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High Voltage Direct Current Transmission

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ABSTRACT OF THE
MASTER THESIS

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This thesis is focused on the application and development of HVDC transmission technology based on thyristor without turn-off capability. Compared with other macroelectronics in the power field, thyristor without turn-off capability has successful operation experience to ensure reliability and high power ratings to transfer bulk energy.

This thesis covers converter station design and equipments, reactive power compensation and voltage stability, AC/DC filters design, control strategy and function, fault analysis, overvoltage and insulation co-ordination, overhead line and cable transmission, transmission line environmental effects, earth electrode design and development.

With the development of new concepts and techniques, the cost of HVDC transmission will be reduced substantially, thereby extending the area of application.

Acknowledge

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First, I would like to thank my supervisor, Prof. Matti Lehtonen, for the opportunity to study this subject and for his inspiring guidance.

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I give best thanks to my family. Their love and care were supporting me in a foreign country.

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Chapter 1 Introduction

1.1 HVDC Transmission Configurations

In accordance with operational requirements, flexibility and investment, HVDC transmission systems can be classified into two-terminal and multiterminal HVDC transmission systems.

1.1.1 Two-Terminal HVDC Transmission

There are only two converter stations in the point-to-point HVDC transmission system, one rectifier station and the other inverter station. The main circuit and primary equipments of the rectifier station are almost the same as those of the inverter station (sometimes AC-side filter configuration and reactive-power compensation may be different), but the functions of control and protection systems must be configured respectively. There are three different configurations, i.e. monopolar link (positive or negative polarity), bipolar link (positive and negative polarity) and back-to-back interconnection (no transmission line), illustrated in Figure 1.1. [1]

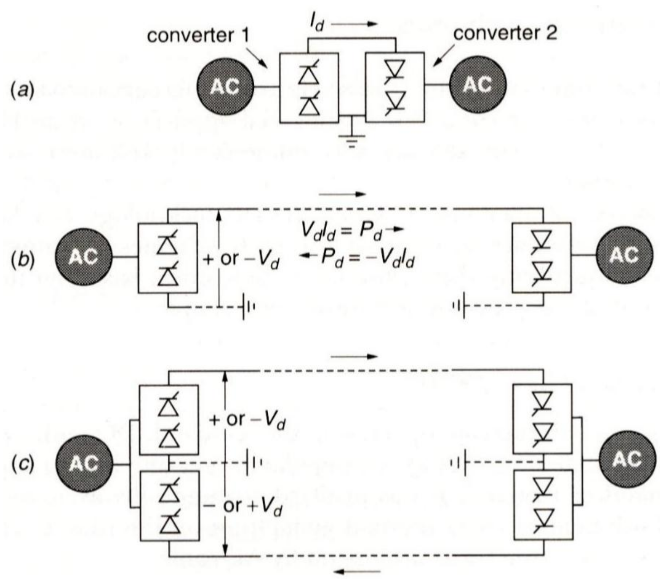

Figure 1.1 Back-to-back interconnection (a), monopolar link (b) and bipolar link (c) [1]

In accordance with circuit modes, monopolar links can be classified into monopolar link with ground (or sea) return and monopolar link with metallic return. For a monopolar link with ground return, earth or sea is used as one conductor line and thereby two converter stations must be grounded necessarily. Since considerable direct current flows through earth or sea continuously, it will give rise to transformer magnetism saturation and underground metal-objects electrochemistry corrosion. Although a monopolar link with ground return can reduce DC-line cost, the reliability and flexibility are relatively less during operations and earth electrodes must be designed with quite high requirements, thereby easily increasing the cost of earth electrode. A monopolar link with ground return is usually employed in the HVDC submarine cable scheme, e.g. Konti-Skan, Fenno-Skan, Baltic cable and Kontek HVDC links. [2] [3] [4] [5] Instead of earth or sea return, a monopolar link with metallic return (low insulation) may be used. Although the DC-line investment and operational cost of monopolar link with metallic return are higher than those of monopolar link with ground return, due to no direct current flowing through earth during operations, transformer magnetism saturation and electrochemistry corrosion can be avoided. Initially, Sweden-Poland Link was planned as a monopolar link with ground return. Finally owing to the environmental impact, Sweden-Poland Link became the first monopolar link with metallic return. [6]

According to circuit modes, bipolar links can be classified into bipolar link with two-terminal neutral ground, bipolar link with one-terminal neutral ground and bipolar link with metallic neutral line. A bipolar link with two-terminal neutral ground was employed in most HVDC transmission schemes, e.g. Three Gorges – Guangdong, Three Gorges – Changzhou, Chandrapur – Padghe and Gezhouba – Shanghai. [7] [8] [9] [10] It has two conductor lines, one positive and the other negative, and earth return can be used as a backup conductor. If one pole is out of service due to a fault, the other pole can operate with earth by using the overload capability. For a bipolar link with one-terminal neutral ground, due to only one-terminal neutral grounded, earth or sea cannot be used as a backup conductor. If faults occur on one pole, the entire bipolar link must be shut down without the possibility of monopolar operation. A major advantage is to ensure no earth current during operations, thereby avoiding some consequences. A bipolar link with one-terminal neutral ground is rarely used, only in English Channel HVDC submarine scheme interconnecting England and France. North Sea cannot be used as a return path due to the interference with ship's magnetic compasses. [11] [12] A bipolar link with metallic neutral line uses three conductor lines, one low-insulation neutral line and two DC-lines. Although the line structure is relatively complex and the line cost is considerably high, due to no direct current flowing through earth, a bipolar link with metallic neutral line can prevent some problems caused by earth current and provide relatively reliable and flexible operating modes. Usually if direct current is not allowed to flow through earth or the site of earth electrode is quite difficult to select, the bipolar link with metallic neutral line can be employed. In London, UK, Kingsnorth underground cable HVDC scheme was built to reduce the short-circuit level in areas of high load density. [13] Part of Hydro-Quebec (Canada)-New England (USA) HVDC scheme employed the bipolar link with metallic neutral line. The earth electrode for the Sandy Pond converter station is located in Sherbooke, Quebec and is connected to the converter station by a metallic return. [14]

In a back-to-back interconnection, both rectifier and inverter are placed on the same site, linking via smooth reactor. Due to no transmission line and low loss, the equipments on the DC side can be designed with relatively low voltage and high current rating, thereby reducing the price of converter transformer, smooth reactor and converter valve. Because the rectifier and inverter are installed in the same valve hall and thus DC harmonics do not interfere with communication, DC filters are not required. [15] [16]

1.1.2 Multiterminal HVDC Transmission

A multiterminal HVDC transmission system is used to connect multiple AC systems or separate an entire AC system into multiple isolated subsystems. In a multiterminal HVDC transmission system, converter stations can be connected in series or in parallel, illustrated in Figure 1.2.

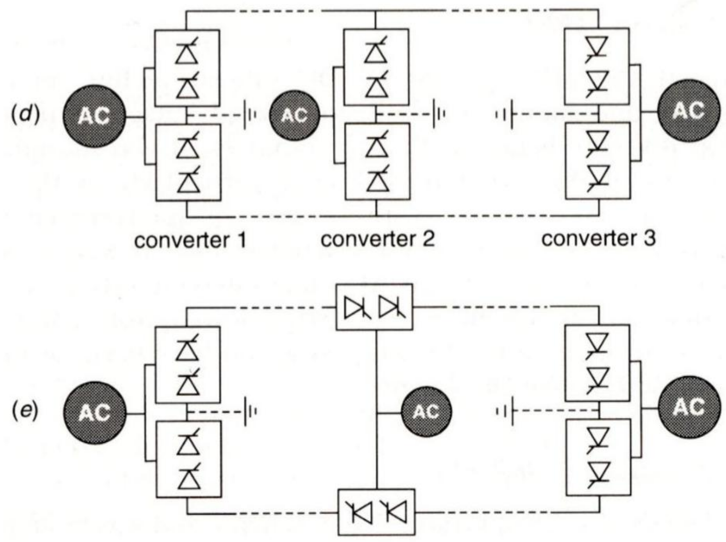

Figure 1.2 Parallel-connected (up) and series-connected (down) configurations [1]

In the series-connected HVDC scheme, the regulation and distribution of active power among converter stations mainly depend on the direct-voltage variation that is achieved by regulating the converter firing-angle or transformer tap-changer. Although the series-connected HVDC scheme can provide advantages, e.g. quick power-flow reversal, excellent reliability and fast fault recovery, due to permanent faults on one portion of DC line, the entire multiterminal HVDC system must shut down, thereby necessarily using double circuits and obviously increasing the line price. In the parallel-connected HVDC scheme, the regulation and distribution of active power among converter stations mainly depend on the direct-current variation that is achieved by regulating the converter firing-angle or transformer tap-changer. For the parallel-connected HVDC scheme, in order to ensure high converter power factor and less reactive power consumption, the firing angle must be maintained in the small variation range during operations and due to constant direct voltage, the load reduction is achieved by lowering direct current, thereby providing lower loss and excellent economic operation. [17]

1.2 HVDC Transmission Characteristics

The development of high rating power electronics strongly influences the development of HVDC technology. In this book, thyristor valve (without turn off capability and with low frequency) is mainly discussed.

1.2.1 HVDC Transmission Advantages

(1) A bipolar HVDC overhead line only requires two conductors with positive and negative polarities, thereby providing simple tower structure, low DC-line investment and less power loss. In comparison with one circuit HVAC overhead line, for the same transmission capacity, HVDC transmission can save approximately 1/3 steel-core aluminium line and 1/3 – 1/2 steel. Compared to a double circuit HVAC line with six conductor bundles, one bipolar HVDC line with two conductor bundles takes much less the width of transmission routine. [18] Under the effect of direct voltage, the capacitance of transmission line is never taken into account. Since capacitive current does not exist, direct voltage maintains the same along the transmission line.

(2) For the AC and DC cables with the same insulation thickness and cross section, the transmission capability for DC cable is considerably higher than that for AC cable. DC cable lines only require one cable for monopolar link or two cables for bipolar link and AC cable lines need three cables, due to three-phase AC transmission. Therefore, the price for DC cable lines is substantially lower than the prices for AC cable lines. Since there is no the cable capacitance in a DC cable transmission, the transmission distance for DC cable is unlimited theoretically.

(3) HVDC links can be used to interconnect asynchronous AC systems and the short-circuit current level for each AC system interconnected will not increase. The interconnected AC systems can be operated with different nominal frequencies (50 and 60 Hz) respectively and the exchange power between interconnected AC systems can be controlled rapidly and accurately.

(4) Due to the rapid and controllable features, HVDC systems can be used to improve the performance of AC system, e.g. the stability of frequency and voltage, the power quality and reliability of interconnected AC systems. For the DC/AC hybrid

transmission system, the rapid and controllable features of HVDC system can also be used to dampen the power oscillations in AC systems, so as to increase AC lines' transmission capacity.

(5) For an HVDC system, earth can be used as the return path with lower resistance, loss and operational cost. For a bipolar link, earth is normally used as a backup conductor. If faults occur on one pole, the bipolar link can be changed into the monopolar link automatically, thereby improving the reliability of HVDC system.

1.2.2 HVDC Transmission Disadvantages

(1) In a converter station, except for converter transformers and circuit breakers, there are converter valves, smoothing reactors, AC filters, DC filters and reactive power compensators. For the same rating, the investment for a converter station is several times higher than the investment for an AC substation.

(2) A converter acts as not only a load or a source, but also a source of harmonic currents and voltages, thereby distorting current and voltage waveforms.

(3) In a conventional converter station, the reactive power demand is approximately 60% of the power transmitted at full load. [19] Since reactive power must balance instantaneously, reactive power compensators must be installed in the converter station, in order to improve the stability of commutation and dynamic voltage.

(4) Without current zero-crossing point, DC circuit breakers are difficult to manufacture, thereby developing multiterminal HVDC systems very slowly. With developing power semiconductors with high switching frequency, DC circuit breaker can be innovated.

1.3 HVDC Transmission Applications

HVDC schemes mainly serve the following purposes.

- Long Distance and Bulk Capacity Transmission

For the same transmission capacity, above a certain distance, an HVDC transmission offers more economic benefits than HVAC transmission. As the transmission distance increases, the transmission capacity for HVAC line is restricted by stability limitation, thereby necessarily increasing additional investment for short-circuit limitation, voltage support, etc.

- Power System Interconnection

In order to optimize the resource utilization, several AC systems intend to be interconnected with the development of power industry, but it will give rise to the problems in the super system. For example, the interconnection for AC systems always increases the short-circuit levels, thereby exceeding the capacity of the existing circuit breakers. AC systems can also be interconnected by HVDC transmission and thereby it not only obtains the interconnection benefits but also avoids the serious consequences.

- DC Cable Transmission

For DC cable, without capacitance current, the transmission capacity is not restricted by transmission distance. Except for the purpose of long-distance and bulk-capacity, DC cables are also widely used across strait in the world. Due to environmental issue, large-capacity power stations are not allowed to build in the vicinity of city. Moreover, it is very difficult to select appropriate the overhead-line routine, owing to high population and load-density. Therefore, using HVDC underground/submarine cables is an attractive solution to deliver power from remote power station to urban load center.

Chapter 2 Converter Station

2.1 Station Design

A converter station consists of basic converter unit, which primarily contains converter valve, converter transformer, smoothing reactor, AC filter, DC filter and so on. Basic converter units can be classified into 6-pulse converter unit and 12-pulse converter unit. Usually most HVDC schemes employ the 12-pulse converter as the basic converter unit. [20] In order to form a 12-pulse converter unit, two 6-pulse converter units are connected in series on the DC side and in parallel on the AC side. AC/DC filters can be configured in accordance with the requirements of 12-pulse converter, thereby greatly simplifying the number of filters, reducing land use and lowering the cost. A 12-pulse converter unit can employ the converter transformer of either two-winding or three-winding.

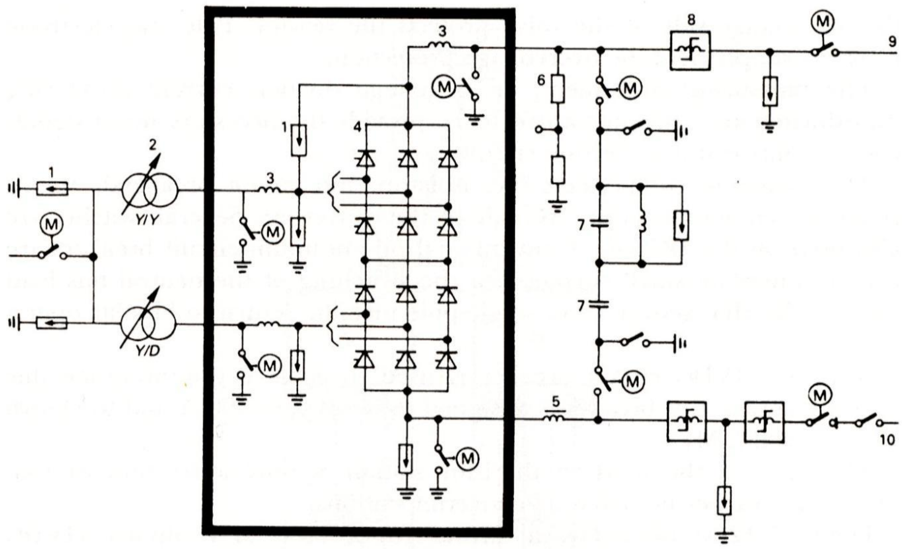

Figure 2.1 The main circuit diagram for one pole of a converter station [21]
1 surge arrester 2 converter transformer 3 air-core reactor 4 thyristor valve
5 smoothing reactor 6 voltage measuring divider 7 DC filter
8 current measuring transducer 9 DC line 10 electrode line

For a 12-pulse converter, the components are shown in Figure 2.1. [21] In order to provide the 30° phase-shift for 12-pulse operation, the transformer valve-side windings must be connected in star-star and star-delta respectively. In order to limit any steep-front surges entering the station, a smoothing reactor is located on the DC side. The measuring equipments, such as voltage divider and current transducer, can provide the accuracy input signals for the control and protection systems. The switching components, such as isolators and circuit breakers, are used for the changeover from monopole metallic return to bipolar operation.

Figure 2.2 indicates the relative space of the various components for a bipolar converter station. [22] The areas of shunt capacitor banks and AC filter banks are the major proportion of the entire area and the valve hall and control room only take a small fraction of the total station area.

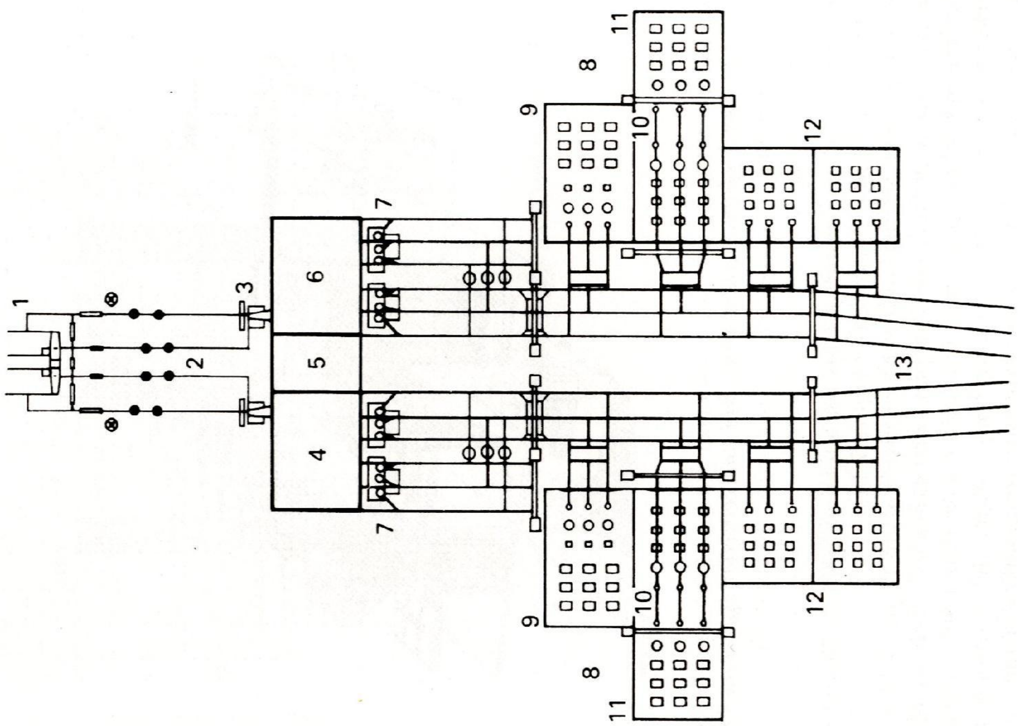

Figure 2.2 The station layout for a bipolar HVDC station [22]
1-DC and electrode lines 2-DC switchyard 3-DC smoothing reactors 4-valve hall, pole I
5-service building with control room 6-valve hall, pole II 7-converter transformers
8-AC harmonic filters 9-high-pass filter 10-eleventh harmonic filter
11-thirteenth harmonic filter 12-shunt capacitors 13-AC switchyard

Figure 2.3 shows a modern compact converter station. [23] In order to reduce the size of a converter station significantly, using new equipments, such as outdoor valves, gas-insulated bus systems, active AC and DC filters, and the container-type control and auxiliary integration systems, play an important role. Furthermore, the use of a gas-insulated bus can avoid pollution deposits on exposed portions of a converter station; the valve building cost can be reduced considerably and all control systems can be tested in the factory. [24] [25]

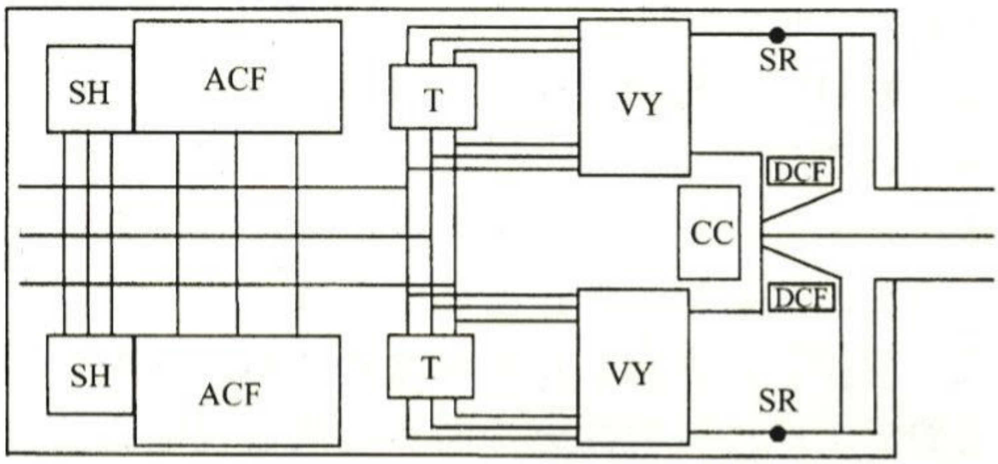

Figure 2.3 The compact station layout for a bipolar HVDC station [23]
ACF-AC filter   DCF-DC filter   VH-valve hall   VY-valve yard   SH-shunt capacitor
SR-smoothing reactor   CC-control and auxiliary modules   T-transformer

2.2 Converter Valve

Until today, most HVDC schemes have applied thyristor valves, which are air insulated, water cooled and suspended indoors. [26]

In order to protect thyristor from overvoltage, excessive rate-of-rise of voltage and rate-of-rise of inrush current, the auxiliary components, such as saturable reactor, voltage dividers, damping circuits and valve firing electronics are necessarily installed together with local thyristor to constitute a valve module, shown in Figure 2.4. [27] Owing to the limited voltage rating for each thyristor, many of them must be connected in series to constitute a converter valve. The converter valves are normally installed inside a valve hall and arranged as three structures suspended from the ceiling of the valve hall.

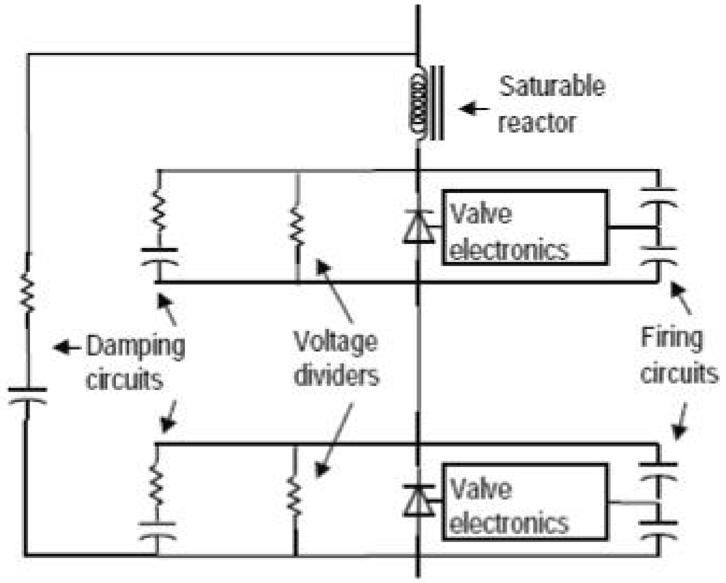

Figure 2.4 The components of thyristor valve module [27]

A valve using electrically-triggered thyristor (ETT) requires electronic thyristor control unit (TCU) to generate trigger pulses for protection and monitoring. All signals, such as the firing signals and the feedback signals, are transmitted by fibre optics. Microcomputers are used in the control room to process the information from the valve and the feedback signals are used to monitor the state of each individual thyristor, so as to detect the faulty thyristor immediately and locate the position of the defective thyristor exactly. Figure 7.9 show the location and basic functions of the Cross – Channel converter valve. [28]

A valve using light-triggered thyristor (LTT) has been developed to eliminate the electronic circuits for converting the light signals into electrical pulses. Powerful light sources at ground level are installed to generate light signals via optical fibres and the light-trggered thyristor is self-protected against overvoltage, thereby eliminating the protecting circuit. [29]

A cooling system is very important to ensure the availability and reliability of a converter valve. Therefore, the valve cooling system must have sufficient cooling capacity and relatively high reliability to prevent leakage and corrosion.

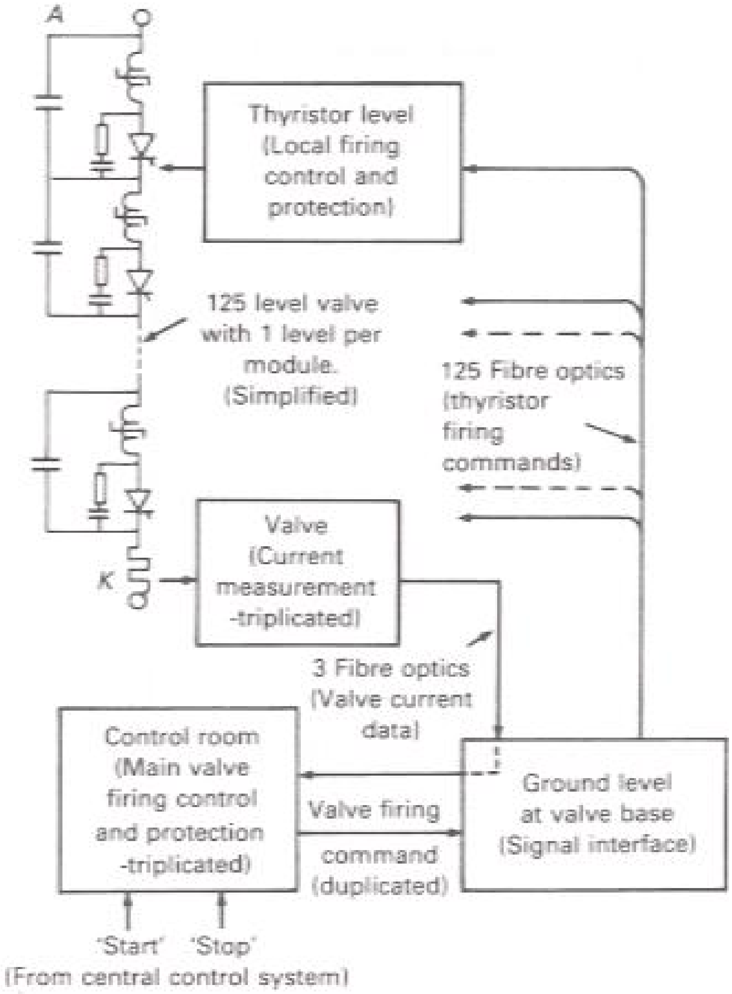

Figure 2.5 Location and basic functions of the Cross-Channel valve electronic systems [28]

For indoor valves, a number of disadvantages are the large costly valve buildings, the complex interface to the electrical equipment, the risk of a valve-building fire and the risk of flashovers across large wall bushings. In order to overcome those disadvantages of indoor valve design, the outdoor valve design can be an effective alternative. An outdoor valve is completely assembled in a modular container and fully tested in the factory, thereby greatly reducing the delivery time and lowering the maintenance cost. In addition, for the outdoor valve, there is no need to build the valve hall and thus the civil content (cost and time) of valve hall is greatly reduced.

2.3 Converter Transformer

A converter transformer is placed on the core location to link the AC network with the valve bridge. Owing to expensive component cost and complicated manufacture technology, the converter transformer is one of most important components.

Usually, modern HVDC systems employ the configuration of one 12-pulse converter for each pole. A converter transformer provides 30º phase shift between two 6-pulse converters to obtain the configuration of 12-pulse converter; if the short-circuit occurs on the valve arm or DC busbar, the impedance of converter transformer can restrict the fault current, in order to protect converter valve.

Because the operation of converter transformer is closely related to the nonlinearity caused by converter commutation, compared with ordinary AC transformer, the converter transformer is of different characteristics, such as the short-circuit impedance, test, harmonics, DC-magnetisation, insulation and on-load tap changing. [30]

A converter transformer employs single-phase arrangement or three-phase arrangement. Therefore, for a 12-pulse converter, the standard configurations of converter transformer banks can be: six single-phase two-winding transformers; three single-phase three-winding transformers; two three-phase two-winding transformers and one three-phase three-winding transformer.

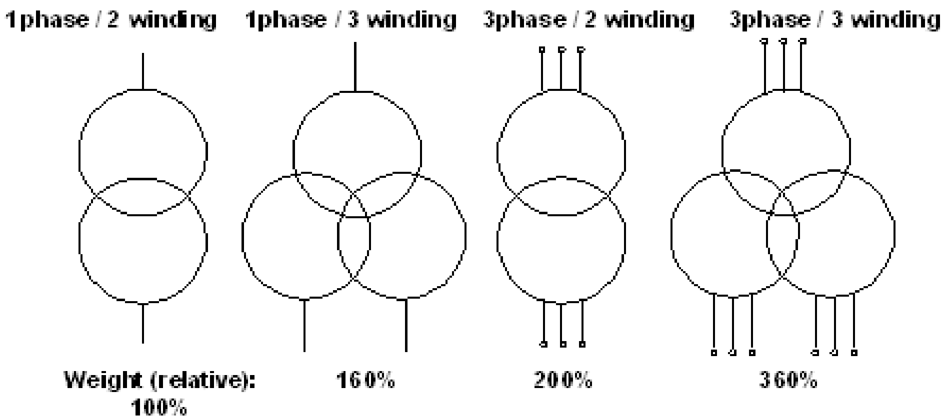

Figure 2.6 The types of converter transformer [31]

In accordance with the voltage requirement, the configuration of converter transformer depends on transformer ratings, transport conditions and the layout of converter station. For the converter transformer with medium capacity and voltage, the three-phase transformer can be selected, in order to reduce material consumption, land use and loss, especially no-load loss. For the converter transformer with relatively large capacity and high voltage, the single-phase transformer groups can be selected, especially without transport limitations, compared with single-phase two-winding transformer, the single-phase three-winding transformer is of less core, oil tank, bushing and on-load tap changer.

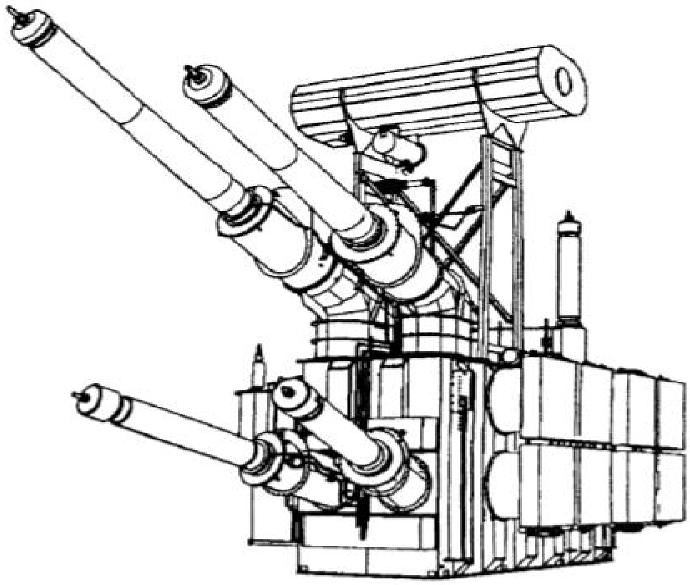

Figure 2.7 One large single-phase three-winding converter transformer with its valve side bushings mounted for entering the valve hall [30]

2.4 Smoothing Reactor

Smoothing reactor can prevent steep impulse waves caused by DC lines or DC switching yard entering the valve hall, thereby avoiding the damage to the converter valve due to overvoltage stress.

Excessive inductance likely results in overvoltages during operations, thereby lowering the response speed. In order to select the suitable reactor inductance, the main considerations are: to limit the rate of rise of the fault current; to smooth the ripples of direct current; to prevent the intermittent current at low-load condition; to arrange the parameters of DC filters with the reactor inductance; to prevent the low-frequency resonance at 50Hz, 100Hz.

Smoothing reactors can be classified into dir/air-type and oil-type. Compared to the oil-type smoothing reactor, the air/dry-type smoothing reactor has the following advantages.

A dry/air-type smoothing reactor is installed on the high-voltage side. Only porcelain support insulators have to be taken into considerations, thereby improving the reliability of insulation. Without oil-insulated systems, the air/dry-type smoothing reactor cannot cause fire hazard and environmental effects. For air/dry-type smoothing reactors, reversal of voltage polarity only produces the stresses on the support insulators. Without limitations of critical electric-field strength, the support insulator of air/dry-type smoothing reactor is very similar to that of other busbars. Without iron-core constructions, the phenomena of magnetism saturation cannot occur under fault conditions, thereby always maintaining the same inductance. Since the capacitance between air/dry-type smoothing reactor and ground is much smaller than the capacitance between oil-type smoothing reactor and ground, air/dry-type smoothing reactors require relatively lower impulse insulation level.

Figure 2.8 Air-core smoothing reactor in the Kontek HVDC transmission [32]

In contrast to air/dry-type smoothing reactor, the oil-type smoothing reactor has the following advantages.

With iron-core constructions, the oil-type smoothing reactor likely increases the reactor inductance. The oil-paper insulation system is very feasible and reliable. The oil-type smoothing reactor is installed on the ground, thus providing the excellent anti-seismic performance.

Figure 2.9 Oil-insulated smoothing reactor in the Rihand – Dehli HVDC transmission [32]

Chapter 3 Reactive Power Management

For line commutated converters, no matter at the rectification or inversion state, an HVDC system need to absorb capacitive reactive power from AC systems. Therefore, the converter is always the reactive-power load to AC system. The reactive power is expressed in terms of the active power, i.e.

$$Q = P \tan\varphi \qquad (3-1)$$

Where;

Q is the reactive power consumed by converters, P is the active power on the DC side of converters, φ is the phase difference between the fundamental-frequency voltage and current components.

Besides the active power, the reactive power consumed by converters is also related to some operating parameters very sensitively, such as firing angle and extinction angle. In the normal operation, when the conversion power is close to the rated power, all possible control modes are employed to minimize the reactive power consumed by converters; when the conversion power is much less than the rated power, AC filters must be added to eliminate harmonics and converters are used to absorb surplus reactive power.

3.1 Reactive Power Balance

For a converter station located close to a power station or power station group, when an HVDC system operates at high load, generators can provide part of reactive power, in order to reduce the number of equipments providing capacitive reactive-power; when an HVDC system operates at low load, generators can absorb part of overcompensation reactive power, in order to reduce the number of equipments supplying inductive reactive-power. Fully utilizing the reactive-power capability of AC system to balance the reactive power can reduce the reactive-power compensation capacity provided by the converter station, save the investment of the reactive-power compensators (capacitor and reactor), reduce the load-rejection overvoltage level at the instant of HVDC system sudden interruption. [33] [34]

For a converter station located in a load center, the AC-busbar voltage of converter station is required to maintain basically constant. Under the high-load mode, due to inadequate reactive-power compensation and AC-voltage drop, the converter station is required to compensate part of reactive power. Under the low-load mode, due to surplus reactive-power and AC-voltage rise, the converter station is required to absorb part of reactive power.

3.2 Voltage Stability

AC voltage depends on the active-power and reactive-power characteristics of the converter. In order to minimize AC-voltage variations, the supplied reactive-power must match the reactive-power consumed by converters. Therefore, a converter station must install reactive-power compensators, in order to provide reactive power and satisfy filtering requirements. If generators are close to the sending-end of HVDC system, appropriately using generators is always more economical and effective to handle most reactive power demands and maintain AC voltage within an acceptable range. For weak AC systems, it is necessary to install static var compensators or synchronous compensators. [35]

When the HVDC system deblocks, if the minimum number of AC filters are suddenly added, the reactive power consumed by converters will be much less than the reactive power supplied by AC filters, thereby resulting in the reactive-power impact on the AC system and causing AC-voltage fluctuation. If the HVDC system operates at low load, adding the minimum number of AC-filters will lead to surplus reactive power and thus it is very difficult to regulate AC voltage. Furthermore, under the most severe condition, it is necessary to block the HVDC system. If the HVDC system operates at high load, due to insufficient reactive power in the sending-end converter station, the local generators must be regulated immediately to supply reactive power, in order to avoid the reduction of AC-busbar voltage. [36]

3.3 Reactive Power Compensators

In the converter station, the reactive-power compensators can be primarily classified into the following categories. [37]

1. AC Filter and Capacitor Bank

If the connected AC system is not very weak, AC filters and capacitor banks are usually employed. Besides harmonics elimination, AC filters can also provide fundamental-frequency reactive power. In order to meet reactive power demands, only using capacitor banks for reactive power compensation can provide much better economic solution rather than improving the capacity of AC filter.

2. Static Var Compensator

In order to regulate reactive power smoothly and quickly, static var compensators, such as AC self-saturated reactors, thyristor-controlled reactors and thyristor-switched capacitors, can be employed. In addition, if the receiving-end AC system is weak, using static var compensators can also improve dynamic AC-voltage stability, thereby enhancing the control stability for HVDC system and increasing the speed of response.

3. Synchronous Compensator

For a very weak AC network relative to the capacity of HVDC system, synchronous compensators are required to install in the receiving-terminal converter station, especially from a remote power station to a high-density load centre, and synchronous compensators are of the slow response characteristic, thereby causing a certain problem especially in the lack of local generation. However, using synchronous compensators can increase the short-circuit ratio, thereby reducing the sensitivity to transients.

Selecting suitable reactive-power compensatiors mainly depends on the AC-DC system strength, which is generally expressed by the short-circuit ratio, i.e. the ratio of the AC-system short-circuit capacity to DC-link power. If the short-circuit ratio is greater than 3, capacitors and reactors are only considered; if the short-circuit ratio is between 2 and 3, voltage stability must be calculated and the reactive-power compensatiors with voltage control capability can be considered; if the short-circuit ratio is less than 2, when using conventional conversion technology, installing synchronous compensators is the most effective method. [38]

Chapter 4 AC Filter Design

4.1 AC Harmonics

Line commutated converters discussed in this book generate characteristic harmonics, non-characteristic harmonics (including cross-modulation harmonics) on the AC side.

1. Characteristic Harmonics

Characteristic harmonics are based on the following ideal conversion circumstances: AC-busbar voltage is of the constant-frequency ideal sinusoidal waveform; for a converter transformer, phase-impedances or ratios are the same; two converter-transformers are of the same impedances or ratios; converter firing pulses are of equally-spaced; the current flowing through DC-circuit is ideal direct current. [39]

2. Non-Characteristic Harmonics

In practice, the operating circumstances are always not ideal. The non-ideal factors are: the ripples exist in direct current; the harmonics exist in AC voltage; AC fundamental-frequency voltages are asymmetrical with negative-sequence voltage; for a converter transformer, phase-impedances are not identical; two converters are of different firing-angles; due to different converter-transformer ratios, two converters are of different commutating voltages; two converter-transformers are of different impedances; converter firing pulses are not of equally-spaced. [40]

4.2 Design Criteria

1. Voltage Distortion

Because the system harmonic impedance is small, the flow of harmonic current cannot cause the serious problem. Therefore, the reduction of harmonic voltage to an acceptable level at the converter station is a more effective criterion for filter design. In general, the voltage distortion caused by individual harmonics (V_n) and the total harmonic voltage distortion are specified factors. The total harmonic voltage distortion is defined as

$$V_{TD} = \sqrt{\sum_{n=2}^{\infty} V_n^2} \qquad (4-1)$$

2. Telephone Interference Factor (TIF)

An early telephone system was based on open-wire communications disturbed by power-lines likely. Therefore, concerning with filter design, the telephone interference factor must be taken into account to approximately assess the effect of the distorted voltage or current waveform of a power line on telephone noise. The TIF is defined as

$$\mathrm{TIF} = \frac{1}{V}\left[\sum_{f=0}^{\infty}\left(K_f P_f V_f\right)^2\right]^{1/2} \qquad (4-2)$$

$$V = \left[\sum_{f=0}^{\infty} V_f^2\right]^{1/2} \qquad (4-3)$$

Where;

K_f = 5000(f/1000) = 5f,
P_f = C-message weighting,
V_f = r.m.s. voltage of frequency f on the power line.

4.3 Passive AC Filters

For instance, most HVDC schemes use conventional passive AC filters with successful experience. Active AC filters and continuously tuned AC filters were rarely installed in HVDC schemes. [41] Therefore, only passive AC filters are discussed in this book. A passive filter is parallel with the connected AC system and also regarded as bypass path for harmonics, thereby providing very low impedance under the harmonic frequency.

AC filters are used not only to eliminate harmonic currents, but also to supply part of fundamental-frequency reactive-power. In accordance with the frequency-impedance characteristics, conventional passive filters are of tuned filters (normally tuned for one or two frequencies, at most three frequencies), high-pass filters (relatively low impedance over a wide range of frequency) and multi-tuned high-pass filters (tuned filters combined with high-pass filters).

4.3.1 Tuned Filters

1. Single-Tuned Filter

The circuit and impedance-frequency characteristic of single-tuned filter are shown in Figure 4.1.

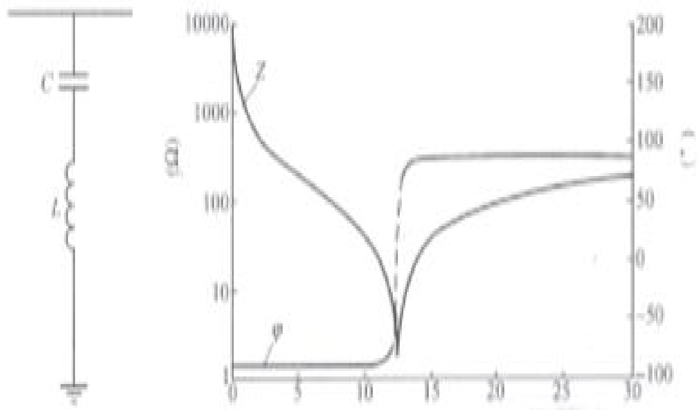

Figure 4.1 The circuit and impedance-frequency characteristic of single-tuned filter [42]

The main conditions to determine filter parameters are fundamental-frequency reactive-power capacity per single filter under rated voltage, and tuning frequency. A single-tuned filter is more sensitive to the frequency deviation and normally tuned for the characteristic harmonics, i.e. the 5^{th}, 7^{th}, 11^{th} and 13^{th}. Because 12-pulse converters have been used widely, the single-tuned filters are not installed any longer in new HVDC schemes.

2. Double-Tuned Filter

The circuit and impedance-frequency characteristic of double-tuned filter are shown in Figure 4.2.

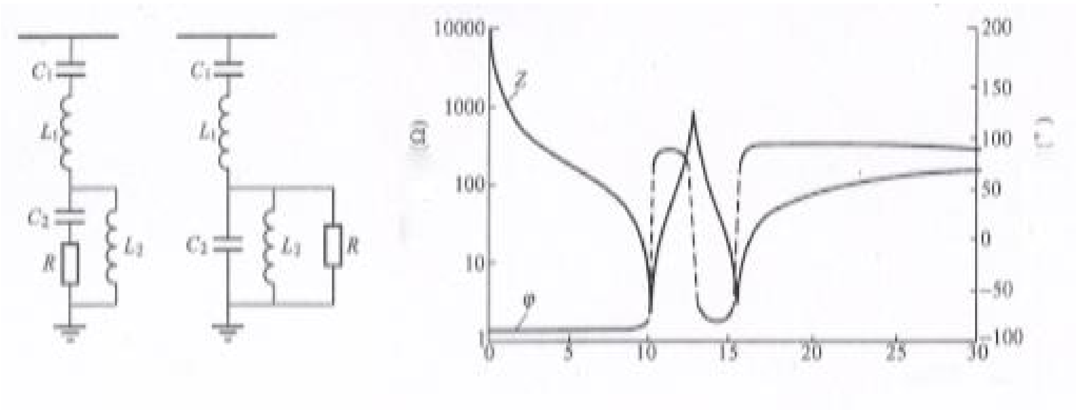

Figure 4.2 The circuit and impedance-frequency characteristic of double-tuned filter [42]

The main conditions to determine filter parameters are fundamental-frequency reactive-power capacity per single filter under rated voltage, double tuning frequencies and parallel-circuit tuning frequency. A double-tuned filter can cancel double characteristic harmonics and produce much lower loss than two single-tuned filters together. The double-tuned filter is the most popular filter in modern HVDC transmission schemes. [43]

3. Triple-Tuned Filter

The circuit and impedance-frequency characteristic of triple-tuned filter are shown in Figure 4.3.

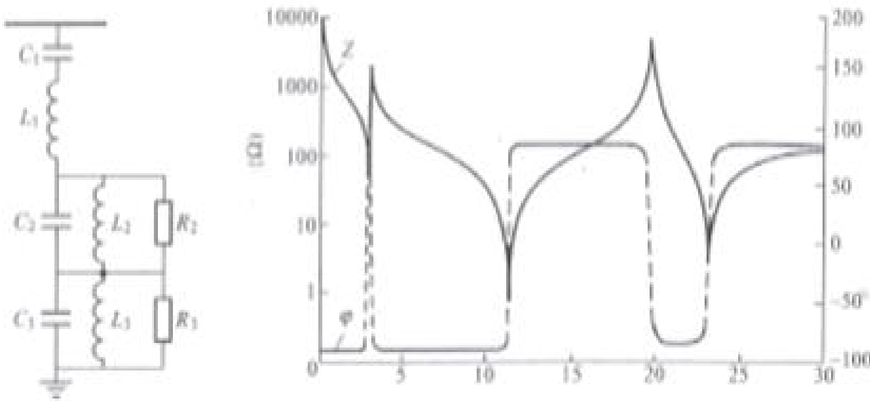

Figure 4.3 The circuit and impedance-frequency characteristic of triple-tuned filter [42]

A triple-tuned filter can eliminate three harmonics, thereby substantially reduce the land use. For the triple-tuned filter, the number of high-voltage circuit breakers and capacitors are less than the double-tuned filter. The most outstanding advantage of triple-tuned filter is the convenient reactive-power balance characteristic at low load. [44]

4.3.2 Damped Filters

1. Second-Order High-Pass Damped Filter

The circuit and impedance-frequency characteristic of second-order high-pass damped filter are shown in Figure 4.4.

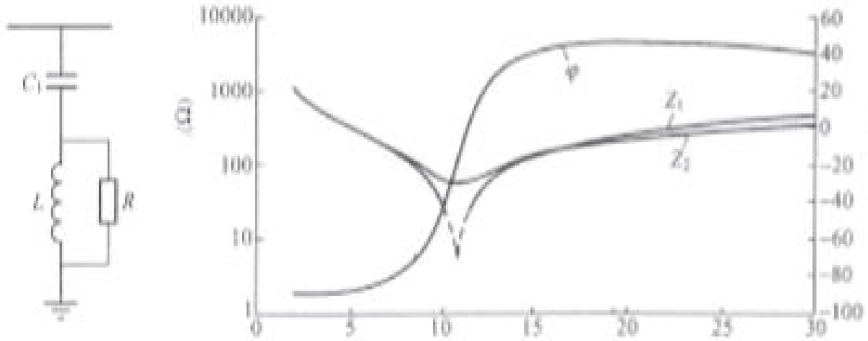

Figure 4.4 The circuit and impedance-frequency characteristic of second-order high-pass damped filter [42]

Except for selecting suitable damped resistance, the component parameters of second-order high-pass damped filter are similar to those of single-tuned filter. The second-order high-pass damped filter was used frequently in early HVDC schemes.

2. Third-Order High-Pass Damped Filter

The circuit and impedance-frequency characteristic of third-order high-pass damped filter are shown in Figure 4.5.

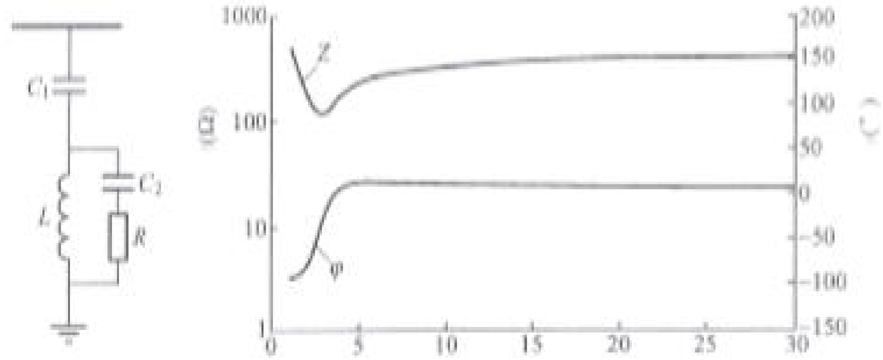

Figure 4.5 The circuit and impedance-frequency characteristic of third-order high-pass damped filter [42]

Except for selecting suitable damped resistance, the tuning frequency of parallel circuit must be also selected to determine the component parameters. The fundamental-frequency loss of third-order high-pass damped filter is lower than that of second-order high-pass damped filter.

3. Type-C Damped Filter

The circuit and impedance-frequency characteristic of type-C damped filter are shown in Figure 4.6.

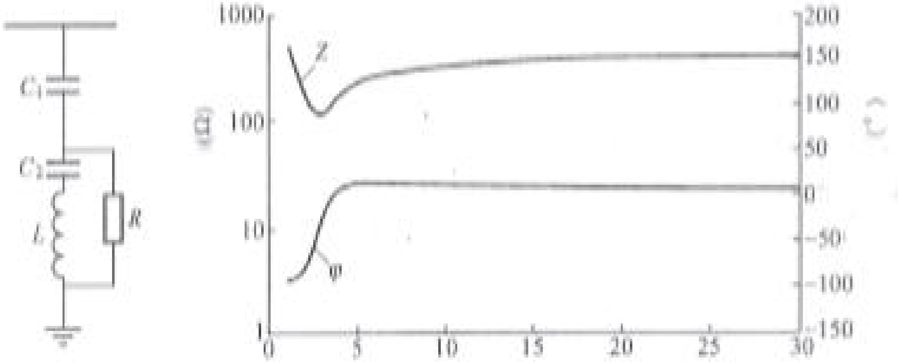

Figure 4.6 The circuit and impedance-frequency characteristic of type-C damped filter [42]

A type-C damped filter was developed from the third-order high-pass damped filter. The main factors to determine component parameters are fundamental-frequency reactive power, resonance condition, resonance frequency and damped requirement. For instance, the type-C damped filter is widely used for low-order harmonics. [45]

4. Double-Tuned High-Pass Damped Filter

A double-tuned high-pass damped filter is used to eliminate harmonics over a wide range of frequency. In compared with the above damped filters, the performance of double-tuned high-pass damped filter has no obvious merits.

Chapter 5 DC Filter Design

5.1 DC Harmonics

Line commutated converters generate characteristic and non-characteristic harmonics on the DC side.

1. Characteristic Harmonics

Characteristic harmonics are based on the following ideal conversion circumstances: the AC-busbar voltages of the converter are purely three-phase symmetrical sinusoidal waves; the current flowing through the converter is ripple-free direct current; the parameters of the converter itself are three-phase absolutely symmetry; the control system of the converter produces perfectly equally-spaced converter firing pulses.

Under above ideal conditions, converters generate direct voltage on the DC side. According to Fourier analysis, for a 6-pulse bridge converter, direct voltage contains harmonics of order 6n (i.e., 6^{th}, 12^{th}, 18^{th}, etc.) and for a 12-pulse bridge converter, direct voltage contains harmonics of order 12n (i.e., 12^{th}, 24^{th}, 36^{th}, etc.).

In the early 1990s, when built U.S.A Intermountain Power Project HVDC transmission, owing to DC earth electrode lines and DC lines erected on the same tower, the DC-side harmonics exceeded the normal standards seriously. [46] The capacitance of the DC neutral point to ground has the important effect on the 18^{th} harmonic, while the stray capacitance of the converter to ground has the important effect on the distribution of DC-side harmonic currents. Therefore, the equivalent circuit shown in Figure 5.1 was used to express the 3-pulse model of DC-side harmonics for a 12-pulse converter. [47] In the 3-pulse model of DC-side harmonics, for various harmonic-voltage sources, the amplitudes of harmonic voltages are the same and equal to 1/4 of the values of the 12-pulse model's harmonic voltages.

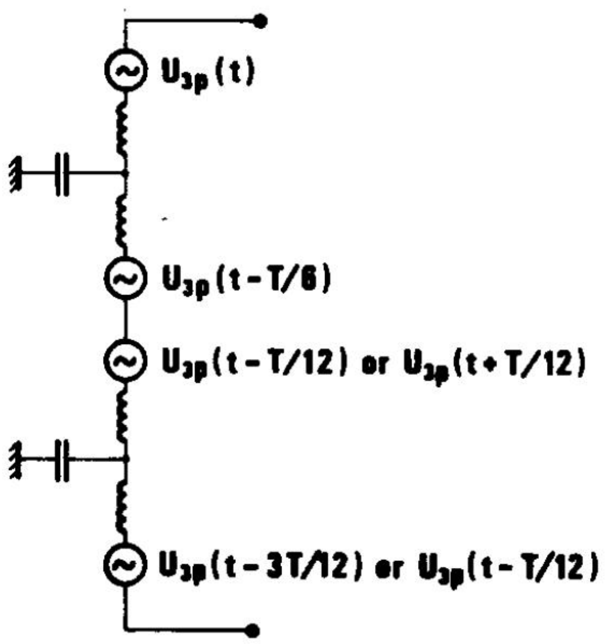

Figure 5.1 The novel 3-pulse model of DC-side harmonics for a 12-pulse converter [47]

U_1 – U_4 – 3-pulse harmonic voltage source;

Z_1 – Z_4 – 1/4 12-pulse converter internal impedance;

C_1, C_2 – the stray capacitance of the converter transformer to ground

2. Non-Characteristic Harmonics

The factors, which produce the DC-side non-characteristic harmonics, can be classified into the following categories.

(1). AC system voltages are never perfectly balanced and undistorted, and the system impedances are not exactly equal in the three phases. Therefore, the AC busbar voltages contain the harmonic voltages and generate the non-characteristic harmonic voltages on the DC side.

(2). For a 12-pulse converter, the transformer turn ratios and transformer reactances are not identical for the star-star connected converter transformer and the star-delta connected converter transformer. For a converter transformer, the transformer leakage reactances are unbalanced in the three phases. As a result, unequal commutation reactances also cause non-characteristic voltages on the DC side.

(3). In accordance with practical situations, the unequal operating parameters of two-pole converters must be calculated. The amplitudes and phasors of harmonics must be fully considered respectively.

5.2 Design Criteria

In order to reduce the harmonic hazard, the overhead-line HVDC systems usually install the DC filters, but the back-to-back and full-cable HVDC systems are not required to install the DC filters. Therefore the DC filters are mainly designed to overcome the interference on the open-wire communications. In order to assess the interference level, the harmonic voltage and current profiles along the HVDC line, especially electromagnetic induction from harmonic currents, must be carried out comprehensively. Moreover, due to the disturbances at both ends of the link, the profits from each end must add their effects necessarily. [48]

There is no unified DC-side harmonic indexes defined by the international conferences, and the DC-side harmonic standards must be evaluated in the HVDC system respectively. The DC-side harmonic indexes (DC filter performance) contain induced noise voltage (INV), equivalent disturbing current (EDC) and DC-line harmonic current limit. [49] Until 1970s, in the planning stage of the HVDC transmission system, the induced noise voltage was no longer used, and the equivalent disturbing current was widely employed to design the DC filters.

Close to parallel or cross communication lines, the comprehensive interference effect produced by all the harmonic currents of the DC lines can be expressed by the single-frequency (800 Hz) harmonic current, so-called the equivalent disturbing current. [50]

$$I_{eq}(x) = [I_e(x)^2{}_S + I_e(x)^2{}_R]^{1/2} \qquad (5-1)$$

Where;

$I_{eq}(x)$ is the 800 Hz equivalent disturbing current at any point along the transmission corridor, $I_e(x)_S$ is the magnitude of the equivalent disturbing current component due to harmonic voltage sources at the sending end, $I_e(x)_R$ is the magnitude of the equivalent disturbing current component due to harmonic voltage sources at the receiving end, x denotes the relative location along the transmission corridors.

The equivalent disturbing current, which is caused by harmonic voltages, highly depends on the harmonic weights. The standard harmonic weighting curves are used to take into account the sensitivity of the human ear to the harmonic frequencies. Two harmonic weighting factors are in common use:

The psophometric weighting by the CCITT [51], extensively used in Europe;

The C-message weighting by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI), used in the USA and Canada. [52]

Figure 5.2 shows that the difference between these two harmonic weighting curves is very slight and that the human ear has a sensitivity to audio-frequencies that peaks at about 1 kHz. [53]

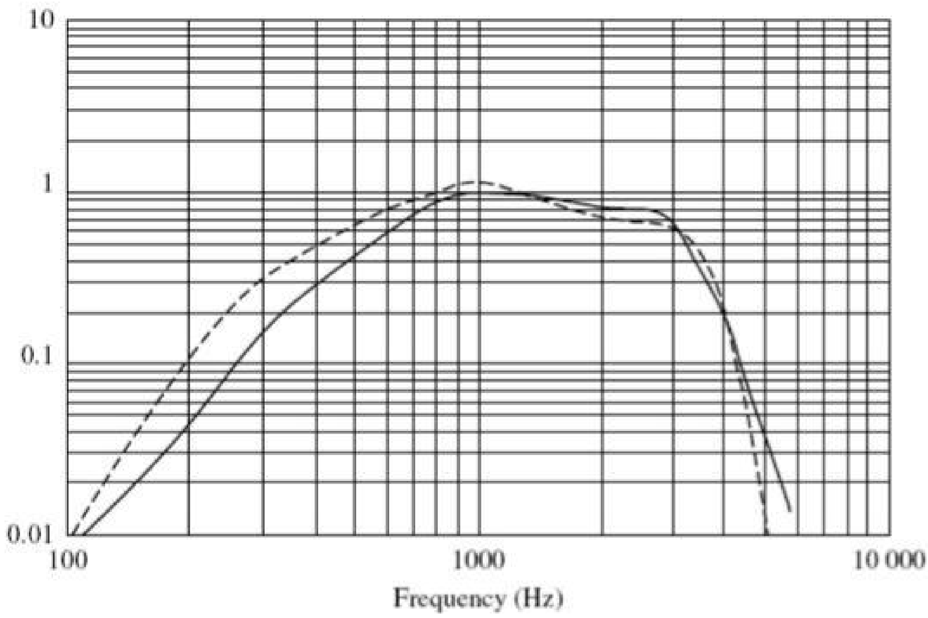

Figure 5.2 C-message (real-line) and psophometric weighting (dash-line) factors [53]

5.3 Active DC Filter

Passive DC filters had been employed in most HVDC schemes. In 1991 the world's first active DC filter was commissioned in the Konti-Skan HVDC link. [54]

Usually a DC filter is connected between the pole busbar and the neutral busbar. The structure of passive DC filter is similar to that of AC filter, such as single-tuned, double-tuned and triple-tuned circuits with or without high-pass characteristic. A capacitor is installed between the neutral busbar and ground, thereby providing low-impedance path for harmonic currents of order 3n (i.e., 3^{rd}, 6^{th}, 9^{th}, etc.). In the Three Gorges-Changzhou HVDC project using 12-pulse converter, passive double-tuned (12/24 and 12/36) DC filters are finally installed. [55]

It is feasible to install active filters on both AC and DC side. Active AC filters also provide reactive power, but the capacity of super-capacitor is limited owing to the price. Therefore, active AC filters are mainly used for harmonic elimination and reactive power compensation can be solved by other alternatives. On the DC side, without the reactive power demand, active DC filters are only used to reduce harmonic currents that enter into the DC line, so as to avoid telephone interference.

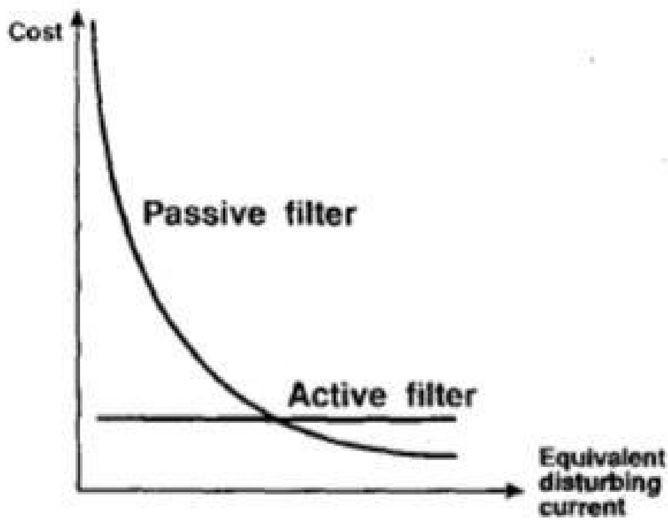

Figure 5.3 The cost of DC filter versus the equivalent disturbing current [56]

According to different equivalent disturbing currents, the cost of active DC filters compared to passive DC filters is shown in Figure 5.5. The cost of passive filter can increase dramatically when the equivalent disturbing current reduces; however, since active filter can eliminate all harmonics within the whole range of frequency variation, the cost of active filter remains constant. [56]

Based on present passive filter, an active filter is composed of passive part and active part, and they are connected either in series or in parallel. [57] [58] The main components of the active filter are shown in Figure 5.6. A current transducer can measure the harmonic currents in the DC-line, and a control system injects the harmonic currents into the DC line with the same magnitude but opposite phase as the original harmonic currents in the DC-line. Thereby the DC-side harmonic current on the DC-line is cancelled.

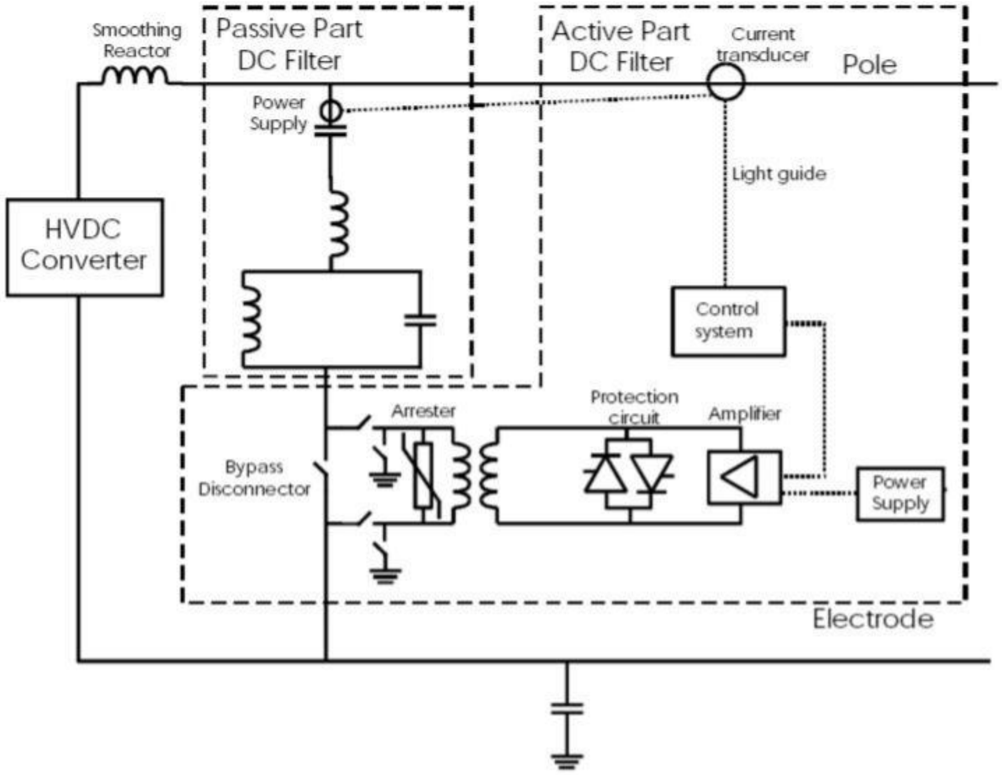

Figure 5.4 The topology of an active filter [54]

Chapter 6 Control System

In a two-terminal (point-to-point) HVDC transmission system, the capacity and direction of power flow can be controlled rapidly, so as to satisfy the operational demands for the entire AC/DC hybrid systems. In this book, the control system is only designed for the two-terminal HVDC transmission system, in order to provide the following fundamental control functions.

1. controlling the starting and stopping sequences of an HVDC transmission system;

2. controlling the capacity and direction of transfer power;

3. controlling the abnormal operations of converters and the disturbances of AC systems interconnected;

4. when faults occur, protecting the equipments of the converter station;

5. monitoring a variety of operating parameters for converter stations and DC lines, and supervising the information of the control system itself;

6. enhancing the interface to the equipments of the AC substation and improving the link with operators.

6.1 Multiple Configurations

In order to meet the indexes of availability and reliability required by HVDC systems, all the control systems employ the design of multiple configurations, usually using the double-channel design, one channel is active and the other channel is on the hot standby status. When faults occur in the active channel, the hot standby channel is automatically switched to the active status and automatic switching actions should not cause the obvious disturbances to the transfer power. In some cases, the triple-channel design is employed. For example, Gezhouba – Nanqiao, ThreeGorge – Guangdong HVDC systems and Russia

– Finland back-to-back HVDC system all employ the triple-channel design. As the channel number increases, the equipments' investment and components' fault will increase correspondingly. In general, the double-channel design is a rather better selection.

6.2 Control System Levels

A complicated control system using different levels can improve the reliability and flexibility of system operation and maintenance, in order to minimize the influence and hazard extent caused by control faults.

According to the level concept, all the control components are divided into bipole function (highest level), pole function and valve group function (lowest level) respectively. In order to reduce the faults' influence scope, all the control functions must be put into the utmost low level and especially the number of the control components concerning with bipole function must minimize.

For reasons of reliability, the control system of a modern HVDC scheme is generally divided into four-level hierarchies from top to down, i.e. system (overall) control hierarchy, bipole (master) control hierarchy, pole control hierarchy and converter (bridge) control hierarchy. [59] Figure 6.1 shows the control-level system of a bipolar HVDC system.

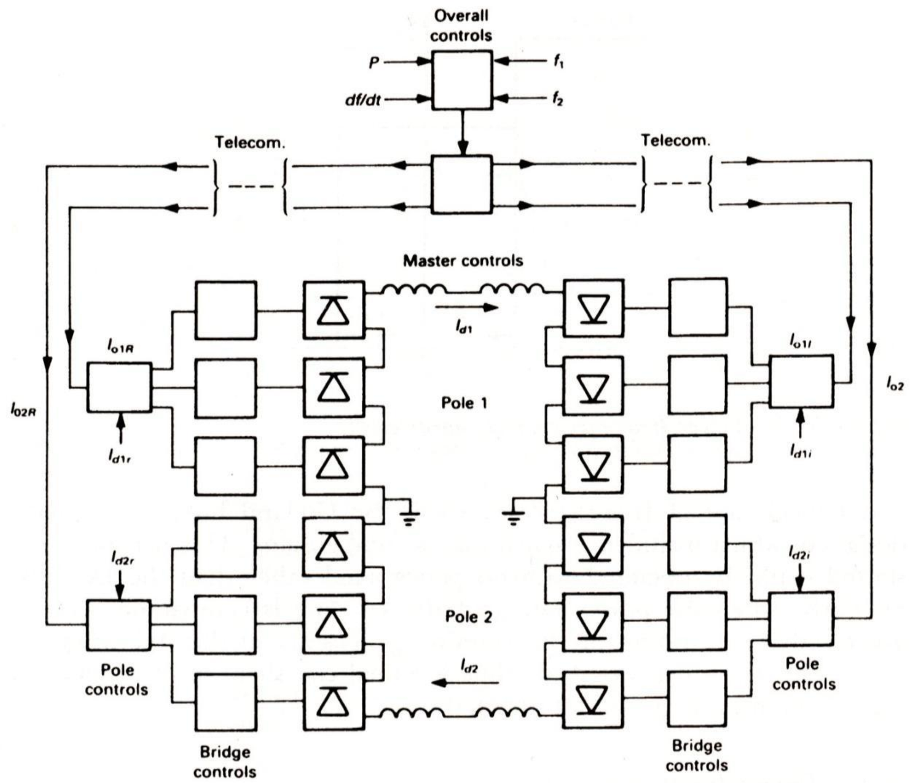

Figure 6.1 The block diagram of level structure for the control system [59]

For only one converter unit in each pole, in order to simplify structures, the pole control and converter control can group together as one control hierarchy; for only one bipolar line, the system control and bipole control usually group together as one hierarchy. Among all converter stations, only one is regarded as the master control station and others as slave control stations; the system control and bipole control are set in the master control station, in order to send out control commands via communication systems and coordinate the operation of the whole system.

1. Converter Control Hierarchy

A converter control hierarchy is used to control the converter's firing phase. The main control functions of the converter control hierarchy are: converter firing-phase control; constant current control; constant extinction-angle control; direct voltage control; maximum and minimum firing-angle limit control; maximum and minimum direct-voltage limit control; maximum and minimum direct-current limit control; converter unit blocking and deblocking sequence control.

2. Pole Control Hierarchy

A pole control hierarchy is used to control one pole. For a bipolar HVDC transmission system, if one pole is isolated due to a fault, the other pole must operate independently and complete the main control functions. Therefore, one pole control hierarchy is completely independent from the other and each pole control hierarchy must configure the utmost control functions. The main functions of the pole control hierarchy are:

(1) in order to control direct current, the pole control hierarchy provides the current orders to the converter control hierarchy and the master control station transfers the current orders to the slave control station through communication systems;

(2) in order to control DC power, direct current orders are determined by power orders and actual direct voltages, and power orders are defined by the bipole control hierarchy;

(3) the starting and stopping controls for one pole;

(4) fault process controls, such as phase-shift stopping, automatic restarting and voltage-dependent current limit;

(5) remote controls and communications between converter stations for the same pole.

3. Bipole Control Hierarchy

A bipole control hierarchy is used to control two poles simultaneously for a bipolar HVDC transmission system, in order to coordinate and control the bipolar operations via the commands. The main functions of bipole control hierarchy are:

(1) bipolar power orders are determined by the power command, which is ordered by the system control hierarchy;

(2) the direction control for power transfer;

(3) the current balance control for bipolar link;

(4) AC-busbar voltage control and reactive power control of the converter station.

4. System Control Level

A system control hierarchy is the highest-hierarchy control level in the HVDC transmission system. The main functions of system control hierarchy are:

(1) a system control hierarchy communicates with power system dispatch center, in order to accept the control commands from the dispatch center and to transfer the corresponding operating information to the communication center;

(2) in according with the transfer-power command from dispatch center, the system control hierarchy distributes the transfer power among all the DC lines;

(3) emergence power support control;

(4) power flow reversal control;

(5) current and power modulation control, damp control for damping AC system oscillations, AC system frequency or power/frequency control.

6.3 Converter Firing Phase Control

Converter firing phase control is used to change the firing phase of the converter valve. An ideal control system for a converter must meet perfectly symmetrical and sinusoidal waveforms with the firing angles occurring at exactly equal intervals and in the appropriate cyclic sequence. [60] Deviations from such ideal conditions give rise to two basically different control methods. Two basic types of control methods have been used for the generation of converter firing pulses:

1. Individual phase control (IPC)

2. Equidistant pulse control (EPC)

6.3.1 Individual Phase Control

An individual phase control method was widely used in the early HVDC converter. The characteristics of individual phase control are: the firing-phase control circuit is installed individually and respectively for each converter valve; the firing pulses are generated individually for each converter valve and determined by the zero crossing of commutation voltage in order to determine the firing-instant phase and maintain the identical firing angle for each valve.

In general the three-phase voltage-waveforms are more or less asymmetrical, and although the firing angles for all the valves are equal, the phase intervals of the cyclic firing pulses are not equal. The unequal phase-intervals of the firing pulses will give rise to the non-characteristics harmonic currents and voltages on the AC and DC sides respectively. The low-order non-characteristics harmonic currents flowing into the AC systems will further cause AC-voltage distortion and zero crossing spacing, thereby causing more unequal firing-pulse intervals and producing even more considerable non-characteristic harmonics. In addition, the unequal firing-pulse intervals will produce DC bias magnetisation on the converter transformers and thereby increase the transformer's losses and noise. The harmonic instability is the main disadvantage for individual phase control. [61] [62]

6.3.2 Equidistant Pulse Control

An equidistant pulse control method ensures the equal phase-intervals between the cyclic firing pulses as a target. Each converter solely installs one phase-control circuitry which generates a series of equal-interval firing-pulse signals. In accordance with a specific sequence, these pulses are in turn transferred to the corresponding valve's firing-pulse generator to trigger the valve.

If the three-phase voltage-waveforms are symmetrical, the equidistant pulse control ensures the identical firing angles for all the valves. If the three-phase voltage-waveforms are asymmetrical, even with the unequal firing angles, the equidistant pulse control method can effectively suppress the non-characteristic harmonics in order to avoid the harmonic instability. [63] [64]

6.4 Converter Control Mode

As electronics technologies have developed rapidly in recent years, the fully microprocessor control has been employed widely in the world. However, the fundamental control principle – current margin mode, was used as an effective control method since Gotland HVDC scheme in 1954. [65]

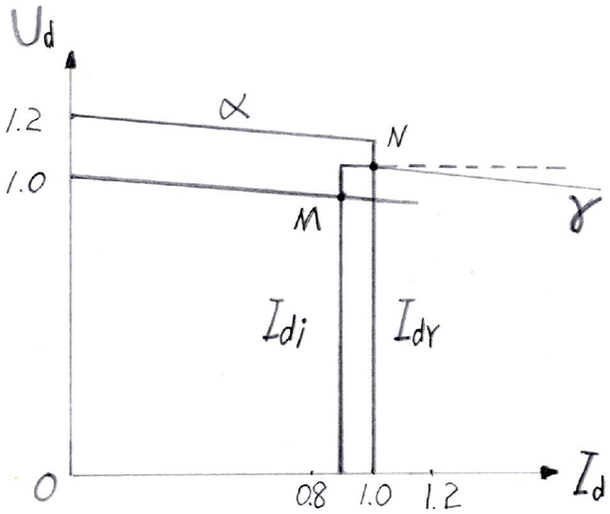

Figure 6.2 Basic control characteristics schematic diagram [65]

The basic control mode of two-terminal HVDC system is simply shown in Figure 6.2. The rectifier-side characteristic consists of two segments: constant direct current and constant minimum firing angle. The inverter-side characteristic consists of two segments: constant direct current and constant extinction angle or constant direct voltage (dash-line shown in Figure 6.2). In order to avoid regulation instability caused by two-terminal current regulators working simultaneously, the setting of the inverter-side current regulator is lower than that of the rectifier-side current regulator, termed current margin. According to the current margin control principle, the current margin must be maintained no matter under the steady-state operation or under the transient situation. In most HVDC systems, the current margin is set at 10% of the rated direct current.

Under normal operation, usually the rectifier is operated at the constant direct current and the inverter is operated at the constant extinction angle or the constant direct voltage, and the normal operating condition is represented by the intersection point N as shown in Figure 6.2; when considerably reducing the rectifier-side AC-voltage or substantially increasing the inverter-side AC-voltage, the rectifier automatically shifts to the constant minimum firing angle control mode and the inverter automatically shifts to the direct current control mode, and the operating condition is represented by the intersection point M as shown in Figure 6.2.

6.5 Control System Functions

1. Starting/Stopping Control

In order to reduce overvoltage and overcurrent, and to decrease the impact on two-terminal AC systems, the normal starting and stopping procedures for an HVDC transmission system must be executed strictly by following a prescribed series of steps and sequences. [66]

- Normal Starting Main Sequences

(1). the converter-transformer network-side's circuit-breakers are closed respectively in the two-terminal converter stations, so as to energize the converter transformers and converter valves.

(2). DC-side switches are operated respectively in the two-terminal converter stations, so as to connect DC circuits.

(3). adding the appropriate AC-filter branches respectively in the two-terminal converter stations.

(4). when the firing angle is equal to 90º (or greater than 90º), the inverter is deblocked initially, and then the rectifier is deblocked.

(5). according to the direct-voltage variation, the inverter-side direct-voltage regulator (or extinction-angle regulator) gradually increases direct voltage up to the operating setting (or extinction-angle setting).

(6). at the same time, according to the direct-current variation, the rectifier-side current regulator gradually increases direct current up to the operating setting.

(7). when increasing the direct voltage and direct current to the settings, the starting procedure completes and the HVDC transmission system is on the normal operation.

AC-filter banks are added group by group during the normal starting procedure, so as to satisfy the requirements of reactive-power compensation and harmonics elimination. The time of normal starting procedure generally depends on the capabilities of AC-systems at both ends, taking as short as several seconds or as long as several tends of minutes.

- Normal Stopping Main Sequences

(1). according to the variation of direct current, the rectifier-side current regulator gradually decreases direct current down to the allowable minimum value. As DC power decreases, AC-filter banks are switched out group by group, so as to satisfy the requirements of reactive-power balance.

(2). the rectifier firing pulses are blocked and the remaining AC-filter banks are switched out on the rectifier side.

(3). when direct current reduces to zero, the inverter firing pulses are blocked, and the remaining AC-filter banks are switched out on the inverter side.

(4). DC-side switches are operated respectively in the two-terminal converter stations, so as to disconnect between DC lines and converter stations.

(5). AC switches are operated respectively in the two-terminal converter stations, so as to trip the circuit breakers on the converter transformer network sides.

2. Power Control

- Constant Power Control

Constant power control is the primary control mode in HVDC schemes. Usually, the transfer power can be controlled by changing the current order of direct current regulator. Constant-power control mode can fully exploit the fast response characteristics of direct current regulation loop. Moverover, under the transient state, due to the extreme variations of direct voltage, the current order may fluctuate considerably.

- Constant Current Control

Usually the response of constant-current control-loop is faster than that of constant-power control-loop. Therefore, in order to enhance the system stability, constant current control is used during extreme disturbances.

3. Power-Flow Reversal Control

Using the fast controllability of the HVDC transmission system can automatically reverse the direction of power flow during operations. The power-flow reversal only depends on the polarity change of direct voltage and is automatically executed by the prescribed sequences, and the time of power-flow reversal primarily depends on the requirements of two-terminal AC systems to DC-power change and the constraints of DC-system main circuits. [66]

4. Modulation Functions

The modulation functions are required to fully exploit the controllability of HVDC system, in order to enhance the AC-system dynamic performance, and thus the modulation functions are so called the supplementary controls of HVDC transmission system. Since

1976 the power modulator was installed in Pacific Intertie HVDC scheme to damp the parallel AC-line's oscillations, the HVDC modulation has considerable advantages on grid interconnection and power system stability.

The modulation functions designed fully depend on the requirements of the connected AC systems. The modulation functions usually include power run-ups, power run-backs, frequency control, reactive power modulation, damping control, power modulation and so on. [67] [68] [69] [70]

Chapter 7 Fault Analysis

The characteristics of internal and external faults are rather different, and must be studied separately.

7.1 Converter Faults

Converter faults can be classified into main circuit fault and control system fault. Short-circuit faults can occur at different locations of the converter station, as shown in Figure 7.1.

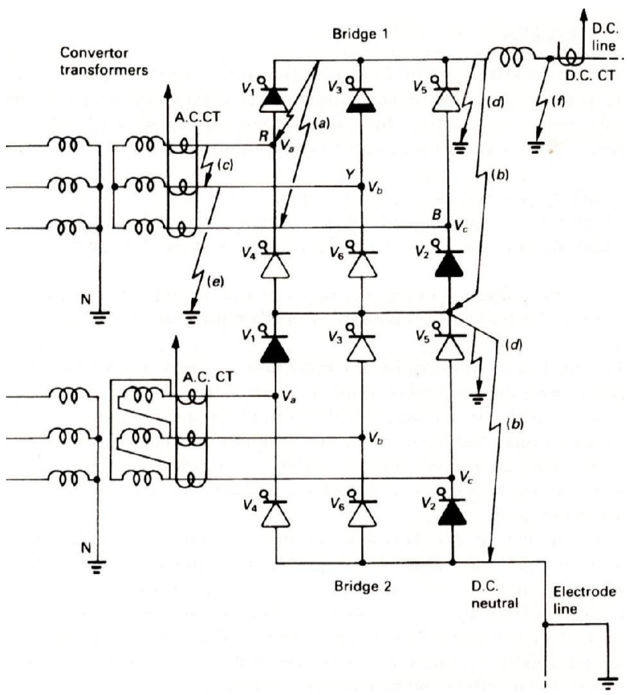

Figure 7.1 The locations of short-circuit faults in one 12-pulse converter [71]

1. Converter Valve Short Circuit Fault

- Rectifier Valve Short Circuit

A valve short-circuit is the most serious fault, due to the valve internal or external insulation breakdown, or the valve short-circuited, and the fault location of valve short circuit is shown in Figure 7.1 (a). A rectifier valve must withstand the reverse voltage during the non-conduction period. If the peak value of the reverse voltage leaps extremely or the water cooling system leaks considerably, the valve insulation may be damaged, thereby causing the short circuit across valve.

The characteristics of valve short circuit are: the two-phase short circuit and three-phase short circuit occur alternatively on the AC side; the current flows through the fault valve from the reverse direction and increases dramatically; the AC-side current increases significantly, and thereby the converter valve and converter transformer withstand considerable current more than the normal current; the DC-busbar voltage and DC-side current of the converter bridge fall down.

- Inverter Valve Short Circuit

An inverter valve withstands the forward voltage during most of non-conduction period. The excessive high voltage or the rate of rise of voltage is likely to break the valve insulation, thereby causing the short circuit.

2. Inverter Commutation Failure

A commutation failure is the common fault of the inverter and is caused by the inverter valve short circuit, the AC-system frequency spectrum, the inverter firing-pulse lost and the inverter-side AC-system faults. [72] [73]

The characteristics of commutation failure are: the extinction angle is lower than the time of valve recovery block; the direct voltage of 6-pulse inverter reduces to zero during a certain period; direct current increases temporarily; the fundamental frequency components penetrate into the DC system; the open circuit occurs temporarily on the AC side and the current decreases. [74]

3. Converter DC-side Terminal Short Circuit

A DC-side terminal short circuit is the short-circuit fault occurred between converter DC-side terminals and the fault locations are shown in Figure 7.1 (b).

- Rectifier DC-side Terminal Short Circuit

When the rectifier DC-side terminal short circuit occurs, the converter valve still maintains the unidirectional conduction characteristic. The characteristics of the rectifier DC-side terminal short circuit are: the two-phase short circuit and three-phase short circuit occur alternatively on the AC side; the conduction-valve current and AC-side current increase dramatically, and the fault value is many times higher than the normal value; the short circuit causes the DC-line-side current to fall down; the converter valve maintains the forward-direction conduction.

- Inverter DC-side Terminal Short Circuit

When the inverter DC-side terminal short circuit occurs, the DC-line current rises up. Due to DC-side smoothing reactor, the rate of rise of the fault current is quite slow and the short-circuit current is relatively small. When the inverter DC-side short circuit occurs, the current flowing through the inverter valve will reduce rapidly to zero and the short-circuit fault causes no harm to the inverter and converter transformer. In fact, when each valve is fired, the momentary charge current still exists. Usually the fault current can be controlled via the current regulator, but the short circuit cannot be cleared.

4. Converter AC-side Phase-to-Phase Short Circuit

A converter AC-side phase-to-phase short circuit directly leads to AC-system two-phase short circuit and the fault location is shown in Figure 7.1 (c).

- Rectifier AC-side Phase-to-Phase Short Circuit

A rectifier AC-side phase-to-phase short circuit can cause the two-phase short-circuit current on the AC side. Therefore, the rectifier will loose the two-phase commutating voltage and direct voltage, direct current and transmission power will reduce rapidly.

- Inverter AC-side Phase-to-Phase Short Circuit

An inverter AC-side phase-to-phase short circuit results in the two-phase commutating voltage lost and the abnormal phase on the inverter. Therefore, the inverter commutation failure occurs and the DC-circuit current rises up and the AC-side current falls down.

5. Converter AC-side Phase-to-Ground Short Circuit

For a 6-pulse converter, the fault of the converter AC-side phase-to-ground short circuit is similar to that of the valve short circuit. For a 12-pulse converter, the fault location is shown in Figure 7.1 (e).

- Rectifier AC-side Phase-to-Ground Short Circuit

For a 12-pulse rectifier, no matter single-phase-to-ground short circuit occurs at the high-voltage or low-voltage terminal's 6-pulse converter, the DC neutral busbar is always one part of the short-circuit loop. When the rectifier AC-side phase-to-ground short circuit occurs, the second-order harmonic component will penetrate into the DC side. If the inherent frequency of the DC circuit is close to the second-order harmonic frequency, it may lead to the DC-circuit resonance.

- Inverter AC-side Phase-to-Ground Short Circuit

For a 12-pulse inverter, the fault 6-pulse inverter occurring commutation failure causes direct current to increase. No matter single phase-to-ground short circuit occurs at the high-voltage or low-voltage terminal's 6-pulse converter, the two-phase short circuit causes the AC-side current and DC-neutral-terminal current to increase.

6. Converter DC-side to Ground Short Circuit

Ground short-circuit faults at the DC side contain the ground short-circuit faults occurring at the middle point of 12-pulse converter, the DC high-voltage terminal and the DC neutral terminal. The fault locations are shown in Figure 7.1 (d and f).

7. Control System Faults

A converter is controlled by the firing pulses to ensure the normal operation of HVDC system. Abnormal firing pulses can result in control system faults and thus lead to the malfunction of the converters.

- Misconduction Faults

If misconduction faults occur on the rectifier side, the slight increase of direct voltage causes direct current to increase slightly; if misconduction faults occur on the inverter side, direct voltage reduces or commutation failure occurs, thereby increasing direct current.

- Nonconduction Faults

A valve nonconduction fault is caused by lost firing pulse or gate control-circuitry fault. If nonconduction faults occur on the rectifier side, direct voltage and direct current reduce; if nonconduction faults occur on the inverter side, direct voltage reduces and direct current rises.

8. Converter Auxiliary Components Faults

In order to protect thyristors, cooling equipments (air-cooled, water-cooled or oil-cooled) must be installed. Cooling system's faults will cause the temperature of heat-exchange agent to rise, following the abnormal phenomena of flow and quality.

7.2 AC-side Faults

Due to AC-system faults, the depressed voltage at the converter terminals will either reduce or eliminate the power transmitted.

1. AC-side Three-Phase Short-Circuit Faults

When AC-system faults occur, the operation of HVDC link is influenced by the speed of AC-voltage drop, the amplitude and the phase shift of AC-system voltage.

- Rectifier-side AC Three-Phase Short-Circuit Faults

For remote three-phase faults, the rectifier commutating voltage drops slightly. For close-in three-phase faults, the rectifier commutating voltage drops significantly. Therefore, the converter is greatly influenced by close-in three-phase faults until the rectifier commutating voltage reduces to zero. Since there is no overvoltage and overcurrent generated on the DC components, it is not necessary to stop the DC system. After AC system faults are cleared, DC-power recovers very quickly with the recovery of AC-system voltage.

- Inverter-side AC Three-Phase Short-Circuit Faults

A short circuit occurring at the inverter side causes the reduction of AC busbar voltage at the inverter station and commutation failures, thus producing large direct-current peaks. The rate and amplitude of depressed AC voltage is related to the weak or strong AC system and the remote or close-in three-phase fault at the inverter. When a fault occurs sufficiently close to the inverter end or an AC system is relatively weak, the amplitude of commutating voltage decreases dramatically and quickly, thereby easily causing commutation failures.

For AC faults close to the inverter, the DC-power transfer is illustrated in Figure 7.2 [75]

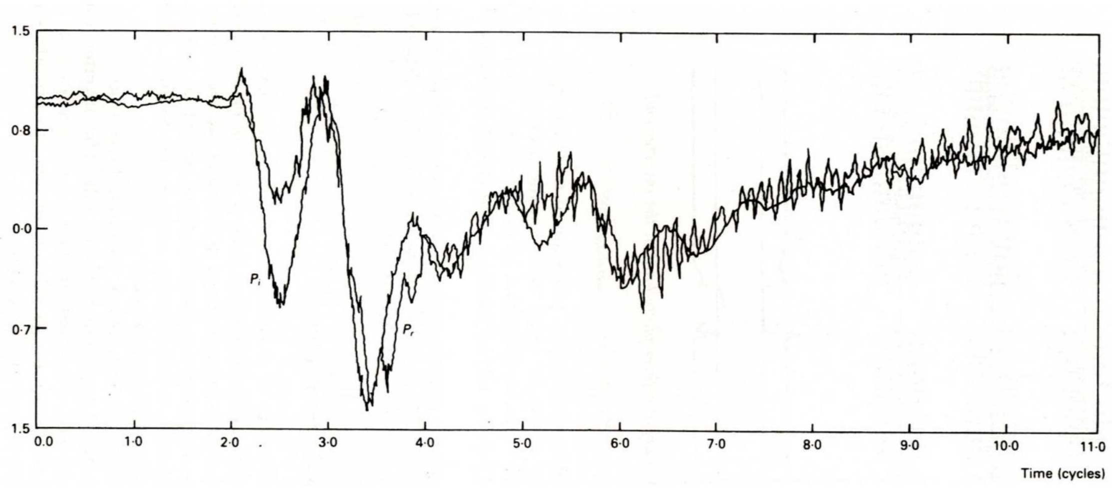

Figure 7.2 Converter DC power following a three-phase fault at the inverter end [75]

P_i = inverter power waveform P_r = rectifier power waveform

2. AC-side Single-Phase Short-Circuit Faults

Single-phase faults are AC-system common faults, usually ground flashover. Single-phase faults are unsymmetrical faults, which contain components of positive sequence, negative sequence and zero sequence. Commutating voltage is highly influenced by the circuit mode of converter transformer.

Because of the lack of symmetry, double-frequency (second harmonic component) modulation is introduced on the DC side. For a weak AC system, double-frequency modulation will produce heavy oscillations. [76]

When the fault of single-phase to ground occurs near the Haywards converter station in the New Zealand system, the response to a staged 60 ms AC fault is shown in Figure 7.3. [77]

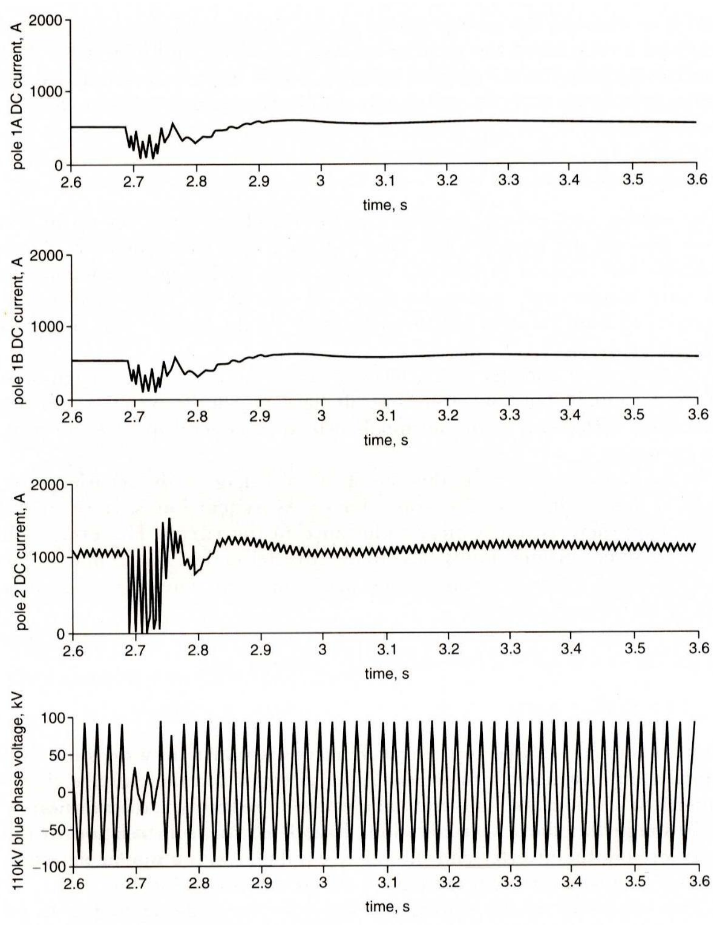

Figure 7.3 The response to a staged AC fault [77]

- Rectifier-side AC Single-Phase Faults

As single-phase faults occur on the rectifier-side AC system, unbalanced commutating voltage can produce the second-order harmonic on the DC system. Like three-phase faults, direct current and voltage relatively decrease during faults period, but the reduction of power is smaller than that during three-phase faults.

- Inverter-side AC Single-Phase Faults

In order to ensure sufficient extinction angle, firing angle must be reduced immediately and commutation failure can recover normal commutation within several tends of millisecond. Commutation failure cannot occur, following normal sequence commutation; with considerable second harmonic component, the average value of the inverter direct voltage is lower than the normal value. The reduced firing angle must be limited by the inverter minimum firing angle.

3. Converter Transformer and Auxiliary Components Faults

The internal faults of a converter transformer will cause the winding temperature, oil temperature, oil flow, oil potential, gas and pressure to change. The faults of auxiliary components (oil pump, fan and motor) cause the converter transformer to malfunction. Different faults and switching operations will produce the inrush current and harmonic components during a certain time. AC-network switching operations may produce abnormal overvoltage on the converter and converter transformer.

4. AC-Filter Faults

Usually an AC-filter consists of capacitor, inductor, resistor and surge arrester. If ground faults occur on these components, the high-voltage terminal and ground terminal currents will appear the differential value and the current flowing through AC-filter will increase substantially.

5. Station Power System Faults

In order to prevent all converter stations from losing power sources simultaneously, an adjacent AC system usually provides two or three power sources to a converter station. In order to avoid causing the circulating current, only one power source works effectively and others are back-up power sources. When faults occur in the effective power source, the back-up power sources are automatically switched. If the design of station power system is not suitable, switching station power systems may cause the operation of HVDC system to shut down. The faults of station power system lead to the corresponding voltage dip initially, and this characteristic can be utilized to design the fast switching control and protection. [78]

7.3 DC-Line Fault

Lightning strike, contamination or branch may reduce the DC-line insulation level, and further produce the flashover of DC-line to ground. As the short circuit of DC-line to ground occurs, direct voltage falls and direct current rises on the rectifier side, and direct voltage and direct current fall on the inverter side.

In accordance with the New Zealand link parameters, using a digital model, a typical DC-line fault, is illustrated in Figure 7.4. [79]

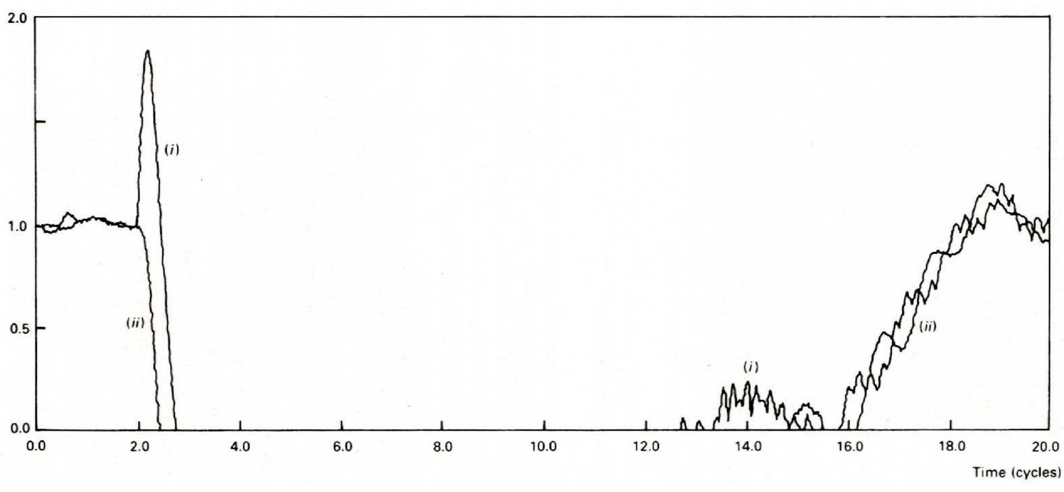

Figure 7.4a Direct current waveform during a DC-line fault [79]

(i) Rectifier end (ii) Inverter end

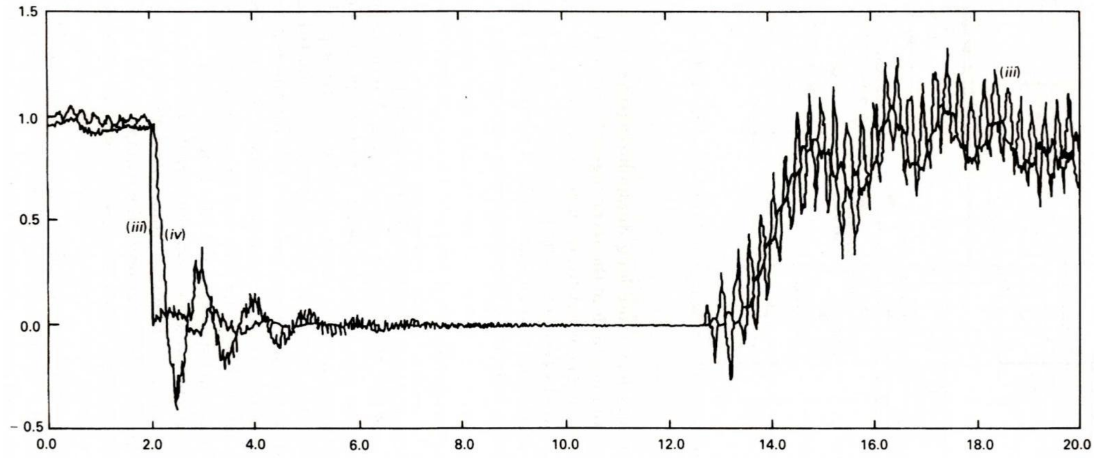

Figure 7.4b Direct voltage waveform during a DC-line fault [79]
(iii) Rectifier-line end (iv) Inverter-line end

1. Lightning Strike

For a bipolar HVDC link, two poles cannot be stroke simultaneously by lightning at the same location. Usually DC lines are stroke by lightning very shortly. Lightning strike causes direct voltage to rise momentarily and then to fall, and discharge current causes direct current to rise momentarily. If DC-lines' insulations cannot withstand momentary increasing voltage, discharge phenomena will occur. [80]

2. Ground Flashover

Owing to environmental influences (contamination, trees, fog, snow), the insulation of the DC-line tower becomes badly, thereby causing ground flashover. Especially when ground flashover occurs at the DC lines, the changes of direct voltage and current will propagate from flashover points to the converter stations. Sudden changing voltage, usually caused by ground fault, may lead to DC-line sudden discharge phenomenon, thereby producing inrush current. These continued wave reflections produce high-frequency transient voltage and current on the lines. [81]

3. High-Impedance Ground Fault

When high-impedance ground short-circuit faults (trees touch DC lines) occur in the DC lines, the variations of direct voltage and current cannot be detected by the traveling wave protection; partial direct current is short-circuited, and two direct-currents at both terminals will appear the differential value. [82]

4. DC-Line and AC-Line Touch

Long-distance overhead DC-lines may cross over many AC-lines of different voltage levels. AC/DC-lines touch faults may occur during long-term operations, thereby appearing fundamental frequency AC-components in DC-lines' current.

5. DC-Lines Broken

When serious faults (DC-lines' tower collapse) occur, the DC lines may break simultaneously. The broken DC-lines cause the DC system to open-circuit; direct current falls down to zero and the rectifier voltage rises up to the maximum limit value.

Chapter 8 Overvoltages and Insulation Co-ordination

8.1 Overvoltage Protection Devices

Due to lightning strikes, switching, faults, HVDC systems can generate overvoltages with a variety of waveforms. In order to protect equipment and to limit overvoltage level, overvoltage protection devices are required to install, thereby improving the system reliability and reducing the equipment costs.

Due to simple structure, low price, sturdiness, durability and high energy absorption capability, protective-gaps were used as primary overvoltage protection devices in most early HVDC schemes, but discharging-voltage instability and no automatic arc-suppression capability are main shortcomings. Because an HVDC system provides the perfect control system, after the protective-gap operates, direct current can automatically drop to zero, in order to suppress arc.

For AC and DC surge arresters, there are great differences in the operating condition and working principle. The main differences are:

1. AC surge arresters can cut off the current at natural zero-crossing instant. DC surge arresters are not of natural zero-crossing points, and it is relatively difficult to suppress arc;

2. All capacitive components are on the full-charging state during the normal operation. Once a certain surge arrester operates, all capacitive components will discharge through this surge arrester. Therefore, the energy-absorption capacity of DC surge arrester is much higher than that of conventional AC surge arrester;

3. DC surge arresters can produce substantial heat very seriously under the normal operation;

4. In some DC surge arresters, two terminals are not grounded;

5. For DC surge arresters, the requirement of external insulation is very high.

Until 1960s silicon-carbide DC surge arresters had been put into operation. Compared to protective gap, silicon-carbide surge arresters had greatly improved protective characteristics. But the protective characteristic of silicon-carbide surge arrester is still not prefect, and the residual voltage cannot be reduced effectively. In order to reduce the equipment insulation level, the rated value of surge arrester must be reduced. Under such situation, in order to maintain safety operations, silicon-carbide surge arresters with series gaps have been extensively used in HVDC schemes.

In 1970s metal-oxide surge arresters started to emerge with the development of technology. Metal-oxide surge arresters have now taken over the overvoltage protection devices in HVDC schemes. [83] The main advantages of metal-oxide surge arresters are less space, simple structure, high energy absorption capability, excellent nonlinearity, excellent pollution-resistance performance, strong arc-suppression capability and the lack of gap spark-over transient. The volt-amp characteristic of metal-oxide surge arrester is much superior to that of silicon-carbide surge arrester, and thus series-connected spark gaps are not required any more. Therefore, metal-oxide surge arresters are sometimes so-called gapless surge arresters. In conventional HVDC transmission systems, gapless zinc-oxide surge arresters are predominantly employed as overvoltage protection devices. They consist mainly of zinc-oxide but contain additives of other metal oxides. Typically, a zinc-oxide disc can carry thousands of amps at twice the nominal voltage.

8.2 Overvoltages Studies

In order to consider the insulation co-ordination of converter station, a variety of possible overvoltages need to be discussed separately.

8.2.1 AC-side Overvoltages

1. Transient Overvoltage

Transient overvoltage is the overvoltage lasting several cycles to hundreds of cycles. Transient overvoltage can develop directly on the equipment and will cause the switching overvoltage to rise. The most typical transient overvoltage occurs on the AC-busbar of converter station and influences the AC-busbar surge arrester directly. This kind of transient overvoltage is transferred to the valve side via the converter transformer, thereby influencing the converter-valve surge arrester.

2. Switching Overvoltage

AC-busbar switching overvoltages are caused by the AC-side faults and switching. Normally switching overvoltage with relatively high amplitude maintains only half a cycle. Switching overvoltages influence the insulation level of AC-busbar equipments and the energy-absorption capacity of AC-side surge arresters. Switching overvoltages can be also transferred to the converter valve side via the converter transformer, thereby becoming the initial condition caused by the internal fault of the converter.

3. Lightning Overvoltage

AC-line intrusion-waves and the direct-strike lightning of the converter station can generate lightning overvoltages on the AC-busbar of the converter station. Because there are incoming lines, equipments (AC filters and capacitor banks) which can considerably damp the lightning wave, AC-busbar surge arrester, in general, the lightning overvoltage of converter station is less severe than that of conventional substation. Moreover, owing to an effective shield of converter transformer, lightning waves cannot intrude into the converter valve side. Therefore, under the normal condition, lightning overvoltages are usually not regarded as the key to AC overvoltage and insulation co-ordination in the converter station, and directly considered in accordance with conventional AC substation rules.

8.2.2 DC-side Overvoltages

1. Transient Overvoltage

Transient overvoltages generated on the DC side of the converter station mainly include two categories below.

- AC-side Transient Overvoltage

When converters operate, transient overvoltages generated on the AC busbar can propagate into the DC side of converter station, owing to a variety of origins, thereby mainly causing considerable energy to pass through surge arresters.

- Converter Faults

When the faults such as partially-missing pulses, commutation failures, and fully-missing pulses occur within the converter, internal converter disturbances give rise to AC-fundamental voltages penetrating into the DC side. If the main parameters of the DC side are not configured correctly, the resonance frequencies close to the fundamental frequency exist. Due to the enlargement effect caused by resonances, overvoltages can be generated during a relative long-term on the DC side. An example of fundamental-frequency resonance which occurred during early operation of the Cahora-Bassa scheme is shown in Figure 8.1. [84]

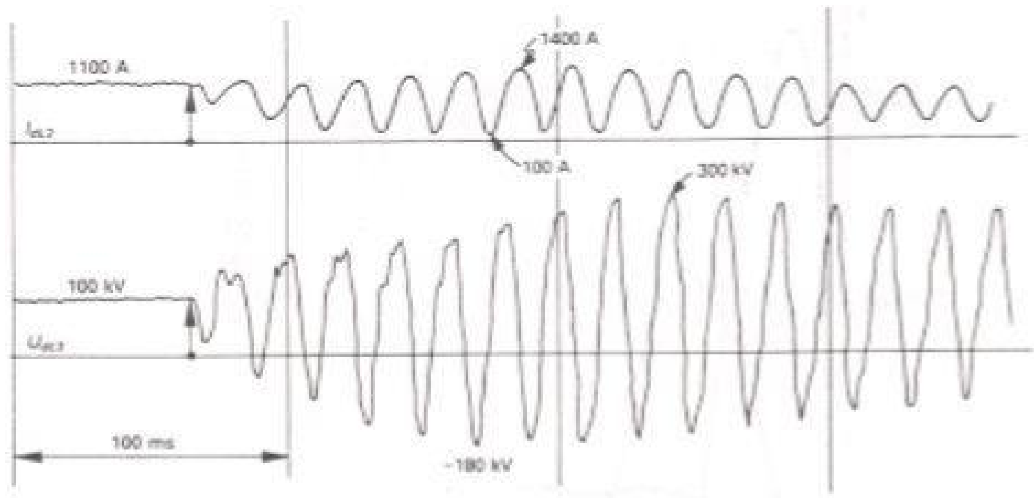

Figure 8.1 Line current and voltage recorded at the inverter during missing pulse condition in a rectifier bridge (1980 CIGRE) [84]

2. Switching Overvoltage

Switching overvoltages generated within the converter mainly include two categories below.

- AC-side Switching Overvoltage

AC-side switching overvoltages can be transferred to the converter via the converter transformer. Due to the protection effect of AC-busbar surge arresters, the overvoltages transferred to the DC side usually do not produce considerable stresses on the DC equipments.

- Short Circuit Fault

When short-circuit faults occur within converters, due to the inrush AC-current and discharges caused by DC filter capacitors, switching overvoltages are normally generated on the converter and DC neutral equipments. The most typical short-circuit location is between the valve-side terminal of the converter transformer and the converter valve.

8.2.3 DC-Line Overvoltages

1. Lightning Overvoltage

Direct-strike and back-strike lightnings can generate lightning overvoltages on the DC lines, and lightnings will propagate into the DC switching yard along the DC lines. Direct-strike lightning can generate lightning overvoltages on the DC switching yard as well.

2. Switching Overvoltage

Switching overvoltages generated on the DC lines mainly include two categories below.

When two poles operate, due to monopole-to-ground short circuit occurrence, switching overvoltages will induce on the healthy pole. Except for the design of DC line tower head, this kind of switching overvoltage also influences the overvoltage protection and insulation co-ordination on the DC switching yards of converter stations at both terminals. The overvoltage amplitude depends on the parameters of line and the two-terminal circuit impedances. [85]

When the opposite terminal of the DC lines is open-circuit and the local terminal of the DC lines is deblocked with the minimum firing angle, excessive high overvoltages are generated on the open-circuit terminal of the DC lines. [86] This kind of overvoltage can develop not only on the DC lines, but also possibly on the opposite-terminal DC switching yard and non-conducting converters. Figure 8.2 shows the overvoltage developed on the DC line when the rectifier is deblocked with full rectifier voltage against an open inverter end.

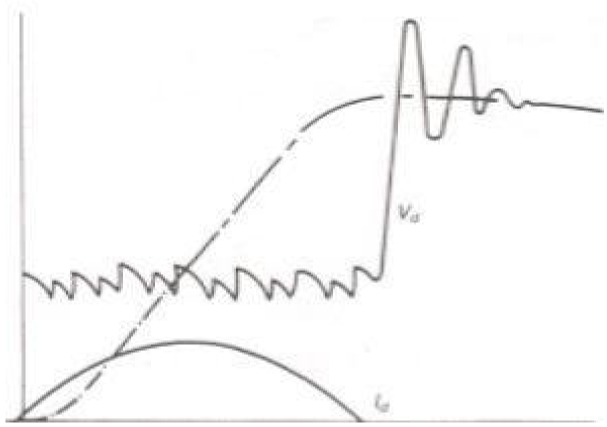

Figure 8.2 Deblocking with full rectifier voltage against an open inverter end [86]

8.3 Insulation Co-ordination

In accordance with the arrangement of surge arresters, a converter station can be divided into three zones, i.e. AC zone, converter zone and DC-yard zone. The surge arresters of the AC zone are very similar to that of the conventional AC substation; the surge arresters of the converter zone are mainly used to protect the thyristor converter valves and the converter transformers; the surge arresters of the DC-yard zone are mainly used to protect the DC-yard equipments. The main principle of surge arrester arrangement is: the overvoltages generated on the AC side should be limited by AC-side surge arresters; the overvoltages generated on the DC side should be limited by DC-side surge arresters; the important equipments are parallel with the surge arresters individually to be protected.

The typical arrangement solution of surge arresters for a 12-pulse converter is shown in Figure 8.3. [87]

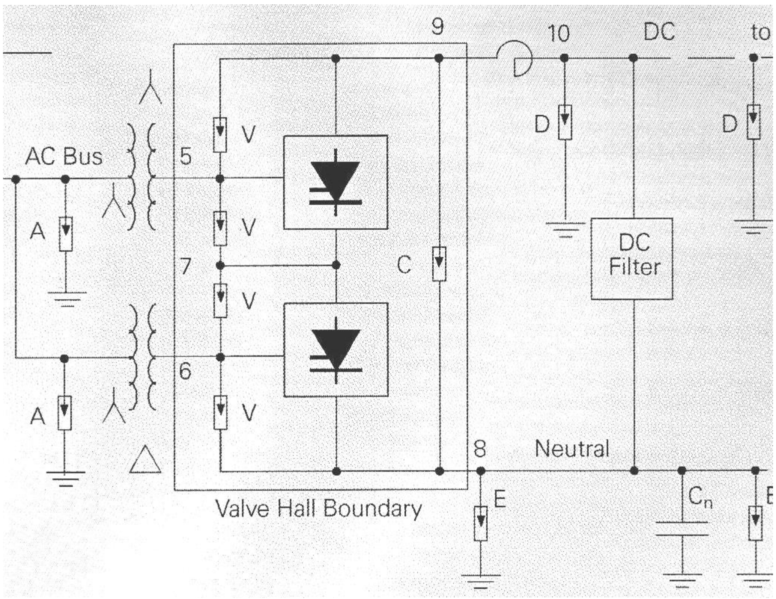

Figure 8.3 The typical arrangement solution of surge arresters for a 12-pulse converter [87]

The practical arrangement solution of surge arresters may be slightly different with the above solution. For an air-insulated smoothing reactor, in order to reduce the vertical insulation level, the surge arrester is directly parallel with the reactor after the economic and technical comparison; for an oil-insulated smoothing reactor, the reactor is protected by surge arresters installed on the two ends. The 6-pulse converter bridge arrester can be replaced by series-connected valve-arresters. In order to reduce the insulation level on the valve-side windings of star-star connected transformer, the 6-pulse converter bridge busbar arrester can be used.

Owing to different structures of AC and DC filters, surge arresters have to be arranged individually and respectively. Two typical arrangements of surge arresters for AC and DC filters are shown in Figure 8.4. [87] For the high-voltage capacitors, the dedicated surge arresters are not required to install. For the low-voltage reactors and resistors, parallel-connected surge arresters must be installed.

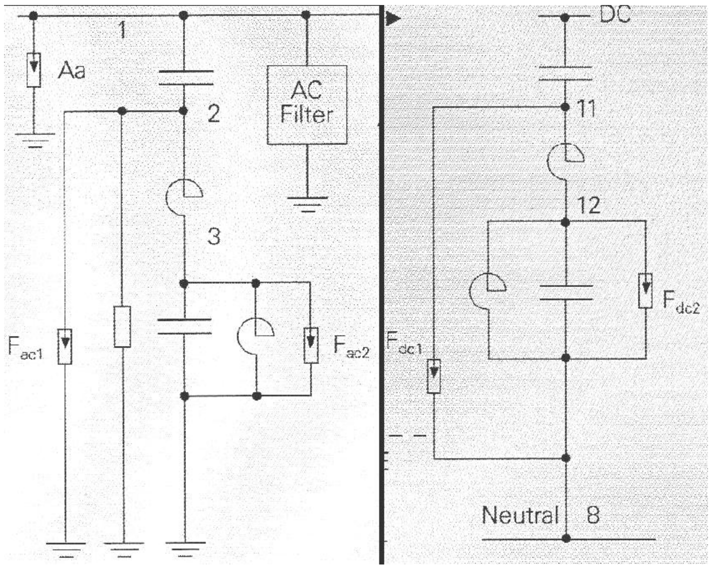

Figure 8.4 Surge arrester arrangement for AC filter (left) and DC filter (right) [87]

The rated voltage and energy absorption capability of surge arresters are referred to as the parameters of surge arresters. The rated voltage of the surge arrester must be selected in accordance with the maximum continuous operating voltage and the transient overvoltage, thereby mainly determining the insulation level and protection level. The energy absorption capability of the surge arrester determines whether the surge arrester, under overvoltages, can consume the energy safety or not, thereby influencing the protection level.

Chapter 9 Transmission Lines

According to applications, HVDC transmission lines can be classified into overhead line, cable line and electrode line. During the design of transmission lines, the appropriate selection depends on the locations of converter stations, the terrains of lines route and the crowded situations of land use.

9.1 Overhead Line

9.1.1 Conductor Cross-section

In the early design of HVDC overhead lines, thermal limitations were mainly considered and electric-field effects were much less considered. As the voltage levels increase gradually, the selection of conductor cross-section depends largely on corona discharges and electric-field effects. [88]

In accordance with the transfer capacity of HVDC system, several models of conductor cross-section were initially selected and then analyzed from the result of economical comparison, thereby finally deciding the most appropriate cross-section. In order to restraint the influence on the environment, the potential gradient of conductor surface, audible noise and radio interference must be taken into account.

9.1.2 Insulation Level

In order to design the insulation level of overhead line, all possible flashover paths, e.g. conductor to earth, tower, ground wire, and positive-conductor to negative-conductor, must be taken into account. It is very important to appropriately determine insulation levels, for example, as the distance between two poles increase, the potential gradient of conductor surface will fall down and the corona loss will reduce. Under reliable operating conditions, due to the expensive price of DC insulator, selecting the appropriate insulation level provides considerable economic benefits for overhead-lines' construction.

1. Tower-Head Air Gap

Air-gap breakdown voltage and insulator flashover voltage are related to atmospheric conditions (pressure, temperature, humidity). In the design of the overhead-line external insulation, the external insulation discharge voltage, under the standard atmospheric condition, must be corrected according to different atmospheric conditions.

2. DC-Line Lightning Protection

Although the hazard caused by lightning-strike overvoltage on the extra high-voltage DC overhead lines is less severe than that on the AC lines, the ground wires must be erected along the entire route, so as to improve the reliability of system operation. Owing to the horizontal arrangement for two poles, two ground (lightning) wires are also arranged horizontally.

Under the same lightning current and tower height, with the increase of working voltage, the striking distance factor will obviously decrease. Dealing with the effect of working voltage, under the circumstance of the same average height (or very slight difference) for ground wires and conductors, the striking distance will not be approximately equal between the lead to ground wires and the lead to conductors. With the increase of working voltage, the rate of lightning shielding failure will increase.

Dealing with the effect of working voltage, under different operating modes, the line lightning-strike endurances are different in an HVDC transmission line. For an HVDC overhead line, when towers and ground wires are struke by lightning, on one pole having polarity opposite to overvoltages, the voltages on the tower-head air-gap and insulator-bunch are the sum of lightning-impulse voltage and DC working-voltage, and for the other pole, the voltages are the difference. Therefore, a bipolar HVDC overhead line is of natural imbalance insulation characteristics under lightning-strike. [89]

9.1.3 Insulator Types

Porcelain insulators, toughened glass insulators and composite insulators had been employed in the commissioned HVDC overhead lines. Toughened glass insulators and porcelain insulators are mostly employed in the world, and composite insulators are mainly employed in the areas of contamination and inconvenient cleaning.

Composite insulators are of high strength, light weight and excellent pollution-proof performance. Owing to the hydrophobic status of composite insulators, under the same creepage distance and pollution degree, the pollution flashover voltage of composite insulators is 60% - 70% higher than that of porcelain or glass insulators. Consequently, for the flashover voltage, the effect of un-uniform pollution distribution (along the top and bottom surfaces) on the composite insulator is smaller than that on the porcelain or glass insulator. The DC pollution flashover gradient under hydrophobic status is 153% higher than that under hydrophilic status according to the research conditions. [90] Owing to simple shaping technology, under the circumstance of the unchanged insulator-bunch length, different creepage distances can be obtained easily. Moreover, the price of composite insulators is cheaper than that of porcelain or glass insulators, composite insulators are unlikely to damage and are not required to clean or maintain.

9.1.4 Insulator Numbers

For DC overhead lines the number of insulator elements is usually determined by the normal voltage under contamination circumstances. For example, in places close to the sea the number of insulator elements was increased to reduce salt pollution problems. If the pollution levels are very low, the DC-voltage withstand level on switching surge or impulse flashover performance has to be taken into considerations. In order to suitably arrange the insulation level of DC overhead lines according to contamination situation, the materials of contamination tests and the distribution situations of pollution areas must be collected to carry out the different levels of contamination.

9.1.5 Steel Tower

DC overhead lines are classified into monopolar lines and bipolar lines. Most of DC overhead lines are the bipolar lines erected on the same tower and the positive-polarity and negative-polarity conductors are arranged on two sides of steel tower. The design principles used in AC overhead lines also determine the dimension of DC overhead lines and hence the tower designs of DC overhead lines are very similar to those of AC overhead lines.

Under normal circumstances, more tower types employed in an HVDC scheme can consume much less steels, but more tower types can increase the investment of design, manufacture and installation. Therefore, the tower types employed in HVDC schemes are required to consider comprehensively in accordance with long route, complicated terrain and various atmospheres.

9.1.6 Ground Wire

In order to ensure the safety operation and to prevent the trip fault caused by direct-strike lightning, it is necessary to install ground wires. In recent years, in order to satisfy the requirements of telecommunications, OPGW (optic fibre ground wire) has already employed. On one hand, OPGW used as ground wires, must take fairly effect as a safeguard against lightning, so that the characteristic of sag of span of OPGW is very similar with that of the other ground wire erected on the same tower. On the other hand, when the short-circuit faults occur on the transmission lines, the short-circuit current will cause the temperatures of OPGW and the other ground wire to increase. When the short-circuit current is extremely high, as the temperature increases dramatically, it may cause fibre optics to be damaged. In order to avoid the temperature beyond permissible value, when selecting OPGW, the consideration of thermal stability must be taken into account.

9.2 Cable Line

9.2.1 Application and Development

DC cable can transmit bulk power over long distances. DC cable is mainly employed as submarine cable and underground cable. In twenty years, the application of DC transmission has made considerable progress, and DC cables have already been used in many schemes. In 2000, the 2800 MW, ± 500 kV Kii-channel undersea scheme was commissioned with highest DC voltage in the world. [91] The 600 MW, 450 kV, 250 km long Baltic cable connecting Sweden and Germany was commissioned in 1994. [92] The 700 MW, ± 450 kV, 580 km long NorNed link is the longest submarine cable transmission commissioned in 2007. [93]

Owing to thermal limitations, the power of AC cables increases in proportion to the voltage of AC cables, and the charging current within AC cables increases with the distance and with the square of the voltage. Therefore, unlike for overhead transmissions, AC cable transmission only uses relatively low voltages over very short distances. In order to avoid the conductor-core overheat within AC cables, the power transmitted by AC cables is much less than the natural power. Consequently, the shunt reactors must be installed along the route, so as to counteract excessive high voltages at the middle or end of lines. For relative long-distance submarine cables, it is impossible to employ AC transmission in practice, and using DC cable lines is rather feasible.

9.2.2 Cable Insulation

When reversing the power-flow direction, the current direction maintains unchanged while the voltage polarity changes. Therefore, DC cable must withstand fast reversal of voltage polarity. In addition, due to the transient fault caused by converter, it gives rise to instantaneous oscillation overvoltage added to DC voltage. Under the most severe condition, the peak value of transient overvoltages may reach to twice working voltage.

Although the structures of DC cables are very similar to those of ordinary AC cables, the working conditions of DC-cable insulation are much excellent than those of AC-cable insulation. For DC cables, the effective value of the voltage is also the peak value of the voltage, and the losses of DC-cable insulation are much less than those of AC-cable insulation under the same voltage. Consequently, for DC-cable insulation the thermal instability has become less important. In addition, the breakdown voltage of AC-cable insulation is related to the working time, but there is no such problem on the DC cable.

9.2.3 Cable Types

The development of DC cable took the successful experience from AC cable, so that the structure of DC cable is very similar to that of AC cable. There are three types of DC cable; oil filled, gas pressurized and mass impregnated, often referred to as solid cables. XLPE is a fourth type, so far studied and employed widely.

1. Mass-Impregnated Cable

The great bulk of cables are of the mass-impregnated type in earlier installations. The advantages of mass-impregnated cable are simple structure, convenient manufacture and maintenance and low cost. Due to no need for supplying oil and cooling effect of seawater, the mass-impregnated cable is likely to use for long-distance submarine installation. Figure 9.1 shows the development of the maximum power per cable and the maximum operating voltages of the mass-impregnated cables. [94]

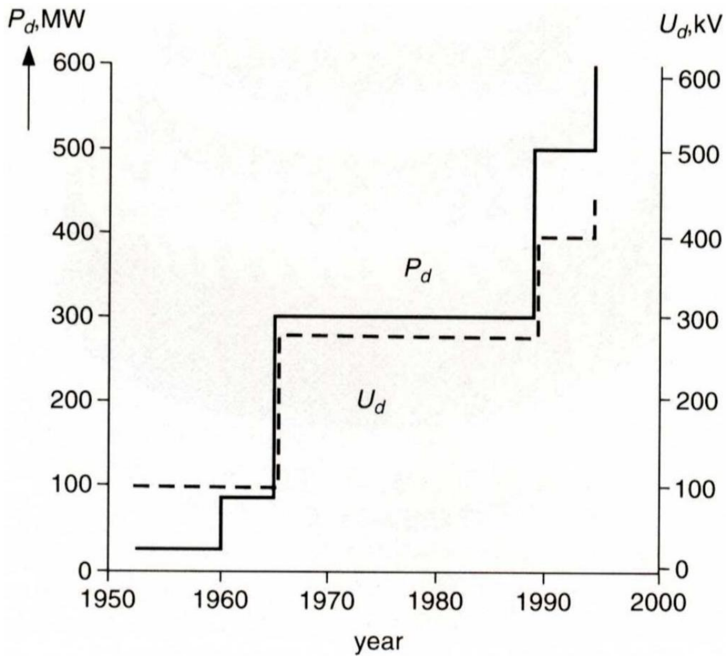

Figure 9.1 Maximum power per cable and operating voltage of realized HVDC submarine mass-impregnated cables [94]

2. Oil-Filled Cable

Oil-filled cables were generally installed and developed across land (without intermediate pressure/feeding stations). Oil-filled cables can provide more excellent technical features than other types of cables. For example, oil-filled cables can withstand higher insulation working stresses than mass-impregnated cables. As the technical problem for supplying oil over long-distance settles down, oil-filled cables can be used as submarine cables.

3. Gas-Pressurized Cable

Gas-pressurized cables can withstand relatively high insulation working stresses, thereby likely using for long-distance submarine installation and great depth installation. Due to extreme high manufacture working stresses and sealing effect, gas-pressurized cables have not been manufactured for DC use since the 1960s.

4. Crosslinked Polyethylene (XLPE) Cable

XLPE has become an accepted insulation now as an alternative to oil filled cables. Owing to simple structure and robustness, XLPE cables are suitably used as submarine cables. Recently only steel-wire armoured XLPE cables are widely paid attention in the world.

9.2.4 Cable Structures

1. Conductor Core

The conductor core of the DC cable is usually made of copper and the cross-sectional area of the conductor core depends on rated current, permissible voltage drop, short-circuit capacity and so on. When selecting the structure of conductor core, sea water permeation after fault must be highly considered.

2. Insulation Layer

The insulation layer thickness of the DC cable must satisfy simultaneously the following requirements:

(1) For rated DC voltage, at no-load condition, the working stress on the conductor's surface must be lower than the permissible value.

(2) For rated DC voltage, at full-load condition, the working stress on the outer casing must be lower than the permissible value.

(3) The insulation layer thickness must withstand the impulse test voltage.

(4) Under rated current, the conductor's temperature must be lower than the permissible value.

3. Outer Protective Layer

There is no induced voltage on the metallic sheath and armour, and the sheath losses are not existed in the DC cable. The structure of outer protective layer mainly depends on environmental corrosion and mechanical damage, especially for submarine cables.

4. Metallic Sheath

In order to ensure the reliability and flexibility of the metallic sheath, until today DC cables usually employ the galvanized sheath. For oil-filled or gas-pressurized cables, several layer metallic tapes must be added as the reinforcing layer.

5. Corrosion-Proof Layer

Owing to the effect of the leakage current and other currents (used sea water as return circuit), the electrolysis corrosion will occur on the metallic sheath and reinforcing layer. Consequently, the plastic sheath is usually added to prevent electrolysis corrosion.

6. Armour

In order to prevent mechanical damages, steel tapes or armoured steel wires are covered outside the corrosion-proof layer in accordance with specific circumstances. Submarine cables usually employ steel wires armoured cables. When carrying and laying submarine cables, owing to the dead weight of submarine cables, considerable mechanical stresses are generated on the cable, while submarine cables are easily attacked by sea animals.

A typical design is the 250 kV DC cable of the Skagerrak scheme laid at a depth of 550 m, illustrated in Figure 9.2. [95]

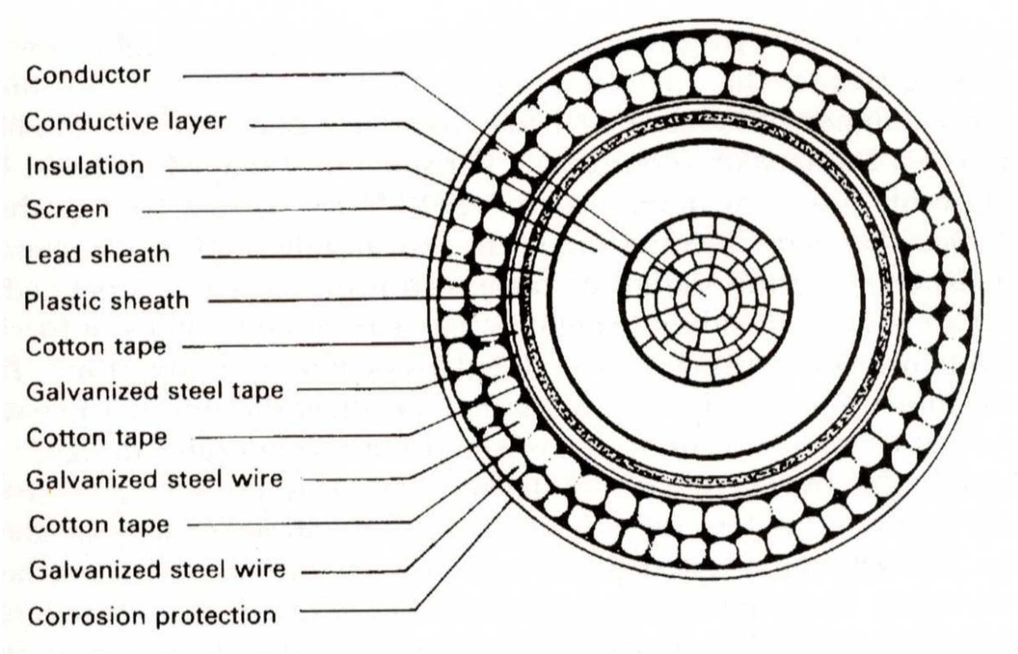

Figure 9.2 The cross section of the double-armoured DC cable [95]

9.3 Earth Electrode Line

An earth electrode line transfers direct current into earth, thereby using earth (or seawater) as the return conductor with cheap costs and low losses. Compared to the metallic return with the same distance, earth return provides substantially low resistance and low power losses correspondingly. Using earth return can develop the HVDC transmission system gradually in accordance with the requirement of transmission capacity. In a bipolar HVDC transmission system, when one pole or converter is shut down, the half-capacity power can still be transmitted by using the other pole and earth return.

9.3.1 Insulation Level

The current flows into earth via earth electrode and electrode line under normal operating conditions, thereby causing the voltage drop on the electrode line. Even under monopolar operating conditions, the voltage potentials on the electrode line are only several thousands of voltages. From the terminals of converter station to earth electrode, the voltage potentials reduce linearly along the electrode line.

9.3.2 Conductor Cross-section

The earth electrode line has several characteristics below.

1. The current only flows through the conductor and earth electrode, thereby causing the low voltage drop on the line.

2. The earth electrode line and earth electrode are usually used to fix the neutral potential of converter station. The current flowing through electrode lines is only 1% at rated current.

3. The earth electrode line is usually tens of kilometers.

In accordance with the above situations, the conductor cross-section of earth electrode lines only depends on thermal stability conditions under the most severe operating mode. Therefore, such conductors can not only save the capital costs, but also satisfy the transmission requirement.

Chapter 10 Transmission Line Environmental Effects

As a significant technology issue, the environmental effects must be taken into considerations and the electromagnetic environment is directly related to the corona characteristics of transmission line, i.e. corona loss, DC electric-field effect, radio interference and audible noise. [96] In order to design the DC lines, corona loss, DC electric-field effect, radio interference and audible noise must be controlled in the appropriate extent.

10.1 Corona

If the potential gradient of conductor surface exceeds a specific critical value, atmospheric ionization following visual discharge, termed DC-line corona, will occur in the vicinity of DC-line conductor and the electrically charged ions caused by conductor corona will move towards the conductor of the opposite polarity or deviate from the conductor of the same polarity. Therefore, the entire space is fulfilled with electrically charged ions.

The movement of electrically charged ions forms the corona current around the DC transmission line, thereby producing the energy loss termed corona loss. The electric-field strength of the conductor surface, which leads to the line corona, is termed the corona critical electric-field strength or the initial corona electric-field strength. The initial corona electric-field strength of small-diameter conductor is higher than that of large-diameter conductor. The critical degree of corona discharge is directly related to the electric-field strength of the conductor surface, especially the surface maximum electric-field strength. [97]

According to the testing, the DC-line corona is of the following characteristics: [98]

(1) In the rainy days, the increased corona loss in the DC line is much less than that in the AC line.

(2) If the electric-field strength of the conductor surface maintains a certain value, no matter in the rainy or sunny days, with the increase of the number of bundle conductor, the DC-line corona will increase.

(3) In the specific range (0 – 10 m/s) of wind speed, with increasing the wind speed, the DC-line corona loss usually increases.

(4) Under the specific voltage, for the bipolar lines, the corona loss of each pole is 1.5 – 2.5 times that of the monopolar line.

(5) Under the specific voltage, no matter in the bipolar or monopolar operating mode, the corona loss of the positive pole is approximately identical to that of the negative pole.

10.2 Electric-Field Effect

If the electric-field gradient of the conductor surface exceeds the initial corona electric-field gradient, ionization will occur in the atmosphere close to the conductor surface and the space charges caused by ionization will move along the electric-flux direction.

The electric-field strength under DC line mainly depends on the critical degree of conductor corona discharge. Figure 10.1 shows the distribution diagram of the electric-field strength under the 450 kV overhead line. The highest electric-field strength occurs directly under the overhead conductor, both with monopolar and bipolar transmissions, and the lowest electric-field strength normally occurs at the symmetrical center of bipolar conductors. The distribution shown in Figure 10.1 is the most ideal circumstances without wind. In addition, the electric-field may be strengthened further by external factors in terms of the weather, seasonal variations and relative humidity. [99] The displacement velocity of positive and negative ions, under the electric field, is at the same scale with the wind velocity. Therefore, even in the very slow wind velocity (1m/s), the distribution of the electric-field will be distorted.

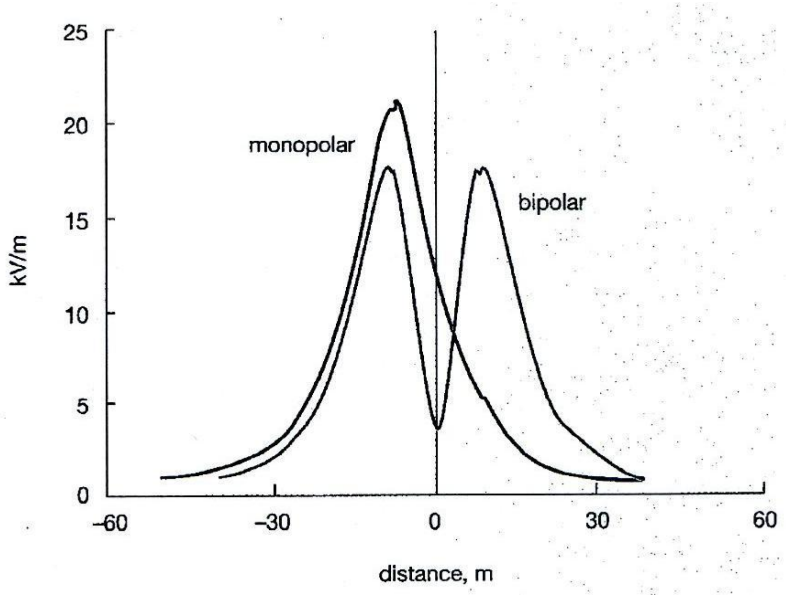

Figure 10.1 The electric field of monopolar and bipolar 450 kV overhead lines [99]

At the same voltage level, the electric-field strength under DC line is higher than the electric-field strength under AC line. Under normal operations, without the induced phenomenon of capacitor coupling, for AC and DC electric-fields, the same strengths produce the different effects.

The electric-field and ionic current density are related to the electric-field strength of the conductor surface and the corona initial electric-field strength. With the specific geometric size of lines, higher the electric-field strength of the conductor surface or lower the corona initial electric-field strength, higher the electric-field and ionic current density. Therefore, either lowering the electric-field strength of the conductor surface or increasing the corona initial electric-field strength can reduce the electric-field and ionic current density.

10.3 Radio Interference

Under the normal operating voltage, the DC-line conductors always produce a certain degree of corona discharge with the ionic current in the vast space. Furthermore, it gives rise to the radio interference in the vicinity of DC lines. The corona discharge process is of pulsating characteristics, thereby producing the current and voltage pulses on the DC-line conductors.

For the conductor of negative polarity, the corona discharge points are generally well-distributed on the entire conductor surface and the repeatedly emerged pulses are of almost identical amplitudes with low values. Compared with the conductor of positive polarity, the radio signals are interfered slightly by the corona discharge from the conductor of negative polarity.

For the conductor of positive polarity, the corona discharge points are randomly distributed on the entire conductor surface and the continuous discharge points are mostly located on the drawbacks of the conductor surface. The discharge pulses are of high amplitudes and irregular distribution. The corona discharge from the conductor of positive polarity is the principal source of radio interference.

As the distance away from DC line increases, the radio interference caused by conductor corona gradually attenuates. For bipolar DC lines, the conductor of positive polarity is the main source and the symmetric center of radio interference, which attenuates transversely from the symmetric center to both sides. With the increase of frequency, the DC-line radio interference gradually reduces. The spectrum characteristics of the DC line are very similar to those of the AC line.

With the increase of the humidity, the DC-line radio interference tends to reduce, and with increasing the temperature, the DC-line radio interference tends to increase. But the pressure variations have no obvious influences on the radio interference.

(1) The DC-line interference level in rainy days is approximately 3dB lower than that in sunny days. Compared with the AC line, the DC-line interference level is obviously different under different weather conditions.

(2) Wind causes the DC-line radio interference to increase; especially the most severe consequence is caused by the wind direction flowing from negative polarity to positive polarity. [100]

(3) In the late-autumn and early-winter seasons, owing to fairly low temperature and quite high atmospheric humidity, the DC-line radio interference is relatively low. In the

winter and early-autumn seasons, the radio interference is close to the average value. In the summer season, dust, insect and bird's droppings always stick on the conductors and the wind velocity is considerable high, consequently, owing to considerable high temperature and rather low atmospheric humidity, the DC-line radio interference is the highest level. [100]

10.4 Audible Noise

As voltage levels increase gradually, in order to design DC line properly, audible noise caused by corona discharge must be considered as an important factor. Since serious audible noise often makes the residents close to lines annoyed, when designing and constructing the DC lines, audible noise must be limited within a suitable range.

For DC lines, the corona of the positive-polarity conductor is the main source of audible noise and the audible noise attenuates transversely towards both sides of DC lines. However, the symmetry axis of audible noise is not the center of bipolar lines, but the positive-polarity conductor. With the increase of the distance, the audible-noise attenuation is much slow than the radio-interference attenuation. As the distance increases one time, the audible-noise attenuation is approximately close to 2.6dB (A). [100]

Audible noise caused by AC-line corona is composed of two parts, one part is the wide frequency band noise (primary part in AC noise) caused by positive polarity injection discharge and the other part is the pure tone (multiple of fundamental frequency) caused by the back and forth movement of charged ion in the vicinity of conductor, due to periodic-voltage variation.

In sunny days, AC-line audible noise is fairly small. In little rainy, fog and snow days, dripping water sticks on the conductor surface, thereby causing considerable audible noise. DC-line audible noise in rainy days is less than that in sunny days and the noise in snow days is slightly different with the noise in sunny days. Therefore, when designing the DC line, the audible noise in sunny days must be considered primarily. [100]

Chapter 11 Earth Electrode

11.1 Earth Electrode Effects

For two-terminal HVDC transmission systems commissioned, the main circuit modes can be classified into monopole with ground return, monopole with metallic return, bipole with two terminals grounded, bipole with one terminal grounded and bipole with two terminals ungrounded. For monopole with metallic return, bipole with two terminals ungrounded and bipole with one terminal grounded, due to one point grounded or ungrounded, there is no current in the ground and earth electrodes are only used to clamp the neutral-point electric-potential. For monopole with ground return and bipole with two terminals grounded, earth electrodes are used not only to clamp the neutral-point electric-potential, but also to provide the path for direct current.

11.2 Earth Electrode Operational Features

Except for obvious merits, using ground return also brings the adverse effects caused by considerable direct current, i.e. electromagnetic effect, thermodynamic effect and electrochemical effect.

- Electromagnetic Effect

As considerable direct current injects into earth via earth electrode, a constant direct-current field arises in the soil of electrode site, thereby rising ground potential and producing surface step voltage and touch potential. Therefore, the electromagnetic effect may bring the following consequences.

(1) A direct-current field can change the ground magnetic field nearby earth electrodes, thereby influencing the magnetic compass.

(2) Rising ground potential may give rise to adverse effects on the underground pipelines, armoured cables and electrical equipments grounded, which are close to electrode site.

(3) Land electrodes create potential differences at the earth surface, termed step voltage, which can cause shock currents. Surface step voltage and touch potential nearby electrode site may influence human being and animals. For a human-body resistance of 1000 Ω, the maximum safe current flowing through the body is recommended as the limit value of 5 mA. [101]

- Thermodynamic Effect

Earth electrodes are buried in different soils, thereby obtaining different resistances. Due to the effect of direct current, the temperature of earth electrode will increase, especially at the temperature reaching to a certain extent, the moisture in the soil will evaporate, and thus the conduction performance of the soil will become worse and even loose operational capability. Therefore, for land electrodes (including coastal electrodes), the soil around electrode site must have sufficient humidity, considerable heat-capable coefficiency, excellent electric-conduction and heat-conduction performances, in order to ensure the perfect thermal stability performance during the operations. [102]

- Electrochemical Effect

Due to direct current flowing through earth, electro-corrosion occurs not only in earth electrode, but also in the underground metallic equipments or power system grounded.

11.3 Electrode Site Selection

In accordance with the operational features of earth electrode and the circumstances of current distribution in the ground, selecting a suitable electrode site must satisfy the following conditions. [103]

(1) An earth electrode is located a certain distance away from the converter station, usually 8 – 50 km. If an earth electrode is very close to the converter station, earth

current easily injects into the grounding grid of the converter station, thereby influencing the safety operation of power system equipments and corroding the grounding grid. If an earth electrode is too far away from the converter station, the investment of electrode line will increase and the neutral-point electric-potential in the converter station will be excessive high. In addition, the electrode site must be sufficient distance away from some important AC substations, usually larger than 10 km.

(2) Earth electrodes must be placed in the wide terrain with excellent conductivity (low soil resistivity), especially in the vicinity close to the electrode site, the soil resistivity is generally under 100 Ωm, in order to reduce the cost of earth electrode, lower the surface step voltage and ensure the safety and stability operation.

(3) Soil must have sufficient water to maintain humidity, even under the worst situation that considerable direct current flows through earth electrode over a long period. The soil of earth surface (close to earth electrode) must be of excellent thermal characteristics, i.e. high heat-conductivity and large heat-capacity, so as to reduce the size of earth electrode.

(4) There are no important and complicated underground metallic equipments around electrode site, so as to avoid the corrosion in the underground metallic equipments or the unnecessary grounding investment for electrical equipments.

(5) Earth surface used to bury earth electrode must be sufficiently large flat area, thereby providing benefits i.e. convenient installation and operation, and excellent operational features of earth electrode.

(6) An appropriate electrode site must provide convenient route and cheap investment for electrode line.

11.4 Earth Electrode Design

Earth electrodes commissioned in the world can be classified into land electrodes and sea electrodes. According to different conditions for electrode sites, land electrodes and sea electrodes are arranged into different patterns respectively.

1. Land Electrode

Land earth electrodes mainly use electrolyte in soil as conducting medium. In accordance with bury methods, land earth electrodes can be classified into horizontal land electrodes and vertical land electrodes.

A horizontal land electrode is usually laid at the depth of few meters owing to low resistivity of surface layer soil, shown in Figure 11.1. Therefore, a horizontal land electrode has the advantages of convenient installation and low cost, and especially is well suited to the conditions of low-resistivity surface layer soil, wide ground and smooth terrain.

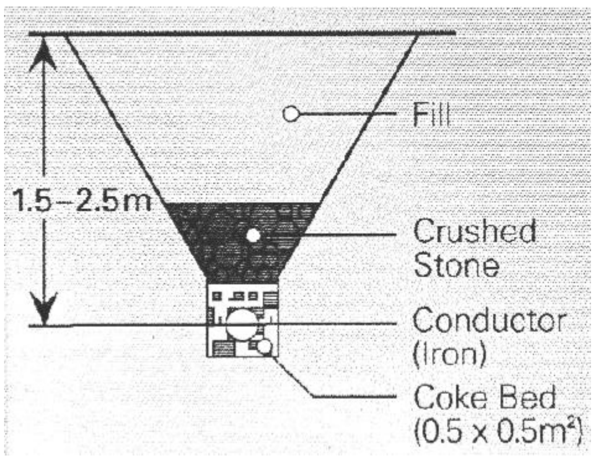

Figure 11.1 The cross section through a horizontal land electrode [104]

The bottom of the vertical land electrode is few tens of meters deep in common, in some cases the depth of up to few hundreds of meters, and thus the current can flow into the deep-layer ground directly through the vertical land electrode, thereby causing less influence on environment. A vertical land electrode is commonly well suited to the electrode site with high surface-layer soil resistivity and fairly low deep-layer soil resistivity, or the electrode site limited by land use, shown in Figure 11.2.

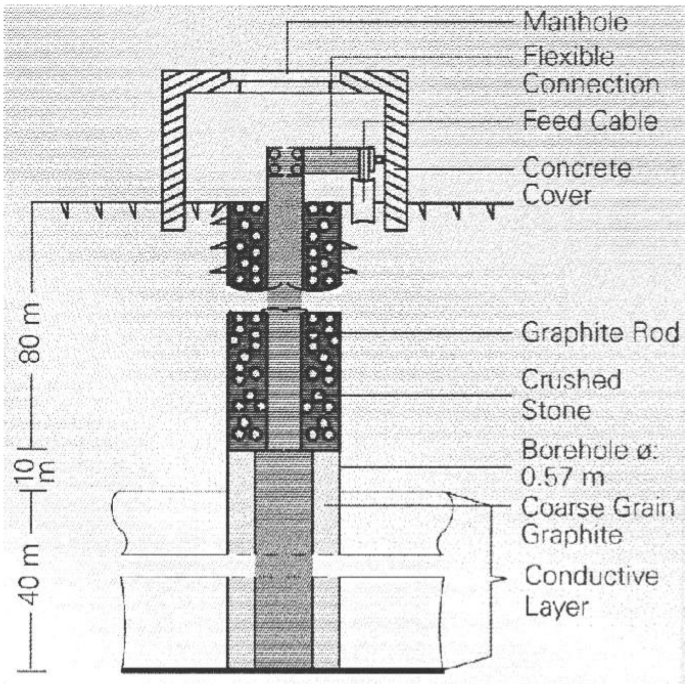

Figure 11.2 The vertical electrode at the Southern Cahora Bassa HVDC station [104]

2. Sea Electrode

Sea electrodes mainly use sea water as conducting medium and sea water has much better conductivity than land. In accordance with the arrangement modes, sea electrodes are classified into coastal electrodes and submarine electrodes.

The conducting elements of the coastal electrode must be enclosed by robust protective equipments, in order to avoid the impact from wave and ice. Most coastal electrodes are arranged linearly along the coastline, so as to obtain the minimum grounding resistance.

The conducting elements of the submarine electrode are laid in the seawater, and the dedicated supporting and protective equipments are used to strengthen conducting elements and prevent wave and ice from impacting. If only using cathodic operation, the submarine electrode shown in Figure 11.3 provides a rather economic solution. Due to the polarity change caused by power-flow reversal, each of earth electrodes must be designed in accordance with anodic requirements.

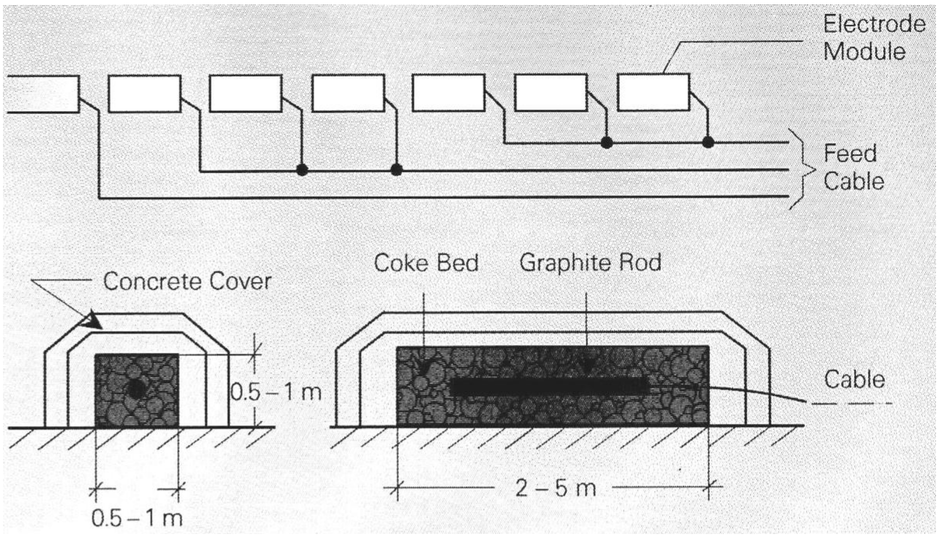

Figure 11.3 The submarine electrode (cathodic operation) [104]

11.5 Earth Electrode Development

1. Deep Hole Ground Electrode

In a submarine HVDC transmission or nearby a converter station close to sea, it is feasible to build a compact seashore or seawater ground electrode. An ordinary ground electrode requires substantial land areas and must be placed at the location of relatively low soil resistivity. Under such a condition, a deep hole ground electrode can reach into the earth layer of quite low soil resistivity, thereby causing relatively low potential and potential gradient on the earth surface. The first deep hole ground electrode had been installed in the Baltic cable project.

The advantages of deep hole ground electrode are: the location of ground electrode is fairly close to the converter station; using relatively short earth electrode line, thereby reducing loss; reducing interferences and the risk of lightning strike; easily seeking the appropriate location of earth electrode; improving the feasibility of HVDC monopolar operation.

2. Common Earth Electrode

For planning bulk hydropower outgoing transmission schemes, due to complex terrain especially in a mountainous area, multiple sending-terminal converter stations are located very closely; for two or more HVDC systems feeding into the same AC network, multiple receiving-terminal converter stations are placed electrically close to each other in the high-density load center; thereby causing the significant difficulties in site selection of earth electrode. Aiming at such a circumstance, the design scheme of common earth electrode by multiple HVDC systems is required. This design scheme has obvious advantages in reducing influences of earth currents on environment; the appropriate electrode site selection and electrode design can enhance the system safety and reliability; a common earth electrode not only reduces electrode-site land uses, but also lowers overall cost. However, both earth electrode resistance and electrode line resistance must be restricted within a certain range; the electrode site selection and common earth electrode design must satisfy relatively high requirements; the common earth electrode shared by multiple converter stations requires reliable and available dispatching and communication.

11.6 Influence of Earth Electrode Current

While considerable direct current injects into ground via earth electrode, a constant direct current field is formed in the vicinity of electrode site. Meantime, if there are transformers with neutral-point grounded, underground metallic pipelines and armoured cables close to electrode site, owing to these metallic equipments providing much perfect conduction paths rather than earth soil, partial earth currents flows along and through these metallic equipments towards remote places, and thus it may cause unfavourable consequences to system operation and transformer. [105]

In some countries, the transformers (above 110 kV) neutral-points are mostly grounded directly. If the substations are located within the vicinity of earth electrodes current-field, the electric-potential differences are generated among substations within the current-field. Direct current flows into one substation (the transformer neutral-point) and flows out of the other substation (the transformer neutral-point). If considerable direct current flows through the transformers windings, it may give rise to the following harmful effects on power systems. [106]

(1) Transformer-core magnetism saturation. Since transformer-core magnetism saturation occurs, it may cause the temperature, loss, noise of the transformer to increase. [107]

(2) Influence on electromagnetism-induced voltage transformer. While direct current flows into electromagnetism-induced transformer, owing to inaccuracy measurements, it may cause the corresponding relay protective devices to maloperation.

(3) Electro-corrosion. While direct ground current flows through the grounding grid (mat) of power system, it may give rise to electro-corrosion in the grounding grid.

In order to reduce the effect of earth current, the following measurements must be considered.

(1) The interception measurements from source are: rotationally arranging the HVDC system operating modes and reducing the circuit modes of monopole ground-return.

(2) The conduction measurements are: building reliable current path or dedicated line and reducing the grounding resistance of earth electrode.

(3) The isolation measurements are: rationally configuring the grounding points and grounding modes of AC-system transformers.

Chapter 12 Conclusion

As some countries are planning to exploit the natural resources (hydro and low-grade coal fields), from a technical, economic and environmentally point of view, the HVDC transmission will be employed with extensive foreground, due to the merits of long distance (more than 1500 km), large capacity (more than 5 GW), flexible control and convenient dispatching. In order to compete with the HVAC transmission, the future development trend for the HVDC transmission is to employ the modular, standard and duplicated design, so as to significantly lower the cost.

With the development of larger-diameter thyristor, the number of thyristors in series will reduce substantially, thereby simplifying the design and lowering power loss. Because considerable components for electrically triggered unit can be cancelled, light-triggered thyristor is of the advantages, i.e. higher performance and lower price. In addition, the functions of overvoltage protection and state monitor can be integrated into light-triggered thyristor as well. Each air-insulated valve can be installed inside the outdoor container and thus there is no need to build large valve hall, thereby enhancing the reliability and reducing the cost.

Since harmonics must be eliminated in accordance with more strict criteria and the complicated algorithm can be implemented with the excellent performance of digital signal processor, active filters will play an important role, especially on the DC side of the converter station.

The controller based on digital signal processor has been developed dramatically and thus the control system is of high reliability, fully hot redundancy, numerous control points and considerable data processing capacity. Due to fully digitalization, the number of control cubicle installed in the control room has reduced significantly. Moreover, the controller based on digital signal processor can also provide more advanced control algorithm, lower maintenance, better fault diagnostic and on-line monitor function.

Lots of HVDC schemes have been commissioned in the world and the present experience can be referenced during the construction. However, concerning with different geographical and climatic circumstances (high altitude, heavily polluted contamination, snow, heavily icing region, rainy), corona characteristics and overvoltage and insulation co-ordination must be carried out in each case respectively.

Although the environmental effects of transmission lines can be limited under the allowable level, the environmental criterion is related to the entire cost. Therefore, according to the practical arrangement of transmission lines, the environmental effects must be measured on the specific case.

Due to complex terrain like mountainous area or large-scale load center with high-population density, an ordinary earth electrode, which requires substantial land areas, can be replaced by deep hole ground electrode or common earth electrode.

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