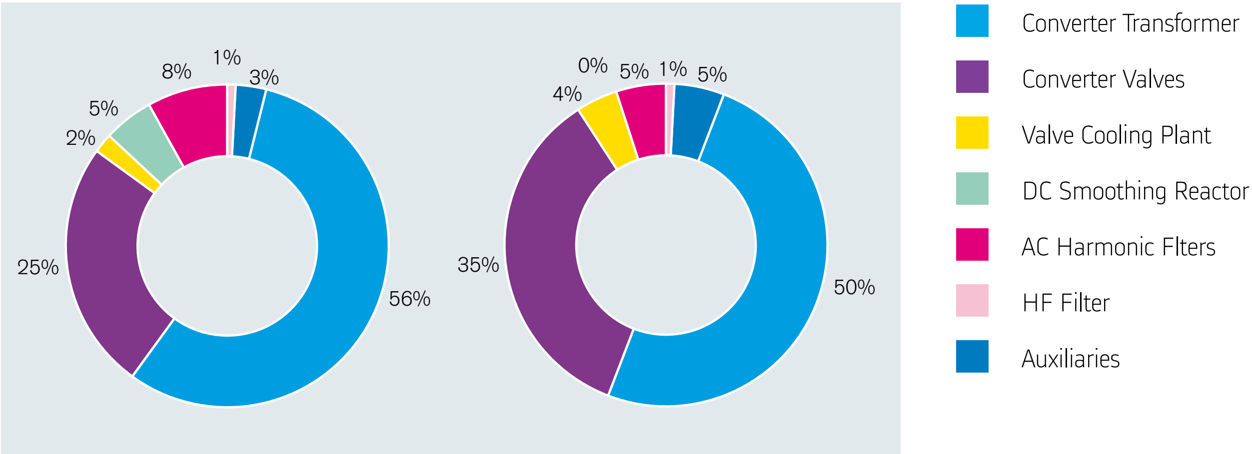


Figure 28.1: Typical Split of Losses Within an HVDC Transmission Scheme

Figure 28.2: Typical split of Losses Within a Back-to-Back HVDC Scheme

29 CONTRACT STAGE STUDIES FOR A HVDC CONTRACT

Alstom Grid has the capability to undertake a wide variety of power system and environmental studies in order to assist a purchaser in developing a HVDC scheme. Presented below is a description of recommended studies performed during the contract phase of a HVDC converter scheme construction.

Typical Contract Reports

Title	Main Scheme Parameters
Objective	To define the range of operating conditions of the HVDC scheme and the major component ratings.
Design Data Expected from Study	Consistent operating data for the HVDC scheme under different operating conditions, the number of thyristor valve levels and the converter transformer rating.
Equipment Affected	Thyristor valves, converter transformers and reactive power banks (AC harmonic filters).
Methodology	The steady-state operating parameters of the HVDC scheme across its operating power range are calculated for coherent operating conditions. The various operating parameters, equipment tolerances and measurement errors that are applicable to the scheme are varied between studies in order to explore the boundaries of the HVDC scheme's operation.

Typical Contract Reports

Title	**Reactive Power**
Objective	To establish the necessary sub-bank rating and switching sequence to meet the reactive power control requirements of the scheme.
Design Data Expected from Study	Reactive power bank/AC harmonic filter bank MVAr rating, switching sequence of banks under different operating conditions and converter reactive power absorption capability utilisation.
Equipment Affected	Reactive power bank/AC harmonic filters.
Methodology	The HVDC converter absorption under all extremes of operating condition tolerances, measurement errors and operating DC voltage are established as part of the Main Scheme Parameters reports. From this converter absorption, the total reactive power required, allowing for the appropriate tolerance conditions, is established. Using the reactive power exchange limits, established switch points will be calculated which keep the net reactive power interchange of the converter plus AC reactive power banks with the AC systems within the established limits.

Typical Contract Reports

Title	Harmonic Filter
Objective	To evaluate the AC side harmonic currents generated by the converters as a function of DC power and to establish an AC harmonic filter solution which meets the harmonic limits of the project.
Design Data Expected from Study	Filter design topology, component values and rating data.
Equipment Affected	AC harmonic filters.
Methodology	The analysis performed by Alstom Grid establishes the combinations of the AC system and converter conditions, such as frequency, temperature, transformer impedance, etc; which would give rise to the maximum levels of harmonic distortion at the terminals of the HVDC station. The harmonic currents generated by the rectifier and inverter of the HVDC converter are evaluated using a digital computer program called JESSICA. The JESSICA program calculates the magnitude of the individual harmonic currents from a mathematical analysis of the frequency domain behaviour of the converter. The performance of the AC harmonic filters and their operational losses are calculated using the network harmonic penetration program HARP. The program models the filters and the injected currents from the converters. A standard mathematical maximisation technique is used to search each harmonic impedance area to find the impedance which produces the maximum value of voltage at a chosen node, or of current in a chosen branch. This system impedance is inserted into the impedance matrix of the circuit being analysed for the harmonic current penetration study. The program then solves Ohm's law, using standard matrix mathematics techniques. This procedure is repeated for each harmonic of interest.

Typical Contract Reports

Title	**RI, TVI and PLC Filter.**
Objective	To evaluate the high-frequency interference generated by the converters and to establish a PLC filter and RF screening solution which meets the limits for the project.
Design Data Expected from Study	PLC filter design topology, component values and rating data. RF shielding of the valve halls.
Equipment Affected	PLC filters, valve hall RFI screen.
Methodology	The components of the converter station will be modelled in the appropriate frequency range to the necessary level of detail. Of most importance will be the converter transformers, the converters and the PLC filters. The PLC frequency noise will be calculated at the relevant busbars with a range of transmission line impedances over the range of PLC frequencies of interest. The radiated interference at 15 m from the substation fence will be calculated taking into account practical levels of RF screening applied to the valve halls.

Typical Contract Reports

Title	Insulation Coordination
Objective	To establish the appropriate protective levels of station surge arresters and hence BIL, clearance and creepage of station equipment.
Design Data Expected from Study	The study will yield protective levels of station surge arresters, equipment BIL and creepages and clearances on the DC side of the converter transformer.
Equipment Affected	All insulation.
Methodology	From the maximum valve winding and DC voltage along with the specified maximum AC system operating voltage, the appropriate surge arrester protective levels are calculated based on historical data. From this data, the insulation levels of primary equipment are calculated as well as the insulation levels of insulators. The calculated insulation level for insulators is corrected to provide an insulator which will provide the necessary withstand flashover probability for the DC side equipment. Clearances between equipment on the DC side of the converter transformer are also calculated.

Typical Contract Reports

<table>
<tr><th>Title</th><th>Transient Overvoltage Study</th></tr>
<tr><td>Objective</td><td>The objective of this study is to determine the transient overvoltage and current stresses on major converter station equipment including surge arresters, which form a basis for their insulation coordination. Surge arrester energy absorption requirements will also be determined.</td></tr>
<tr><td>Design Data Expected from Study</td><td>Transient overvoltage levels. Surge arrester protection levels and energy absorption.</td></tr>
<tr><td>Equipment Affected</td><td>Converter station equipment, filters and surge arresters.</td></tr>
<tr><td>Methodology</td><td>The disturbances considered can be categorised as:

a) Switching impulse studies involving fault application and clearance on the converter AC busbars, simulation of transformer and other energisation events and filter switching events. For these studies, the transformers in the vicinity of the converter stations are represented by electromagnetic models which include non-linear saturation effects. The close proximity of the filters to the transformers can give rise to ferroresonance effects, particularly if the filters and transformers become isolated from the main system. Non-linear transient effects of surge arresters are also represented as appropriate.

b) Lightning on the incoming DC side lines, and filter busbar flashovers to ground

The insulation levels of the station equipment will be coordinated with the protective levels of the surge arresters and the stresses on the latter determined to achieve suitable arrester and equipment design.

The transient overvoltages to be studied under this heading are faster than those of the fundamental frequency temporary overvoltage type, occupying a much shorter time scale with faster rise time. They must therefore be studied with a fast electromagnetic program. In the calculations, all circuit components (R, L and C) of the converter and close-up equivalent AC system are represented as necessary including adjacent lines, modelled by distributed parameters representations or equivalent Pi and T sections as appropriate. Stray capacitance, transformer saturation and surge arresters are included where appropriate and all phases are represented separately.

A range of operating conditions is investigated, together with events leading to transient overvoltages, in order to determine worst overvoltages and energy duties of AC and DC side surge arresters and other components.</td></tr>
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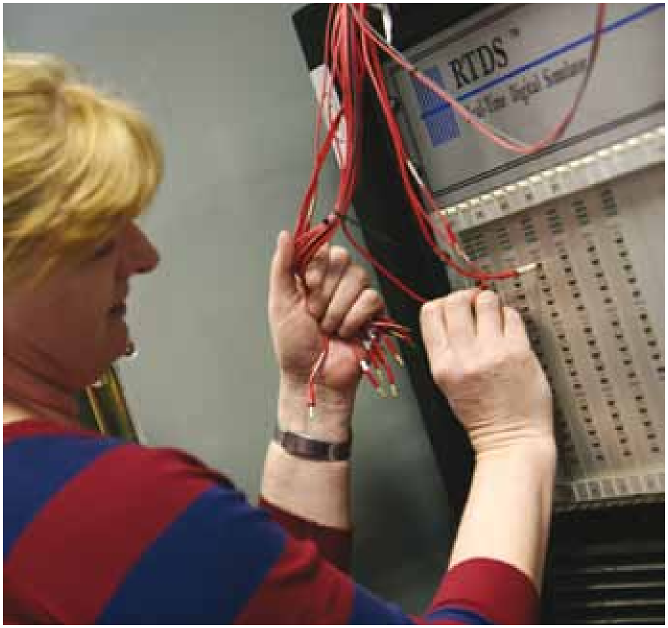
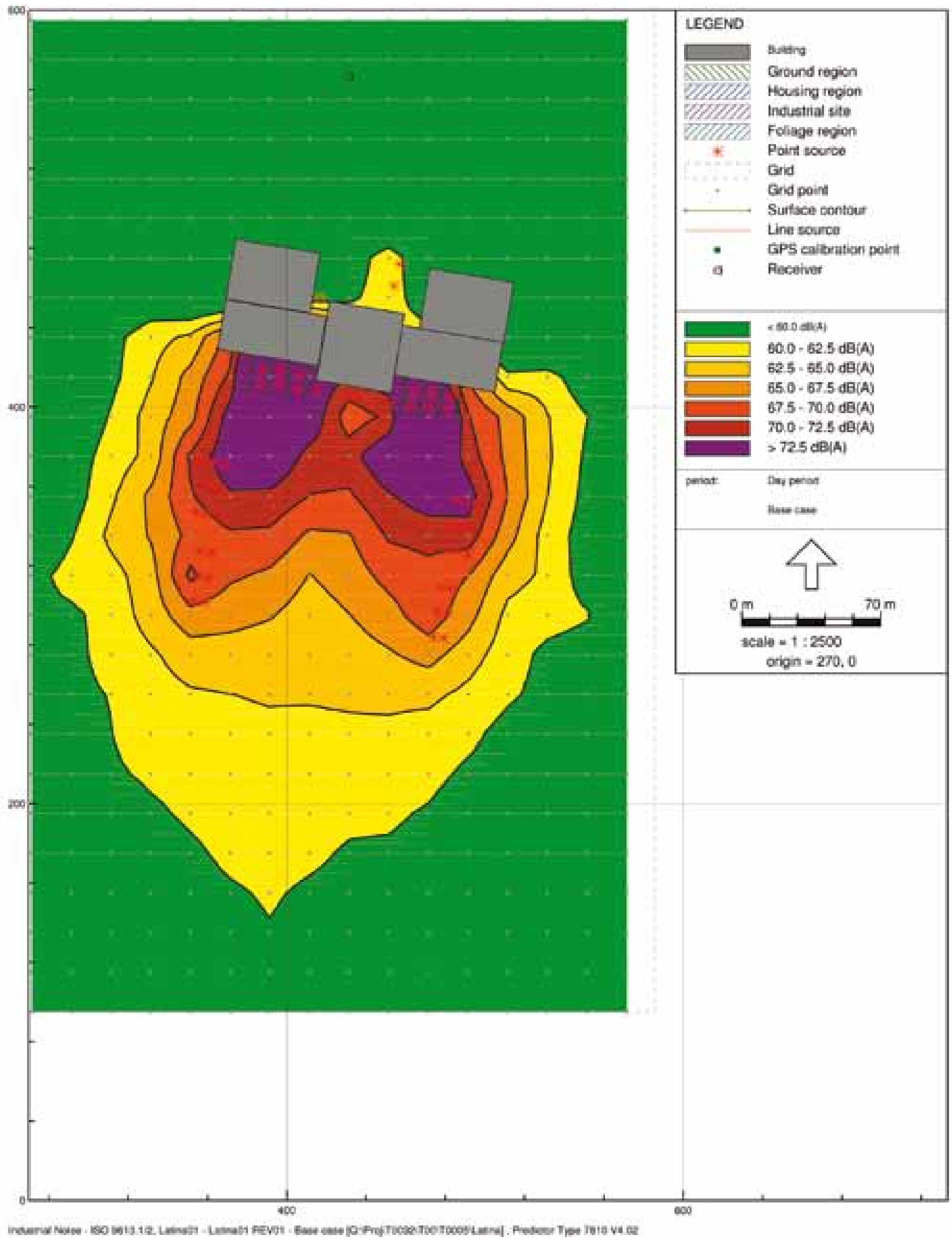
Typical Contract Reports

Title	Control System Dynamic Performance Study
Objective	The objective of this study is to optimise the control parameters to provide stable operation and good dynamic performance of the HVDC scheme. This study will be primarily carried out using physical controls and Alstom Grid's Real Time Digital Simulator (RTDS).
Design Data Expected from Study	Static characteristics, control system functions and parameters, verification of stability, response times and fault recovery.
Equipment Affected	Control equipment
Methodology	High voltage equipment in the respective converter stations (e.g. converter transformers, AC/DC filters and DC filters) as well as relevant generators and step-up transformers will be represented in the simulator model. Derived equivalent AC system network models will be used to represent the AC systems. This Dynamic Performance Study will be used to achieve the following objectives: • Evaluation of DC control and protection functions. • Confirmation of stable operation. • Confirmation of static characteristics and control set points. • Evaluation of the performance of the AC/DC system for different DC system control modes. • Evaluation of DC system performance for DC-side disturbances such as converter blocking, pole blocking, and valve winding faults, including demonstration of protective shutdown when required. • Demonstration of the DC system response in accordance with the specified response criteria, including control system step responses and recovery from AC system faults. • Demonstration of the DC system transient response for reactive component switching • Studying the interaction with local machines during disturbances. • Evaluation of the performance of the DC system during severe AC faults and subsequent to fault clearing. This will include the evaluation of DC power run-backs, if necessary, to achieve stable system recovery.


RTDS

Typical Contract Reports

Title	Audible Noise
Objective	To investigate the acoustic noise levels at the site boundaries.
Design Data Expected from Study	Confirmation that the equipment design meets the maximum acoustic noise limits at the boundary.
Equipment Affected	Acoustically-active equipment including converter transformers, converter transformer coolers, filter capacitors, air conditioning and valve cooling heat exchangers.
Methodology	Individual equipment suppliers' information giving the acoustic noise predicted for individual items will be modelled in a graphical representation of the site layout. The predictor software performs the acoustic noise calculations using the methodology set out in the following standards. • ISO 9613-1: Attenuation of sound during propagation outdoors, Part 1: Calculation of sound by the atmosphere (first edition 1993-06-01). • ISO 9613-2: Attenuation of sound during propagation outdoors, Part 2: General method of calculation (first edition 1996-12-15). • VDI 2571: Schallabstrahlung von industriebauten (Sound emission from industrial buildings).



Audible noise plot

Typical Contract Reports

Title	Fundamental Frequency Overvoltage Studies (FFTOV)
Objective	The objective of this study is to assess the performance of the DC interconnection, its controls and compensating equipment and the overvoltage limiting feature in response to large load rejection disturbances in the equivalent AC/DC system, in order to determine the resulting temporary overvoltages.
Design Data Expected from Study	Maximum fundamental frequency transient overvoltages experienced by system electrical power equipment.
Equipment Affected	Electrical power equipment in the vicinity of the HVDC converter stations.
Methodology	For specified base cases of the system, equivalent network (and load) transient type studies (for a short period of a few cycles) will be made for a partial and a full load rejection conditions. AC system outage condition situations are studied similarly. The appropriate study cases will be repeated with and without the reactive power absorption mode (TCR mode) of control for voltage limiting actions in order to determine its effects, characteristics and ratings. The study requires all the usual load flow and transient stability type data/models of the network impedances, loads, generators/controls and operating levels/features. The study does not necessitate a very large, full AC network to be modelled in order to achieve its objectives of converter station design/assessment. The maximum fundamental frequency TOVs occur when there is loss of power transmission in the HVDC link, which can occur due to: a) Blocking of the link. This causes the converter transformer circuit breakers to open thereby isolating the converter station. Any delay in tripping the filters will cause high overvoltages due to the prior rejection of the HVDC link reactive power demand which affects both ends of the link. b) Three-phase solid faults close in to the converter HV busbars which can also cause loss of DC transmission, although the converter transformers remain connected for this scenario. Following clearance of the fault, TOVs can be high in the period before full power transfer is re-established.

Typical Contract Reports

Title	Reliability and Availability
Objective	To define the overall reliability and availability of the converter station equipment, confirm the equipment design and the recommended spares to meet the specified requirement.
Design Data Expected from Study	The energy availability and the Forced Outage Rate associated with different scheme configurations.
Equipment Affected	All significant plant items are considered as part of the evaluation.
Methodology	A reliability study model is built by grouping together smaller models, known as 'subsystems'. A subsystem is a collection of components (or smaller subsystems) whose individual reliabilities can be combined together on the basis of their inter-relationships (dependencies) to provide an overall measure of subsystem reliability. The subsystem is then treated as a single component with its own failure and repair characteristics. In this way, a reliability study model can be simplified by consideration of its reliability in modular fashion into a smaller quantity of representative subsystem modules. There are no fixed rules regarding the way in which components are combined together to form subsystems; the choice is based on the nature of the plant and the experience of existing installations. Examples of subsystems are: a) Converter valve, comprising; thyristors, gate units, monitoring units, ground-level electronics, cooling components, etc. b) Harmonic filter, comprising: inductors, capacitors, resistors, CTs, isolators, AC circuit breakers, etc. A reliability study model of a complete system is built up by relating together all the subsystems which it contains in terms of the effect of their failures on the other subsystems.

Typical Contract Reports

Title	**Losses**
Objective	To calculate the 'as manufactured' losses of the converter station.
Design Data Expected from Study	Total operational loss from plant.
Equipment Affected	None.
Methodology	The converter station losses for operation under nominal AC system voltage and frequency conditions and with nominal equipment parameters at an outdoor ambient temperature of typically 20 °C will be presented. The study will compile results from equipment factory tests along with the proposed nominal operating conditions and present the total converter station losses in accordance with the formulae defined in IEC 61803 or, if prefered by the client, IEEE Std 1158.

30 REFERENCES

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[3] BT Barrett, NM MacLeod, S Sud, AI Al- Mohaisen, RS Al-Nasser, "Planning and design of the AL Fadhili 1800MW HVDC Interconnector in Saudi Arabia", CIGRÉ Session 2008, B4- 114.

[4] RP Burgess, JD Ainsworth, HL Thanawala, M Jain, RS Burton, "Voltage/var control at McNeill Back-to-Back HVDC convertor station", CIGRÉ Sesson 1990, p.14-104.

[5] NM MacLeod, DR Critchley, RE Bonchang, "Enhancing the control of large Integrated AC Transmission Systems using HVDC technology", Powergrid Europe conference, Madrid, Spain, May 2007.

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31 APPENDIX

Questionnaire – Data Requirements for an HVDC Scheme

The importance of each question is defined by the following categories:

A A list of the minimum information required to enable a formal quotation to be prepared

B A list of minimum information required to enable a budgetary proposal to be made, e.g. for feasibility study

C A list of the additional, minimum technical definitions required at the time of an order award

Please note that it is in the interest of the User to specify in the enquiry as much of this information as possible - for which purpose we would be pleased to offer our advice if required - since, although Tenderers can make their own assumptions when data is missing, this can lead to difficulties when tenders are adjudicated.

Category	**1.**	**AC System for each terminal**
	1.1	Voltage
A B		nominal
A B		maximum continuous
A B		minimum continuous
A		maximum short time and duration
A		minimum short time and duration
	1.2	Frequency
A B		nominal
A B		maximum continuous
A B		minimum continuous
A		maximum short time and duration
A		minimum short time and duration
A B	1.3	Short circuit levels, maximum and minimum, for each stage of the development
A B	1.4	Insulation levels
A	1.5	Creepage and clearance distances
A	1.6	Harmonic impedance

A	1.7	Distortion and/or TIF limits for AC system. Which harmonics are to be assessed?
A	1.8	Is the AC system solidly or resistance earthed?
A	1.9	What are the design constraints (number of feeders, security criteria, current user practice, etc) for the AC switching station? Are there other large transformers connected to the converter station busbar? If so, give transformer ratings, reactances, tap range, etc.
A	1.10	Give details of undervoltages and durations for AC system faults,both during the faults and during the fault clearance period for both main and back-up protection, for single phase and three phase faults if they are different.
A B	1.11	Give results of AC system disturbance studies including transient voltage and frequency variations, and details of any limits on acceptable VAr generation/absorption and switching during and after the disturbance.
A B	1.12	a) What is maximum permitted step voltage change arising from filter switching? b) What is the maximum permitted ramped voltage change and over what time duration?
A B	1.13	What is maximum temporary (<1 sec) overvoltage that existing equipment can withstand? Are there any other significant limits on permissible temporary overvoltage?
A B	1.14	How much reactive compensation is required (i.e. what power factor is to be achieved) at the AC terminals at various transferred power levels up to full load?
A	1.15	Give details of outgoing AC lines from each converter station.
A	1.16	Give negative sequence voltage on each converter station AC busbar, and existing harmonic voltages.
	2.	**DC System**
A B	2.1	Is power flow required in both directions?

A B	2.2	What is the nominal power to be converted into DC? (It is usually convenient to define this at the rectifier DC output terminals). Note that if the power flow is unidirectional, then the rating of the inverter can be made less than that of the rectifier.
A B	2.3	Is an overload capability required? If so how much and for how long and under what conditions of ambient temperatures?
A B	2.4	What are the ratings and parameters of the DC line, or cable? Where possible, include: • Voltage rating and location at which this is to be defined. • Current rating • Resistance of each line or cable • Inductance of each line or cable • Capacitance of each line or cable • Harmonic impedance of each line or cable • Length of each line or cable • Equivalent circuit for each pole
A B	2.5	What are the permitted limits for harmonic current injection into the DC line?
A B	2.6	Is monopolar operation required either in emergencies orcontinuously?
A B	2.7	Is ground current allowed either in emergencies or continuously?
A B	2.8	Are ground (return) electrodes to be provided? If so give: • Details as in question 2.4 above for both electrode lines • Electrode resistance (predicted) • Electrode type (sea or land) and approximate location
A	2.9	Information relevant to any possible electromagnetic coupling to other adjacent circuits, and the nature of the possible disturbances liable to be produced by such coupling.
A	2.10	Details of any requirements for switching DC lines
A	2.11	What is the time scale for any staged development?

with tolerances

A	2.12	What are the capitalised costs for fixed and variable losses and at what power loading do they apply?
A	2.13	In order that the quantities of spares required may be determined,give details of the energy availability and station reliability targets, preferred maintenance intervals and design criteria to be adopted (information to include cost of loss of service for availability and reliability optimisation).
	3.	**Generators (if applicable)**
A B	3.1	What are the ratings and parameters of the generators? Include: • MVA • Voltage (including harmonic content) • Power factor • Reactances, both transient and sub-transient direct axis.
A B	3.2	What are the ratings and parameters of the generator transformers? Include: • MVA • Voltage ratings • Percentage reactance • Connection
A	3.3	Will the generators be designed to absorb harmonics from the converters?
A	3.4	What are the in-service dates for the generators?
A B	3.5	Will control be provided to limit AC busbar voltage variation? If so what will the voltage limits be, and what maximum reactive power can the machines safely absorb?
A	3.6	Is the generating station at the same site as the converter station? If not, give details of the AC lines between generating station and converter station including: • Length of lines • Number of lines, voltage ratings • Impedance and characteristics of each line

	4.	**Auxiliary Supplies, for each terminal**	
A	4.1	Give details of preferred voltages and frequencies to be used for the auxiliary power system and sources of auxiliary power supply, i.e. will supply be provided from a generating station or will contractor have to supply auxiliary power transformers connected to the AC busbars?	
A	4.2	Define whether start up of auxiliaries is to be manual or automatic.	
A	4.3	If auxiliary supply is being provided by the customer, give details of reliability of supply and disturbances. If the auxiliary supply is to be provided by the Contractor, define redundancy requirements.	
	5.	**Controls and Telecoms**	
A	5.1	Locations from which control instructions may be received	
A	5.2	Control philosophy to be explained. To what extent is automatic control preferred to giving detailed responsibility to the operator?	
A	5.3	Any operation requirements to be defined, i.e. power and/or current control, rate of change of power, etc.	
C	5.4	Define the performance required during and after disturbances in either AC system	
C	5.5	Define any restrictions on the recovery from DC disturbances arising from the requirements of the AC system	
C	5.6	Define the disturbances liable to occur in either AC system and the control objectives required of the DC system in such circumstances such as supplementary control signals in response to AC frequency or voltage at one or more terminals.	
C	5.7	Control desk or panel requirements	(a) what are the particular requirements?
A B	5.8	Protection requirements	
A	5.9	Requirements for line fault protection	

A	5.10	Requirements for line fault location	(b) What are the system practices which should be followed for operational convenience?
A	5.11	Requirements for alarm annunciation	
A	5.12	Requirements for sequential event recording	
A	5.13	Requirements for disturbance recording	
A	5.14	Supervisory system requirements	
A	5.15	Is an HVDC power line carrier (or fibre optic cable communications) system to be provided by the contractor and, if so, what information will be carried on it?	
A	5.16	Details of any interface between power line carrier (or fibre optic cable communications) and any other telecommunication system(s).	
A	5.17	Arrangements for communication during the construction/commissioning stage, between sites and from each site to national and international circuits for telephone, printer, fax, etc.	
A	5.18	Requirements for permanent facilities to be provided by the contractor for telephone, telex, fax, etc., circuits.	
A	5.19	Map of route of DC line (if applicable) showing sites, and respective distances, for power line carrier repeater stations, indication of any suitable auxiliary power supplies that may be available at these sites.	

	6.	**The following general information is required for each site:**
A	6.1	Extent of supply to be clearly defined especially any services or equipment to be provided outside the converter station.
A	6.2	Interfaces with equipment or services outside the scope of supply to be clearly defined
A B	6.3	Site conditions: (a) Ambient temperatures (i) nominal (ii) maximum (iii) minimum (iv) maximum wet bulb and coincident dry bulb (b) Altitude (c) Maximum wind speed (d) Maximum depth of snow (e) Rainfall (f) Isokeraunic levels (g) Range of relative humidity (h) Incidence of air pollution (salt or industrial)
A	6.4	What are the RFI limits and where are they to apply?
A	6.5	What are the low frequency electromagnetic field limits ?
A	6.6	What are the audible noise limits and where are they to apply?
A B	6.7	Are the sites in an earthquake zone; if so what forces do structures and building have to be designed to withstand?
A	6.8	Local structural/building codes, defining what factors have to be applied to forces due to wind and/or snow, when designing buildings and structures.
A B	6.9	What are the maximum loading gauges and weight restrictions at the ports and on the routes to each site?

A	6.10	Maps of the areas of the sites showing the areas available for the converter station and those available for ground or sea-shore electrodes.
A	6.11	Site surveys including soil analysis especially in the areas of the ground electrodes if these are required.
A	6.12	Maps showing the location of the outgoing AC lines and DC linesfrom the converter stations.
A	6.13	Details of auxiliary supplies that will be available, during construction and installation.
A	6.14	Details of water supplies, available at the sites, including flow rates and chemical analysis.
A	6.15	What language should be used on drawings and instructions?
A	6.16	Details of any preferred materials that will utilize local resources, e.g. copper or aluminum, brick or concrete.
A	6.17	Standards and specifications to be used, stating the order of precedence. This list should also include specific standards relating to items of equipment including Busbars, Transformers, Switchgear, Cabling and Wiring, Insulation Oil, Civil Works and Structures, Equipment Finishes, Painting, Drawings and Drawing Symbols.
C		If the customer has any standard specification for control and protection circuits, e.g. control circuits for circuit breakers, then copies of these should be provided.
A	6.18	Are IEC Test Standards applicable?
A	6.19	Define what office and workshop facilities are to be provided, e.g.should workshops be capable of handling major items such as converter transformers?
A	6.20	Define any restrictions applicable to indoor, oil-filled equipment.

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