# **1b. Application Guide for HVDC Transmission**



Modules for Maturing HVDC Electric Transmission Knowledge

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Module Objectives:	<ol> <li>Introduction to long-distance HVDC transmission, Back-to- back HVDC systems, Hybrid AC/DC transmission, and Multi- terminal HVDC systems</li> <li>Trends and innovations in HVDC transmission technologies.</li> </ol>

## Abstract

This tutorial of Application Guide for HVDC Transmission offers comprehensive insights into the applications and innovations in HVDC transmission systems. It begins by exploring the advantages of HVDC long-distance transmission over traditional HVAC systems, such as reduced transmission losses and enhanced stability, illustrated with practical implementation examples. The tutorial then introduces the back-to-back HVDC system by detailing the definitions, benefits, and real-world applications, which are significant for enhancing the flexibility and reliability of power transmission networks. Further, the guide delves into hybrid AC/DC transmission, addressing the motivations for combining these technologies and their operational advantages, such as increased grid flexibility and efficiency. The guide also addresses multi-terminal HVDC (MTDC) systems, focusing on their configuration and fault protection strategies. Additionally, it explores future trends and innovations in HVDC technology, including advancements in converter technology, new materials, and methods that promise improved system performance. Emerging applications, such as the integration of HVDC with energy storage systems and the increasing demand for DC power, are also discussed. This guide serves as a valuable resource for understanding both current applications and future potential of HVDC transmission technologies, providing readers with a thorough understanding of the field and preparing them for evolving challenges and opportunities.

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## Acronyms

-	
AC	Alternating current
AI	Artificial intelligence
B2B	Back-to-back
DC	Direct current
EI	Eastern Interconnect
ERCOT	Electric Reliability Council of Texas
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LCC	Line-commutated converters
MTDC	Multi-terminal HVDC
P2P	Point-to-point
PDCI	Pacific DC Intertie
PV	Photovoltaic (PV)
ML	Machine learning
MMC	Modular multilevel converter
SC	Silicon carbide
UHVDC	Ultra-high-voltage direct current
VSC	Voltage source converters
WBG	Wide bandgap (WBG)
WECC	Western Electricity Coordinating Council
XLPE	Cross-linked polyethylene

## Nomenclature

### **1b-1.** Introduction

#### 1b-1.1. Overview of HVDC Transmission

High Voltage Direct Current (HVDC) transmission has been used for the efficient transfer of electricity over long distances, underwater cables, and interconnecting asynchronous power grids. Unlike traditional High Voltage Alternating Current (HVAC) systems, which suffer from higher losses and stability issues over extended distances, HVDC provides a more efficient and reliable alternative. The technology is particularly useful for bulk power transmission, renewable energy integration, and international power exchanges [1].

The fundamental advantage of HVDC lies in its ability to minimize transmission losses and voltage drops. By using direct current (DC), HVDC systems eliminate reactive power losses associated with alternating current (AC) transmission, allowing for greater power transfer capacity over the same infrastructure. Additionally, HVDC back-to-back stations enable the interconnection of power grids operating at different frequencies or operation conditions, which is crucial for integrating regional and international power systems [2]. Modern HVDC systems employ advanced power electronics, such as thyristor-based line-commutated converters (LCC) and voltage source converters (VSC), to convert AC to DC and vice versa efficiently [3].

HVDC transmission is also beneficial for submarine power cables, such as those connecting offshore wind farms or linking islands to mainland grids. It is also widely used for overhead transmission in regions where building new HVAC lines is challenging due to right-of-way constraints. While the initial cost of HVDC converter stations is higher than that of AC substations, the overall economic benefits—such as reduced transmission losses, lower operational costs, and enhanced grid stability—often outweigh the upfront investment [4].



Figure 1. HVDC Evolution: From Inception to Global Integration

As the global energy landscape shifts toward decarbonization and renewable integration, HVDC technology plays a critical role in enabling large-scale wind and solar power transmission. The increasing adoption of multi-terminal HVDC grids and flexible interconnections is paving the way for more resilient and efficient energy networks. With continuous advancements in power electronics and grid management technologies, HVDC transmission is expected to become a cornerstone of modern power systems, supporting the transition to a sustainable and interconnected energy future [5].

HVDC transmission has evolved significantly since its origins in Thomas Edison's Pearl Street Station in 1882, with the first commercial HVDC system, the Gotland link (1954, Sweden, 100 kV, 20 MW), demonstrating its feasibility. The Moscow–Kashira system (1961) became the first bipolar HVDC project, followed by the Pacific DC Intertie (1965,  $\pm 400$  kV, 3,100 MW, U.S.), which enabled large-scale power transfers. International HVDC interconnections emerged with the Cross-Channel Link (1986, 2,000 MW) between the UK and France, facilitating energy trade. In the 21st century, advancements in Ultra-High Voltage DC (UHVDC) saw milestones like Jinping–Sunan (2010,  $\pm 800$  kV, 7,200 MW, China) and Changji–Guquan (2018,  $\pm 1,100$  kV, 12,000 MW, China), which set global records for voltage and capacity. In 2021, the North Sea Link (720 km, 1.4 GW) became the world's longest subsea interconnector. Looking ahead, HVDC is expected to underpin a significant role in the DOE's Transmission Expansion Planning for 2050 [69]. This plan emphasizes the need to approximately double to triple the 2020 transmission capacity by 2050 to accommodate demand growth and ensure reliability. This expansion includes significant investments in HVDC infrastructure to facilitate the integration of renewable energy sources and enhance interregional connectivity.

Year	Project Name	Voltage Level (kV)	Power Capacity (MW)	Key Significance
1882	Pearl Street Station	-	-	First DC power system (Thomas Edison)
1954	Gotland HVDC Link	100	20	First commercial HVDC system
1961	Moscow–Kashira HVDC	-	-	First bipolar HVDC system
1965	Pacific DC Intertie	±400	3,100	Enabled large-scale power transfer in the U.S.
1986	Cross-Channel Link	270	2,000	First UK-France HVDC interconnection
2010	Jinping–Sunan UHVDC	±800	7,200	Key milestone in Ultra-HVDC transmission
2018	Changji–Guquan UHVDC	±1,100	12,000	Set world record for voltage and capacity
2021	North Sea Link	±525	1,400	Longest subsea HVDC interconnector
2050*	DOE's Transmission Expansion Plan	-	-	Future vision of hybrid AC/DC grid

Table 1. Key Milestones in HVDC Transmission Systems

#### 1b-1.2. Importance and Benefits of HVDC

HVDC transmission offers significant advantages over HVAC systems, making it essential for modern power networks.

One of the key benefits of HVDC is higher **transmission efficiency**. HVDC systems can reduce transmission losses to approximately 3% per 1,000 km, compared to 7–10% for HVAC over the same distance. This efficiency is particularly beneficial for **long-distance and bulk power** 

**transmission**, where HVDC can economically transmit more than 10 GW over thousands of kilometers, such as in China's Changji-Guquan  $\pm 1,100$  kV Ultra-HVDC line, which transmits 12 GW over 3,324 km with a transmission efficiency of over 95%.

HVDC also facilitates the **interconnection of asynchronous grids**, enabling power exchange between networks operating at different frequencies, such as the  $\pm 500$  kV Quebec-New England interconnection, which allows reliable power transfers between Canada and the U.S. Additionally, HVDC improves system **stability and control** by regulating power flows within milliseconds, reducing the risk of grid disturbances, and supporting voltage stability.

From an **environmental and economic** perspective, HVDC requires fewer transmission lines and narrower right-of-way corridors, reducing land use by 30–50% compared to HVAC. It also enables efficient **renewable energy integration**, such as offshore wind farms in Europe, where over 6 GW of offshore wind capacity is connected through HVDC links like the North Sea Link (720 km, 1.4 GW).

Finally, HVDC enhances grid **reliability and security** by reducing congestion, preventing cascading failures, and strengthening resilience against disturbances, making it a crucial technology for the sustainable development of global power systems.



Figure 2. Advantages of HVDC Transmission in Modern Power Networks

### 1b-1.3. Classification of HVDC Transmission Technologies

While HVDC technologies can be classified in various ways, this module categorizes them into four main types: HVDC long-distance transmission, HVDC back-to-back stations, multi-terminal HVDC (MTDC), and hybrid AC/DC transmission.

- HVDC long-distance transmission is used to efficiently transfer power over vast distances with minimal losses.
- HVDC back-to-back stations provide a reliable means of connecting asynchronous power grids.
- MTDC systems enable flexible and resilient power exchange among multiple terminals, making them suitable for integrating renewable energy sources.
- Hybrid AC/DC transmission combines the strengths of both AC and DC systems to enhance grid stability and efficiency in a grid with significant penetration of HVDC transmissions embedded in an AC network.

In the following sections, each of these technologies will be explored in detail. Their key features and benefits will be discussed, real-world examples will be provided, and industry insights will be shared.

## 1b-2. HVDC Long-Distance Transmission

### 1b-2.1. Features and Benefits

HVDC transmission offers numerous advantages over High Voltage Alternating Current (HVAC) transmission, particularly for long-distance power transmission. This section will briefly discuss the traditional point-to-point (P2P) HVDC transmission, while section 4 will discuss multi-terminal DC (MTDC) systems in detail.

A key benefit of HVDC long-distance P2P transmission is the lower transmission losses associated with HVDC [6]. Unlike HVAC systems, HVDC does not suffer from the skin effect, which leads to higher losses at high frequencies. Additionally, HVDC systems have lower dielectric losses in the transmission line insulation, resulting in overall reduced electrical losses during power transmission.



Figure 3. Comparison of AC and DC systems in cost efficiency versus distance

When it comes to efficiency, HVDC transmission outperforms HVAC, especially for long distances [7]. HVDC is typically more efficient for distances above 600 kilometers for overhead lines and about 50 kilometers for submarine cables. The break-even distance, where HVDC becomes more cost-effective than HVAC, varies based on factors such as the cost of converters, the amount of power to be transferred, and transmission line expenses. This efficiency makes HVDC an attractive option for high-power, long-distance transmission projects. Figure 3 shows a comparison of AC and DC systems in cost efficiency and transmission distance.

HVDC transmission also eliminates the issues related to reactive power that HVAC systems face. Reactive power can complicate voltage control and necessitate additional compensation equipment, which is not required in HVDC systems [8]. This simplification in power management is particularly beneficial for long-distance transmission where reactive power can significantly affect system performance. Another significant advantage of HVDC systems is their increased stability and control [9]. HVDC allows for precise control over power flows, enabling quick responses to system disturbances and improving the overall stability and reliability of the power grid. This capability is particularly useful for integrating renewable energy sources, which can be variable and unpredictable.

Moreover, HVDC transmission requires fewer transmission lines compared to HVAC for the same amount of power, reducing the right of way and minimizing environmental impact [10], as shown in Figure 4. This is because HVDC lines can transmit more power over a single line. Lastly, HVDC facilitates the interconnection of asynchronous grids, allowing power transfer between different regions or countries without the need for synchronization. This interconnection is crucial for international power trading and enhancing grid reliability.



Underground line with HVDC Light or AC cable

Figure 4. Comparison of AC and DC systems in right of way and environmental impact.

#### 1b-2.2. Real-world Examples

High Voltage Direct Current (HVDC) long-distance transmission has been successfully implemented in multiple large-scale projects worldwide, demonstrating its ability to enhance grid efficiency, stability, and renewable energy integration.

One of the most well-known HVDC projects is the Pacific DC Intertie (PDCI), which connects the Bonneville Power Administration in the Pacific Northwest to the Los Angeles Department of Water and Power in California. As shown in Figure 5, spanning over 1,360 kilometers, the PDCI was commissioned in 1970 and has undergone multiple upgrades, bringing its current capacity to 3,100 MW [11]. This system allows the efficient transfer of surplus hydroelectric power from the Pacific Northwest to meet the high energy demand of Southern California during peak hours. In turn, during periods of high hydropower generation, PDCI can transfer excess power southward, stabilizing the regional grid. While the primary power flow direction is north-to-south, the PDCI

can also transmit power in the south-to-north direction with certain operational limitations. The intertie has played a crucial role in preventing blackouts, particularly during extreme weather events, highlighting the resilience and reliability of HVDC transmission.



Figure 5. Map of the route and stations of the PDCI, along with the Pacific Alternation Current Intertie (PACI) [12]

Another major implementation is the North Sea Link (NSL), a 720-kilometer subsea HVDC interconnector between the United Kingdom and Norway as shown in Figure 6. Commissioned in 2021, it has a transmission capacity of 1,400 MW and enables the bidirectional exchange of renewable energy between the two nations [13]. The interconnector allows the UK to import surplus Norwegian hydropower during periods of low wind energy production while exporting excess wind-generated electricity to Norway when demand is lower. By facilitating flexible power sharing, the NSL enhances energy security and supports the transition to a low-carbon grid in both countries.



#### Figure 6. Location of the North Sea Link connecting the UK and Norway

China has been a global leader in the deployment of HVDC for long-distance power transmission, integrating its remote renewable resources with major consumption centers. One of its most ambitious projects is the Xiangjiaba–Shanghai HVDC link, which transmits power from the Xiangjiaba hydroelectric plant in southwest China to the industrial hub of Shanghai. Spanning over 2,071 kilometers, this ultra-high-voltage direct current (UHVDC) link operates at ±800 kV and has a massive transmission capacity of 6,400 MW. These males it one of the most powerful HVDC systems in the world [14]. By delivering clean hydroelectric power from western China to densely populated eastern cities, the project reduces dependency on coal-fired generation and mitigates transmission bottlenecks. China has implemented multiple similar UHVDC transmission projects, including the Zhundong–Wannan and Baihetan–Jiangsu links, which push the boundaries of HVDC scalability.

In South America, the Belo Monte–Rio de Janeiro HVDC project in Brazil exemplifies the role of HVDC in integrating large-scale hydropower. As shown in Figure 5, this ±800 kV, 2,092-kilometer transmission system transports power from the Belo Monte hydroelectric plant, located in the Amazon basin, to the southeastern load centers, including São Paulo and Rio de Janeiro. With a transmission capacity of 4,000 MW, the project provides a stable and efficient means of delivering renewable energy to Brazil's most populous and industrialized regions [16]. The HVDC link minimizes losses over vast distances and ensures grid reliability, particularly during dry seasons when hydropower availability fluctuates.



Figure 7. Map of the routes and stations of the Belo Monte-Rio HVDC transmission [15]

These global implementations highlight the strategic advantages of HVDC technology in overcoming geographical barriers, balancing energy supply, and reducing transmission losses. The increasing adoption of multi-terminal HVDC networks and intercontinental interconnections is paving the way for a more interconnected and resilient global energy system.

### 1b-2.3. Industry Insights

The expansion of HVDC long-distance transmission is reshaping the energy landscape, addressing key challenges such as integrating renewable energy, reducing transmission losses, and enhancing grid stability. Several industry trends and innovations are driving the next generation of HVDC deployment.

**Higher voltage levels**: One significant trend is the increasing voltage levels in Ultra-HVDC systems (UHVDC, greater than  $\pm 800$  kV), which improve efficiency and power transfer capacity over longer distances. Recent projects in China, such as the Changji–Guquan UHVDC link, have pushed voltage ratings to  $\pm 1,100$  kV, enabling a record-breaking transmission capacity of 12,000 MW over 3,284 kilometers [17]. These advancements are setting new benchmarks for the feasibility of intercontinental HVDC interconnections, which could eventually link renewable energy sources across different continents.

**Transition towards multi-terminal HVDC**: Another key development is the growth of multiterminal HVDC grids (see section 1b-3), which allow power to be transmitted flexibly between multiple nodes rather than just between two points. Traditional point-to-point HVDC systems are effective for bulk power transmission, but multi-terminal configurations enable more dynamic and resilient networks. The European Supergrid Initiative, for example, envisions a pan-European HVDC network that connects offshore wind farms, solar farms, and hydro resources across multiple countries [18]. This approach enhances grid redundancy and energy security, making it a critical enabler of large-scale renewable energy integration.

Advancement in power electronics: The role of HVDC circuit breakers and advanced power electronics is also evolving rapidly. Innovations such as hybrid circuit breakers, pioneered by ABB and Siemens, are enabling the real-time fault isolation of HVDC grids, making multi-terminal HVDC systems more feasible [19]. Meanwhile, the shift from LCC to VSC is improving the flexibility of HVDC systems, allowing for easier integration with weak AC grids and offshore wind farms. These VSC-based HVDC systems are particularly useful for urban power supply, where AC grid reinforcement is difficult.

**Policy and investment trends**: Beyond technological advancements, policy and investment trends are also shaping the HVDC market. Governments worldwide are prioritizing HVDC transmission as part of their net-zero carbon strategies. The European Green Deal, for instance, includes major funding allocations for transnational HVDC corridors, while the United States' Bipartisan Infrastructure Law has designated HVDC transmission as a critical component for modernizing the grid [20].

**Fusion with AI and digital twin**: In recent years, the convergence of HVDC technology with artificial intelligence (AI) and digital twin modeling is expected to further optimize grid operations. AI-driven predictive analytics can enhance real-time HVDC control, while digital twin simulations enable proactive grid management, reducing operational risks and improving asset longevity [21]. These innovations will be instrumental in developing the next-generation smart grids, where HVDC will serve as the backbone of a globally integrated power system.

### 1b-3. HVDC Back-to-back Stations

#### 1b-3.1. Features and Benefits

HVDC Back-to-back systems are specialized configurations of HVDC technology where the rectifier and inverter are located in the same station, with no DC transmission line between them. These systems convert AC to DC and then back to AC, enabling the connection of two asynchronous AC networks [22]. The primary objective of back-to-back HVDC systems is to facilitate the transfer of power between independent power grids that operate at different frequencies or are not synchronized. Back-to-back HVDC systems can also be installed in ac transmission network as a power flow control device. This allows for the integration of diverse power systems, enhancing grid stability and enabling the efficient distribution of electricity across different regions.



Figure 8. Illustration of Back-to-Back HVDC stations connecting two power systems

Back-to-back HVDC systems offer several benefits. First, they provide the ability to connect asynchronous grids, which is crucial for the stability and flexibility of interconnected power systems. This interconnection helps prevent cascading failures by isolating disturbances within one network and not allowing them to propagate to the connected grid. Second, back-to-back HVDC systems enhance the transfer capacity between regions without the need for long-distance transmission lines, making them cost-effective for specific applications [9]. Furthermore, these systems contribute to improved power quality and reliability. By enabling precise control over power flow and frequency, back-to-back HVDC systems can help manage and stabilize the grid during fluctuations and peak demand periods. They also support the integration of renewable energy sources, which can be intermittent and require stable grid conditions for effective utilization [23].

However, back-to-back HVDC systems also face challenges [23]. A critical challenge is the high initial cost associated with the converter stations. The installation of sophisticated power electronics and control systems can be expensive and require significant initial investment. Further, the maintenance and operation of these systems require specialized knowledge and skills, which can increase operational costs. Despite these challenges, the benefits of enhanced grid stability, increased transfer capacity, and improved power quality often justify the investment in back-to-back HVDC systems [24]-[25].

#### 1b-3.2. Real-World Examples

Back-to-back HVDC stations serve as a critical technology for interconnecting asynchronous power grids, such as the Western Electricity Coordinating Council (WECC) and the Eastern Interconnect (EI) in the U.S. This ensures the seamless transfer of power between two grids that operate independently, without requiring synchronization of their frequencies. Examples of such installations include the Virginia Smith Converter Station in Nebraska, which was completed in 1988. It is the first interchange between eastern and western United States electrical grids. The station can transfer a maximum power of 200 megawatts and the voltage used is 55.5 kV. Other stations are shown in Figure 9.



Figure 9. Map of the Back-to-back HVDC stations connecting EI, WECC and ERCOT [26]

The Châteauguay HVDC Back-to-Back Station, located near Montreal, Quebec, is Canada's largest back-to-back HVDC converter station [27]. Commissioned in 1984, it was designed to facilitate the exchange of electricity between the Hydro-Québec grid and the New York Power Authority network, which operate asynchronously. The station was originally built with a 1,000 MW capacity and has played a crucial role in enhancing grid reliability and energy trade between Canada and the United States. A significant upgrade in 2022 increased the station's capacity by 50% to 1,500 MW, improving its efficiency and operational flexibility. The upgrade involved replacing aging components with modern HVDC Light technology, enhancing control capabilities, and reducing environmental impact. The station employs thyristor-based line-commutated converters (LCC), which were among the most advanced technologies at the time of its construction. The Châteauguay HVDC station ensures stable power transfer by mitigating frequency and phase discrepancies between the two grids. It enhances power system resilience, facilitates renewable energy integration, and supports cross-border electricity trade. As a critical infrastructure component, it continues to be an essential asset in North America's interconnected power system, ensuring seamless and efficient energy exchange.

Japan's HVDC back-to-back stations play a crucial role in connecting the country's two asynchronous power grids, which operate at 50 Hz in the east and 60 Hz in the west. This frequency divide dates back to the early 20th century when Tokyo adopted German 50 Hz generators while Osaka sourced 60 Hz equipment from the U.S. To enable efficient power exchange across this divide, Japan has developed multiple HVDC back-to-back stations that facilitate frequency conversion and ensure grid stability [28]. One of the most significant facilities is the Shin-Shinano Frequency Converter Station, commissioned in 1977 and expanded in 1992 and 2008, bringing its total capacity to 600 MW. It was the first station built to directly link the two grids and remains a key interconnection point. Other major stations include the Higashi-Shimizu and Sakuma Frequency Converter stations. The back-to-back stations are shown in Figure 8, along with Japan's 60 Hz and 50 Hz grids. These back-to-back stations use VSC [29] and LCC [30] to efficiently transfer electricity while minimizing losses. They provide grid resilience, helping to stabilize power supply, especially during peak demand or emergencies. Their role has become even more critical as Japan integrates more renewable energy sources, ensuring a balanced and flexible power network. Collectively, these stations form a backbone of Japan's interconnected electricity system, enabling energy security and efficient nationwide power distribution



Figure 10. Map of Japan's HVDC back-to-back stations connecting 60 Hz grid in the west and 50 Hz grid in the east.

#### 1b-3.3. Industry Insights

HVDC back-to-back (B2B) stations play a critical role in modern power systems by enabling the interconnection of asynchronous grids. These systems are particularly valuable in regions where different power grids operate at distinct frequencies or where geographical isolation prevents direct

synchronization between networks. The ability to transfer power seamlessly between these independent grids enhances reliability, supports grid stability, and provides flexibility in electricity supply.

**Enhancing Grid Stability and Reliability:** B2B HVDC stations act as buffer zones between asynchronous grids, converting AC to DC and back to AC. This unique capability allows for controlled power exchange between systems that would otherwise not be able to support each other, such as grids operating at different frequencies. By facilitating smooth power transfers, B2B stations mitigate the risk of grid instability and cascading failures. For example, the Eel River HVDC back-to-back station in Canada connects the power grids of Quebec and New Brunswick, ensuring a reliable flow of electricity even though the two grids operate at different frequencies (60 Hz and 50 Hz, respectively). This interconnection has proven to be vital in maintaining system stability, particularly during periods of high demand or unforeseen grid disturbances [31].

**Cost-Effectiveness and Scalability:** B2B HVDC stations are often more cost-effective than building extensive transmission infrastructure to synchronize grids through traditional AC connections. They provide a practical solution for interconnecting grids over shorter distances, where the cost of laying new transmission lines for conventional AC systems may be prohibitive. Furthermore, the scalability of HVDC technology allows for the gradual expansion of power exchanges as demand grows, making B2B HVDC systems a flexible and adaptable solution for future grid developments [32].

**Future Outlook:** As the global energy landscape continues to evolve, HVDC back-to-back stations will play an increasingly important role in facilitating the transition to renewable energy, enhancing grid stability, and enabling cross-border electricity trade. With advances in HVDC technology, such as higher voltage capabilities and improved converter efficiency, the scope for deploying B2B systems is expanding. As more regions seek to interconnect their grids and manage the growing share of intermittent renewable resources, B2B HVDC systems are poised to be a key enabler in achieving these goals. Their ability to support reliable, stable, and flexible power exchange will be essential as grids become more interconnected and complex [34].

### **1b-4.** Multi-terminal HVDC (MTDC)

#### 1b-4.1. Features and Benefits

Multi-terminal HVDC (MTDC) systems represent an advanced development in HVDC technology, enabling multiple converter stations to be interconnected within a single DC grid. Unlike traditional point-to-point HVDC systems, which connect only two locations, MTDC systems facilitate the integration of several terminals [35], allowing for more complex and flexible power distribution networks. This configuration supports the efficient transmission of electricity across vast distances and different regions, enhancing grid reliability and resilience.

The primary concept behind MTDC systems is the creation of a DC network that can dynamically manage power flows between multiple points [36]. This flexibility is crucial for integrating renewable energy sources, such as offshore wind farms, that are distributed across various locations. MTDC systems can balance generation and load more effectively, ensuring stable and continuous power delivery even when individual converters or lines experience faults or require maintenance.



Figure 11. Illustration of a system with MTDC

The configuration of MTDC systems involves several key components, including converter stations, DC transmission lines, and control systems [37]. Converter stations in MTDC networks use VSCs due to their ability to provide independent control of active and reactive power, as well as their capability to operate in weak AC grids. These converters are interconnected by high-voltage DC lines, creating a network that can span across regions or even countries.

There are two primary configurations for MTDC systems: radial and meshed networks [38]. Radial configurations are simpler, with a central hub connected to multiple terminals. This setup is easier to manage but less flexible in power distribution. In contrast, meshed networks offer multiple

pathways for power flow, enhancing redundancy and reliability. Meshed MTDC systems can reroute power in case of faults or line outages, ensuring continuous operation and reducing the risk of power interruptions.

The control systems for MTDC networks are various and require advanced algorithms to manage power flows and maintain system stability [30]. These control systems must coordinate the operation of all converters and manage the interactions between the DC and AC grids. Effective control strategies are essential for optimizing the performance of MTDC systems and ensuring they can respond dynamically to changes in generation and load.

Fault protection in MTDC systems is a critical aspect that ensures the safety and reliability of the network. The primary challenge in MTDC fault protection is the rapid identification and isolation of faults to prevent damage to equipment and minimize service disruptions [39]. Unlike AC systems, where fault currents can be managed relatively easily, DC faults can cause severe and fast-rising currents that require immediate intervention. One approach to fault protection in MTDC systems is the use of DC circuit breakers [40]. These breakers are designed to interrupt high DC currents quickly, isolating the faulty section of the network and allowing the rest of the system to continue operating. Recent advancements in DC breaker technology have improved their speed and reliability, making them a viable solution for MTDC networks. Another method involves fault detection algorithms integrated into the control systems of MTDC networks [41]. These algorithms continuously monitor the network for abnormal conditions and can trigger protective actions when a fault is detected. Coordinated protection schemes that involve both DC breakers and advanced fault detection algorithms are essential for ensuring the robust operation of MTDC systems.

#### 1b-4.2. Real-World Examples

Several real-world projects showcase the deployment of Multi-terminal HVDC (MTDC) systems, demonstrating their ability to enhance grid stability, support renewable energy integration, and enable efficient power distribution across vast distances.

A notable example is the North Sea Wind Power Hub under development in the North Sea. This project aims to connect offshore wind farms from multiple countries, including Denmark, the Netherlands, Germany, and Norway, through an offshore HVDC grid or to a centralized HVDC hub. The system is designed to transmit up to 10 GW of renewable energy across borders, supporting the EU's renewable energy targets. The North Sea Wind Power Hub will be the world's first multi-terminal offshore grid and will improve the stability and flexibility of the regional power systems, enabling better integration of intermittent renewable energy sources like wind power [43].

In China, the Zhoushan five-terminal HVDC project is a significant example of a MTDC system. This project connects the Ningbo and Zhoushan islands with the Shanghai Luchao Station, forming part of China's push to integrate renewable energy sources from offshore wind farms and facilitate the efficient transmission of electricity across different regions. The MTDC network has a total capacity of 1,000 MW and spans around 230 kilometers, with connections facilitating the transfer of power between the islands and the main grid in Shanghai. This project enhances China's ability to integrate offshore wind power, providing a stable and reliable power flow across regions with varying demand and generation profiles. This system not only reduces transmission losses but also

improves grid stability by enabling the flexibility to redistribute power during periods of high demand or when a terminal station experiences faults or maintenance. By leveraging MTDC technology, the system supports China's growing renewable energy ambitions, particularly for offshore wind energy, which is a key focus of their renewable energy strategy [44].



Figure 12. The Zhoushan five-terminal MDTC Project deployed in China (2024)

The East-West Interconnection Project in India also employs an MTDC configuration, linking the country's eastern and western power grids. This system improves the exchange of power between regions with varying generation capacities and helps stabilize the grid during periods of high demand or when renewable generation is intermittent. This project has been pivotal in increasing energy reliability and supporting the integration of renewable resources, especially in India's renewable-rich eastern states [45].

These examples underscore the increasing adoption of MTDC systems in large-scale projects designed to optimize power transmission, reduce transmission losses, and enhance grid reliability across different regions.

#### **1b-4.3.** Industry Insights

As global energy systems shift toward more interconnected and renewable-based networks, MTDC systems are emerging as a vital solution. Unlike conventional point-to-point HVDC systems, MTDC networks facilitate power exchange across multiple nodes, increasing the flexibility and resilience of energy grids.

**Deployment challenges**: One of the primary challenges in deploying MTDC systems is the complexity of control and coordination. Managing multiple converter stations in an interconnected grid requires advanced algorithms and real-time data analytics to ensure system stability and optimal power flow. The coordination of AC and DC grids, each with different operational

characteristics, remains a technical hurdle. The complexity is compounded by the need for highperformance converter stations, which can be costly to install and maintain. Additionally, fault protection remains a challenge due to the unique nature of DC fault currents, which are harder to manage compared to AC systems. Developing efficient DC circuit breakers and fault detection systems is crucial to ensuring safe and reliable MTDC operation [46]. Another challenge is the high initial cost associated with the installation of MTDC infrastructure, which involves substantial investment in converter stations, control systems, and transmission lines. While these systems can offer long-term benefits in terms of reduced transmission losses and improved system resilience, the upfront financial commitment can be a barrier, especially for developing economies or regions with limited access to capital.

**Offshore renewable energy integration and decarbonization**: Despite these challenges, the future of MTDC systems looks promising, driven by ongoing technological advancements and the global shift towards renewable energy integration for decarbonization. One key trend is the expansion of offshore wind energy projects, which rely heavily on MTDC systems for the transmission of electricity over long distances. For example, the North Sea Wind Power Hub is set to become the world's largest offshore wind grid, interconnecting several countries through an MTDC system. Such projects highlight the increasing importance of MTDC in renewable energy transmission, and they are expected to expand as nations aim to achieve their climate targets [47]. This capability of MTDC will support government's efforts to reduce reliance on fossil fuels and facilitate the global shift to cleaner energy [48].

**Enhancing grid reliability and resilience**: As the demand for interconnection between national grids grows, MTDC systems are poised to play a pivotal role in enabling cross-border energy exchanges. These systems allow countries or regions with surplus renewable energy to export power to countries or regions with higher energy demand. The ability to create flexible, meshed DC grids offers enhanced reliability and redundancy, making them an essential tool for energy trading and balancing supply and demand across regions [49].

**Emerging enabling technologies**: The continued development of DC circuit breaker technologies is another critical area to watch. Faster, more reliable breakers will allow MTDC systems to operate safely even during faults, which will improve the stability and robustness of the overall system. Additionally, the development of advanced grid control and monitoring systems using artificial intelligence (AI) and machine learning (ML) will provide operators with real-time insights, enabling more efficient and predictive management of MTDC networks.

## 1b-5. Hybrid AC/DC Transmission

### 1b-5.1. Features and Benefits

Hybrid AC/DC systems, which combine both alternating current (AC) and direct current (DC) transmission technologies, are increasingly recognized for optimizing electrical grid performance. Although all current HVDC systems are embedded in an AC network, the hybrid AC/DC transmission system in this module is defined as an AC power grid with multiple HVDC links which perform a significant operational role such as transferring a significant amount of electrical energy, connecting two asynchronous grids, and/or maintaining system stability, security and reliability.

In domestic settings, AC grids are predominantly used due to their compatibility with household appliances and ease of distribution [50]. On the other hand, industrial and commercial consumers benefit from DC grids, as they offer more efficient power delivery for high-demand applications and advanced industrial processes.



Figure 13. AEP conceptual 765kV backbone system consisting of hybrid AC/DC systems [50]

An important advantage of hybrid AC/DC systems is their ability to increase transmission capacity. By incorporating the strengths of both AC and DC systems, hybrid grids enable higher power transfer capabilities than traditional AC or DC systems alone [51]. This increased capacity is crucial for transmitting larger amounts of power over long distances, addressing the growing energy demands of modern society. Additionally, the integration of AC and DC technologies helps to reduce transmission losses, enhancing overall system efficiency.

Another key benefit of hybrid systems is their contribution to improved grid stability. Hybrid AC/DC grids offer enhanced fault ride-through capabilities, allowing the grid to remain operational even during faults or disturbances [52]. This resilience is particularly valuable in preventing cascading failures and maintaining power supply during unexpected events. Furthermore, hybrid systems provide greater control over power flows, enabling grid operators to

manage and balance the system more effectively. Such precise control is essential during peak demand periods and in facilitating the integration of variable renewable energy sources, such as wind and solar power.

The flexibility of hybrid AC/DC systems is another significant advantage. These systems support the efficient integration of renewable energy by allowing for better transmission and distribution of variable power outputs. As a result, they play an important role in the transition toward a more sustainable energy mix. Furthermore, hybrid grids enhance energy trading and interconnections between different regions, improving grid reliability, resilience, and adaptability of the overall power system [53].

#### 1b-5.2. Real-World Examples

China Southern Power Grid integrates ultra-high-voltage (UHV) AC and UHV DC transmission lines to achieve efficient and reliable power delivery across vast distances. This hybrid system links power generation in remote areas to major consumption centers, covering areas such as Guangdong, Guangxi, and Yunnan. The UHV DC lines have a capacity of 10,000 MW and operate at voltages up to 800 kV. The system is crucial for long-distance power transmission, reducing transmission losses and enhancing grid stability, particularly for energy transfer across the South China Grid. Figure 12 illustrates the major HVAC and HVDC transmission lines in CSG.



Figure 14. The hybrid AC/DC systems in China Southern Grid (CSG) [54]

Turkey has undertaken a major initiative to convert existing high-voltage AC systems to hybrid AC/DC configurations to increase transmission capacity and efficiency. The system aims to optimize the existing transmission infrastructure and meet growing energy demands. While exact MW capacities and voltages are not specified, the hybrid systems are expected to improve grid

flexibility, especially in remote areas with significant renewable energy sources. The initiative is set to enhance the integration of solar and wind power into the Turkish energy grid.

Several medium-voltage hybrid AC/DC distribution systems are being deployed across Europe, with notable installations in Germany, Denmark, and the Netherlands. These systems typically operate at voltages between 110 kV and 220 kV and are designed to enhance grid flexibility and efficiency while facilitating renewable energy integration. In particular, the systems in Denmark are focused on integrating wind energy, with wind farms generating up to 4,000 MW of renewable power. Hybrid systems in these regions allow for better power quality and more efficient distribution of intermittent renewable energy.

#### 1b-5.3. Industry Insights

With increasing energy demands and the need for efficient power transmission, hybrid AC/DC systems are gaining prominence. These systems combine the benefits of both AC and DC transmission, optimizing power flows while enhancing grid stability and resilience.

**Connecting renewable energy sources**: The use of hybrid AC/DC systems is particularly beneficial for connecting remote, renewable energy sources, such as offshore wind farms, to urban centers. These systems enable the efficient transfer of renewable energy while reducing reliance on fossil fuels, thereby supporting the global transition toward cleaner energy. As more countries push toward renewable energy mix. For example, in regions like China Southern Power Grid, hybrid systems incorporating ultra-high-voltage AC and DC lines have been critical in achieving efficient power delivery across vast distances. These hybrid networks are designed to handle capacities up to 10,000 MW and operate at voltages up to 800 kV, addressing the needs of both growing urban areas and remote energy sources [55].

**Enhancing grid resilience and reliability**: Hybrid grids improve grid stability by providing better fault ride-through capabilities and enabling precise control over power flows. These capabilities are essential for maintaining system reliability, especially during peak demand periods or when integrating intermittent renewable sources like solar and wind power. In Europe, medium-voltage hybrid AC/DC systems have been deployed to optimize power distribution, particularly in countries such as Germany, Denmark, and the Netherlands, where they help manage the integration of wind power into the grid. The flexibility offered by hybrid systems also enables energy trading between different regions, further enhancing grid resilience and operational efficiency [56].

**Cost and environment**: These advantages of hybrid AC/DC systems are driving significant investment in grid modernization worldwide. Not only do they reduce the need for new infrastructure, but they also contribute to cost savings and minimizing environmental impact by optimizing existing transmission corridors. As hybrid systems become more advanced, they will continue to play a pivotal role in enhancing energy security, promoting sustainable practices, and ensuring reliable electricity delivery in an increasingly electrified world [57].

## **1b-6.** Summary of HVDC Transmission Technologies

HVDC transmission systems can be categorized into four primary applications, each addressing specific grid needs. The following is a summary of these technologies with their characteristics, advantages, and applications highlighted.

#### HVDC Long-Distance Transmission

- **Objective**: Efficient bulk power transfer over long distances (typically >600 km for overhead lines, >50 km for submarine cables).
- **Topology**: P2P connection between two converter stations.
- Advantages: Lower transmission losses, no reactive power issues, improved grid stability, and reduced right-of-way requirements.
- Applications: Inter-regional and intercontinental power transfer, offshore wind integration (e.g., Pacific DC Intertie, North Sea Link, Xiangjiaba–Shanghai UHVDC link).

#### **HVDC Back-to-Back Stations**

- **Objective**: Interconnect asynchronous AC grids or grids with different operating conditions.
- **Topology**: Two converter stations located within the same facility (without a transmission line).
- Advantages: Seamless power exchange between different AC networks, enhances grid reliability, prevents cascading failures.
- Applications: Connecting different power grids (e.g., Virginia Smith Converter Station, Eel River HVDC link, Gotland HVDC link).

#### Multi-Terminal HVDC (MTDC)

- **Objective**: Interconnect multiple converter stations within a DC grid to enhance flexibility and redundancy.
- **Topology**: Can be radial or meshed, involving multiple terminals linked by DC lines.
- Advantages: Improved power distribution, increased reliability through redundancy, ideal for integrating multiple renewable sources.
- Applications: Offshore wind farm clusters, large inter-regional transmission projects (e.g., Zhoushan five-terminal HVDC project, North Sea Wind Power Hub).

#### Hybrid AC/DC Systems

- **Objective**: Optimize power transfer by combining AC and DC transmission for better efficiency and flexibility.
- Topology: Integration of AC and DC lines within the same grid, typically using VSCs.
- Advantages: Increased transmission capacity, reduced losses, enhanced fault ride-through capability, better control of power flows.
- Applications: Integration of renewable energy sources, enhancing existing transmission infrastructure (e.g., China Southern Power Grid hybrid AC/DC network, European hybrid AC/DC distribution systems).

Table 2 below provides a comparison of the four main HVDC technologies and their applications. Each of these plays a crucial role in modernizing power transmission and enhancing grid stability globally.

HVDC Type	Objective	Topology	Key Advantages	<b>Example Applications</b>
HVDC Long- Distance Transmission	Bulk power transfer over long distances	Point-to-point (P2P)	Low losses, no reactive power, stability	Pacific DC Intertie (PDCI), North Sea Link, Xiangjiaba– Shanghai UHVDC
HVDC Back-to- Back Stations	Interconnect asynchronous AC grids	No transmission line	Grid synchronization, prevents failures	Virginia Smith Converter Station, Eel River HVDC, Gotland HVDC
Multi-Terminal HVDC (MTDC)	Connect multiple points in a DC grid	Radial or Meshed	Grid flexibility, redundancy, renewable integration	North Sea Wind Power Hub, Zhoushan Five-Terminal Project,
Hybrid AC/DC Systems	Improve grid efficiency & flexibility	AC + DC mix	Enhanced transmission, reduced losses	China Southern Power Grid, European hybrid networks, Turkish HVDC hybrid initiative

Table 2. Comparison of Different HVDC Transmission Technologies

## **1b-7.** Future Trends and Innovations in HVDC Transmission

### 1b-7.1. Technological Advancements

#### Advances in Converter Technology

The future of HVDC transmission is significantly shaped by advances in converter technology. VSCs are undergoing continuous improvements, offering higher efficiency, enhanced control capabilities, and better integration with renewable energy sources [58]. Modern VSCs are designed to handle higher voltages and currents, enabling the transmission of greater amounts of power over longer distances with reduced losses. These advancements are crucial for developing more robust and flexible HVDC grids that can meet the growing demand for electricity while integrating an increasing share of renewable energy.

A key innovation in converter technology is the development of modular multilevel converters (MMCs). MMCs provide numerous advantages over traditional converter designs, including lower harmonic distortion, reduced filtering requirements, and enhanced scalability. These features make MMCs particularly suitable for large-scale HVDC projects and MTDC systems. The modular nature of MMCs also allows for easier maintenance and upgrades, contributing to the overall reliability and longevity of HVDC infrastructure [59].

Moreover, modern converters are incorporating advanced control algorithms to enhance performance and reliability. These algorithms enable precise power flow control, efficient fault management, and improved grid stabilization—critical functions for HVDC systems operating in complex and dynamic grid environments. An emerging trend in this field is the integration of artificial intelligence (AI) and machine learning (ML) techniques into converter control systems, further enhancing the adaptability and efficiency of HVDC technology [60].

#### New Materials and Methods

The development of new materials and methods is another critical area of innovation in HVDC technology. High-performance insulation materials, such as cross-linked polyethylene (XLPE) [61], are increasingly used in HVDC cables to improve their durability and operational efficiency. XLPE cables offer superior electrical properties, higher thermal stability, and greater resistance to environmental stress compared to traditional insulation materials. These advantages make XLPE cables ideal for both underground and submarine HVDC applications, where reliability and longevity are paramount.



Figure 15. New insulation materials boosts HVDC cable performance [62]

In addition to insulation materials, advancements in semiconductor technology are playing a pivotal role in the evolution of HVDC systems. Wide bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), are being explored for their potential to enhance the performance of HVDC converters. WBG semiconductors can operate at higher voltages, temperatures, and frequencies than conventional silicon-based devices, which result in more efficient and compact converters. The adoption of WBG technology is expected to lead to significant improvements in the overall efficiency and cost-effectiveness of HVDC systems [63].

Innovative methods for constructing and maintaining HVDC infrastructure are also emerging. Techniques such as real-time condition monitoring and predictive maintenance are being implemented to ensure the reliability and safety of HVDC systems [64]. These methods involve advanced sensors and data analytics to monitor the health of HVDC components, predict potential failures, and schedule maintenance activities proactively. By minimizing downtime and preventing unexpected outages, these innovative approaches contribute to the overall resilience and efficiency of HVDC networks.

### 1b-7.2. Emerging Applications

#### Integration with Energy Storage

The integration of HVDC transmission systems with energy storage technologies represents a significant emerging application in power system operation. As renewable energy sources such as wind and solar power become more prevalent, the need for reliable and efficient energy storage solutions has grown. HVDC systems are increasingly being paired with advanced energy storage technologies to enhance grid stability and reliability [65]. This combination allows for the storage of excess energy generated during periods of low demand and its release during peak demand times, thus balancing the supply and demand more effectively.

One notable advantage of integrating energy storage with HVDC systems is the enhanced ability to manage intermittent renewable energy sources. Energy storage systems can store surplus energy when generation exceeds demand and discharge it when generation is low, thereby mitigating the variability of renewable energy and ensuring a steady power supply. This integration also supports the creation of more resilient power systems by providing backup power during outages or grid disturbances [66]. Furthermore, the combination of HVDC and energy storage can facilitate the development of microgrids and islanded systems, providing localized energy solutions that can operate independently from the main grid when necessary.

#### Growing needs for DC

The growing needs for DC power grid in various applications are driving innovations in HVDC technology. With the increasing adoption of renewable energy sources, Electric vehicles (EVs), and DC-powered electronic devices, the demand for efficient DC power transmission and distribution is rising [67]. HVDC systems offer several advantages over traditional alternating current (AC) systems, including reduced transmission losses, the ability to interconnect asynchronous grids, and improved power quality.

The expanding integration of renewable energy sources leads to the need for DC power grid. Solar photovoltaic (PV) systems and many types of wind turbines inherently generate DC power. It can be inefficient if we convert such power to AC for transmission and then back to DC for end-use. Using HVDC for direct transmission from these renewable sources to load centers or storage facilities can significantly reduce conversion losses and improve overall system efficiency.

EVs and their associated charging infrastructure also contribute to the growing demand for DC power. HVDC systems can facilitate the efficient transmission of power to fast-charging stations, reducing charging times and improving the user experience [68]. Furthermore, DC microgrids, which integrate renewable energy sources, energy storage, and loads on a common DC bus, are emerging as an effective way to enhance energy efficiency and reliability in residential, commercial, and industrial settings.

## **1b-8.** Summary of main learning points

The main learning points of the Application Guide of HVDC transmission addressed in this module are summarized as follows.

First, a comprehensive introduction is provided to the application of HVDC transmission technologies, beginning with a historical overview and progressing through system classifications, key configurations, and future development trends.

HVDC transmission has evolved from early experiments in the late 19th century to become a core technology for modern power systems. Milestones such as the Pacific DC Intertie, the North Sea Link, the Gotland link, the WECC-EI Back-to-back stations, and recent ultra-high-voltage projects in China have demonstrated HVDC's capability for large-scale, efficient, and reliable power transfer across long distances and challenging environments.

The importance of HVDC lies in its high transmission efficiency, system controllability, and ability to connect asynchronous grids. Compared to HVAC, HVDC reduces transmission losses, minimizes land use, and supports stable operation, especially in systems with high penetration of renewable energy. Its application enhances interregional connectivity, facilitates cross-border electricity trade, and strengthens the resilience of power systems against disturbances.

HVDC technologies were categorized into four main types in this module, each with distinct features, applications, and benefits:

- Long-Distance HVDC Transmission is used for bulk power transfer over extended distances, with point-to-point topology and reduced transmission losses. Notable examples include the Pacific DC Intertie (PDCI), North Sea Link, and Xiangjiaba–Shanghai UHVDC.
- **Back-to-Back HVDC Stations** enable power exchange between asynchronous AC systems without requiring long-distance DC lines. Installations like the Virginia Smith Converter Station and Eel River HVDC link illustrate their use in regional grid interconnection.
- **Multi-Terminal HVDC (MTDC)** configurations involve multiple converter stations within a shared DC network. They improve operational flexibility and are increasingly used in offshore wind integration and large regional interconnections, such as the Zhoushan project and the North Sea Wind Power Hub.
- **Hybrid AC/DC Transmission** integrates both AC and DC systems to enhance efficiency and flexibility in existing grids. Examples include China Southern Power Grid and the conceptual hybrid backbone systems in Europe and Turkey.

Emerging trends discussed in this module highlight continued innovation in converter design, insulation materials, and system control. The integration of HVDC with energy storage technologies, along with growing demands for DC power in urban infrastructure and data centers, signals a strong future for HVDC deployment.

### Problems

**Problem 1**: Which of the following is NOT a typical advantage of HVDC transmission compared to HVAC?

- A. Lower transmission losses over long distances
- B. Ability to interconnect asynchronous grids
- C. Requires more right-of-way than AC transmission
- **D.** Improved power flow control and system stability

#### **Solution**: C

HVDC systems actually require *less* right-of-way than AC systems, often reducing land use by 30–50%.

**Problem 2:** Which of the following HVDC technologies is specifically used to connect two asynchronous AC grids at a single location?

A. HVDC long-distance transmission
B. HVDC back-to-back stations
C. Multi-terminal HVDC systems
D. Hybrid AC/DC transmission

#### *Solution*: B

Back-to-back stations are used to connect different AC systems without the need for long DC transmission lines.

Problem 3: Which HVDC project is known for being the longest subsea interconnector as of 2021?

A. Changji–Guquan UHVDC
B. North Sea Link
C. Pacific DC Intertie
D. Gotland Link

#### *Solution*: B

The North Sea Link (UK-Norway, 720 km) is the longest subsea HVDC cable as of 2021.

Problem 4: What is the primary benefit of multi-terminal HVDC (MTDC) systems?

- A. Enhanced power routing flexibility and redundancy
- B. High fault levels like AC grids
- C. Low installation cost for short distances
- **D.** Elimination of converters

#### Solution: A

MTDC systems allow multiple converter stations, improving flexibility and reliability in transmission networks.

Problem 5: Which of the following best describes a hybrid AC/DC transmission system?

- A. It uses only DC lines with no AC interface
- B. It combines AC and DC systems within the same network to enhance performance
- C. It converts AC to DC at distribution voltage levels only
- **D.** It is an outdated form of power delivery used before 1950

#### Solution: B

Hybrid AC/DC systems integrate both technologies to leverage their respective advantages.

**Problem 6**: Which of the following is a major technical advancement driving the future of HVDC systems?

- A. Elimination of all converter stations
- **B.** Integration with fossil fuel backup systems
- C. Increased dependency on synchronous machines
- D. Modular multilevel converters (MMC) and new insulation materials

#### Solution: D

Advances in converter design (e.g., MMC) and materials are critical for future HVDC performance and reliability.

**Problem 7**: Which HVDC project holds the current world record for the highest voltage level in operation?

- A. Pacific DC Intertie
- B. North Sea Link
- C. Changji–Guquan UHVDC
- D. Zhoushan Multi-terminal HVDC Project

#### Solution: C

The Changji–Guquan UHVDC transmission project in China operates at  $\pm 1,100$  kV, making it the highest voltage HVDC line in the world.

Problem 8: Why is HVDC considered a key enabler for renewable energy integration?

A. It allows localized voltage fluctuations

**B.** It can efficiently transmit power from remote renewable sources

- C. It supports only coal and nuclear baseload power
- **D.** It delays system response times

#### Solution: B

HVDC enables efficient transmission from remote wind and solar farms to major load centers, supporting grid decarbonization.

Problem 9: Where was the world's first commercial HVDC transmission project implemented?

- A. United States
- **B.** Germany
- C. Sweden
- **D.** China

#### *Solution*: C

The first commercial HVDC project was the Gotland link in Sweden, commissioned in 1954, operating at 100 kV and 20 MW.

**Problem 10**: What are the key advantages of HVDC transmission over traditional AC transmission systems?

#### Solution:

- 1) Long-distance power transmission.
- 2) Lower losses and increased efficiency.
- 3) Ability to interconnect asynchronous grids (e.g., Japan's 50 Hz and 60 Hz networks).
- 4) Improved controllability and stability in the power system.
- 5) Suitable for Offshore wind farms, undersea cables, and intercontinental links.

Problem 11: Name three HVDC transmission projects in the world. Whhat are their impacts?

*Solution*: Major HVDC projects worldwide (e.g., Pacific DC Intertie, North Sea Link, China's UHVDC).

Help in renewable energy integration; Economic and environmental benefits; Challenges in deploying HVDC projects.

**Problem 12**: How does the future of HVDC transmission look in terms of innovation and emerging applications?

#### Solution:

- 1) Advances in converter technology (e.g., VSC-HVDC).
- 2) Integration with energy storage systems.
- 3) Increasing use of HVDC in offshore wind power and smart grids.
- 4) Growth of multi-terminal HVDC (MTDC) networks.

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