Comprehensive Review on Multi Terminal DC Systems in Electrical Power Systems

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Abstract: The development of Multi-Terminal Direct Current (MTDC) systems has gained significant attention in modern power transmission networks due to their superior performance in integrating renewable energy sources, enhancing grid reliability, and improving overall power flow control. MTDC systems extend the conventional two-terminal HVDC systems into multi-terminal configurations, enabling power transfer among multiple locations through high-voltage DC lines. This configuration is especially beneficial in offshore wind integration, long-distance interconnections, and regional power exchange. The MTDC concept provides several advantages such as reduced transmission losses, flexible power control, and improved stability of interconnected grids. The recent advancements in converter technologies, including Voltage Source Converters (VSC) and Modular Multilevel Converters (MMC), have made MTDC systems more feasible and efficient. However, challenges remain in protection schemes, control coordination, and system scalability. This paper provides a comprehensive review of MTDC system architecture, control strategies, applications, and advantages, along with a comparative assessment against traditional AC and point-to-point HVDC systems. The study highlights MTDC's role in the evolution of future smart grids and its potential for ensuring sustainable, reliable, and flexible power systems.

Keywords: *Power Systems, Highvoltage DC Transmission Systems, Multi Teminal DC Systems, Voltage Sourcs Converters.*

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I. INTRODUCTION

The global demand for electrical energy continues to increase rapidly due to industrialization, urbanization, and the proliferation of modern technologies. This rising demand requires power systems to become more efficient, reliable, and sustainable. Conventional AC transmission systems, while well-established, face technical challenges in long-distance transmission and integrating large-scale renewable energy sources located far from load centers. High Voltage Direct Current (HVDC) transmission has emerged as a viable alternative that overcomes many limitations of AC transmission. HVDC allows the transfer of large quantities of power over long distances with minimal losses and enhanced control capabilities[1]-[2].

The concept of Multi-Terminal DC (MTDC) systems extends the basic two-terminal HVDC structure to multiple terminals interconnected within a single DC network. These systems facilitate bidirectional power flow among three or more converter stations, thereby improving system flexibility and reliability. MTDC systems have the potential to form the backbone of future super grids, allowing seamless integration of renewable generation units such as offshore wind farms, solar parks, and hydroelectric plants. They can also connect multiple AC grids operating asynchronously, improving power exchange and stability across regions[3]-[4].

With recent developments in power electronics, particularly in Voltage Source Converter (VSC) technology, the practical realization of MTDC systems has become feasible. VSC-based MTDC systems allow independent control of active and reactive power at each terminal, enabling enhanced grid support and dynamic performance. Modular Multilevel Converters (MMC) further enhance efficiency, scalability, and fault tolerance. These innovations are critical in transitioning toward smart, adaptive grids capable of meeting modern power demands[5]-[6].

MTDC systems also play a significant role in addressing the challenges of integrating renewable energy. Offshore wind farms, often located hundreds of kilometers from shore, require efficient transmission methods. Point-to-point HVDC links are insufficient when multiple farms or regions are involved; hence MTDC networks offer a more flexible and economical solution. Additionally, MTDC facilitates power

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trading between countries and regions, supporting global energy interconnection initiatives[7]-[8]

Despite their promising potential, MTDC systems face several technical and economic challenges[9]. Issues such as DC fault protection, control coordination among multiple converters, and system scalability must be carefully addressed. Moreover, establishing common standards and protection schemes is essential for interoperability and security. Research continues to evolve in these areas, with global projects demonstrating progressive success[10].

II. MTDC SYSTEMS

A. Objectives

The primary objective of MTDC systems is to provide an efficient, reliable, and flexible power transmission solution capable of integrating multiple energy sources and load centers. Specific objectives include optimizing power flow control, reducing transmission losses, facilitating renewable integration, enhancing system reliability, and enabling interconnection between asynchronous networks.

B. Comparison between AC and MTDC Systems

MTDC systems offer distinct advantages over traditional AC systems. While AC transmission suffers from reactive power losses, skin effect, and limited controllability, MTDC systems provide superior efficiency and stability for long-distance transmission. Unlike AC grids, MTDC enables asynchronous interconnection without requiring frequency synchronization. Furthermore, MTDC offers independent control of power at multiple nodes, whereas AC systems rely on voltage and frequency coupling. However, AC systems have the advantage of mature technology and easier protection mechanisms[11].

C. Types of MTDC Systems

MTDC systems are generally categorized into series and parallel configurations, and Radial MTDC systems and Mesh (Ring) MTDC System.

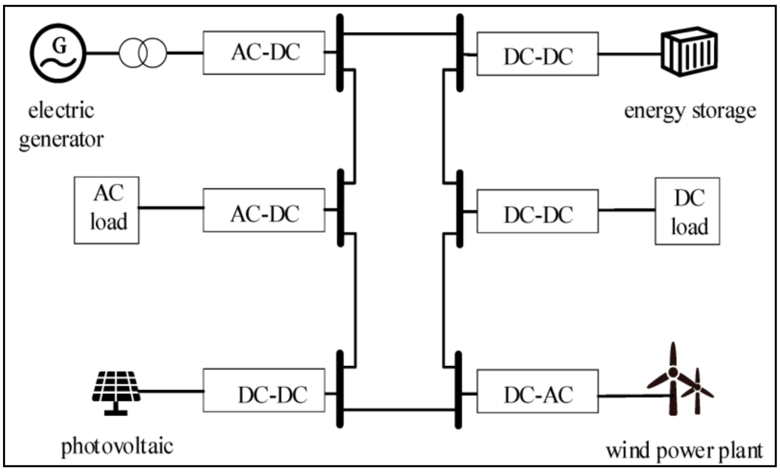

Fig 1 series Type MTDC System

Figure 1 illustrates A Series-Type Multiterminal DC (MTDC) system is an advanced configuration in which multiple DC terminals are connected in series along a common DC transmission line. Unlike parallel MTDC systems, where all converters share the same voltage level, the series-type structure allows each converter station to operate at different voltage potentials while maintaining the same current flow through the line. This arrangement is particularly useful for integrating multiple generation sources and loads that operate at different voltage ratings, such as renewable energy units, conventional generators, and energy storage systems[12].

In the series-type MTDC system, each converter station connected to sources like wind, photovoltaic, or conventional AC generators either injects or absorbs DC power by adjusting its converter output voltage. The total DC link voltage is the sum of the individual converter voltages connected in series. Power balance and voltage regulation are achieved through coordinated control among converters. For instance, when one terminal increases its output voltage, another may decrease to maintain stable system operation. This configuration provides excellent control flexibility for power sharing among multiple terminals and enables long-distance transmission with minimal losses.

Series-type MTDC systems offer several technical and economic advantages. They ensure equal current flow through all terminals, simplifying current control and enhancing system stability. The series connection also allows high-voltage transmission using smaller converter ratings, reducing converter stress and cost. Moreover, this system provides scalability, allowing new terminals to be added without major structural changes. Other benefits include enhanced power transfer efficiency, improved fault tolerance, and reduced conversion losses due to the elimination of unnecessary AC-DC interfaces. Overall, series MTDC systems are highly suitable for interconnecting distant renewable energy sources with central grids.

Series-type MTDC systems are increasingly being deployed in applications requiring high-voltage DC power transmission and multi-source integration. They are ideal for connecting offshore wind farms, photovoltaic power plants, and energy storage units to a common DC bus. In hybrid AC/DC microgrids, these systems facilitate efficient power exchange between renewable sources and loads. They are also

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used in inter-regional grid interconnections, where multiple converter stations operate at different voltage levels to ensure stable energy sharing between geographically separated grids. Additionally, they are being explored for electric railway traction networks and marine energy systems.

The series-type MTDC system represents a promising solution for the next generation of smart and flexible power networks. Its ability to handle diverse voltage levels, support multiple renewable sources, and maintain efficient power flow makes it a key technology for future sustainable energy infrastructures. With advancements in converter technology, fault-tolerant control, and DC protection mechanisms, the series MTDC concept is expected to play a significant role in achieving reliable, stable, and efficient DC transmission systems.

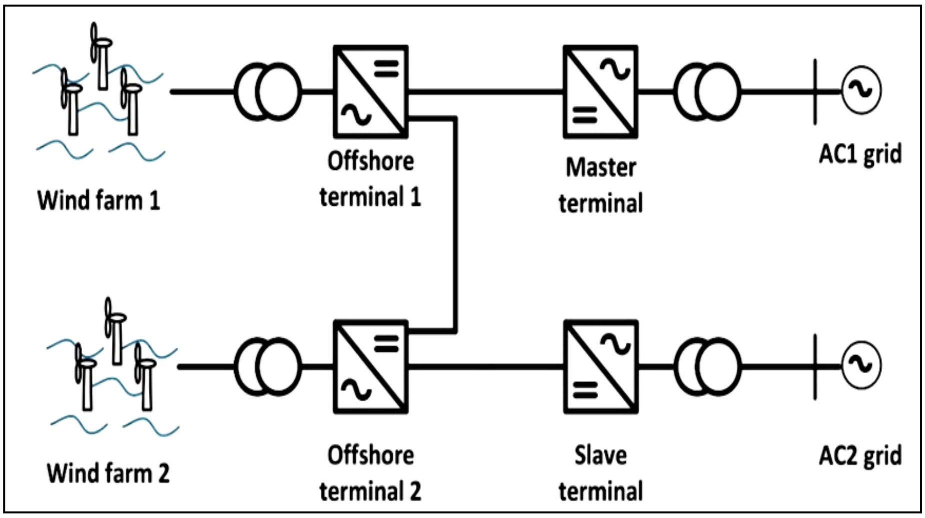

Fig 2 Parallel MTDC Systems

Figure 2 depicts A Parallel-Type Multiterminal DC (MTDC) system is a modern configuration of DC transmission networks where multiple converter terminals are connected in parallel to a common DC bus. Each terminal can act as a source or sink of power, depending on system requirements. This architecture enables multiple generating units, such as photovoltaic (PV) systems, wind power plants, and conventional generators, to supply power simultaneously into a shared DC network. It is widely recognized for its flexibility and suitability for integrating diverse energy resources within smart grids and hybrid AC/DC systems[13].

In a parallel-type MTDC system, all converter stations share the same DC voltage but can independently control their DC current according to their operational roles—generation, storage, or load. For example, converters connected to renewable sources like PV arrays or wind turbines feed power into the DC bus, while energy storage and load converters draw power as required. AC sources are interfaced through AC-DC converters, and DC sources or storage devices through DC-DC converters. Coordinated control of the converters ensures proper voltage regulation, power balance, and fault protection across the system, enabling stable and efficient operation under varying load and generation conditions.

Parallel-type MTDC systems provide several significant advantages. The shared DC voltage facilitates independent current control at each terminal, improving system flexibility and scalability. These systems enable efficient integration of renewable energy sources and energy storage, supporting stable grid operation even with fluctuating generation. They also offer high reliability, as the failure of one converter does not disrupt the entire system other terminals can continue operating normally. Furthermore, the parallel configuration allows easy expansion, as new terminals can be added without major redesign. Reduced conversion losses and improved voltage stability also contribute to higher overall efficiency.

Parallel-type MTDC systems are widely applied in renewable energy integration, offshore wind farms, microgrids, and urban DC distribution networks. They play a crucial role in hybrid AC/DC systems, where multiple sources and loads of both types are interconnected. For instance, in microgrids, PV panels, batteries, and diesel generators can all operate together through a common DC bus. They are also used in electric vehicle charging infrastructures, data centers, and industrial power systems that demand stable and efficient DC power distribution. Additionally, parallel MTDC systems are key components in interconnecting regional grids and supporting long-distance power transmission.

The parallel-type MTDC system is a cornerstone technology for future smart and flexible DC networks, offering excellent controllability, redundancy, and ease of integration for multiple energy sources. Its ability to maintain voltage stability and allow independent power control makes it highly suitable for modern applications where renewable penetration is high. With continuous advancements in power electronics, converter control strategies, and DC fault protection technologies, parallel MTDC systems will play a vital role in building resilient, efficient, and sustainable power transmission networks for the next generation of energy systems.

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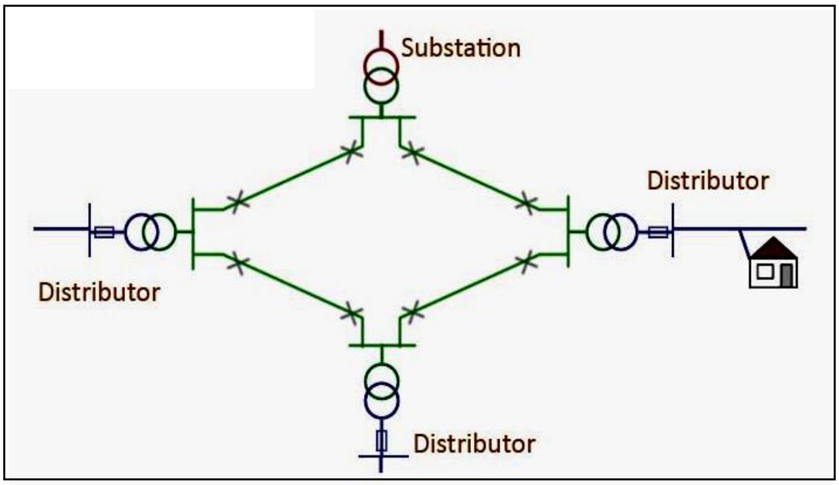

Fig .3 Ring Main MTDC Systems

Figure 3 depicts A Ring Main Multiterminal DC (MTDC) system is an advanced configuration of DC transmission networks where several converter terminals are interconnected in a closed-loop or ring structure. Each terminal connects to a power source, energy storage system, or load through an appropriate power converter (AC-DC, DC-DC, or DC-AC). Unlike radial or parallel systems, the ring topology provides multiple paths for power flow between terminals, ensuring high reliability and redundancy. This type of system is ideal for modern distributed energy networks where renewable energy sources, storage units, and various loads are spread over wide geographical areas[14].

In the ring main MTDC system, all converter stations are connected in a circular DC link, allowing bidirectional power flow. Each station can either inject or absorb power depending on system demands and local generation availability. The DC voltage is maintained uniformly throughout the ring by coordinated converter control. In case of a fault or disturbance in one section of the ring, power can be rerouted through the alternative path, ensuring uninterrupted supply to the loads. The control system plays a critical role in balancing power flow, maintaining voltage stability, and protecting the network against overcurrent or fault conditions[15].

The ring configuration provides several significant advantages over radial or parallel systems. Its inherent redundancy ensures continuous power delivery even if one line or terminal fails, greatly improving system reliability. It supports bidirectional power transfer, enabling dynamic energy exchange between multiple renewable and conventional sources. The topology also reduces power loss and voltage drop by allowing multiple power flow paths, enhancing overall system efficiency. Additionally, the ring main MTDC system is highly scalable new terminals can be added to the ring without major structural changes, supporting future expansion of distributed energy systems.

Ring main MTDC systems are particularly suitable for urban DC distribution networks, smart cities, and industrial zones where multiple substations and loads are interconnected. They are also used in offshore wind power collection, renewable microgrids, and regional interconnection systems, where continuous and stable DC supply is critical. In transportation systems such as electric railways or metro networks, the ring configuration ensures uninterrupted operation even in case of line failure. Furthermore, ring main MTDC networks are being explored for future DC-based power grids and high-reliability energy distribution in critical infrastructures like hospitals and data centers.

The Ring Main MTDC system represents a robust and flexible solution for integrating multiple distributed energy sources into a single, resilient DC network. Its ability to maintain continuous power supply through multiple transmission paths makes it ideal for smart, decentralized, and renewable-rich power systems. With rapid developments in power electronics, converter control algorithms, and DC protection technologies, ring main configurations are expected to play a vital role in next-generation smart grids. As energy systems move toward higher efficiency and sustainability, the ring main MTDC topology will become a key architecture for ensuring reliable and intelligent DC power distribution.

D. Advantages

MTDC systems exhibit several advantages including improved transmission efficiency, flexible power flow control, enhanced grid stability, and reduced environmental impact. They enable large-scale renewable integration, support energy trading between regions, and enhance system redundancy. Additionally, MTDC reduces dependency on long AC transmission corridors and mitigates technical limitations such as reactive losses and frequency stability concerns.

E. Applications

MTDC systems are widely applied in offshore wind integration, regional power interconnections, and renewable energy hubs. They are essential for connecting remote renewable sources to load centers, interconnecting national grids, and developing supergrid architectures. MTDC is also pivotal in enhancing energy security and facilitating cross-border electricity exchange.

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III. CONCLUSION

The transition toward sustainable and intelligent power networks necessitates advanced transmission technologies such as MTDC systems. Their ability to interconnect multiple terminals, manage power dynamically, and integrate renewable energy sources positions them as a cornerstone for future smart grids. Although challenges in protection, control, and standardization persist, continuous advancements in converter technologies and control algorithms are steadily addressing these issues. The implementation of MTDC networks promises to revolutionize global power transmission by offering flexibility, efficiency, and reliability. Thus, MTDC systems are poised to play a vital role in shaping the modern and sustainable power systems of tomorrow.

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