

# HVDC TRANSMISSION FOR LONG-DISTANCE POWER TRANSFER: A COMPREHENSIVE REVIEW

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**ABSTRACT** High Voltage Direct Current (HVDC) transmission technology has emerged as a highly efficient, stable, and economically viable method for long-distance and bulk-power transfer, especially across regions requiring interconnection of asynchronous grids. Over the last few decades, technological advances in converters, controllability, and insulation systems have strengthened HVDC's position in modern power networks. This review paper provides an extensive analysis of HVDC transmission systems, covering their historical development, operating principles, configurations, technological components, control strategies, economic feasibility, environmental implications, and comparative advantages over HVAC systems. Recent innovations—including Voltage Source Converters (VSC-HVDC), modular multilevel converters (MMC), ultra-high-voltage DC (UHVDC) systems, and offshore renewable power integration—are critically evaluated. Case studies from China, India, Europe, and North America highlight real-world performance in long-distance power transfer. Challenges such as converter cost, harmonic issues, protection difficulties, and cyber-security vulnerabilities are examined along with future pathways toward hybrid AC/DC grids and smart power flow management. The paper concludes that HVDC will remain an essential enabler of global energy transition, facilitating large-scale renewable integration, cross-border interconnections, and long-haul transmission with minimal losses.

**Keywords:** HVDC transmission, long-distance power transfer, VSC-HVDC, UHVDC, AC/DC comparison, MMC converters, renewable energy integration, grid interconnection.

## 1. Introduction

High Voltage Direct Current (HVDC) transmission has increasingly become the backbone of long-distance power transfer, allowing efficient delivery of bulk electricity across hundreds or thousands of kilometres with lower losses than conventional High Voltage Alternating Current

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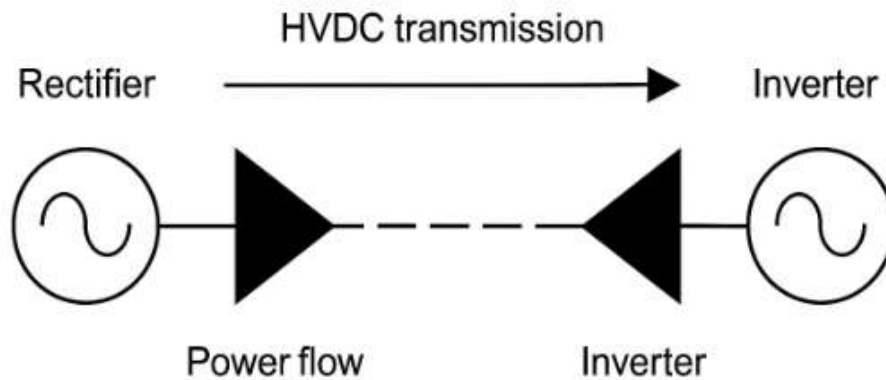
(HVAC) systems. The demand for HVDC technology has significantly grown due to increasing reliance on renewable energy, the need for interconnecting geographically distant grids, and the necessity of reducing transmission losses and improving grid stability (Hingorani & Gyugyi, 2012). Modern power systems require dynamic, flexible, and controllable transmission solutions capable of handling rapid fluctuations from renewable sources. This technological shift has positioned HVDC as a vital enabler of reliable, low-carbon energy systems (Bahrman & Johnson, 2014). The key objective of this paper is to provide a comprehensive review of HVDC transmission, including its operational characteristics, technical architecture, advantages, limitations, economic considerations, applications, challenges, and future trends.

## 2. Historical Background and Evolution of HVDC Technology

The concept of transmitting electric power using direct current was explored in the early 20th century, with practical development beginning in the 1950s following advancements in mercury-arc converters. Early HVDC lines—such as the Gotland link in Sweden (1954)—demonstrated the feasibility of DC power transfer over long distances (Padiyar, 2011). Subsequent innovations, including silicon-controlled rectifiers (SCRs) in the 1970s and the rise of thyristor-based converter stations, resulted in improved controllability and efficiency (Arrillaga, 1998). In the 1990s, the introduction of Voltage Source Converters (VSC-HVDC) marked a breakthrough, enabling independent control of reactive and active power, black-start capability, and grid interconnection in weak networks (Bahrman, 2008). Recent developments in modular multilevel converters (MMC) have enabled ultra-high-voltage direct current (UHVDC) systems exceeding  $\pm 1100$  kV, now widely deployed in China for distances above 2000 km (Xu et al., 2018).

## 3. Basic Operating Principles of HVDC Transmission

HVDC systems function by converting AC to DC at the sending end, transmitting power over long distances, and reconverting DC back to AC at the receiving end through converter stations. The direction of power transfer is controlled by varying the converter firing angles or modulation indices in VSC-based systems. DC transmission eliminates the reactive power component, thereby reducing losses and allowing precise power flow management (Kimbark, 1995). In addition, HVDC systems are designed to manage fault currents efficiently and maintain power quality through advanced filtering and control mechanisms.



**Figure 3.1 Operating Principle of AC–DC–AC Conversion in HVDC**

#### 4. HVDC System Configurations

HVDC transmission links may be classified into technological and structural configurations:

##### 4.1 Point-to-Point Systems

The most common configuration connects two distant substations, enabling controlled bidirectional power flow. This design is prevalent in UHVDC projects transferring bulk power from remote hydroelectric or wind resources.

##### 4.2 Back-to-Back HVDC Stations

Used for asynchronous grid interconnections, back-to-back stations consist of rectifier and inverter components located at the same site, enabling power exchange without long transmission lines (Padiyar, 2011).

##### 4.3 Multi-Terminal HVDC (MTDC) Systems

Although less common due to protection complexities, MTDC systems offer significant flexibility for integrating multiple generation sources and loads. Recent VSC designs have improved MTDC feasibility (Marquardt, 2010).

#### 5. Components of HVDC Transmission Systems

HVDC systems comprise specialized components selected for high reliability, reduced maintenance, and long-distance transmission efficiency.

##### 5.1 Converter Stations

Converter stations, consisting of rectifiers and inverters, are the most critical and expensive components. Line-commutated converters (LCC) use thyristors and rely on the AC grid for commutation, making them unsuitable for weak grids (Bahrman, 2008). In contrast, VSC-HVDC stations provide self-commutation and superior dynamic control.

## 5.2 Transmission Medium

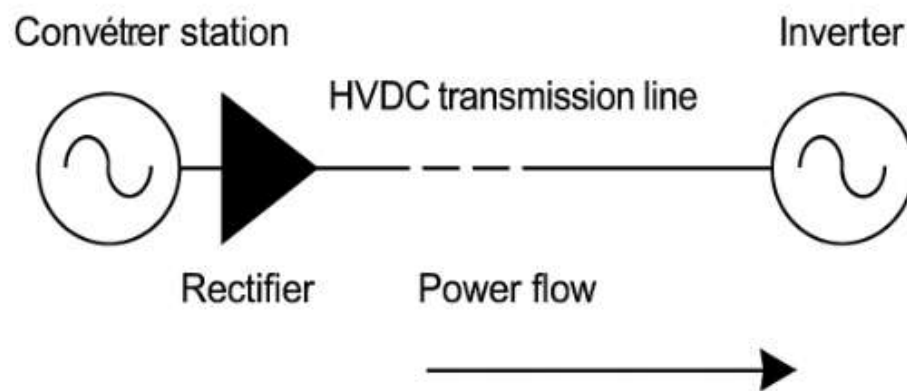
HVDC power is transmitted through overhead lines, submarine cables, or underground cables. DC cables experience lower dielectric stress and lower charging current compared to HVAC cables (Cigre, 2014).

## 5.3 Smoothing Reactors and Filters

Smoothing reactors minimize ripple current while harmonic filters limit frequency distortion introduced by converter switching.

## 5.4 Reactive Power Compensation

LCC-HVDC requires reactive power compensation, typically provided by shunt capacitors or synchronous condensers.



**Figure 5.1 Major Components of an HVDC Transmission Link**

## 6. Comparison Between HVAC and HVDC Transmission

A major motivation for adopting HVDC is its superiority over HVAC for long-distance and bulk power transmission. Table 1 summarizes key comparisons.

**Table 1. Comparison Between HVAC and HVDC Transmission**

| Parameter           | HVAC                           | HVDC                                  |
|---------------------|--------------------------------|---------------------------------------|
| Transmission losses | Higher due to reactive power   | Lower, no reactive component          |
| Stability limits    | Constrained by line length     | Long-distance transfer possible       |
| Cost effectiveness  | Economical for short distances | Economical beyond break-even distance |

|                    |                                        |                                      |
|--------------------|----------------------------------------|--------------------------------------|
| Synchronization    | Requires grid synchronization          | Enables asynchronous interconnection |
| Control over power | Limited                                | Highly flexible, precise             |
| Cable transmission | Limited length due to charging current | Excellent for long submarine cables  |

Sources: Hingorani & Gyugyi (2012); Cigre (2014)

## 7. HVDC Converter Technologies

### 7.1 Line-Commutated Converters (LCC-HVDC)

LCC systems use thyristors and require strong grid conditions for commutation. They offer high power capacity but produce harmonics and need reactive power support (Arrillaga, 1998).

### 7.2 Voltage Source Converters (VSC-HVDC)

VSC systems use IGBTs and allow black-start capability, improved harmonics, and independent active-reactive control. This makes them ideal for integrating offshore wind farms (Bahrman & Johnson, 2014).

### 7.3 Modular Multilevel Converters (MMC)

MMC technology improves waveform quality, reduces filter requirements, and enhances scalability for UHVDC applications. It is now the preferred design for next-generation HVDC systems (Xu et al., 2018).

## 8. HVDC Control and Protection Strategies

Control systems ensure reliable operation and stable power transfer through active/reactive power control, voltage regulation, and fault management. Protection remains a significant challenge since DC faults propagate faster due to the absence of natural current zero crossing (Marquardt, 2010). VSC-HVDC systems now employ fast DC circuit breakers, fault-blocking IGBT modules, and advanced protection algorithms.

## 9. Economic Considerations of HVDC Projects

HVDC transmission becomes more cost-effective than HVAC over long distances due to lower line losses and reduced right-of-way needs. Although the initial cost of converter stations is high, operational costs decrease over time. Break-even distance is typically 600–800 km for overhead lines and 50–80 km for submarine cables (Bahrman, 2008). Economic benefits also

derive from improved grid reliability, renewable integration, and reduced blackouts (IEA, 2020).

## **10. Applications of HVDC Transmission**

### **10.1 Long-Distance Bulk Power Transfer**

Countries with remote generation sites—such as hydroelectric plants in China and Canada—use HVDC for power transport exceeding 2000 km.

### **10.2 Offshore Wind Integration**

HVDC technology, especially VSC-HVDC, enables offshore wind farms to transfer power efficiently to mainland grids (Zhao et al., 2019).

### **10.3 Asynchronous Grid Interconnection**

HVDC links allow power exchange between unsynchronized grids, enhancing stability and increasing overall reliability.

### **10.4 Urban Underground and Submarine Transmission**

DC cables offer reduced footprint, lower inductive losses, and increased capacity for urban networks and underwater applications.

## **11. Case Studies of HVDC Projects Worldwide**

### **11.1 Xiangjiaba–Shanghai UHVDC (China)**

A  $\pm 800$  kV, 2071 km link transmitting 6400 MW from southwest hydro resources to east China (Xu et al., 2018).

### **11.2 North-Sea Link (Norway–UK)**

A 720 km submarine VSC-HVDC link enabling cross-border power trading and renewable integration.

### **11.3 Champa–Kurukshetra UHVDC (India)**

A  $\pm 800$  kV, 3000 km link supporting renewable power transfer from central India to load-dense northern regions (CEA, 2020).

### **11.4 Pacific Intertie (USA)**

One of the earliest major HVDC links, transmitting hydroelectric power across the western United States.

## **12. Environmental and Technical Impacts**

HVDC significantly reduces transmission losses, minimizes land usage, and lowers environmental impact compared to HVAC systems. However, technical concerns include converter noise, electromagnetic fields, and electrode station impact (Cigre, 2014). VSC-

HVDC systems offer improved environmental benefits due to reduced harmonic filtering requirements.

### 13. Challenges in HVDC Transmission

HVDC projects face challenges such as high converter costs, complex protection requirements, DC fault detection difficulties, and cybersecurity vulnerabilities (IEA, 2020). Additionally, the lack of standardized HVDC grids remains a barrier to multilateral interconnection development.

### 14. Future Trends in HVDC Transmission

Future HVDC systems will increasingly incorporate MMC technology, hybrid AC/DC grid structures, advanced protection schemes, and digital twins for dynamic control. The rise of global renewable energy corridors and cross-border interconnections—such as the proposed Global Energy Interconnection (GEI)—will rely heavily on HVDC technology (Liu, 2015). Smart-grid integration and AI-based predictive control will also revolutionize HVDC operations.

### 15. Conclusion

HVDC transmission has proven to be a superior technology for long-distance and large-capacity power transfer, offering lower losses, improved controllability, asynchronous interconnection capability, and better compatibility with renewable energy. Continued technological advancements in converter design, protection mechanisms, UHVDC implementation, and VSC applications will strengthen HVDC's role as an essential infrastructure asset in the global energy transition. The future expansion of hybrid AC/DC grids, offshore wind hubs, and international supergrids further underscores the vital importance of HVDC systems for a sustainable energy future.

### REFERENCES

1. Arrillaga, J. (1998). High voltage direct current transmission. IET.
2. Bahrman, M. (2008). Overview of HVDC transmission. IEEE Power & Energy Magazine, 6(3), 54–56.
3. Bahrman, M., & Johnson, B. (2014). The ABCs of HVDC transmission technologies. IEEE Transactions on Power Delivery, 29(1), 1–7.

4. Bitaraf, H., & Rahman, S. (2012). Renewable integration through HVDC. *IEEE Systems Journal*, 6(1), 52–59.
5. CEA. (2020). Report on India's HVDC transmission systems. Central Electricity Authority.
6. Cigre. (2014). HVDC transmission: Operational experiences. CIGRE Study Committee B4.
7. Hingorani, N. G., & Gyugyi, L. (2012). *Understanding FACTS and HVDC*. Wiley-IEEE Press.
8. IEA. (2020). *World energy outlook 2020*. International Energy Agency.
9. Kimbark, E. W. (1995). *Direct current transmission*. Wiley.
10. Liu, Z. (2015). *Global energy interconnection*. Academic Press.
11. Marquardt, R. (2010). Modular multilevel converters: State of the art and future developments. In *IEEE IECON Conference Proceedings*.
12. Mohan, N., Undeland, T., & Robbins, W. (2017). *Power electronics: Converters, applications, and design*. Wiley.
13. Nayak, P., & Singh, B. (2017). Control of VSC-based HVDC transmission. *IET Power Electronics*, 10(12), 1535–1544.
14. Ntambwe, F., & Saha, T. K. (2016). HVDC link reliability assessment. *Electric Power Systems Research*, 141, 573–584.
15. Padiyar, K. R. (2011). *HVDC power transmission systems*. New Age International.
16. Ramachandran, V., & Gupta, S. (2020). Cybersecurity challenges in HVDC grids. *IEEE Access*, 8, 145–157.
17. Rudervall, R., Charpentier, J., & Sharma, R. (2000). HVDC transmission systems: Technology review paper. World Bank.
18. Sharma, A., & Jain, S. (2021). Role of HVDC in renewable energy integration. *Energy Policy*, 149, 112038.
19. Van Hertem, D., & Ghandhari, M. (2010). Multi-terminal VSC-HVDC grids. *IEEE Transactions on Power Delivery*, 25(3), 1743–1751.
20. Xu, Z., et al. (2018). Development of China's UHVDC transmission projects. *Electric Power Systems Research*, 154, 20–27.
21. Zhang, L., & Tang, G. (2019). Protection of hybrid HVDC grids. *IEEE Transactions on Power Delivery*, 34(1), 19–29.
22. Zhao, C., Xiao, W., & Chen, Z. (2019). VSC-HVDC system for offshore wind power. *Renewable Energy*, 135, 1297–1307.