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HVDC TRANSMISSION SYSTEMS

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Dedication

To the pioneers of electrical engineering whose relentless pursuit of innovation has illuminated the path towards sustainable energy transmission. This dedication is a tribute to their visionary spirit and tireless efforts in advancing HVDC transmission systems, shaping the future of global energy networks.

Table of Contents

List of Table of Figure

Abstract

High Voltage Direct Current (HVDC) transmission systems have emerged as a pivotal solution in modern electrical engineering, revolutionizing the way power is transmitted over long distances. This research delves into the fundamental principles, technological advancements, and practical applications of HVDC transmission systems. It explores the underlying concepts of HVDC technology, including converter stations, transformers, and control systems, elucidating their role in achieving efficient and reliable power transmission. Through a comprehensive analysis, this study highlights the advantages of HVDC systems, such as enhanced efficiency, grid stability, and integration of renewable energy sources. Moreover, it examines the challenges and future prospects of HVDC transmission, addressing issues related to cost, converter complexity, and environmental impact. By shedding light on the intricacies of HVDC technology, this research contributes to the understanding and advancement of sustainable energy transmission, paving the way for a resilient and interconnected global power infrastructure.

1.1 Introduction

Transmission and distribution of electricity started with direct current but was inefficient due to the power loss in conductors compared to alternating current transmission. Large quantities of electrical energy are transmitted using three phases alternating current but this method of transmission has a constraint in that there’s a limit to the distance that bulk amount of alternating current unless some form of reactive compensation is used. Alternating current or A.C can be used for overhead transmission for over a distance of 50km with reactive compensation. The present thesis investigates deferent transmission line systems for transmitting bulk energy from renewable sources. Specially, two systems will be focused on: the high-voltage alternating current (HVAC) system and the high-voltage direct current (HVDC) system. In order to determine the most efficient way of transmitting bulk energy from renewable sources, different aspects of the aforementioned two types of systems are analyzed. Limitations inherent in both HVAC and HVDC systems have been discussed. However, for very high-power transmission, AC transmission is disadvantageous for example undersea transmission. But with the invention of mercury arc rectifiers and thyristors valves HVDC transmission became feasible. The world's first commercial HVDC transmission link, was built in 1954 between the Swedish mainland and the island of Gotland, with a rating of 20 MW, 200 A and 100 kV. Today, the highest functional DC voltage for DC transmission is +/- 600kV. D.C transmission is now an integral part of the delivery of electricity in many countries throughout the world.

1.2 Comparison of AC and DC Transmission

The merits of two modes of transmission (AC & DC) should be compared based on the following factors.

Disadvantages of HVDC and HVAC

Both HVDC and HVAC systems have several limitations. More specifically, the

disadvantages of HVDC are as follows:

1. Compared to converter stations used in the HVAC systems, converter stations

used in the HVDC are expensive and complicated.

2. The design and operation of multi-terminal HVDC systems are sophisticated compared to HVAC.

3. Current and voltage harmonics are generated during conversion, which requires

expensive filters.

4. The presence of high-frequency constituents in the DC transmission causes interference in the communication systems near the HVDC system.

5. The grounding of the HVDC system is complex and complicated.

In its turn, the HVAC systems have the following limitations:

1. Compared to HVDC, HVAC has a very high interference with communication

lines

2. It is impossible to connect two unsynchronized HVAC (e.g., a 60Hz to a 50Hz

line).

3. Compared to the HVDC systems, the HVAC systems are more likely to experience corona effects during bad weather compared to HVDC.

4. Unlike in HVDC, inductive and capacitive parameters are a limiting factor in the HVAC systems.

1. Economics of transmission.
2. Technical Performance.
3. Reliability

1.3 Economics of Power Transmission

1. In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop. Also, there is no leakage or charging current of the line under steady conditions. A DC line requires only 2 conductors whereas AC line requires 3 conductors in 3-
2. phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line. Break- even 2. distance is one at which the cost of the two systems is the same. It is understood from the below figure that a DC line is economical for long distances which are greater than the break-even distance.
3. System Cost Elements for a Constant Power (MW) Transmitted and a
4. Constant Transmission Length

HVAC Cost Terms	**HVDC Cost Terms**
Right-of-Way	Right-of-Way
Load density per acre of ROW	Load density per acre of ROW
Transmission voltage	Transmission voltage
Conductor specifications (Size and type)	Conductor specifications (Size and type)
Substations equipment, switching stations breakers, transformers, and station civil work	Rectifier, inverter, filter, DC circuit breakers, smoothing reactors and station civil work
System reinforcement	System reinforcement
Environmental impact	Environmental impact
N/A	Conversion of voltage from AC to DC and Vice-a-Versa

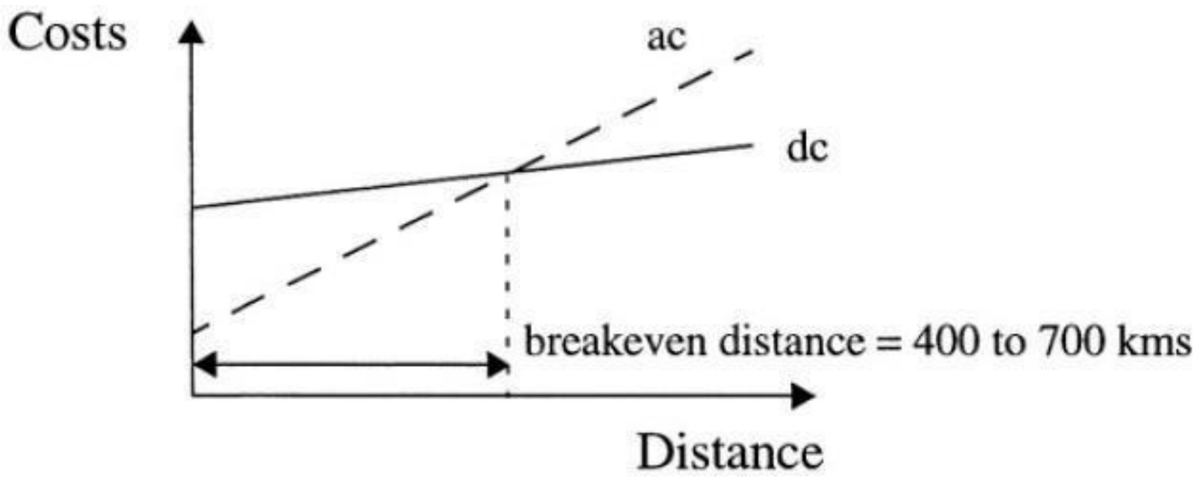

Figure1. 1:*Relative costs of AC and DC transmission lines vs distance*

1.4 Technical Performance

Due to its fast controllability, a DC transmission has full control over transmitted power, an ability to enhance transient and dynamic stability in associated AC networks and can limit fault currents in the DC lines. Furthermore, DC transmission overcomes some of the following problems associated with AC transmission.

1.5 Stability Limits

The power transfer in an AC line is dependent on the angle difference between the voltage phasors at the two-line ends. For a given power transfer level, this angle increases with distance. The maximum power transfer is limited by the considerations of steady state and transient stability. The power carrying capability of an AC line is inversely proportional to transmission distance whereas the power carrying ability of DC lines is unaffected by the distance of transmission.

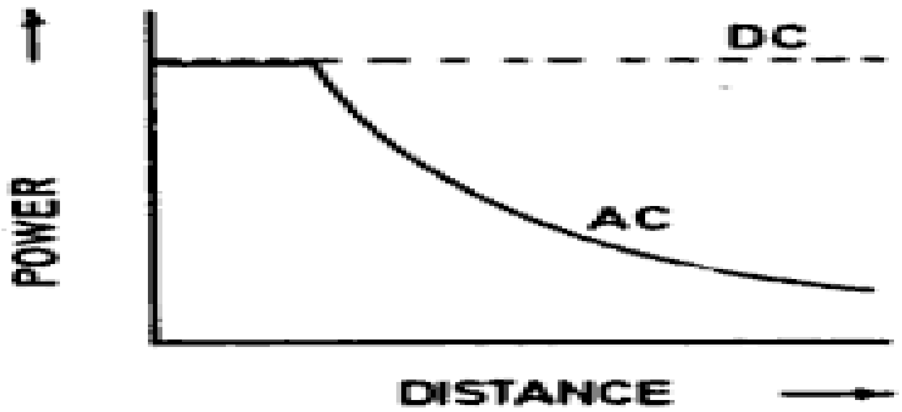

Figure1. 2: Power Transfer Capability vs. Distance

1.6 Voltage Control

Voltage control in ac lines is complicated by line charging and voltage drops. The voltage profile in an AC line is relatively flat only for a fixed level of power transfer corresponding to its Surge Impedance Loading (SIL). The voltage profile varies with the line loading. For constant voltage at the line ends, the midpoint voltage is reduced for line loadings higher than SIL and increased for loadings less than SIL. The maintenance of constant voltage at the two ends requires reactive power control as the line loading is increased. The reactive power requirements increase with line length. Although DC converter stations require reactive power related to the power transmitted, the DC line itself does not require any reactive power. The steady-state charging currents in AC cables pose serious problems and make the break-even distance for cable transmission around 50kms.

1.7 Line Compensation

Line compensation is necessary for long distance AC transmission to overcome the problems of line charging and stability limitations. The increase in power transfer and voltage control is possible through the use of shunt inductors, series capacitors, Static Var Compensators (SVCs) and, lately, the new generation Static Compensators (STATCOMs). In the case of DC lines, such compensation is not needed.

1.7 Problems of AC Interconnection:

The interconnection of two power systems through ac ties requires the automatic generation controllers of both systems to be coordinated using tie line power and frequency signals. Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to:

1. The presence of large power oscillations which can lead to frequent tripping, Increase in fault level, and
2. Transmission of disturbances from one system to the other.
3. The fast controllability of power flow in DC lines eliminates all of the above
4. problems. Furthermore, the asynchronous interconnection of two power systems can only be achieved with the use of DC links.

1.8 Ground Impedance

In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to the high magnitude of ground impedance which will not only affect efficient power transfer, but also result in telephonic interference. The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (monopolar operation). The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow. While operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents. Hence, single pole operation of dc transmission systems is possible for extended period, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.Disadvantages of DC Transmission:

The scope of application of DC transmission is limited by

1. High cost of conversion equipment.
2. Inability to use transformers to alter voltage levels.
3. Generation of harmonics.
4. Requirement of reactive power and
5. Complexity of controls.

Over the years, there have been significant advances in DC technology, which have tried to overcome the disadvantages listed above except for (2). These are:

1. Increase in the ratings of a thyristor cell that makes up a valve.
2. Modular construction of thyristor valves.
3. Twelve-pulse (and higher) operation of converters.
4. Use of forced commutation.
5. Application of digital electronics and fiber optics in the control of converters.

1. **Reliability**

The reliability of DC transmission systems is good and comparable to that of AC systems. The reliability of DC links has also been very good.

There are two measures of overall system reliability-energy availability and transient reliability.

2. **Energy availability:**

Energy availability = 100 (1 – equivalent outage time) /Actual time

Where equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage.

3. **Transient reliability:**

This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems.

Transient reliability = 100 X No. of times HVDC systems performed as designed No. of recordable AC faults

Recordable AC system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault. Both energy availability and transient reliability of existing DC systems with thyristor valves is 95% or more.

4. Application of DC Transmission

Due to their costs and special nature, most applications of DC transmission generally fall into one of the following three categories.

a) Underground or underwater cables: In the case of long cable connections over the breakeven distance of about 40-50 km, DC cable transmission system has a marked advantage over AC cable connections.

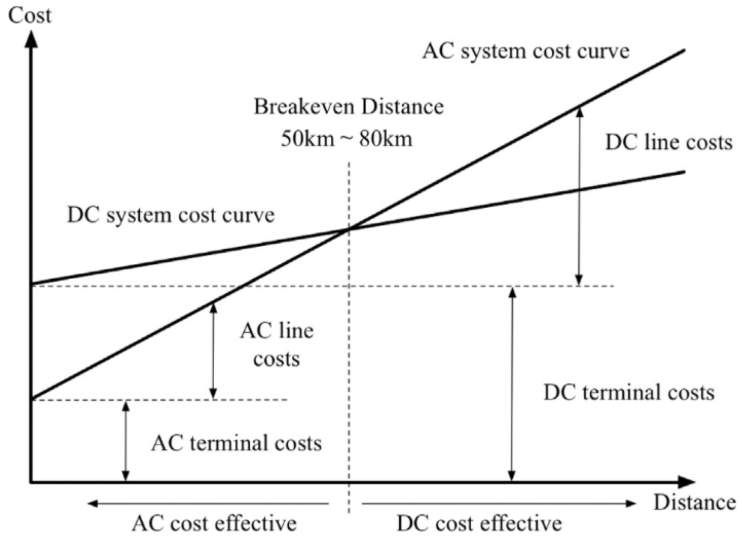

***Figure1. 3**: Costs of AC and DC Underwater Cable Based on Distance*

Examples of this type of applications were the Gotland (1954) and Sardinia (1967) schemes. The recent development of Voltage Source Converters (VSC) and the use of rugged polymer DC cables, with the so-called "HVDC Light" option, are being increasingly considered.

Long distance bulk power transmission:

Bulk power transmission over long distances is an application ideally suited for DC transmission and is more economical than ac transmission whenever the breakeven distance is 6 exceeded.

b) Stabilization of power flows in integrated power system:

In large interconnected systems, power flow in AC ties (particularly under disturbance conditions) can be uncontrolled and lead to overloads and stability problems thus endangering system security. Strategically placed DC lines can overcome this problem due to the fast controllability of DC power and provide much needed damping and timely overload capability. The planning of DC transmission in such applications requires detailed study to evaluate the benefits

Presently the number of DC lines in a power grid is very small compared to the number of AC lines. This indicates that DC transmission is justified only for specific applications. Although advances in technology and introduction of Multi-Terminal DC (MTDC) systems are expected to increase the scope of application of DC transmission, it is not anticipated that the AC grid will be replaced by a DC power grid in the future. There are two major reasons for this: First, the control and protection of MTDC systems is complex and the inability of voltage transformation in dc networks imposes economic penalties. Second, the advances in power electronics technology have resulted in the improvement of the performance of AC transmissions using FACTS devices, for instance through introduction of static VAR systems, static phase shifters, etc. Based on the controllability and configuration valves are classified into four types as under

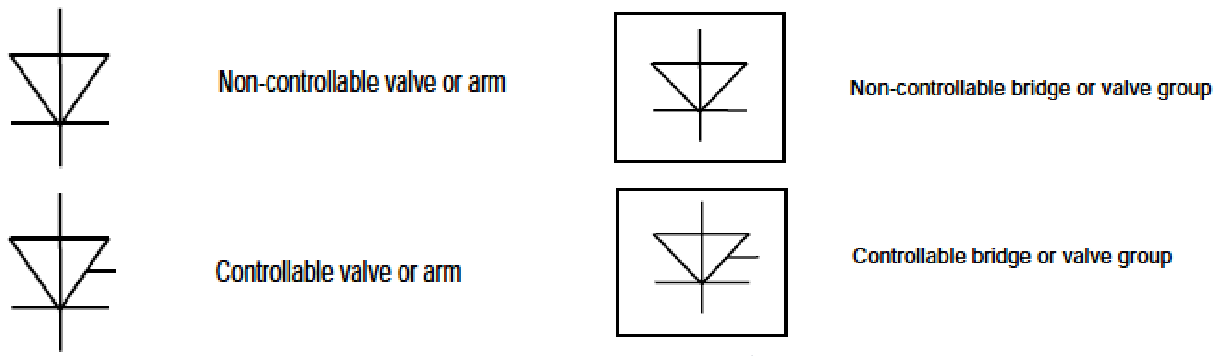

Figure1. 4: Controllability and configuration valves Type

1.Back-to-Back

1) frequency changing

2) asynchronous connection

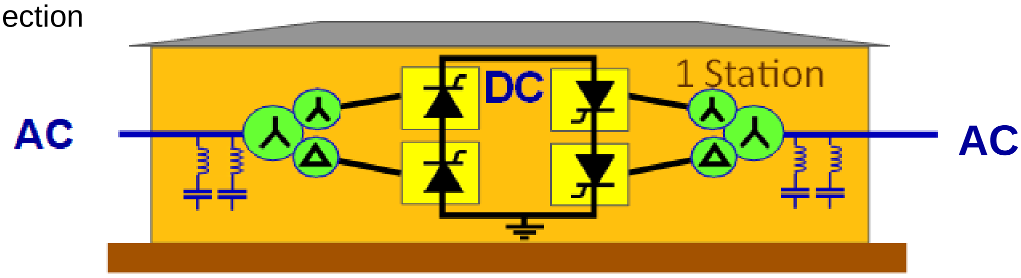

Figure1. 5: Back-to-Back

2.Point-to-Point Overhead Line

1. Bulk transmission
2. overland

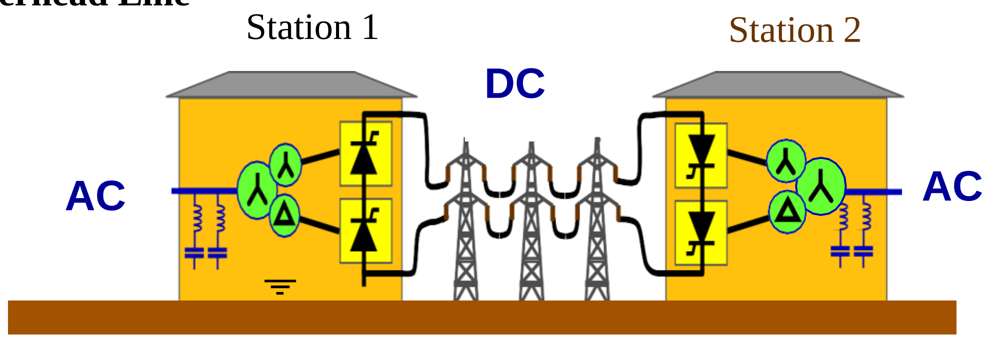

Figure1. 6: Point-to-Point Overhead Line

3.Point-to-Point Submarine

1) bulk transmission

2) underwater or underground

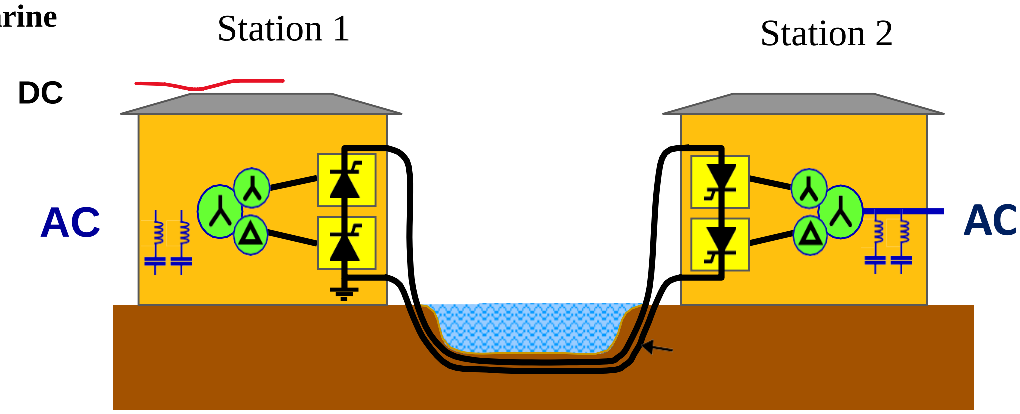

Figure1. 7:. Point-to-Point Submarine

Types of HVDC Links

Three types of HVDC Links are considered in HVDC applications which are

1) Monopolar Link:

1) A monopolar link as shown in the above figure has one conductor and uses either

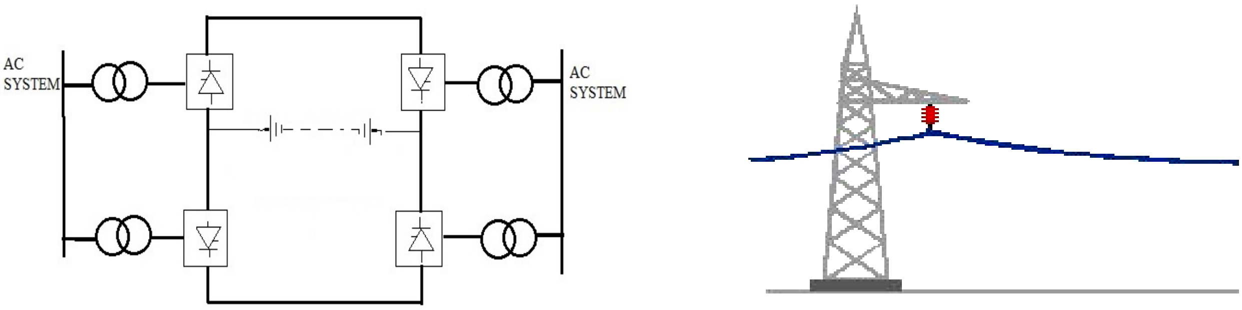

Figure1. 8:Monopolar Link Type

ground and/or sea return. A metallic return can also be used where concerns for harmonic interference and/or corrosion exist. In applications with DC cables (i.e., HVDC Light), a cable return is used. Since the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity, a monopolar link is normally operated with negative polarity.

2) Bipolar Link:

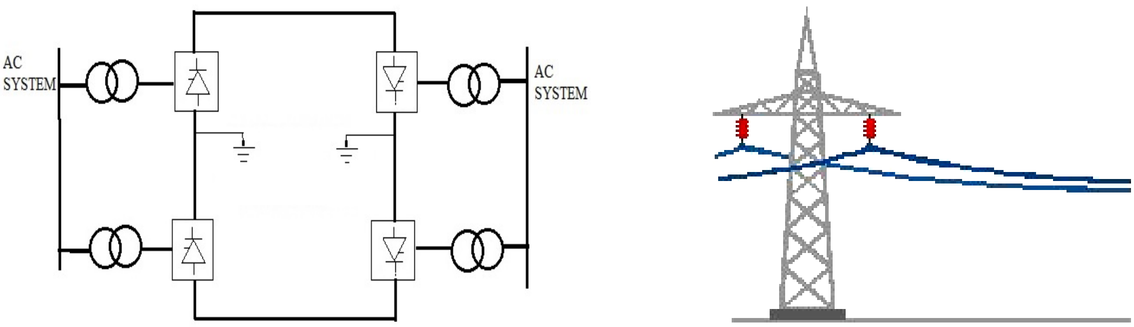

Figure1. 9: Bipolar Link Type

A bipolar link as shown in the above figure has two conductors, one positive and the other negative. Each terminal has two sets of converters of equal rating, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends by the use of a short electrode line. Since both poles operate with equal currents under normal operation, there is zero ground current flowing under these conditions. Monopolar operation can also be used in the first stages of the development of a bipolar link. Alternatively, under faulty converter conditions, one DC line may be temporarily used as a metallic return with the use of suitable switching.

3) Homopolar Link:

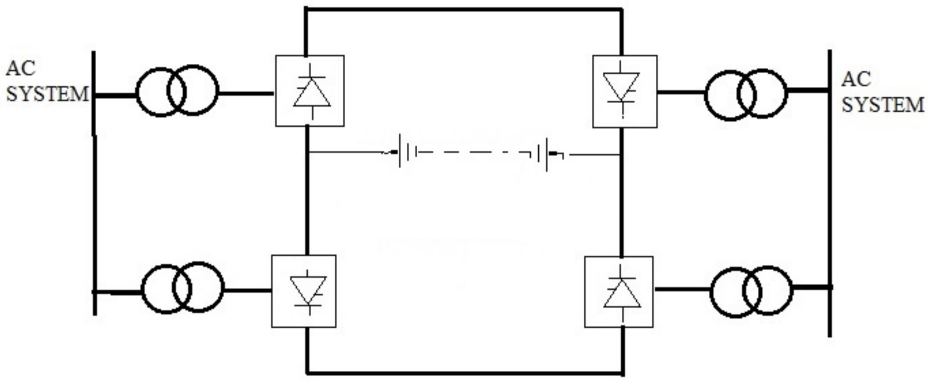

Figure1. 10: Homopolar Link Type

In this type of link as shown in the above figure two conductors having the same polarity (usually negative) can be operated with ground or metallic return. Due to the undesirability of operating a DC link with ground return, bipolar links are mostly used. A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages.

1.9 HVDC Converter Station

The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point-to-point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control.

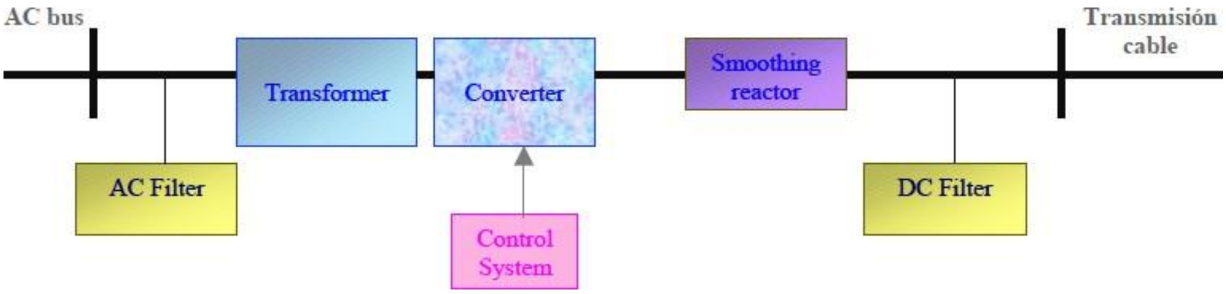

Figure1. 11: HVDC Converter Station

Transmission Tower:

An EHT transmission tower consists of the following parts:

1. The peak of the tower (the portion above the top cross arm)
2. The cross arm (Cross arms of the transmission tower hold the transmission conductor)
3. Cage of transmission tower (portion between tower body and the peak is known as a cage of transmission tower)
4. Transmission Tower Body (The portion from the bottom cross arms up to the ground level)
5. Leg of transmission tower
6. Stub/Anchor Bolt and Base plate assembly of the transmission tower.

The description of each part is given below.

Peak of Transmission Tower

The top portion of the transmission tower is called the peak of the transmission tower.

It is situated above the top cross arm, and it carries an earth shield wire connected to the tip of the tower's peak.

Cross Arm of Transmission Tower

Cross arms hold the transmission conductors. The size of the cross arms is different for the transmission of various voltages.

The dimension of the cross arm depends on the following parameters.

1) Configuration of tower
2) Level of Transmission Voltage
3) Minimum forming angle for stress distribution.

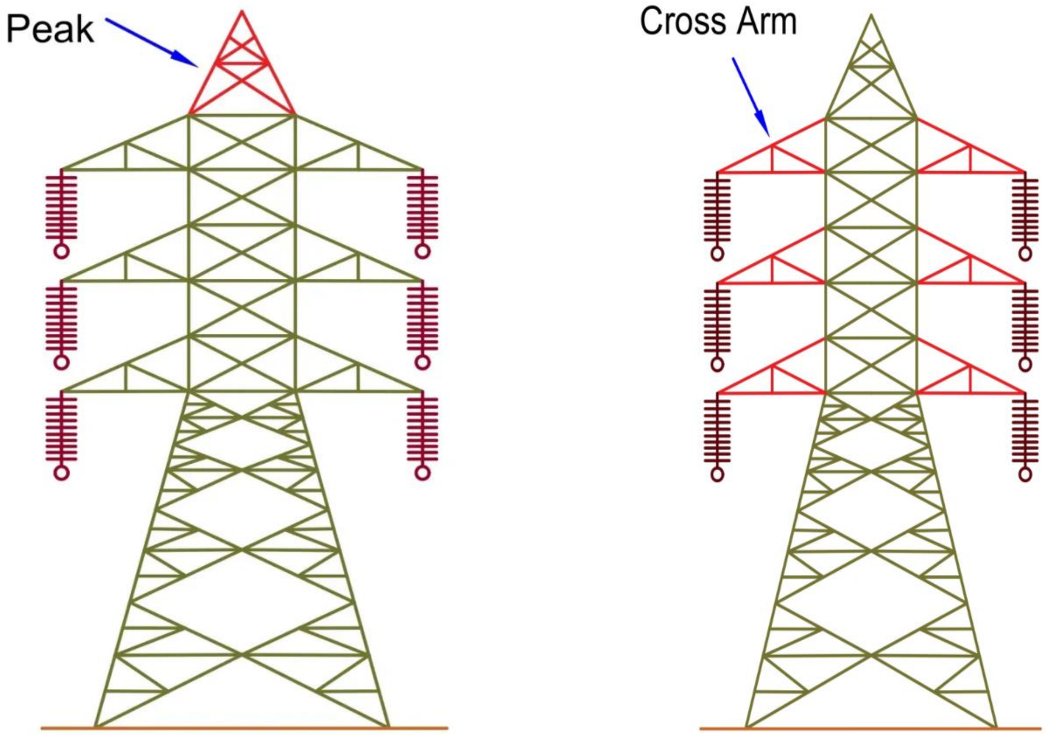

Figure1. 12: Transmission Towers

Cage of Transmission Tower

The part of the tower between the tower body and peak is known as the cage of the transmission tower. The cage holds the cross arms. The shape of the cage may be a square or triangle, depending on the height of the tower.

Transmission Tower Body

The spacing between the lowest cross arm of the tower and the ground is called the transmission tower body.

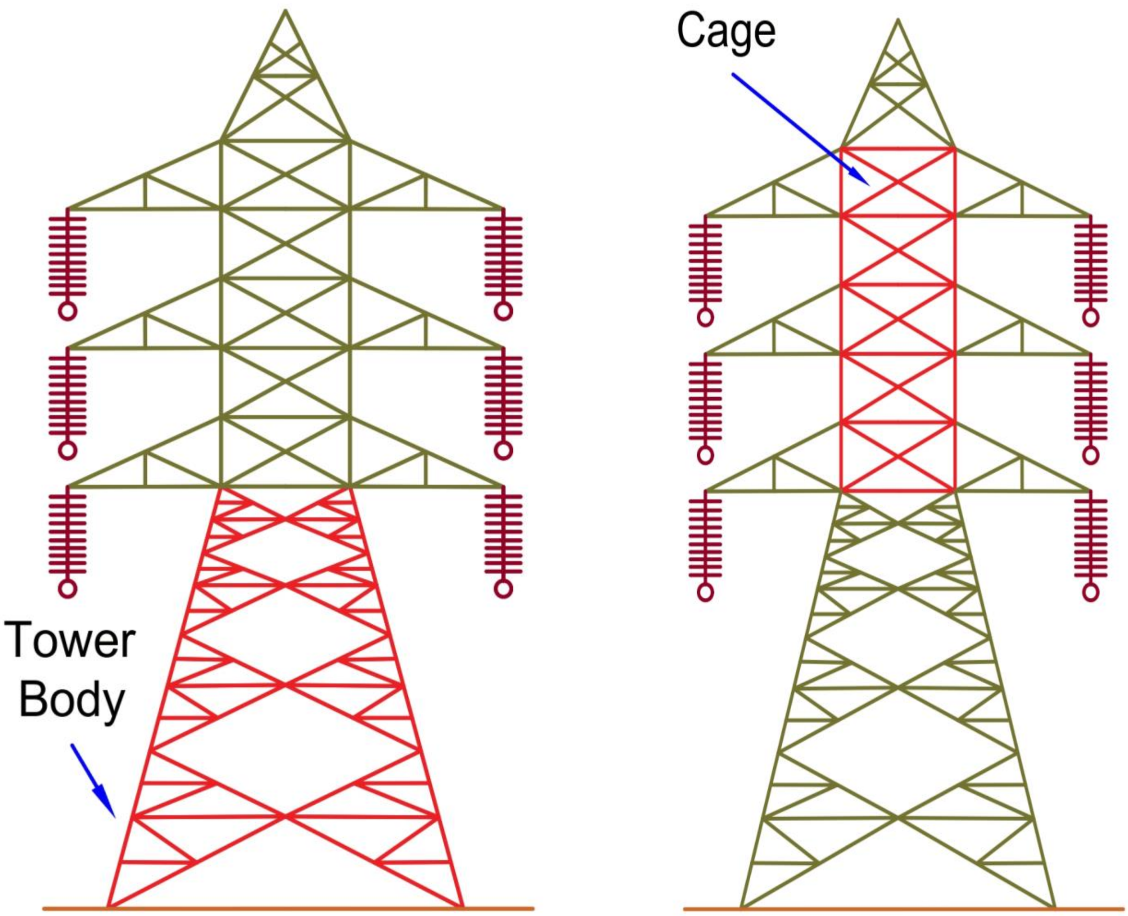

Figure1. 13: Cage and Tower Body of Transmission Tower

2.1 DC Breakers

When closed the DC breaker must have very low losses

•optimum solution mechanical switch

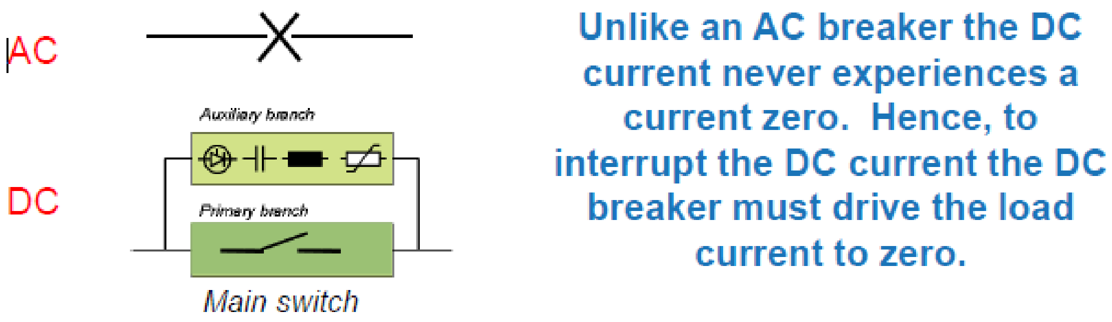

Figure 2. 1: DC Breakers

Modular hybrid solution to drive current to zero

•critical component is the mechanical switch as it has to operate VERY fast to minimize the peak current to be interrupted by the auxiliary branch

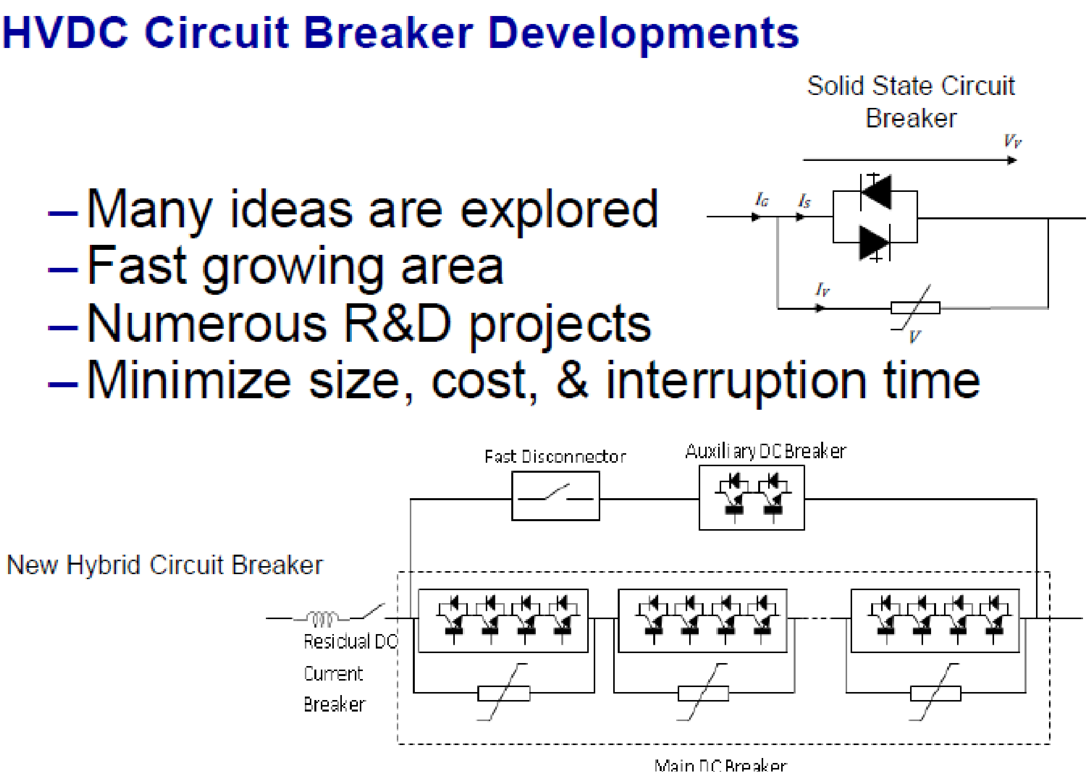

Figure 2. 2: HVDC Circuit Breakers Developments

The NorNed HVDC transmission link the longest underwater high-voltage cable in the world. NorNed is a 580-kilometre (360 mi) long high-voltage direct current submarine power cable between Feda in Norway and the seaport of Eemshaven in the Netherlands, which interconnects both countries' electrical grids. It was once the longest submarine power cable in the world.

The NorNed transmission route

Flat submarine cable

Figure 2. 3: The NorNed HVDC Transmission Link

The 580-kilometer NorNed link, with a 700 MW transmission capacity, is the longest underwater high-voltage cable in the world. The contract is with the two state-owned power grid companies, Tenne in the Netherlands and Statnett in Norway. The interconnection will lead to power trading between the two countries and increase the reliability of electricity supply.

2.1.1 Advantages for the European grid

The security of supply will be improved since production resources in a larger area will be available as a back-up in

the event of network disturbances. The electricity market will benefit as the link will enable electricity trading between two distant, isolated markets.

2.2 Environmental benefits

Scandinavia has a largely hydro-based production system whereas the Netherlands and surrounding countries have a system based largely on fossil fuels. Hydropower is easily regulated and stored in existing dams. This allows the Dutch grid to be optimized by using hydropower to cover peak loads during the day. At night, power can be transported back to Scandinavia, thereby saving electric energy in water dams. The result is more stable output from the fossil-fuel fired. plants, thus minimizing emissions. Additionally, the stabilized grid will allow integration of new renewable generation in the form of wind power.

2.3 The HVDC technology

HVDC technology offers the unique capability to build long underwater or underground cable transmission lines with low losses. Traditional AC transmission systems with underwater cables cannot be longer than about 60 - 100 km. Beyond this the losses are prohibitive. The NorNed cable, with a length of 580 km, has losses of only about 4 percent. HVDC systems, by controlling the power flow, stabilize the grid in the interconnected networks and increase the security of supply. HVDC systems cannot be overloaded and will not contribute to cascade tripping of lines.

Conclusion

High Voltage Direct Current (HVDC) transmission systems represent a critical advancement in electrical engineering, offering numerous benefits for modern power grids. Throughout this study, we have explored the fundamental principles, design considerations, implementation strategies, and practical applications of HVDC technology. HVDC transmission systems provide an efficient and reliable means of transmitting bulk power over long distances, surpassing the limitations of traditional alternating current (AC) systems, especially for interconnecting asynchronous grids, integrating renewable energy sources, and overcoming geographical barriers such as ocean crossings or mountainous terrain. One of the key advantages of HVDC transmission is its ability to minimize transmission losses, enhance grid stability, and optimize power flow control. By employing converter stations equipped with sophisticated control and protection systems, HVDC systems enable precise management of power flows, voltage regulation, and fault detection, thereby improving the overall efficiency and reliability of power transmission networks.

Moreover, HVDC technology plays a pivotal role in facilitating the integration of renewable energy sources into the grid. By enabling the transmission of power from remote renewable energy generation sites, such as offshore wind farms or solar installations, HVDC systems contribute to the decarbonization of the energy sector and the transition towards a more sustainable and resilient energy infrastructure. However, the design, implementation, and operation of HVDC transmission systems also present certain challenges, including cost considerations, converter complexity, voltage compatibility issues, and environmental impacts associated with infrastructure deployment. Addressing these challenges requires careful planning, technological innovation, and collaboration among stakeholders to ensure the successful deployment and operation of HVDC projects.

Despite these challenges, the continued advancements in HVDC technology, along with ongoing research and development efforts, hold promise for further improving the efficiency, reliability, and flexibility of HVDC transmission systems. As the global demand for clean, reliable, and affordable energy continues to grow, HVDC transmission stands poised to play a central role in shaping the future of energy transmission and distribution worldwide.

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Website Links:

1) ABB HVDC: https://new.abb.com/systems/hvdc
2) SiemensHVDC:https://www.siemens-energy.com/global/en/offerings/hvdc.html
3) GE Grid Solutions - HVDC: https://www.gegridsolutions.com/hvdc/
4) CIGRE: https://www.cigre.org/
5) IEEE Xplore: https://ieeexplore.ieee.org/
6) IEA - International Energy Agency: https://www.iea.org/