PREFACE

India's infrastructure sector has seen substantial growth due to increasing population and rapid urbanization over the past few decades. This growth has led to a significant rise in energy consumption and the consequent installation of numerous power generation plants and units. To facilitate efficient power transmission from generation to distribution over long distances, the High Voltage Direct Current (HVDC) system has proven to be highly effective. High-quality electrical installations are crucial for preventing accidents and ensuring the efficient delivery of power.

HVDC transmission lines are designed to transmit electrical power over vast distances with minimal losses, making them exceptionally suited for connecting remote power generation sources—such as hydroelectric dams, wind farms, and solar power plants—to urban centers and industrial hubs. Unlike traditional Alternating Current (AC) transmission systems, HVDC systems offer distinct advantages, including reduced power losses, improved stability, and the capability to interconnect asynchronous power grids.

The technological superiority of HVDC systems lies in their ability to convert AC to DC at the transmission source and subsequently reconvert it back to AC at the receiving end. This conversion process, facilitated by sophisticated converter stations, ensures that HVDC transmission lines can maintain high efficiency and reliability over long distances. Furthermore, HVDC systems are less susceptible to the reactive power issues that often plague AC transmission, thus providing a more stable and controllable power flow.

The implementation of HVDC technology is instrumental in supporting the integration of renewable energy sources into the power grid, contributing to a more sustainable and resilient energy infrastructure. As nations strive to meet their energy needs while mitigating environmental impacts, HVDC transmission lines play a critical role in achieving these objectives.

Ensuring the safety of personnel and equipment against electrical faults necessitates adherence to the protection requirements specified by various Indian Standards. Electrical engineers, technicians, research scholars, and students must be well-versed in these standards and best practices. The Bureau of Indian Standards (BIS), through its Electrotechnical Division Council (ETDC), plays a pivotal role in formulating Indian Standards and Codes in the field of electrical engineering. The HVDC System Sectional Committee, ETD 40, under the ETDC, is tasked with developing standards related to the safety and maintenance of HVDC systems.

This handbook distinguishes itself from other educational resources by providing comprehensive guidance that encompasses both essential foundational knowledge and advanced industry-level execution. Aligned with Indian standards for HVDC systems, it offers extensive technical guidance for the installation and maintenance of these systems. The primary objective is to present the design, installation procedures, and other critical features clearly and straightforwardly. This resource is invaluable for electrical engineers, technicians, research scholars, and students, facilitating a thorough understanding of the fundamental requirements and testing procedures necessary for safe and reliable HVDC installations.

All electrical installations in India are governed by The Indian Electricity Act, 2003, along with the rules and regulations established under it. The provisions of this handbook are supplementary to the mandatory compliance with the Indian Electricity Act, 2003, and the associated regulations.

About the Author

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Shri Shyam Sunder had done B.tech in Electrical Engineering from Delhi College of Engineering, Rohini, Delhi in 1987.

Joined BIS in 1989 and worked across various activities of BIS and in different departments.

Handled Product Certification activities at BIS Branch Office/ Regional Office Level.

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Worked in Electro Technical Department for formulation of the standards on the different subject of Electrical related products.

Worked in laboratory and Handled the Headship of Central laboratory, where initiate various projects for modernisation of lab and to available testing facility of most of the products falls in QCOs.

Handle the Headshop of Central Laboratory, Service Sector Department, Publication Department, Planning & Coordination Department, and Currently Holding Headship of Noida Branch Office.

- **Central Marks Department I (CMD I)** - General Policy Framework for Product Certification Activity and Matters related to Quality Control Orders (QCOs).
- **Central Marks Department II (CMD II)** - Technical Policy Matters on Certification of Nonengineering Products.
- **Central Marks Department III (CMD III)** - Technical Policy Matters on Certification of Engineering Products.
- **Central Lab (CL) -** To support certification scheme, which requires testing of products on regular basis for checking conformity to the relevant Indian Standards, BIS has established a network of labs.
- **Electrotechnical Department (ETD)** - Standardization Activities in the field of Electrotechnology.
- **Noida Branch Office (NOBO)-** Noida Branch Office, acronymic as NOBO, is one of the 41 Branch offices of Bureau of Indian Standards, the National Standards Body of India. It comes under the jurisdiction of the Central Regional Office of BIS.

From the Author

Bureau of Indian Standards (BIS), the National Standard Body of India established under the BIS Act 2016, has the responsibility of Formulation, Promotion and Implementation of National Standards, also known as Indian Standards.

Indian Standards published by BIS together with the Conformity Assessment Schemes form the basis of technical framework that helps Industry to build National Quality Ecosystem. The presence of BIS Standard Mark on a Product provides Third-Party Assurance of Quality, Safety and Reliability to Consumer.

The Nation is going through a phase of massive transformation in Quality Control scenario, requiring product compliance to Standards. The well-being of the Nation largely depends upon the work of the Engineer. "*Today's Engineers are the Nation Builders of Tomorrow*".

Electrical Engineering has a very broad scope, in practice and the text books have been specially designed with basic concepts and principles of Electrical Engineering. Even though textbooks are an invaluable component in building and broadening the knowledge base of every learner, students should have exposure to other types of Reference Books as alternate avenues for strengthening the already acquired knowledge.

This Reference Handbook integrates the learning methodology with practical aspects of testing, accommodating the rich experience contained in the relevant Indian Standards related to specific product. The blend of learning experiences helps students to make the material more real and meaningful and intends to serve as a foundation to build a stronghold in the field of Electrical Engineering, thereby aiding them in delivering their role as Electrical Engineer.

This Handbook draws on the extensive material base from latest Indian Standards available on the subject. The original text has been retained in the interest of providing necessary background to the continuing technical developments. However, users of this reference material are encouraged to refer latest editions of the Indian Standards to gain deep insight on various aspects of the subject. The indigenous Indian Standards can be downloaded free of cost from BIS website www.bis.gov.in or using the link https://www.bis.gov.in/know-your-standard/.

The Electrical Engineering Reference Handbook on High Voltage Direct Current (HVDC) system is an encyclopaedia and not a textbook for learners of Electrical Engineering and would not exist without **Shri Pramod Kumar Tiwari, IAS, Director General, BIS** whose conceptualization of the project on Reference Handbooks along with the vision, support and guidance have made this Handbook, along with so much else possible.

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INTRODUCTION

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INTRODUCTION

1.1 INTRODUCTION

India's rapid urbanization and population growth have significantly increased energy consumption, necessitating the installation of numerous power generation plants. High Voltage Direct Current (HVDC) systems are essential for efficient long-distance power transmission, connecting remote renewable energy sources to urban and industrial areas with minimal losses. This handbook provides comprehensive guidance aligned with Indian standards for the installation, maintenance, and safety of HVDC systems. It is an invaluable resource for electrical engineers, technicians, researchers, and students.

1.2 Indian Standards Pave the Way for Quality Upgradation

One of the major challenges faced by the developing countries is how to transmit and distribute electric power more efficiently. In India, the BIS helps to meet these challenges by publishing Indian Standards which facilitate the industry in manufacturing quality products conforming to the specified requirements of the relevant Indian Standards.

BIS has been developing Indian Standards that deal with various aspects of Electrotechnology through its Electrotechnical Department (ETD), which includes Standardization of electrotechnical aspects of generation, transmission, distribution. Standardizing the transmission and distribution of electricity through prescribing Indian Standards for High Voltage Direct Transmission System the most essential components of a power transmission network, is one of the fields where BIS makes a real difference to the future of the Nation in its quest for high quality products. The compliance of High Voltage Transmission System to Indian Standards aligns with the Government's aim to enhance product quality in the power sector, promote Indian manufacturing, encourage 'Made in India' products, and achieve self-reliance.

1.3 Relevant BIS Technical Committees

1.3.1 *ETD 9 'Power Cables'*

To prepare standards for electric cables and their accessories, without limitations of voltage, current or form of construction but excluding cables for telecommunications and electronic equipment. Standards detailing the requirements of cables for HVDC systems are to be published by this committee, which is:

ETD 9 (24969) 'High Voltage Direct Current HVDC Power Transmission - Cables with Extruded Insulation and Their Accessories for Rated Voltages Up to 320 KV for Land Applications - Test Methods and Requirements'.

1.3.2 *ETD 40 'HVDC Power Systems'*

To prepare standards and guidelines on equipment and performance of high-voltage Direct Current (HVDC) Transmission Systems.

Bureau of Indian Standards liaison with international standards bodies like IEC, ISO etc. for harmonization of Indian standards with international standards and represent indigenous standards at global level. The ETD 9 is the mirror National committee of the following committees in the International Electrotechnical Commission.

a) IEC TC 115 - High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV - Principle (P).

b) IEC TC 22 / SC 22F - Power electronics for electrical transmission and distribution systems - Principle (P).

Following Indian Standards published by the ETD 40 'HVDC Power Systems' Committee

a) IS 14801: 2021/IEC 60633: 2019 High-voltage direct current HVDC transmission Vocabulary (*first revision).*

b) IS 14902 (Part 1) : 2022/IEC TR 60919-1: 2020 Performance of high-voltage direct current HVDC systems with line-commutated converters Part 1 Steady-state conditions (*second revision*).

c) IS 14902 (Part 2) : 2013 Performance of high - Voltage direct current Hvdc systems with line - Commutated converters Part 2 faults and switching (*First Revision*).

d) IS 14902 (Part 3) : 2013 Performance of high - Voltage direct current Hvdc systems with line - Commutated converters Part 3 dynamic conditions (*First Revision*).

e) IS 14911 (Part 1) : 2020/IEC 60700-1 : 2015 Thyristor Valves for High Voltage Direct Current HVDC Power Transmission Part 1 Electrical Testing (*First Revision*).

f) IS 14911 (Part 2) : 2024/ IEC 60700-2:2016+AMD1:2021 CSV Thyristor Valves for High Voltage Direct Current HVDC Power Transmission Part 2 Terminology.

g) IS 15597 : 2023/IEC 61803:2020 Determination of Power Losses In High-Voltage Direct Current HVDC Converter Stations With Line-Commutated Converters (*First Revision*).

h) IS 15617 : 2017/IEC 61954 : 2013 Static var compensators Svc testing of thyristor valves (*First Revision*).

i) IS 16071 : 2013 High - Voltage direct current Hvdc systems - Guidebook to the specification and design evaluation of a c filters.

j) IS 16071 (Part 1) : 2021/IEC TR 62001-1:2016 High-voltage direct current HVDC systems Guidance to the specification and design evaluation of AC filters Part 1 Overview (*First Revision*).

k) IS 16071 (Part 2) : 2021/IEC TR 62001-2:2016 High-voltage direct current HVDC systems Guidance to the specification and design evaluation of AC filters Part 2 Performance (*First Revision*).

l) IS 16071 (Part 3) : 2021/IEC TR 62001-3:2016 High-Voltage Direct Current HVDC systems Guidance to the specification and design evaluation of ac filters Part 3 Modelling (*First Revision*).

m) IS 16071 (Part 4) : 2021/IEC TR 62001-4:2016 High-voltage direct current HVDC systems Guidance to the specification and design evaluation of AC filters Part 4 Equipment (*First Revision*).

n) IS 16075: 2013 Voltage sourced converter Vsc valves for high - Voltage direct current Hvdc power transmission - Electrical testing.

o) IS 16076: 2013 Voltage sourced converter Vsc valves for high - Voltage direct current Hvdc power transmission - Electrical testing.

p) IS 16076 : 2013 High - Voltage direct current Hvdc installations - System tests.

q) IS 16665 : 2017/ IEC TS 61973 : 2012 High Voltage Direct Current HVDC Substation Audible Noise.

r) IS 16666 : 2017/ IEC TR 62544 : 2010 High Voltage Direct Current HVDC Systems-Application of Active Filters.

s) IS 16667 : 2018/ IEC TR 62543 : 2011 High - Voltage direct current Hvdc power transmission using voltage sourced converters Vsc.

t) IS 17575 : 2021/ IEC TR 62681 : 2014 Electromagnetic performance of high voltage direct current HVDC overhead transmission lines.

u) IS 17576 : 2021/ IEC TR 62978 : 2017 HVDC installations Guidelines on asset management.

v) IS 17577 : 2021/ IEC TR 62672 : 2018 Reliability and availability evaluation of HVDC systems.

w) IS 17590 (Part 1) : 2021/ IEC TS 63014-1 : 2018 High voltage direct current HVDC power transmission System requirements for DC-side equipment Part 1 Using line-commutated converters.

x) IS 17591 : 2021/ IEC TR 63127 : 2019 Guideline for the system design of HVDC converter stations with line-commutated converters.

y) IS 17775 (Part 1) : 2021/IEC TR 63179-1 : 2020 Guideline for planning of HVDC systems Part 1 HVDC systems with line-commutated converters.

z) IS 17860 : 2022/ IEC TS 62344 : 2013 Design of earth electrode stations for high-voltage direct current HVDC links General guidelines.

aa) IS 18321 : 2023/ IEC TR 63262 : 2019 Performance of Unified Power Flow Controller UPFC in Electric Power Systems.

bb) IS 18322 (Part 1) : 2023/ IEC 62751-1:2014+AMD1:2018 CSV Power Losses in Voltage Sourced Converter VSC Valves for High-Voltage Direct Current HVDC Systems Part 1 General Requirements.

cc) IS 18322 (Part 2) : 2023/ IEC 62751-2:2014+AMD1:2019 CSV Power losses in voltage sourced converter VSC valves for high-voltage direct current HVDC systems Part 2 Modular multilevel converters.

dd) IS 18323 : 2023/IEC 62823:2015+AMD1:2019 CSV Thyristor valves for thyristor-controlled series capacitors TCSC Electrical testing.

ee) IS 18324: 2023/ IEC 62927 : 2017 Voltage sourced converter VSC valves for static synchronous compensator STATCOM Electrical testing.

ff) IS 18345 : 2023/IEC TR 62757: 2015+AMD1:2019 CSV Fire prevention measures on converters for high-voltage direct current HVDC systems static var compensators SVC and flexible ac transmission systems FACTS and their valve halls.

gg) IS 18597 (Part 3) : 2024/ IEC 60700-3 : 2022 Thyristor Valves for High Voltage Direct Current HVDC Power Transmission Part 3 Essential Ratings Limiting Values and Characteristics.

hh) IS/IEC TR 60071-5 : 2014 Insulation Co-ordination Part 5 Procedures for High-Voltage Direct Current HVDC Converter Stations.

1.4 Electrical Power - Generation, Transmission and Distribution

Electricity is produced by large power plants and then step up to high voltages and then carried over long distances (> 100 km) at high voltages (110 kV or more) by the transmission lines, which is stepped down to the level of the distribution network (11 kV or 415 V), bringing electric power to the consumer. Most power plants generate electricity as AC and the entire system uses AC afterwards since the voltage can be stepped up or down easily by the use of transformers. Bulk power from the generation plant is transported to consumers using transmission lines operating at high voltages. For shorter distance transmission of power (< 100 km), AC transmissions are widely preferred. When the transmission distances are longer (> 500 km), limitations are seen in using AC transmission that why the idea of HVDC transmission line came therefore now for more than 100km and bulk power transmission the HVDC system is preferred.

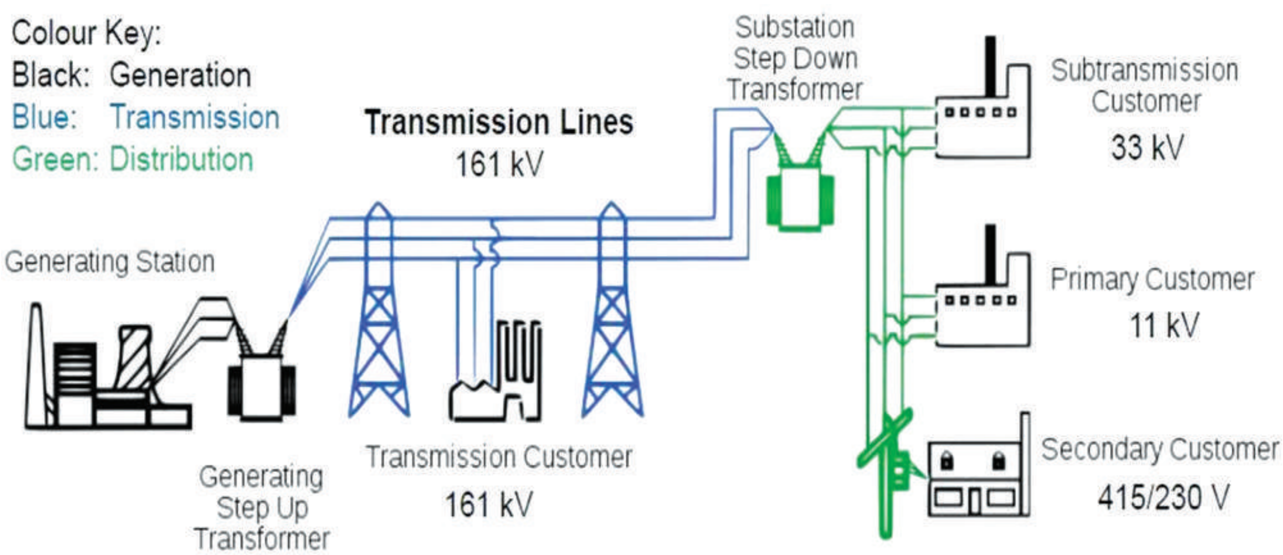

Fig 1 – HVDC Transmission System

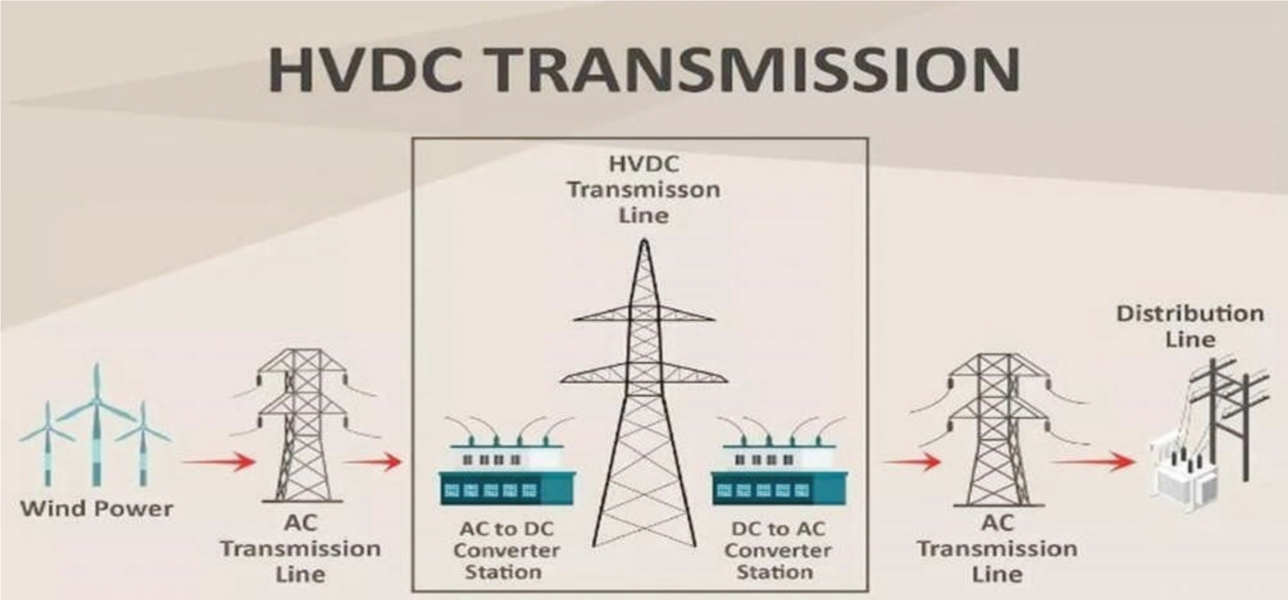

Fig 2 – HVDC Transmission System

1.5 Comparison of HVDC and HVAC

Parameters	**HVDC**	**HVAC**
Type of transmission	DC	AC
Application	HV Power transmission	HV/MV power transmission
Transmitted power and distance	Independent of distance, no limit	Depends on the distance, needs intermediate substations
Losses	Lower	Higher
Cost of Transmission (Conductors and poles)	Low cost: only two conductors are used for transmission and DC cables are cheaper than AC cables.	High cost of transmission
Cost of equipment	Higher	Lower
Station design complexity	Higher	Lower

1.6 Some of the key advantages and disadvantages of HVDC transmission include:

1.6.1 Advantages

- Cheaper for bulk power transmission and more power can be transmitted per conductor per circuit.
- Compared to conventional HVAC lines with six conductor bundles, a bipolar HVDC overhead line has two conductors and as a result requires less space and has less visual impact.
- The conductor cost in DC is also less as compared to AC cables as the size of DC conductors can be smaller as there is no skin effect. Also, there is no need for

the neutral conductor in DC transmission.

- Underground or Undersea cable systems have high amount of capacitance. In case of AC transmission, the capacitance has to be charged all the time when transmission is being done. But, in case of DC transmission, the capacitance has to be charged only in the initial condition when the transmission is started. Considering this, DC transmission is 30% to 40% more efficient than conventional AC transmission in case of underground or undersea cable systems.
- In case of AC transmission reactive power flow due to large cable capacitance limits the maximum possible distance for transmission. But in case of HVDC there is no such limitation, this is why in some cases HVDC is the only viable alternative
- In order to connect two AC system that are not synchronous, HVDC is used. This is because HVDC is asynchronous and as a result can adopt to any rated voltage and frequency it receives.
- The land required and the associated right of way for HVDC overhead transmission line is less than that of an AC line.
- Integration of sustainable assets (renewable resources) into the main transmission grid is possible because in DC transmission any amount of voltage levels can be interconnected.

1.6.2 Disadvantages of HVDC

- Converter substations needed for HVDC are more complex than HVAC as they not only need additional converting equipment but also more complicated control and regulating systems.
- As the flow of power in an HVDC system must be effectively managed by the control framework rather than the characteristic properties of the transmission line, controlling power flow in such systems require continuous communication between all terminals. This makes operating a multiterminal HVDC framework more complex in contrast to conventional AC systems.
- The flow of current through the earth in case of monopole may cause the electro-corrosion of underground metal installations, especially pipelines.
- Difficulty of circuit breaking.

CHAPTER II

TERMINOLOGY

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TERMINOLOGY

2.1 HVDC system

An electrical power system that transfers energy in the form of high-voltage direct current between two or more AC buses.

2.2 Rectifier operation (rectification)

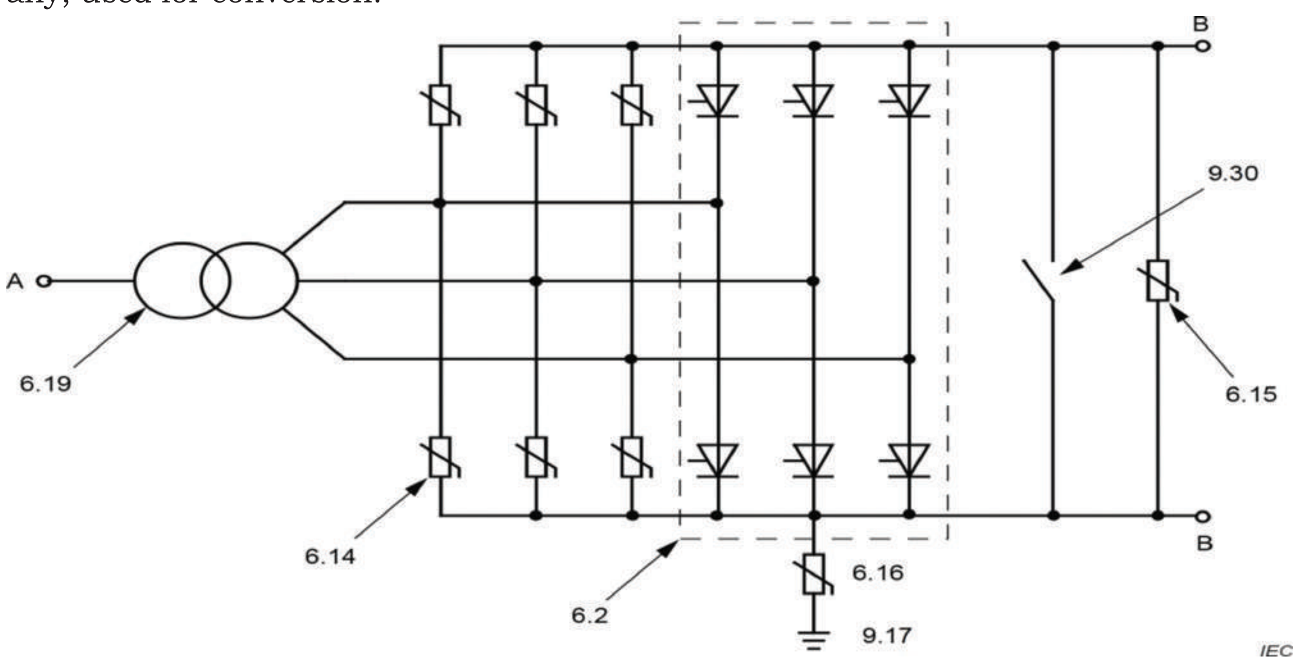
Mode of operation of a converter or an HVDC substation when energy is transferred from the AC side to the DC side.

2.3 Inverter operation (inversion)

Mode of operation of a converter or an HVDC substation when energy is transferred from the DC side to the AC side.

2.4 Converter unit

The indivisible operative unit comprising all equipment between the point of common coupling on the AC side and the point of common coupling-DC side, essentially one or more converter bridges, together with one or more converter transformers, converter unit control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion.



A AC terminals B DC terminals 6.2 Bridge 6.14 Valve arrester 6.15 Converter unit arrester

6.16 Converter unit DC bus arrester 6.19 Converter transformer 9.30 By-pass switch

9.17 Substation earth

Fig 3 – Example of a converter unit

2.5 Converter Bridge

Equipment used to implement the bridge converter connection and the by-pass arm, if used. The term "bridge" may be used to describe either the circuit connection or the equipment implementing that circuit.

2.6 Converter transformer

Converter transformer through which energy is transmitted from an AC system to one or more converter bridges or vice versa.

2.7 Valve

Complete operative controllable or non-controllable valve device assembly, normally conducting in only one direction (the forward direction), which can function as a converter arm in a converter bridge.

2.8 Trigger delay angle (firing delay angle) (α)

Time, expressed in electrical angular measure, from the zero crossing of the idealized sinusoidal commutating voltage to the starting instant of forward current conduction.

2.9 Trigger advance angle (firing advance angle) (β)

Time, expressed in electrical angular measure, from the starting instant of forward current conduction to the next zero crossing of the idealized sinusoidal commutating voltage.

Note: The advance angle β is related to the delay angle á by $\beta = \pi - \alpha$.

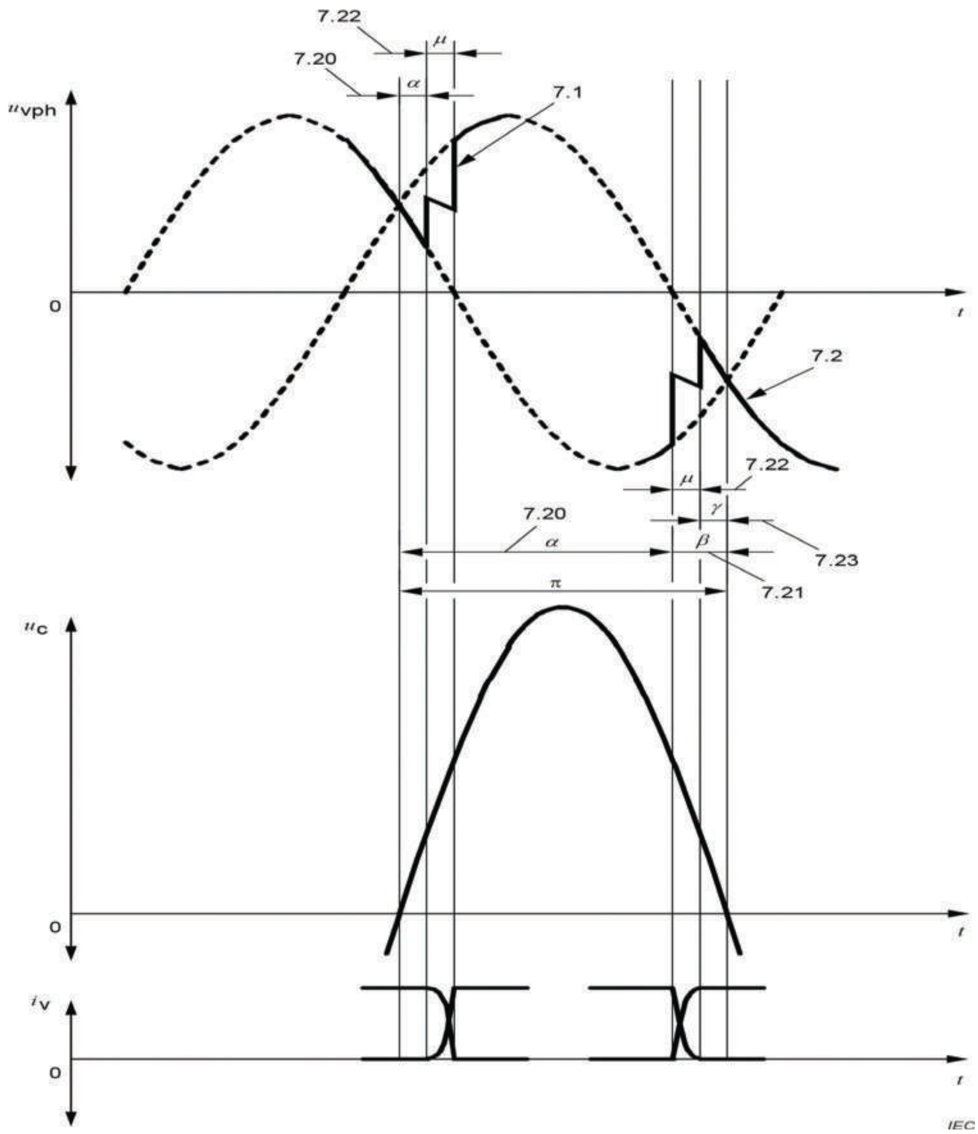
2.10 Overlap angle (μ)

Duration of commutation between two converter arms, expressed in electrical angular measure.

2.11 Extinction angle (γ)

Time, expressed in electrical angular measure, from the end of current conduction to the next zero crossing of the idealized sinusoidal commutating voltage.

[*] IS 14801: 2021/IEC 60633: 2019 High-voltage direct current HVDC transmission Vocabulary (first revision)



Uvph Phase voltage	Uc Commutating voltage	Iv Valve currents	t Time
7.1 Rectifier operation	7.2 Inverter operation	7.20 Delay angle α.	
7.21 Advance angle β.	7.22 Overlap angle μ	7.23 Extinction angle γ	

Fig 4 – Commutation process at rectifier and inverter modes of operation

2.12 AC harmonic filter

Filter designed to reduce the harmonic voltage at the AC bus and the flow of harmonic current into the associated AC system and to prevent amplification of background harmonics on the AC system.

2.13 DC smoothing reactor

The reactor is connected in series with a converter unit or converter units on the DC side for the primary purpose of smoothing the direct current and reducing current transients.

2.14 Smoothing reactor arrester

The arrester is connected between the terminals of a smoothing reactor.

2.15 DC harmonic filter

Filter which, in conjunction with the DC reactor(s) and with the DC surge capacitor(s), if any, serves the primary function of reducing (current or voltage) ripple on the HVDC transmission line and/or earth electrode line.

2.16 HVDC control system

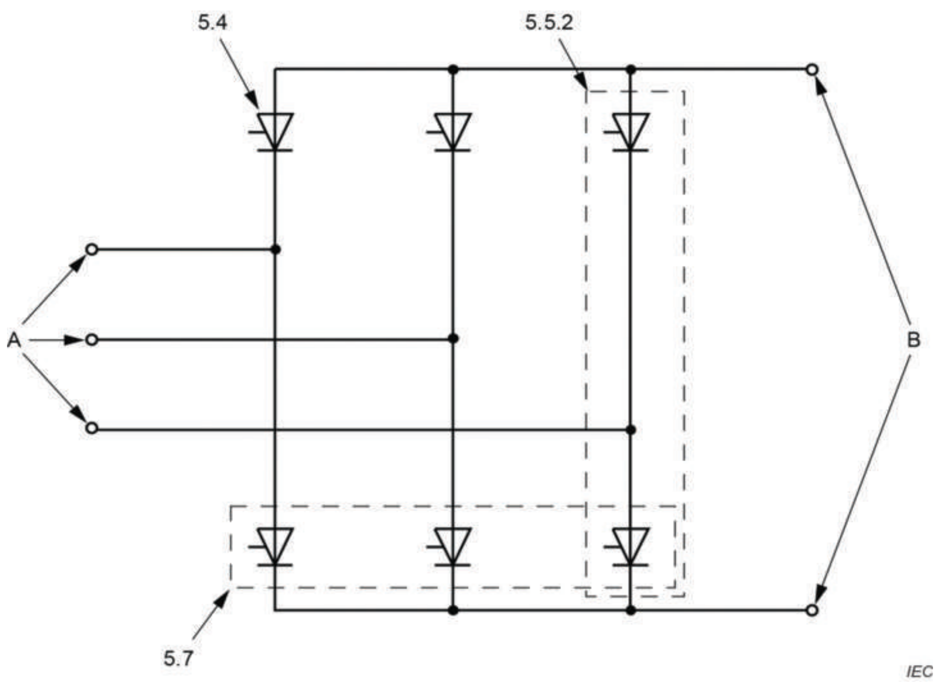
The function of, or the equipment used for, controlling, monitoring or protecting main plant equipment, such as circuit breakers, valves, converter transformers and their tap changers, forming part of an HVDC system.

2.17 HVDC system control

The control system which governs the operation of an entire HVDC system consisting of more than one HVDC substation and performs those functions of controlling, monitoring and protection which require information from more than one substation

2.18 Bridge converter connection

Double-way connection comprising six converter arms such that the centre terminals are the phase terminals of the AC circuit, and that the outer terminals of like polarity are connected and are the DC terminals.



A AC terminals

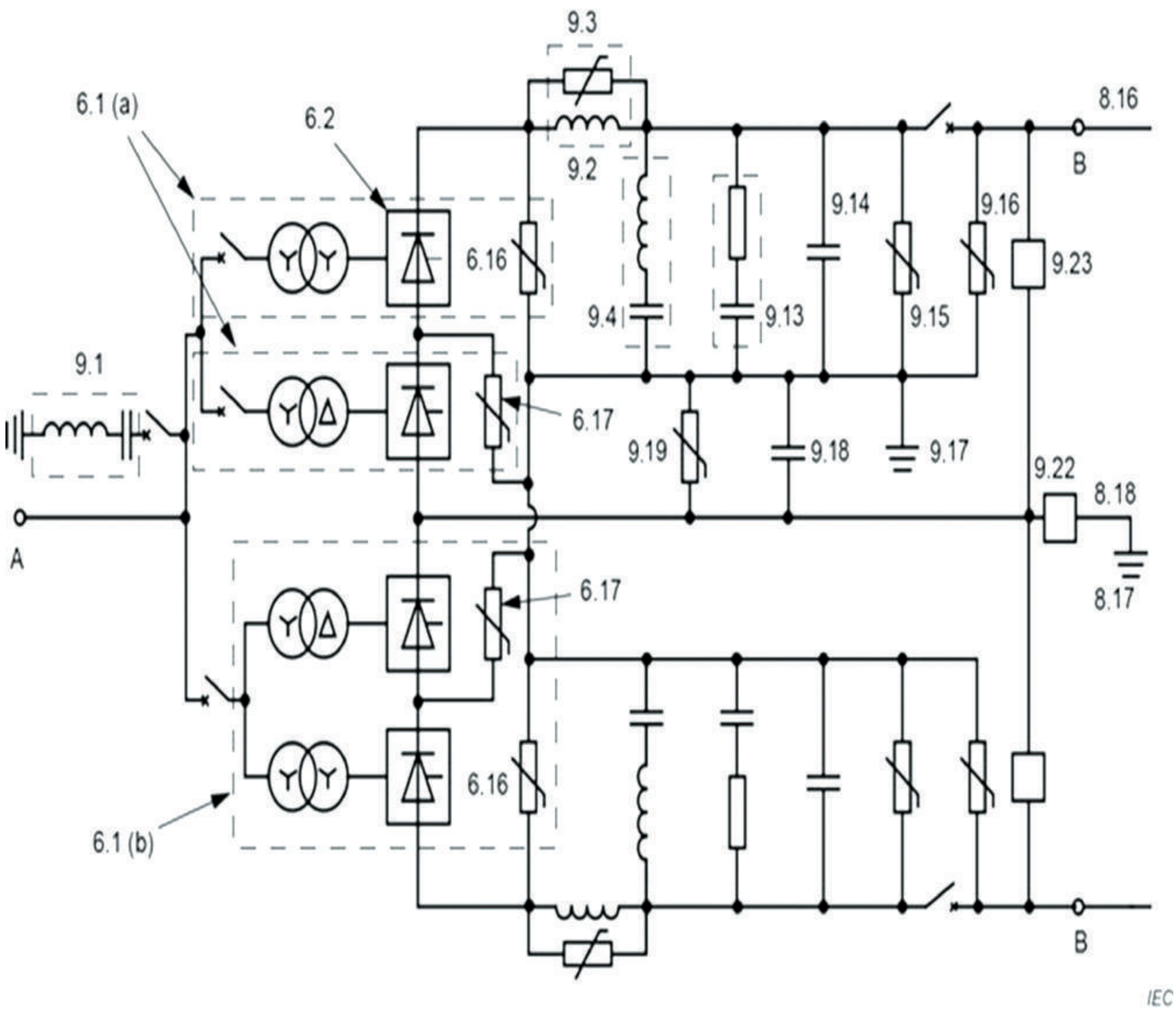
B DC terminals

5.4 Converter arm or valve

5.5.2 By-pass pair

5.7 Commutating group

Fig 5 – Bridge Converter Connection



A AC system
B DC terminal
6.1 (a) Converter unit (p = 6)
6.1 (b) Converter unit (p = 12)
6.2 Converter bridge
6.16 Converter unit DC bus arrester
6.17 Midpoint DC bus arrester
8.16 HVDC transmission line pole
8.17 Earth electrode
8.18 Earth electrode line
9.1 AC filter
9.2 DC smoothing reactor
9.3 Smoothing reactor arrester
9.4 DC filter
9.13 DC damping circuit
9.14 DC surge capacitor
9.15 DC bus arrester
9.16 DC line arrester
9.19 Substation earth
9.18 DC neutral bus surge capacitor
9.19 DC neutral bus arrester
9.22 Metallic return transfer breaker (MRTB)
9.23 Earth return transfer breaker (ERTB)

Fig 6 – Example of an HVDC substation

2.19 Types of HVDC Links

HVDC converter bridges and lines or cables can be arranged into a number of configurations for effective utilization.

2.19.1 Monopolar Link

It uses one conductor, usually of negative polarity. The return path is provided by ground or water. Cost considerations often lead to the use of such systems, particularly for cable transmission. This type of configuration may also be the first stage in the development of a bipolar system.

Instead of ground return, a metallic return may be used in situations where earth resistivity is too high or possible with underground/ underwater metallic structures is objectionable. The conductor forming metallic return is at low voltage.

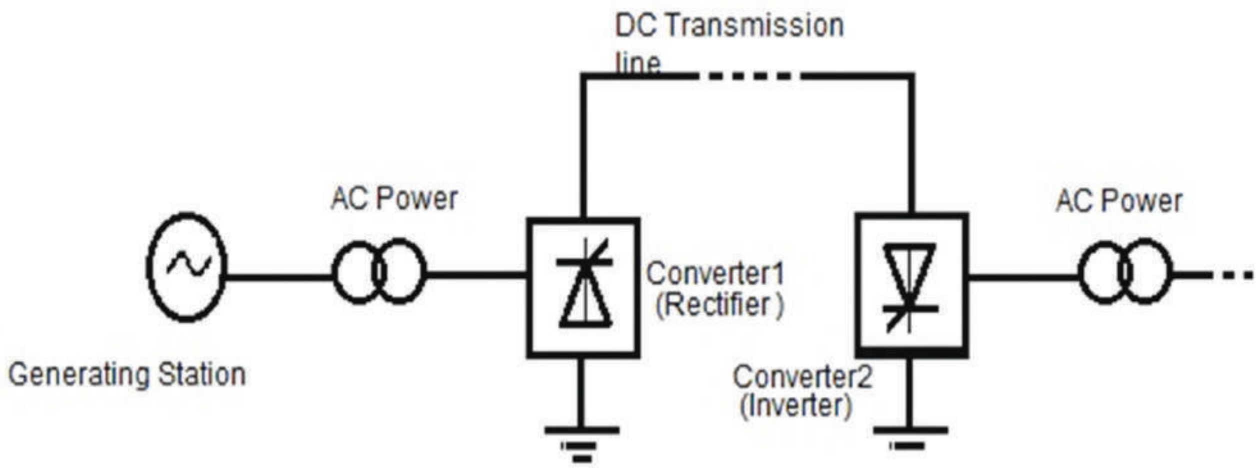


Fig 7 – Monopolar Link

2.19.2 Bipolar links

It has two conductors one positive and the other negative. Each terminal has two converters of equal rated voltage, connected in series on DC side. The junction between converters is grounded.

Normally, the currents in the two poles are equal, and there is no ground current. the two poles can be operated independently. If one pole is isolated due to a fault on its conductor. another pole can operate with ground and thus carry half the rated load or more by using the overload capabilities of its converters and line.

HVDC line is considered to be effectively equivalent to a double-circuit AC transmission line. Reversal of power flow direction is achieved by changing the polarities of two poles through controls. In the situation where ground currents are not tolerable or when a ground electrode is not feasible for reasons such as high earth resistivity, a third conductor is used as a metallic neutral. It serves as a return path when one pole is out of service.

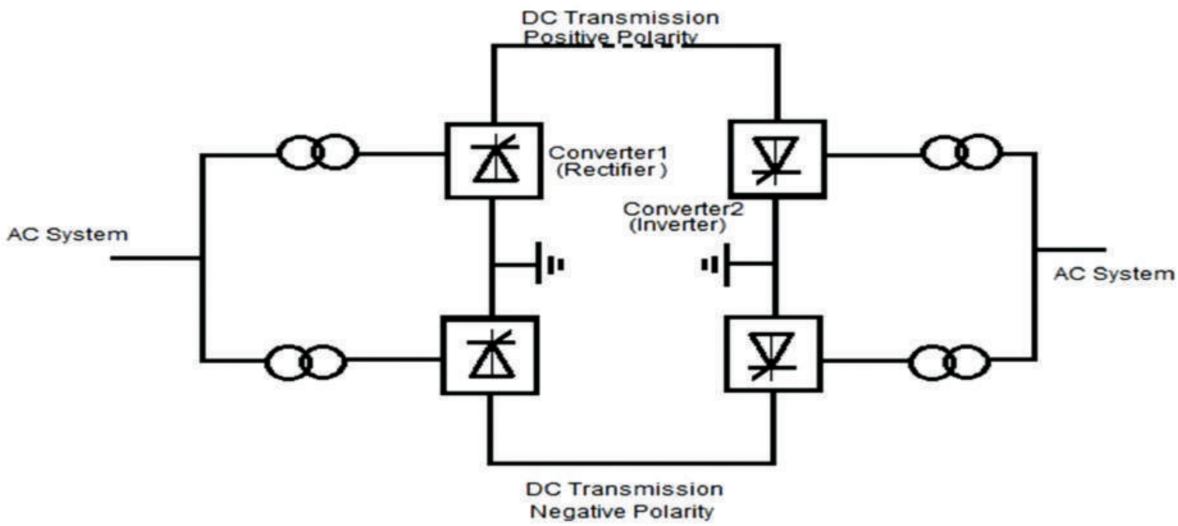


Fig 8 – Bipolar Link

2.19.3 Homopolar links

It has two or more conductors, all having the same polarity. Usually, a negative polarity is preferred because it causes less RI due to the corona. Return path through the ground, where there is a fault on one conductor, the entire converter is available for feeding remaining conductors which, having some overload capability, can carry more than normal power, where the continuous ground current is acceptable, the homopolar link is preferred.

The ground current can have side effects on gas or oil pipeline that lies within few miles of the system electrode. Pipelines act as conductors for the ground current which can cause corrosion of metal. Therefore, configurations using ground return may not always be acceptable.

Each of above HVDC system links usually has cascaded groups of several converters, each having transform bank and a group of values. The converters are connected in parallel on AC side (transformer) and in series on DC side (Valve) to give the desired level of voltage from pole to ground.

2.19.4 Two-terminal HVDC transmission system

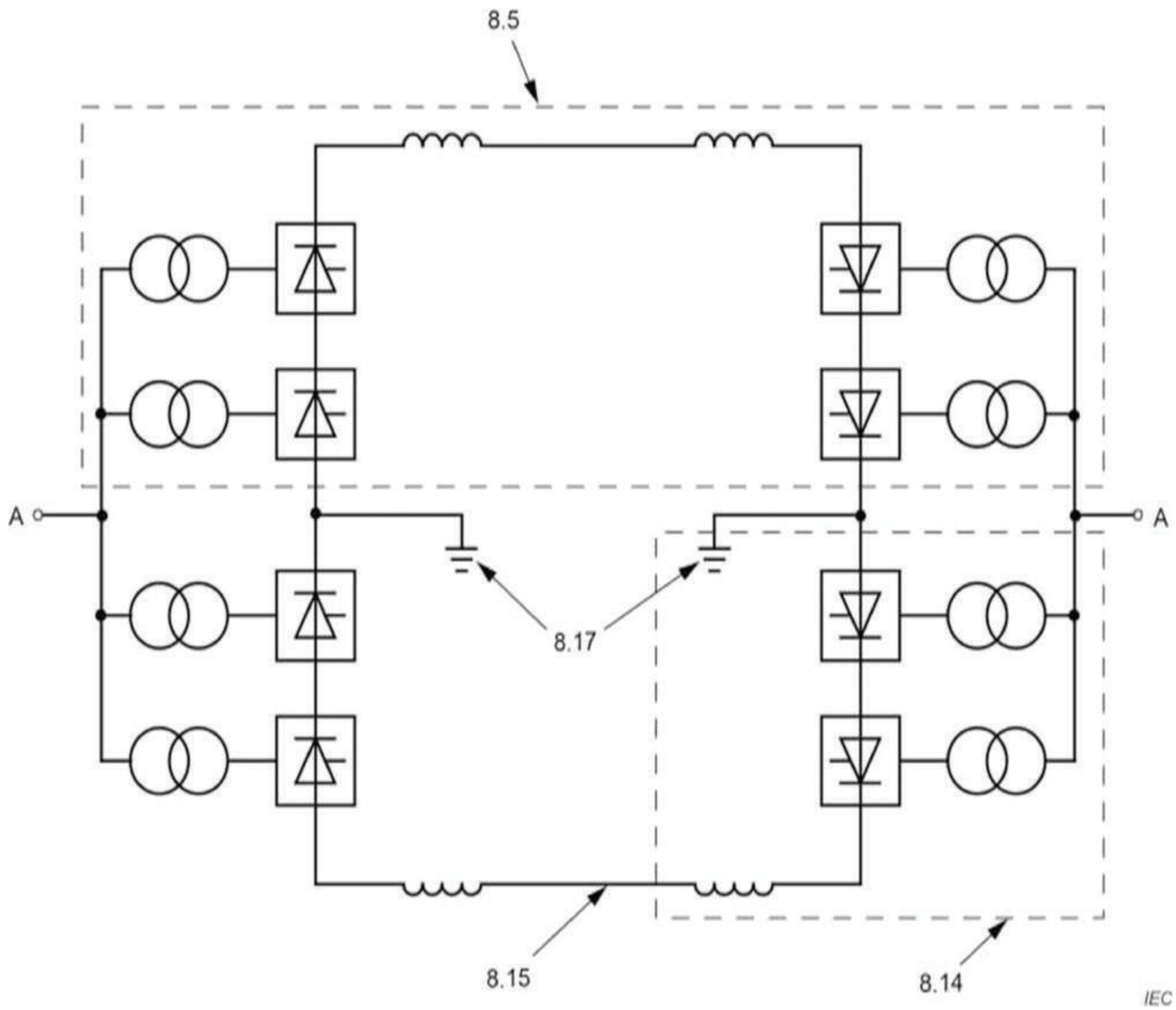
HVDC transmission system consisting of two HVDC substations and the connecting HVDC transmission line(s).

2.19.5 Multiterminal HVDC transmission system (MTDC)

HVDC transmission system consisting of more than two separated HVDC substations and the interconnecting HVDC transmission lines.

2.19.6 HVDC back-to-back system

HVDC system which transfers energy between AC buses at the same location.



A - AC system

8.5 - HVDC system pole

8.14 - HVDC substation pole

8.15 - HVDC transmission line

8.17 - Earth electrodes

Fig 9 – Example of bipolar two-terminal HVDC transmission system

2.19.7 Unidirectional HVDC system

HVDC system for the transfer of energy in only one direction.

Note: Most HVDC systems are inherently bidirectional. However, some systems may be optimized to transmit power in only one preferred direction. Such systems may still be considered as “bidirectional”.

2.19.8 Bidirectional HVDC system

HVDC system for the transfer of energy in either direction.

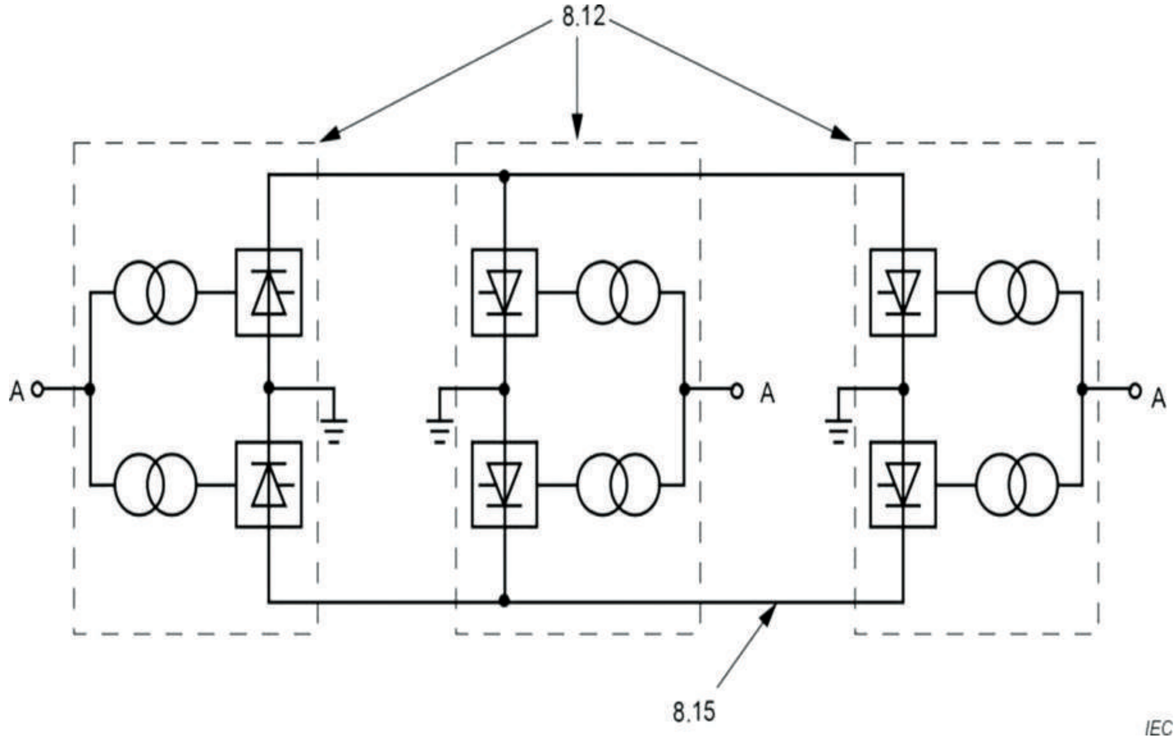
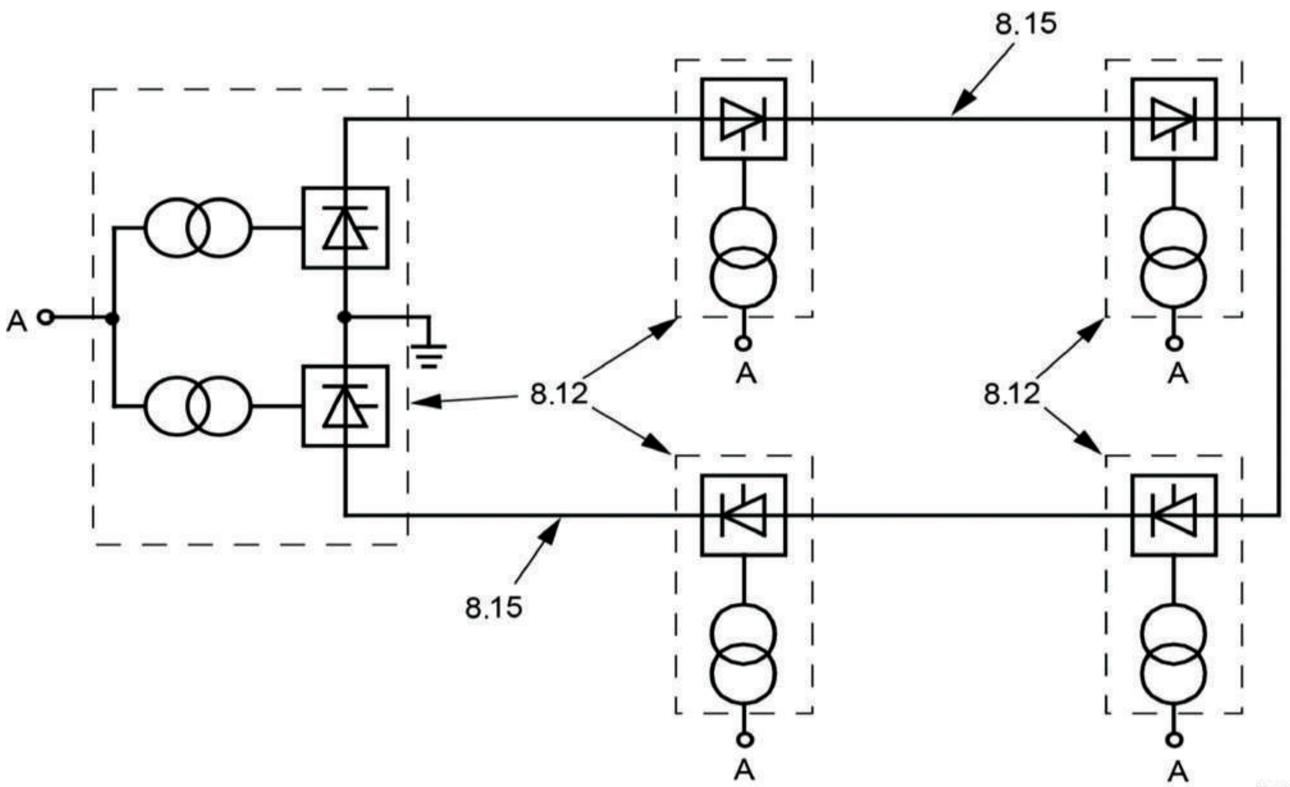


Fig 10 – Example of a multiterminal bipolar HVDC transmission system with parallel connected HVDC substations



A - AC system

8.12 - HVDC substations

8.15 - HVDC transmission line

Fig 11– Example of a multiterminal HVDC transmission system with series connected HVDC substations

2.20 LCC and VSC-based Systems in HVDC Transmission

HVDC (High Voltage Direct Current) transmission systems use two primary converter technologies: LCC (Line-Commutated Converter) and VSC (Voltage Source Converter). Each technology has its advantages and disadvantages, making them suitable for different applications.

2.20.1 LCC (Line-Commutated Converter)

LCC is the traditional and more established technology in HVDC transmission. It uses thyristors as switching devices and relies on the AC system voltage for commutation (the process of turning off the thyristors).

Advantages:

- **Mature Technology:** Proven track record with numerous installations worldwide.
- **High Power Ratings:** Can handle large amounts of power transmission.
- **Lower Cost:** Generally cheaper than VSC technology.

Disadvantages:

- **Reactive Power Consumption:** Requires significant reactive power support from the AC system.
- **Limited Controllability:** Less flexible in controlling active and reactive power flow.
- **Commutation Failure Risk:** Susceptible to commutation failures under certain grid conditions.
- **Harmonics Generation:** Produces more harmonics compared to VSC.

Applications:

- **Long-distance Bulk Power Transmission:** Well-suited for transmitting large amounts of power over long distances.
- **Point-to-point Transmission:** Connecting two specific points without the need for multi-terminal configurations.

2.20.2 VSC (Voltage Source Converter)

VSC is a newer technology that uses IGBTs (Insulated Gate Bipolar Transistors) or other selfcommutating devices. It doesn't rely on the AC system voltage for commutation, giving it more control and flexibility.

Advantages:

- **Independent Control:** Can independently control active and reactive power flow.
- **Black Start Capability:** Can start up without an external AC voltage source.
- **Improved Power Quality:** Produces fewer harmonics compared to LCC.
- **Enhanced Grid Stability:** This can provide reactive power support and voltage control.

Disadvantages:

- **Higher Cost:** More expensive than LCC technology, especially for high power ratings.
- **Switching Losses:** Higher switching losses compared to LCC.
- **Limited Power Rating:** Currently, the maximum power rating for VSC is lower than LCC.

Applications:

- **Offshore Wind Farms:** Connecting offshore wind farms to the onshore grid.
- **Underground/Underwater Cables:** Ideal for cable transmission due to its ability to control reactive power.
- **Multi-terminal HVDC Systems:** Connecting multiple points with flexible power flow control.
- **Weak AC Grids:** Can strengthen weak AC grids and provide stability support.

CHAPTER III

PLANNING AND DESIGN OF HVDC

CHAPTER III

PLANNING AND DESIGN OF HVDC

3.1 Planning

The HVDC system development and integration cycle may be described in terms of six phases, as shown in Figure 12. The main task of HVDC system planning is to develop and select an HVDC scheme based on the conclusions of power network development planning where the network requirements are defined. HVDC system planning uses as a minimum the total transmission capacity and range of connection points previously determined by power network development planning, taking into account current and future conditions of the power system, environment, and other contributing factors. There is a certain degree of repetition and iteration between HVDC system planning and system design (refer to Figure 12). For project feasibility study and scheme comparison, some investigation would be carried out during the system planning phase, and the detailed studies and final design would be accomplished during the system design phase.

The work contents and procedure for planning of an HVDC system are as follows:

- Compare HVDC and AC solutions at high level according to the specific requirements (see Cl 5 of IS17755 (Part 1));
- When HVDC is the only technically feasible solution, or the use of an HVDC scheme has overwhelming advantages, a number of alternative HVDC solutions could be investigated (see Cl 6 of IS 17775 Part 1)). When both HVDC and AC alternatives are technically feasible and neither of them has overwhelming advantages, further analysis is required to confirm the preferred solution;
- Verify the security of supply and stability of each alternative (see Cl 7 of IS 17775 (Part 1);
- Compare the economic efficiency of alternative solutions (see Cl 8 of IS 17775 (Part 1);
- Present the recommended solution (see Cl 9 of IS 17775 Part 1).

*[*] **IS 17775 (Part 1): 2021/IEC TR 63179-1: 2020 Guideline for Planning of HVDC Systems Part 1 HVDC Systems with Line-commutated Converters***

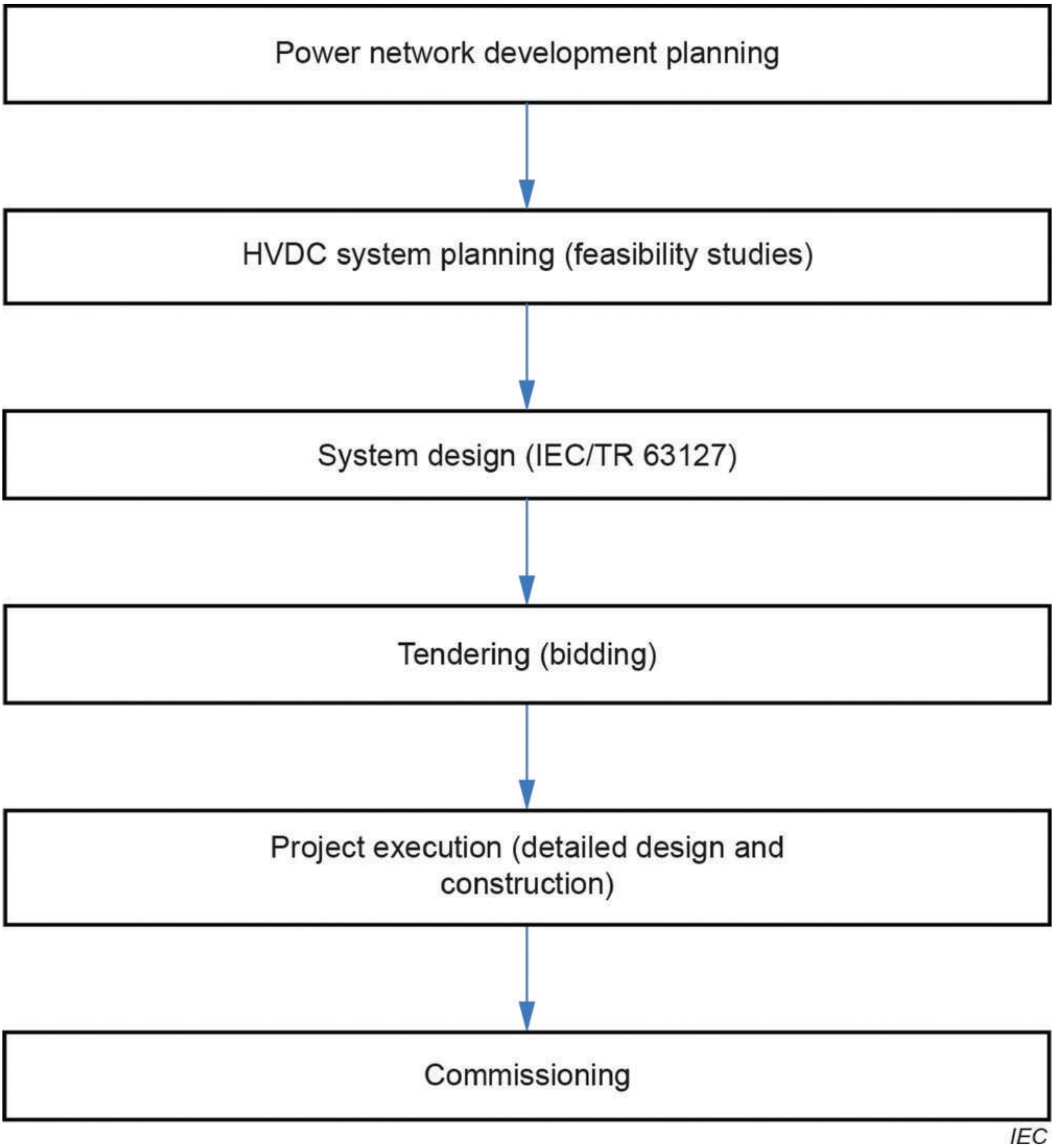


Fig 12 – Phases during integration of a new HVDC system into the power network

The following steps in the planning of an HVDC system are shown in Figure 13.

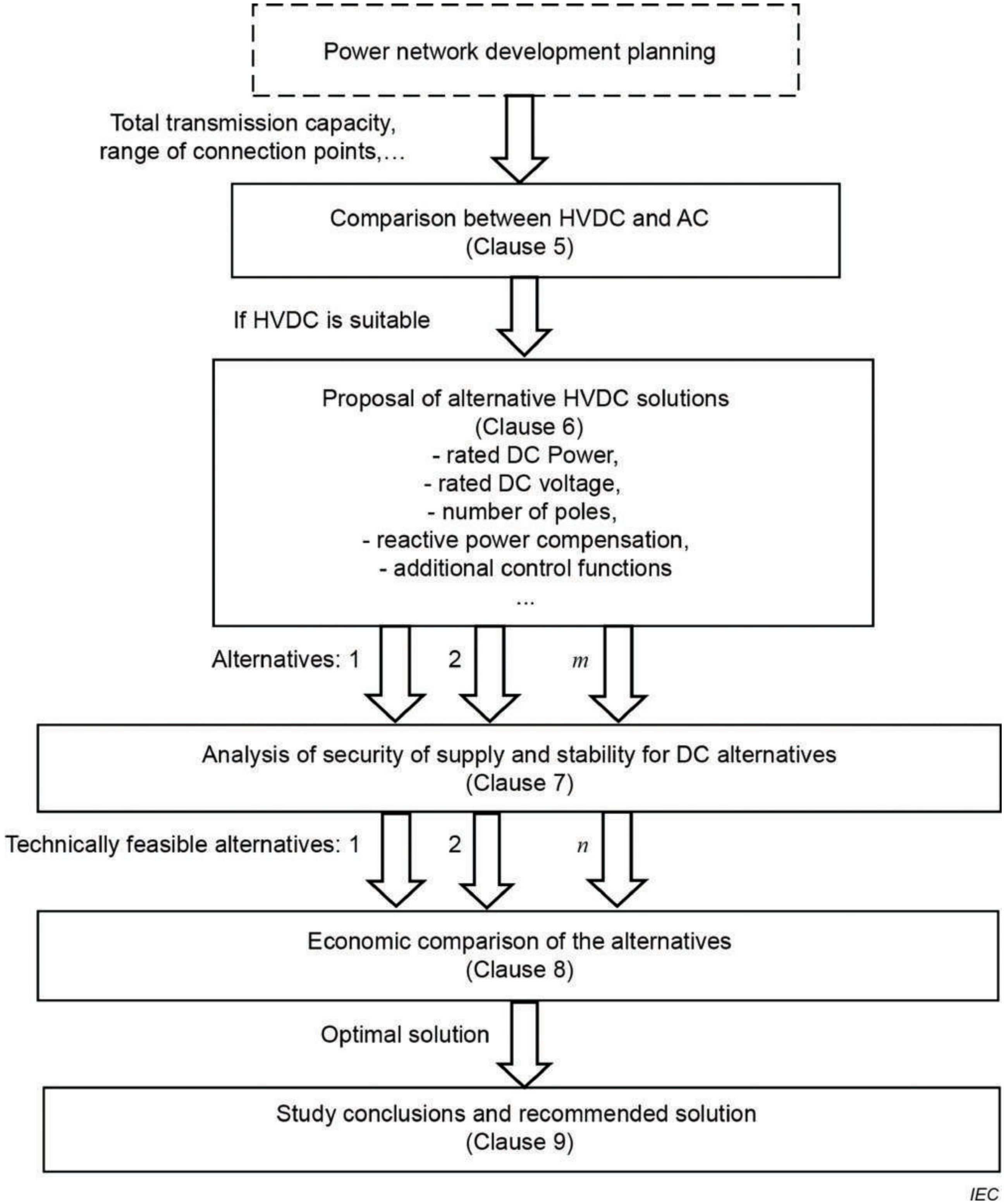


Fig 13 – Procedure for planning an HVDC system

CHAPTER IV

DESIGN OF HVDC

CHAPTER IV

DESIGN OF HVDC

4.1 Overview of HVDC System Design*

In implementing HVDC projects, the purchaser or the supplier will do preliminary system design work to prepare the various required documents needed by the project. Specific studies and simulations are conducted during the system design to find the optimal project schemes and to demonstrate performance. As a minimum, the following main system features should be determined:

- HVDC system ratings;
- HVDC system operation configurations and control modes;
- reactive power compensation and control;
- harmonic filtering;
- AC/DC interaction and control;
- insulation coordination;
- environmental impacts, such as audible noise, electromagnetic fields, etc.

The system design may be conducted in several phases by different parties, such as the purchaser or supplier, during planning, bidding, and detailed design stages, for example, as shown in Figure 10. Different tools and models may be introduced in the system design because of different targets or designs at each stage. One should be very careful to adopt the tools and models in a coordinated manner.

A functional specification for the project is usually prepared by the purchaser before the detailed design. It may consist of project objectives and conditions, grid codes, targeted system performance requirements operation regulations, etc. This functional specification should be treated as both providing inputs and the guide for the system design of an HVDC project. Because the final technology solution is undefined before the detailed design stage, it is always necessary to reserve adequate space in the functional specification for further optimization. The owner will issue the specification as a document for bidding if this is a turnkey project. After t h e evaluation of bidding for the specific technology solution, especially for HVDC control, the owner may choose the appropriate solution. Thus, the system features listed above will be studied in more detail based on the chosen technology solution and some additional studies and surveys usually need to be performed to finalize the system design. Finally, all the equipment ratings and specifications will be prepared.

The flowchart of an HVDC system design is summarized in Fig 14.

* ***IS 17591: 2021/IEC TR 63127: 2019 Guideline for the System Design of HVDC Converter Stations with Line-Commutated Converters***

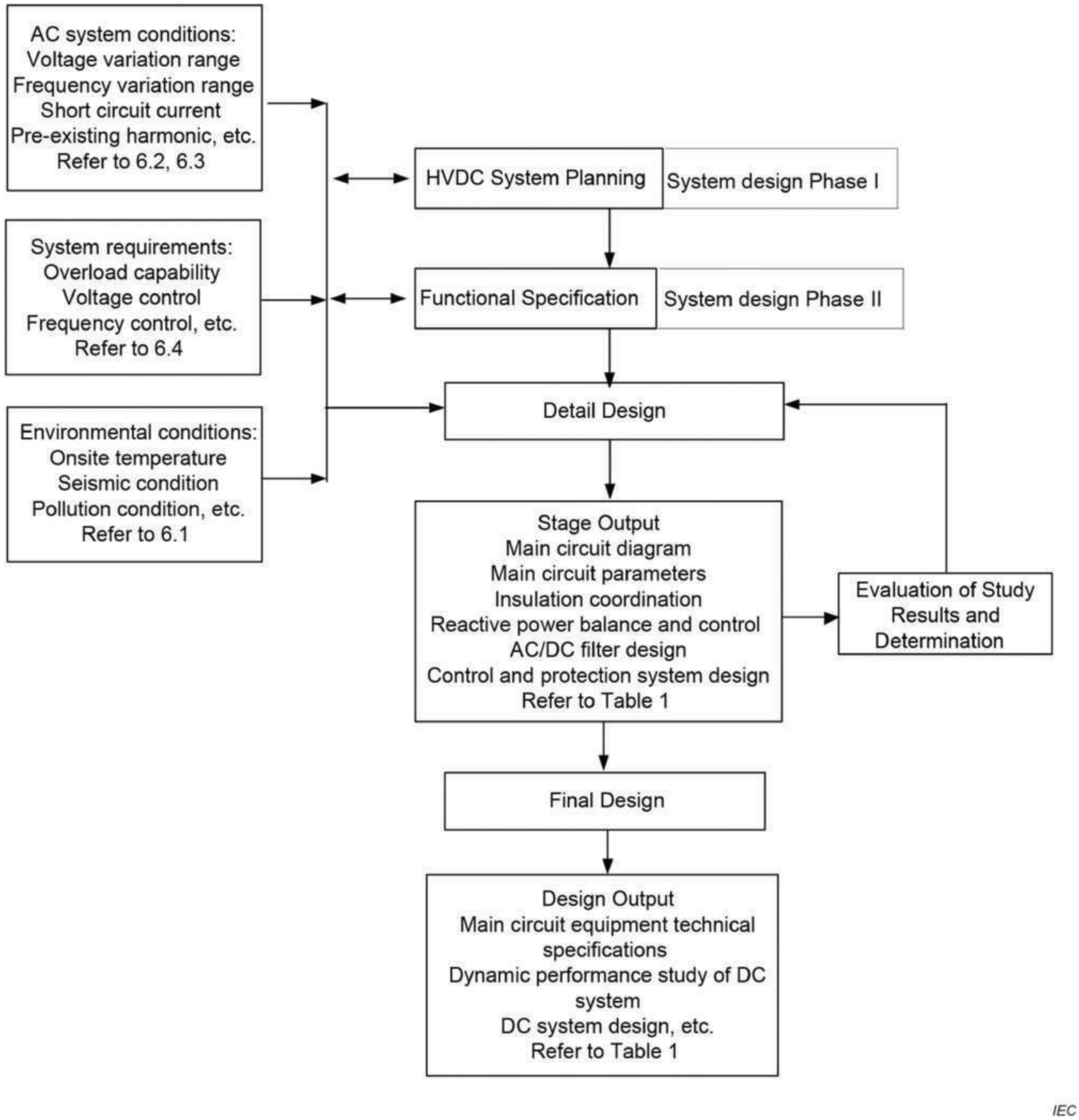


Fig 14 – System design in an HVDC project

CHAPTER V

EQUIPMENT AND MATERIALS REQUIREMENTS FOR HVDC SYSTEM

CHAPTER V

EQUIPMENT AND MATERIALS REQUIREMENTS FOR HVDC SYSTEM

5 Equipment/Material*

The main assets for HVDC installation are given in Table 1 and a typical simplified layout arrangement is in Figure 15.

Table 1 – Main asset components of an HVDC system.

S.N.	Asset	Component/Equipment
1.	Converter	Thyristor valves and valve base electronics. Valve cooling equipment and cooling control
2.	Converter transformer	Converter transformer and associated equipment.
3.	AC filters and high frequency (HF) Filters	AC harmonic filters and shunt capacitor. AC-side high frequency filters for the converter transformer connections to the AC.
4.	Smoothing reactor	Dry or oil filled smoothing reactor connected in series with converter (bridge).
5.	AC shunt reactor	AC shunt reactor and associated component.
6.	DC filters and high frequency (HF) filters	DC harmonic filters and associated component. DC-side high frequency filters for connections to the DC switchyards. DC neutral bus surge capacitors. Blocking filter arrangement, e.g., tuned to fundamental frequency, to mitigate coupling from parallel AC circuits.
7.	DC switchyard equipment	DC measuring devices for current and voltage. DC wall bushings for high voltage and neutral buses. DC switchgear including surge arresters, high speed circuit breakers and any associated equipment needed to ensure current zeros can be achieved, DC high speed switches, high voltage and low voltage disconnectors, earthing switches, bushings, insulators, tubular bus, conductor, connectors and other associated hardware as applicable. DC neutral bus equipment. DC switchyard structures and connections. Fault location coupling devices.

**IS 17576:2021/IEC TR 62978: 2017 HVDC Installations — Guidelines on Asset Management*

S.N.	Asset	Component/Equipment
8.	AC switchyard equipment	AC circuit breaker. Disconnector. Current and voltage transformers. AC switchgear equipment related to converter station and associated equipment including surge arresters, earthing switches, bushings, insulators, tubular bus, conductor, connectors and other associated hardware as applicable.
9.	AC and DC control and protection equipment	Control and protection for the HVDC system, DC converters, DC switchyards, DC transmission line and DC cables, converter transformer, smoothing reactor and DC filter equipment. Control and protection for AC switchyard equipment, AC filter and reactive power compensation equipment. Control and protection for valve cooling system. Station auxiliary system control and protection. Electrode line protection and monitoring systems. Fault location and fault recorder equipment for HVDC transmission lines and HVDC cables. Control equipment required for electrode and electrode line protection and monitoring, and associated communication interfaces for exchanging signals with the associated converter station.
10.	Fire detection and protection systems	Fire detection and alarm systems for the converter stations including but not limited to: All fire protection systems in the valve hall, including the DC switchyard and DC filter buildings and AC switchyard control buildings. Water deluge fire protection systems for oil immersed transformers and reactors and oil filled bushings. Stand-by diesel pump for fire protection. Fire protection water supply and storage.
11.	Electrode stations	Land or sea electrodes. Connecting cables between electrode segments and incoming electrode lines. Disconnects to isolate electrode or segments of the electrode. Current measuring devices for electrode segments. Electrode line protection and monitoring.
12.	Auxiliary AC supply	LVAC supply to cooling and valve for the converter asset. AC distribution board. UPS for AC supply to critical equipment.

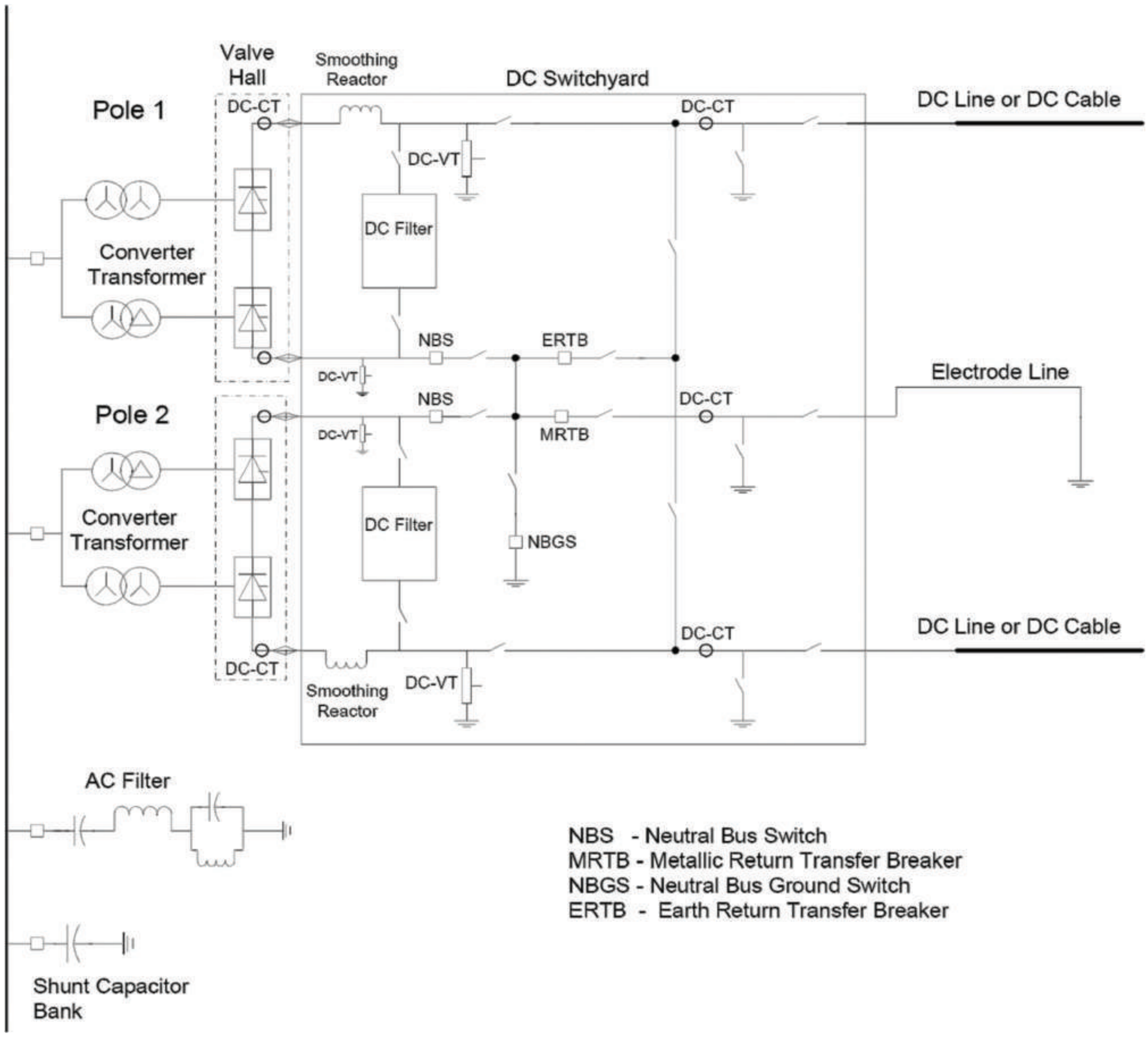


Fig 15 – Typical bipolar thyristor based HVDC system

CHAPTER VI
DEVELOPMENT AND MAINTENACE OF HVDC SYSTEM

CHAPTER VI

DEVELOPMENT AND MAINTENACE OF HVDC SYSTEM

6.1 HVDC Development

6.1.1 General

One of the challenges in HVDC technologies is that most of the HVDC systems and installations are proprietary and very specific to OEM design, especially on control and protection system thyristor valves and associated equipment. The design and characteristics of equipment between OEMs are different and can be compounded based on the technology at a particular time. Both utilities and OEMs often faced a problem in retaining specialized personnel with respect to older HVDC design and technology.

6.1.2 Skill retention and development in HVDC system

The type of specialized skills and knowledge on the high technology content in the HVDC system to be retained by asset managers or asset workers is a fundamental decision for each organization. It will depend on their views of the strategic importance of retaining certain skills or knowledge and the economics of retaining some non-core skills within each organization. Organizations using outsourcing of both intellectual and labour resources claim a number of benefits. However, issues such as the loss of basic technical knowledge or understanding of the condition of their assets and the impact of outsourcing on the skill retention and development of the internal and outsourced workforce are amongst other factors which have to be considered. These issues should be considered when setting up outsourcing models to avoid costly outcomes at a later stage. Organizations proceeding on this path firstly need to identify the mainstream functions for which a distinct knowledge or skill base is an essential component and whether it is a core function or not. Once the extent of these functions in the organization is identified, the relevant skills and the level of retention can be assessed. Before assessing whether a skill or knowledge base is to be retained or outsourced, it is important to have a process to clearly understand who is currently providing the key knowledge. The capacity of the provider to continue to provide the skill over the longer term should be assessed and be able to be monitored.

6.1.3 Factors in Deciding level of HVDC skill Retention

The following factors determine the level or degree to which specific HVDC skills or knowledge should be outsourced and when these processes should be implemented:

- Cost difference if skill is outsourced;
- importance and availability of emergency response;
- completeness of maintenance standards;
- ease or difficulty in specifying and assuring quality performance;

- uniqueness of the skill or knowledge;
- need for internal asset workers to grow their own business using this skill;
- organizational need to exploit new technology;
- need for delegated responsibility in the asset worker;
- level of condition monitoring information available to the asset manager;
- the commonality of strategic directions between the asset manager and worker;
- age of the asset base;
- status and capability of industry training organizations and processes;
- retention of sufficient expertise so that the asset manager can be a knowledgeable buyer of outsourced service provider skills; and
- availability of skills with suppliers and consultants.

Another input to this process is to consider the relevance of different business drivers of internal and external service providers and their synergy with the organizations for different activities.

6.2 HVDC Maintenance

The HVDC converter equipment should be maintained in line with the recommendations of the OEM. Preventive or scheduled maintenance should be coordinated between the two terminal stations to minimize downtime. Planned maintenance on the transmission lines which requires line outages should be carried out at the same time as converter terminal outages.

Scheduled maintenance should not be necessary more than once per year. Considering bipolar operation, the converter station should be designed to permit maintenance on one pole with the other pole in service so that shutdown of the entire bipole is not required for pole maintenance.

Scheduled outages for preventative maintenance and repairs by the owner should be included in the evaluation of availability and will be based on the following:

- Maintenance will be performed with the interval between scheduled maintenance outages as stipulated by the OEM and accepted by the owner.
- Maintenance will be performed in accordance with the OEM maintenance instructions. The OEM should be advised when the work will be carried out and may if he chooses witness all scheduled maintenance work during the availability and reliability monitoring period if specified in the tender document.
- Maintenance and repair will be performed with a qualified working crew of adequate size for the work and trained according to the OEM maintenance training program.
- The objective in corrective maintenance policy or practices of the HVDC system is to achieve high levels of availability and reliability with minimum scheduled outages. The owner or operator should give careful attention to related factors

affecting the HVDC system performance including, but not limited to, sub-system and system testing, spare parts and redundancy of design.

- The HVDC system should be operated and maintained to continue in operation and to prevent undesired power outages or reduced power capacity due to equipment failure, malfunction, or operator error.
- For bipolar operation, special attention should be given in the maintenance procedure of the converter station to avoid bipole outages due to repair work on any equipment failure or any HVDC control system.
- The design basis required for the converter station should be such that under normal balanced bipolar operating conditions, no single failure of equipment furnished should cause a forced outage resulting in a DC power transfer capacity reduction greater than the rating of one pole. Where this is not practical it should be demonstrated that the expected number of incidents in which power transfer capacity reductions greater than one pole when occurred is acceptable and comparable to other recent bipolar systems. For a bipolar operation, the converter station should be designed to permit maintenance on one pole with the other pole in service. The converter station should be designed so that shutdown of the entire station for any corrective maintenance is not required.
- The design of the converter auxiliary system and associated controls and protection should provide corrective maintenance features whereby a single equipment failure should not cause any reduction in DC power transfer capacity. For example, in the event of failure of a portion of the cooling system for a piece of power equipment, the increased temperature rise should not be injurious to the power equipment. All cooling systems should have sufficient reserve capacity built into cooling pumps, cooling fans and heat exchangers to allow for the loss of any single piece of equipment in the cooling system without reduction of the HVDC system power transfer capacity. If necessary, cooling pumps, cooling fans, and heat exchangers should be duplicated to meet this requirement.
- In general, wherever possible, the following design principles should be followed in implementing the corrective maintenance policy of the HVDC system:
- Provision of alarm, fault indication, monitoring and test facilities. Where applicable the components are with fail-safe and self-checking designs.
- Redundant components, with equipment and control circuits of the board using either duplication or triplication with automatic transfer facilities. Where feasible, provide physical separation of redundant control board and circuits for control and protection system.
- Designs which, in the event of component failures, may provide for transfer to a less complex operating mode.
- Provide a clear maintenance or repair procedure and checklist, a n d easily read drawings and manuals with sufficient details and cross-references to facilitate repair, servicing, and maintenance.
- Use of equipment, designed to be maintained, repaired, and operated at the converter station without the need for special operating and maintenance

environment, test equipment, special tools, or complex operating sequences. i) Provision of modular construction to permit rapid replacement of modules with failed components or sub-assemblies.

The owner or operator of HVDC system should provide a record and statistical maintenance report which can be used by site maintenance personnel to track system reliability.

This document mainly covers recommended practices for maintaining HVDC installations after defect warranty period, in particular during the usable lifespan of the asset. Maintenance of new installations during the warranty period should depend on the stipulated contractual terms and conditions agreed upon for the project. During such warranty period, all critical routine or preventive maintenance activities should be implemented together with the OEM and in association with their recommendations as part of the practical training program for the asset maintenance personnel.

6.3 Life extension strategies

There are a number of techniques used in the power utility industry to extend the life of major assets, which include the following options.

a) Refurbishment of existing equipment, for example, control and protection system upgrade, HVDC cooling system overhaul and drying of converter transformer. This approach includes major overhaul activities or remedial maintenance tasks and often involves significant outage times and costs.

b) Derating of equipment to minimize aging. Reduction of the stresses has the same effect of moving the hazard rate function towards the right, or to effectively extend life expectancies in a statistical sense.

c) Increase in maintenance activity or adapting specific maintenance practices to focus on key components for critical equipment. D) Installing on-line monitoring system for critical equipment to ensure operating stresses are kept to a minimum level, where possible.

6.4 Run-to-failure strategies

Certain assets making up the HVDC system may be non-critical with respect to the impact of their failure on the short-term performance or the business values of the company. The preferred strategy for such equipment may be to allow them to run to failure before repairing, refurbishing or replacing with new equipment. For example, run to failure strategy can be applied to non-critical asset which is equipped with on-line monitoring. Spares should however be kept for replacement. In the case of HVDC asset, a thyristor can be treated under this strategy where it is fitted with an on-line thyristor level monitoring. However, forecasting the expected number of in- service failures should be implemented, particularly when significant proportions of the asset are approaching the end of their design lifespan.

6.5 Refurbishment of HVDC system

Technical life assessment should be performed to determine the existing conditions of the HVDC system and its associated equipment. Options to extend the reliability and useful lifetime of the asset should be explored, particularly when it is approaching the end of design life cycle. Decisions to refurbish or rehabilitate an existing HVDC system are typically based on the following assessment criteria.

- Ageing or deterioration of equipment under environmental conditions and overload.
- Obsolescence of equipment technologies – lack of spare parts and support.
- Reliability and availability of main equipment due to prior failures during operation.
- Lack of expertise, knowledge and support of the existing sub-systems.
- Long downtime of the HVDC link due to maintenance constraints.
- Major changes involving the network configuration or the HVDC link.
- Frequent major failures of control system.
- Re-negotiation of bulk power purchase price.
- Proposed increase in asset utilization.
- Proposed increase in power transfer.
- Prolonged operation of the asset for another 10 to 25 years.
- Systematic failures due to equipment design.

The assessment to substantiate the proposed refurbishment work should indicate that it is the most cost-effective and technically viable solution to extend the life of existing HVDC system, without any performance penalty. Refurbishment work typically involves replacing major equipment and critical sub-systems which are approaching their end of useful lifetimes, instead of constructing or installing a completely new DC link of similar rating and type.

In the event of the main equipment being considerably different at both ends, the refurbishment work should be coordinated to commence simultaneously to avoid or 38inimize additional scheduled outages. It is recommended that periodical meetings and discussions be held to update work progress, resolve pending issues and re-align schedules with respect to the refurbishment work, particularly involving utilities and contractors from different nations.

CHAPTER VII
TESTING AND COMMISSIONING

CHAPTER VII

TESTING AND COMMISSIONING

7 TESTS AND COMMISSIONING*

7.1 General

This clause provides general guidelines for testing and commissioning of VSC transmission systems. Emphasis has been put on subsystem and system tests rather than those for components. Testing and commissioning are part of a process that begins in the factory and ends with the handing over of the equipment for commercial operation. There are two distinct phases: factory or off-site testing, and commissioning testing. Off-site testing is usually performed to prove that equipment, including the control system, meets the design criteria. Commissioning tests are performed after the equipment has been delivered to the site and installed. The tests are minimize to test subsystems, systems and overall performance. As a general rule, all parties involved in the project should be included in the tests and all responsibilities clearly defined. General requirements for system testing are similar to those described for LCC-HVDC in IEC 61975.

7.2 Factory tests

7.2.1 Component tests

These tests concern the verification of the single components, including control and protection equipment, before they are sent to site. They may be subdivided into routine tests, aimed essentially at quality control, and type tests which verify that a component has been properly designed to sustain the stresses from potential transients and service conditions. Factory testing of VSC converter valves is covered by IEC 62501. Traditional components such as switchgear, transformers, capacitors, capacitor fuses, reactors, resistors, insulators, voltage and current transformers, surge arresters, etc, are covered by the CIGRÉ B4.48 report Technical Brochure 447, in which the available standards (IEC, IEEE, ANSI) are pointed out and the special tests are introduced.

7.2.2 Control system tests

As with the controls for LCC HVDC systems, the control system for a VSC transmission system, including hardware, software and documentation, can be tested and verified in a factory system test (FST). A real-time simulator will be required that can represent power components and parts of the a.c. system in a sufficiently detailed way. Every effort should be made to test as complete a system as practical, including redundancy, to minimize work on site. Factory system testing is an extensive check of the control and protection system under normal and fault conditions, without the constraints imposed by the real system. Selected on- site system tests will repeat some of the factory system tests,

* *IS 16076 : 2013 High – Voltage direct current Hvdc installations – System tests* but will include the actual transducers and main circuit equipment, as well as actual system conditions (as permitted within system constraints). All software and hardware functions, including

redundancies, should be tested before the equipment is shipped to site for installation and commissioning.

Besides simulator tests identical to those for LCC-HVDC, other tests should be considered that account for the additional modes of operation possible with a VSC. Each mode should be tested both in the factory and during commissioning (e.g., operation of the converter as a STATCOM, black start capabilities, and feeding a passive network). The results obtained from real time simulator tests and system studies (in particular the dynamic performances studies) are the main references used to define the commissioning plan and validate the test results in the field.

7.3 Commissioning tests / System tests

7.3.1 General Commissioning tests are organised in a succession of phases. The first phase is the so-called

“precommissioning tests” executed on single station components to check their condition and functionality after transport and assembly. This phase is followed by the “subsystem tests,” which test several components working together to perform a specific function. These are followed by the

“system tests,” which involve all converter stations and full power transmission. The system tests require careful coordination between all interested parties, in particular the system operators, utilities and industrial customers that could be affected by the tests.

During inspection and testing, all applicable health, safety and environmental requirements and regulations shall be followed. Any deviations should be discussed and resolved at site meetings. Often there is an overlap between commissioning and installation, especially in the area of cable termination. Care must be taken when interconnected subsystems are energised and started up that personnel are notified so that no potentially hazardous conditions exist. For an efficient process, it is important to complete as many as possible of the equipment pre-commissioning checks before energization of the equipment. Most utilities have extensive safety rules that protect workers from accidental electrical contact.

7.3.2 Pre-commissioning tests

Pre-commissioning consists mainly of inspection and equipment tests. Equipment tests include electrical and mechanical tests and simple functional tests confined to a single installed unit. The purpose of these tests is to check the condition of the equipment and verify proper installation. If normal auxiliary power is not yet available, electrical tests can be performed with portable or temporary power supplies. At this stage, settings are verified in protection and control equipment. In those cases where disconnection and reconnection would be required for the equipment tests, precommissioning tests on main circuit equipment should be performed before the main conductors are connected. Equipment tests should be performed as soon as possible after installation, and according to the manufacturer’s recommendations.

7.3.3 Subsystem tests

Subsystem tests verify the proper operation of a group of interconnected or related equipment.

Subsystem testing should be done in stages from small to progressively larger subsystems and should check as many functions as possible. Typical subsystem tests are

7.3.3.1 subsystem functional testing, 7.3.3.2 start-up of auxiliary systems,

7.3.3.3 low-voltage energization.

7.3.4 System tests

7.3.4.1 General

The system tests involve operating the converter(s) in conjunction with the interconnected a.c. transmission system. These tests should not only check for proper performance of the automatic controls during normal changes in references, set points or operating modes, but also take place, in so far as possible, under different network conditions. System tests should also include selected disturbances to verify dynamic performance and robustness. Disturbances can consist of nearby capacitor bank switching, transformer energization, line switching, generator tripping, step responses, or even staged faults where specified, and should cover the most critical conditions evidenced by the system studies and by simulator tests, in so far as the networks allow. Some tests with high potential impact may require special provisions to mitigate the possible adverse system impact of large reactive/active power variations. These will require tight coordination with the transmission system operator (TSO)/utilities of a.c. networks to which the VSC transmission system is connected.

Usually, tests with lower impact on a.c. networks are performed first, followed by the more onerous ones.

7.3.4.2 High-voltage energization

When all prerequisites for high-voltage energisation have been completed, operational authority is transferred to system operators to ensure that all safety rules are followed and that any system constraints are observed. Operational procedures should be formalised beforehand. High-voltage energisation is preceded by final trip tests and “dry run” tests where the operators execute the procedure without actually energising the equipment.

Energization of a.c. equipment follows a step-by-step sequence for the a.c. buses, bays, filters and transformers. This may require temporary disconnection of some high-voltage terminations where disconnect switches are not provided. Equipment should be initially energised for several hours. Checks are made for corona and any abnormal audible noise. Phasing and phase rotation are rechecked with full voltage. During filter energisation, unbalance protections are checked and load checks are made. Visual inspections of all equipment and surge arrester counters are made before and after energisation.

Energisation of the converter and d.c. equipment follows that of the a.c. equipment. In most

cases, valve cooling should be running before energising the converter. With the VSC, the connected d.c. side equipment (i.e., d.c. buswork, d.c. capacitors and d.c. transducers) is energised through the valve anti-parallel diodes when the main a.c. breaker is closed thereby energising the converter.

As an additional check, the converter may be energised via the d.c. side, with the

a.c. connection open. A special d.c. power supply could be provided for this purpose, or the converter at the opposite end of the link could be used as a rectifier to provide this function.

During energisation, d.c. voltage measurements and status signals from individual semiconductor positions should be checked via the valve monitoring. If other converters or d.c. cables are included in the particular application, they should be initially energised separately while isolated from the other converter(s) and interconnecting cables or buswork.

7.3.4.3 Converter operational tests

- **General**

Once the converter and d.c. equipment have been energised and checked out, the converter can be deblocked, sending switching pulses to the valves. Initially this is performed one converter at a time, with the VSC operated in a.c. voltage control or reactive power control. The purpose of the converter operational tests is to check that the converter operates properly with the a.c. network.

During converter operational testing all subsystems, e.g., controls, transducers, auxiliaries and main circuit equipment, are tested together for the first time. Typical tests performed during converter operation are the following:

- **Sequences**

Check that breaker, disconnects and deblock/block and trip sequences operate properly in response to manual, automatic or protective orders. Check that the initial operating condition is neutral minimising the disturbance to the network, e.g., automatic connection of filters, if any, with net zero reactive power exchange through counterbalancing VSC absorption.

- **D.C. voltage control**

Check that the d.c. voltage is controlled to its reference voltage, and that all levels of d.c. voltages are balanced.

- **Measurements**

Check that all controls, indications and measurements have correct polarity, phase and scaling. Take selected measurements of a.c. and d.c. harmonics and distortion. NOTE Final measurements are usually reserved for acceptance tests.

- **Reactive power control**

Check that the reactive power control, if relevant, follows the reference at the selected ramp rate for both inductive and capacitive ranges. Check proper converter reactive power limitations.

NOTE Operating restrictions on a.c. voltage may limit the amount of reactive power that can be exchanged with the a.c. network.

- **A.C. voltage control**

Check that the voltage is controlled to the reference, if relevant, and that the reactive power is stable. Vary slope, reference, deadband and voltage control modes, as provided. Check stability with the a.c. network by reference step response, capacitor bank switching and/or a.c. line switching.

- **Load test**

Check the capability of the cooling equipment, primarily for the VSC valves. Observe the temperatures and sequencing of the cooling equipment as the load is increased.

NOTE - Operating restrictions on a.c. voltage may limit the amount of reactive power that can be exchanged with the

a.c. network, and special provisions shall then be made to reach full output.

- **Disturbance tests**

In addition to the testing of the step responses to regulator references, the converter and its controls should be tested for various internal disturbances (e.g., auxiliary supply changeover, control system changeover, and external disturbances in the a.c. transmission system) to verify proper performance, stability and robustness. External disturbances can consist of switching nearby capacitor banks, transformers, transmission lines, or tripping generators.

7.3.4.4 Transmission tests

Transmission tests involve operation of converters that work together to control the power flow. Such testing requires a very high degree of coordination with the system operator (dispatcher). Typical tests performed during transmission testing are as follows:

- **Sequences**

Check that breaker, disconnects and deblock/block and trip sequences operate properly in response to manual, automatic or protective orders. Check that the initial operating condition is neutral, minimising the disturbance to the network, e.g., zero net reactive or active power exchange.

- **D.C. voltage control**

Energisation of high-voltage d.c. cables, bus work or lines interconnecting the converters. Repeat with the other converter connected. Depending on application and protective strategy, check that the d.c. voltage is controlled to a reference during power transfer and blocking/tripping of one of the other converters.

- **Power control**

Check that the power flow and power ramp rate follow the reference values. Check the power control stability by step response or system disturbance, such as line switching. Check transmission in both directions. Check proper converter real power limitations.

- **Reactive power control**

Check, if relevant, the joint operation of the reactive power control and active power control at the different converters by changing their respective references during the different operating modes.

Check proper converter reactive power limitations.

- **A.C. voltage control**

Check, if relevant, the joint operation of the a.c. voltage control and active power control at the different converters. Check the stability by step response in the power and voltage references, or during system disturbances such as capacitor bank or line switching.

- **Load test**

Ramp up to full power transmission or MVA converter rating for the different operating modes, as permitted by a.c. system and other conditions.

- **Measurements**

Take selected measurements of a.c. and d.c. harmonics and a.c. voltage distortion. NOTE Final measurements are usually reserved for acceptance tests.

- **Redundancy checks**

If the system is equipped with redundant control and protection systems, perform transfers from the active to standby system. Transfers between redundant auxiliary systems should also be checked during operation, e.g., auxiliary power, cooling pumps.

- **Remote control**

Test operation from remote locations. Check all remote indications and control functions. NOTE Much of this work is done beforehand during subsystem testing, but this is the first time that remote system operators have direct control of the system. Previously, operation was from the local level with authorization only from the system operator.

- **Disturbance tests**

In addition to testing the step responses to regulator references, the converter and its controls should be tested again for various external disturbances in the a.c. transmission system to verify proper performance, stability and robustness. External disturbances can consist of switching nearby capacitor banks, transformers, transmission lines, tripping generators, or even staged faults, e.g., d.c. or a.c. overhead line faults, as relevant.

- **Trial operation**

Trial operation allows the owner to operate the integrated system according to its intended purpose from the normal control location. Trial operation does not start until almost all system tests have been successfully completed. During trial operation, observation of the complete system and subsystems takes place. All alarms or abnormal conditions are dealt with as required.

7.3.4.5 Acceptance tests

- **General**

Acceptance tests verify the performance of the system according to the specification on a selected basis. Acceptance tests may involve measurements to verify that interference levels are within the design limits and that other fundamental performance criteria are met.

- **Heat run**

Operate at rated and overload capacity for specified periods of time in different operating modes, if applicable. Monitor temperatures and cooling systems. This test usually takes several hours due to the slow heating of the transformers.

- **Interference measurements**

Verify that harmonics on the a.c. and d.c. sides, audible noise, radio interference, PLC interference, etc., meet the performance requirements.

- **Disturbance response**

Test auxiliary supply changeover, control system changeover, line switching, shunt bank switching, generator tripping or staged faults, as necessary

CHAPTER VIII
REGULATORY REQUIREMENTS

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Regulatory Requirements

The Electrical transmission line design, installation, verification and maintenance must comply with the Central Electricity Authority (Indian Electricity Grid Code) Regulations, 2023, as amended. It shall be noted that any contraventions with the provisions of Electricity Act 2003 and the Rules and Regulations, made, thereunder may attract penal action as per section 146 and responsibilities as per sections 149 and 150 of Electricity Act 2003.

Regulation 180

The 180 Regulation of CEA shall apply to all users, State Load Dispatch Centres, Renewable Energy Management Centres, Regional Load Dispatch Centres, National Load Dispatch Centre, Central Transmission Utility, State Transmission Utilities, licensees, Regional Power Committees, Settlement Nodal Agencies, Qualified Coordinating Agencies and Power Exchanges to the extent applicable.

Bibliography

- *IS 14801: 2021/IEC 60633: 2019 High-voltage direct current HVDC transmission Vocabulary (first revision).*
- *IS 17775 (Part 1): 2021/IEC TR 63179-1: 2020 Guideline for Planning of HVDC Systems Part 1 HVDC Systems with Line-commutated Converters.*
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- *International Journal of Recent Technology and Engineering (IJRTE) HVDC in Indian Power Sector*
- *Indian Electricity Act 2003*