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Multi-Terminal HVDC Grids and DC Circuit Breakers for Future Transmission

WHITEPAPER

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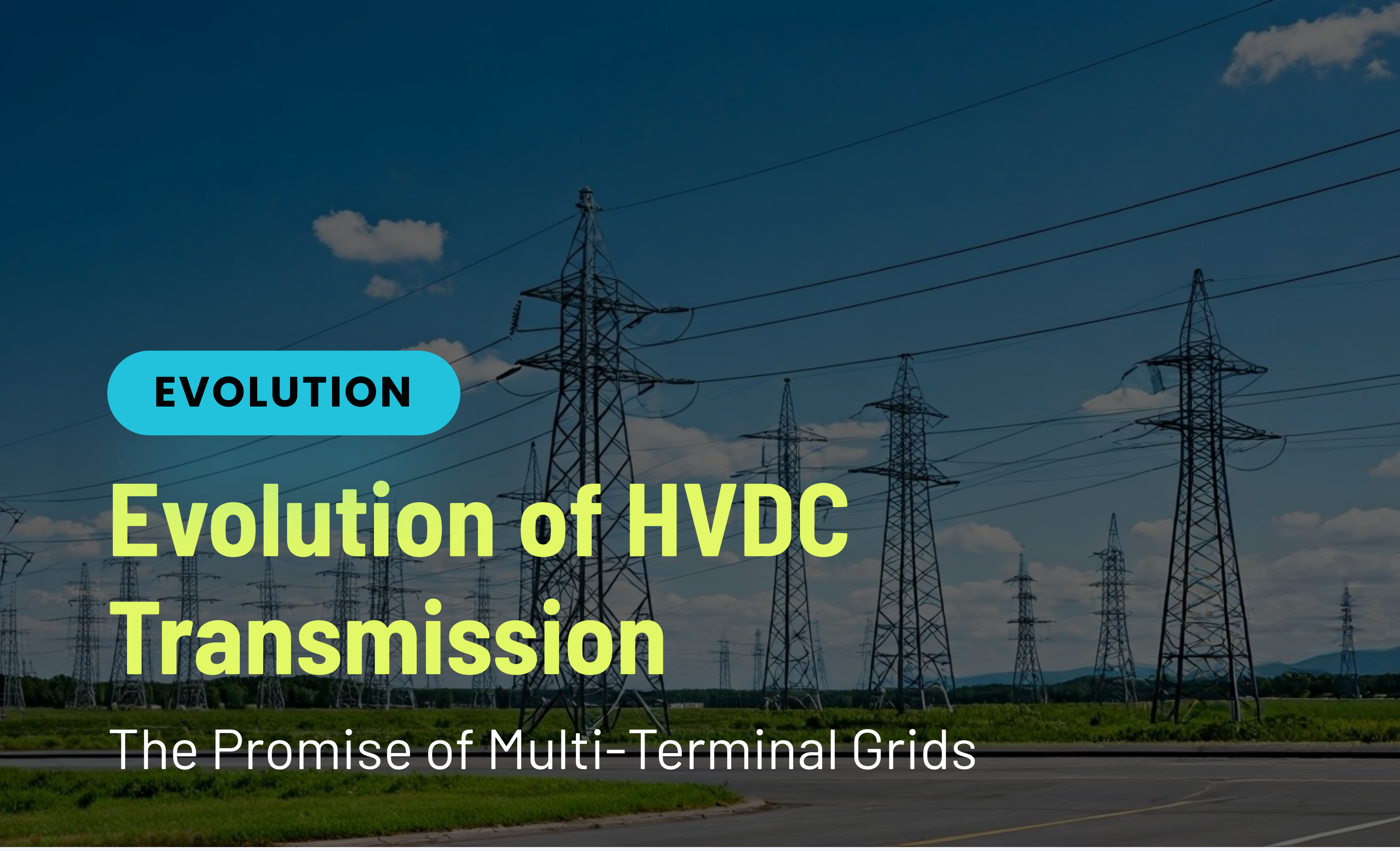
Multi-Terminal HVDC Grids

DC Circuit Breakers for Future Transmission

In the pursuit of a low-carbon future, the expansion of renewable energy across large regions has created an urgent need for more advanced long-distance transmission solutions. High-voltage direct current (HVDC) transmission is increasingly recognized as a key technology for efficiently transferring renewable energy, capable of moving large amounts of power over hundreds of miles with lower losses than traditional alternating current (AC) lines. So far, most HVDC projects have been point-to-point links connecting two locations. However, interest is growing in transforming these individual HVDC links into multi-terminal HVDC grids—interconnected networks that support multiple injection and withdrawal points along a DC corridor. By linking multiple converters and transmission paths into a meshed HVDC grid, system planners envision a more flexible and resilient backbone for delivering renewable energy. Such a network could dynamically route power from distant wind and solar farms to various load centers, balancing regional supply and demand while reducing losses and bottlenecks.

The concept of a continental-scale "HVDC grid" or "supergrid" could significantly improve the reliability and flexibility of renewable energy transmission. However, constructing multi-terminal HVDC grids presents significant technical challenges beyond the established point-to-point configurations. The primary hurdle is developing advanced HVDC circuit breakers and protection systems capable of isolating faults in fractions of a second, without shutting down the entire DC network. Addressing this issue is considered the key to unlocking the potential of future HVDC grids. As we approach 2030, collaborative research and innovation efforts are underway to bridge this technology gap. Industry prototypes of ultra-fast HVDC breakers have been created, and initiatives led by the U.S. Department of Energy (DOE) and others are working to establish standards and designs for the next-generation HVDC grid infrastructure. This whitepaper examines the development of multi-terminal HVDC systems, the vital role of HVDC circuit breakers in enabling these systems, and the ongoing advancements that could make large-scale HVDC grids a reality for renewable energy integration.



EVOLUTION

Evolution of HVDC Transmission

The Promise of Multi-Terminal Grids

HVDC transmission has been utilized for decades to address specific transmission challenges, typically with point-to-point links. Classic projects, such as the Pacific DC Intertie in the western United States or the links from Hydro-Québec to New England, demonstrate how HVDC lines effectively connect distant generation to load centers over long distances. However, these systems traditionally only had two converter stations—a sending terminal and a receiving terminal—essentially creating a dedicated energy highway between two points.

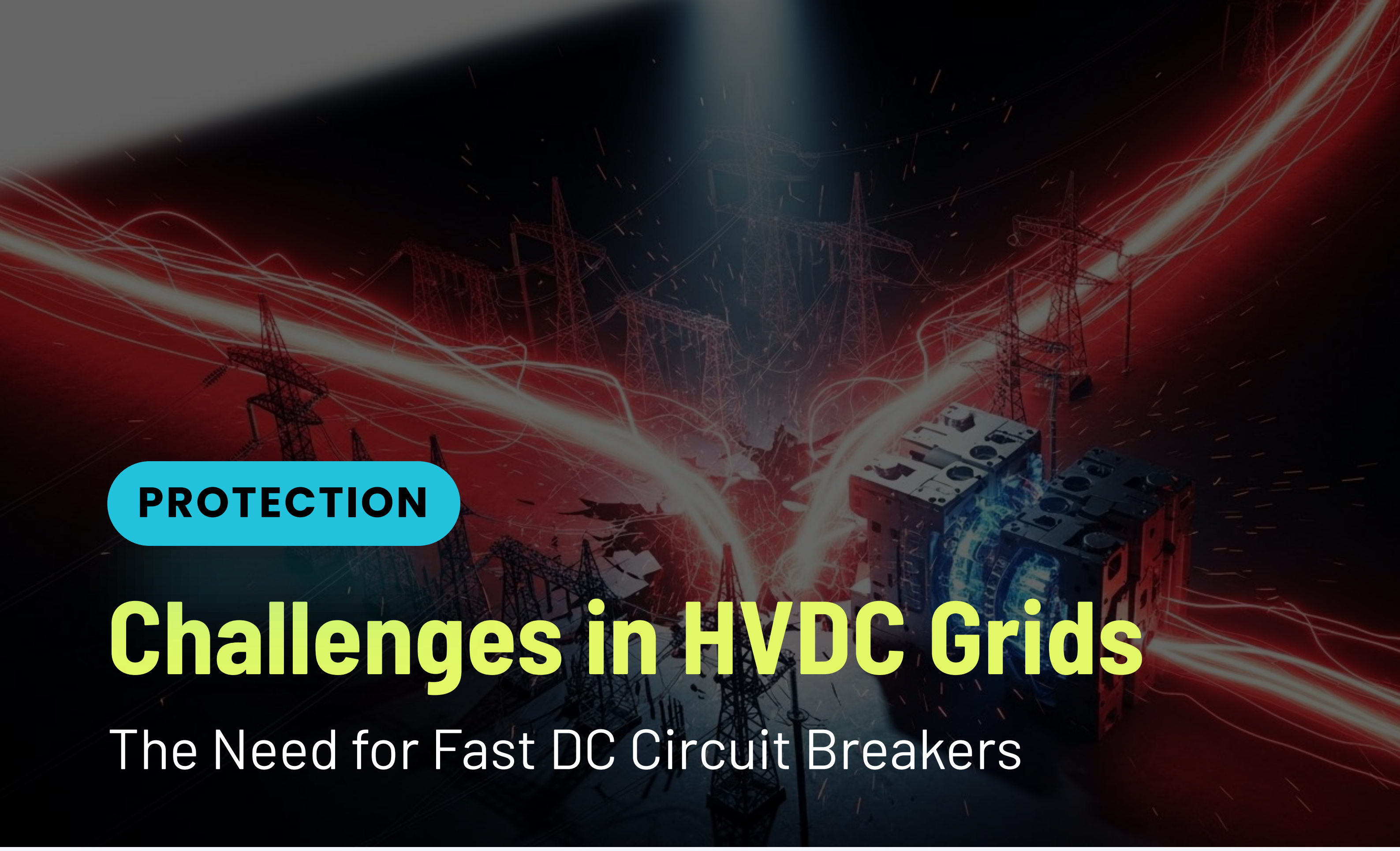
The idea of multi-terminal HVDC developed as engineers realized that a single HVDC line could serve multiple endpoints, similar to an AC grid, if more converter terminals were added along the route. One of the earliest examples was the Hydro-Québec – New England HVDC project, commissioned in stages around 1990, which became the world's first large-scale multi-terminal HVDC system. In its final setup, that ±450 kV line connected hydroelectric generation in northern Québec with two separate AC grids: one serving Montreal and another serving New England near Boston. This innovative project proved that more than two converters could operate on the same DC circuit, offering greater flexibility by enabling power to be injected or withdrawn at multiple points.

Despite that early success, multi-terminal HVDC implementations remained rare in the following decades. Traditional HVDC technology based on line-commutated converters (LCC) imposed technical constraints—such systems required converters to be connected in series along the DC line with a common current, and reversing power flow necessitated reversing the DC voltage polarity, a complexity not conducive to arbitrary network configurations. Moreover, coordinating control among more than two LCC converter stations proved challenging.

The introduction of voltage-source converter (VSC) HVDC technology in the 2000s revived interest in multi-terminal HVDC networks. VSC-based HVDC is naturally more versatile: converters can quickly and independently manage power flow without reversing polarity, and they can even supply passive networks. This enables the development of HVDC networks where multiple VSC converter stations are connected in parallel to shared DC buses or lines, effectively creating a meshed HVDC grid. By around 2010, small multi-terminal VSC HVDC pilot projects appeared, such as a 3-terminal scheme in China's Nan'ao project and multi-terminal demonstrations in Europe, proving the technical feasibility of multi-node HVDC setups.

The promise of multi-terminal HVDC grids lies in combining the efficiency benefits of HVDC transmission with the network's topology and resilience. Instead of isolating each transmission corridor as a single point-to-point link, multiple HVDC lines and converter stations can interconnect, allowing power to flow along alternative paths if one route is constrained or out of service. This provides redundancy and robustness similar to AC meshed grids, but with the controlled power flow and long-distance efficiency that HVDC offers. For example, an offshore HVDC grid could gather power from numerous wind farms at sea and deliver it to multiple onshore locations, thereby balancing wind output variability and providing backup paths in the event of a link failure. On land, an HVDC overlay grid spanning a continent could dynamically direct gigawatts of electricity from high-generation areas (sunny or windy regions) to high-demand regions, supplementing existing AC networks and reducing congestion.

Essentially, the shift from point-to-point HVDC links to multi-terminal HVDC networks is a natural step as renewable energy projects grow. It marks a move from isolated HVDC "highways" toward an integrated HVDC grid that can serve as a continental backbone for clean energy. However, this transition introduces new technical challenges not present in simple two-terminal systems. Most notably, protecting a multi-terminal HVDC grid from faults has become a significant challenge, as explained in the next section.



PROTECTION

Challenges in HVDC Grids

The Need for Fast DC Circuit Breakers

While the idea of an HVDC grid is appealing, it has long been hindered by the challenge of protecting such a system from electrical faults. In a typical AC power grid, when a short-circuit fault occurs on a transmission line, the fault current naturally passes through zero with each AC cycle, allowing standard circuit breakers to disconnect the current and isolate the faulty segment, typically within a few cycles (approximately 0.1 seconds). The AC network is divided into zones by breakers and relays, so a line fault normally only affects that line, while the rest of the grid continues to operate.

In contrast, a high-voltage DC system lacks a natural zero crossing point for the current. If a short circuit occurs on an HVDC line or bus, the current can increase very rapidly, limited only by the small inductance in the circuit. In a multi-terminal HVDC network, a fault on one line will be fed by all the healthy converters connected to the shared DC bus. Without quick action, the fault current could reach damaging levels within just a few milliseconds. Traditional AC circuit breakers are too slow for this situation and, more importantly, cannot interrupt DC currents because they do not self-extinguish like AC arcs.

Historically, the only practical way to manage a DC fault in a point-to-point HVDC link was to shut down the converters themselves. Modern VSC HVDC converters can detect a DC voltage collapse and transition into a blocking mode, stopping the flow of current to the fault. Line-commutated (thyristor) converters also switch off when the AC side drops, or sometimes mechanical protection shorts the DC line and relies on AC breakers at the converter terminals to clear the fault. In either case, the entire HVDC link is de-energized to clear a single fault. In a simple two-terminal link, this may be acceptable (similar to losing that transmission line until it can be re-energized). However, in a multi-terminal HVDC grid, a single line fault could potentially cause the voltage on the entire DC network to collapse if not isolated. All connected terminals would likely trip offline, resulting in multi-gigawatt power outages. This is clearly an unacceptable outcome for critical grid infrastructure meant to provide reliable power.

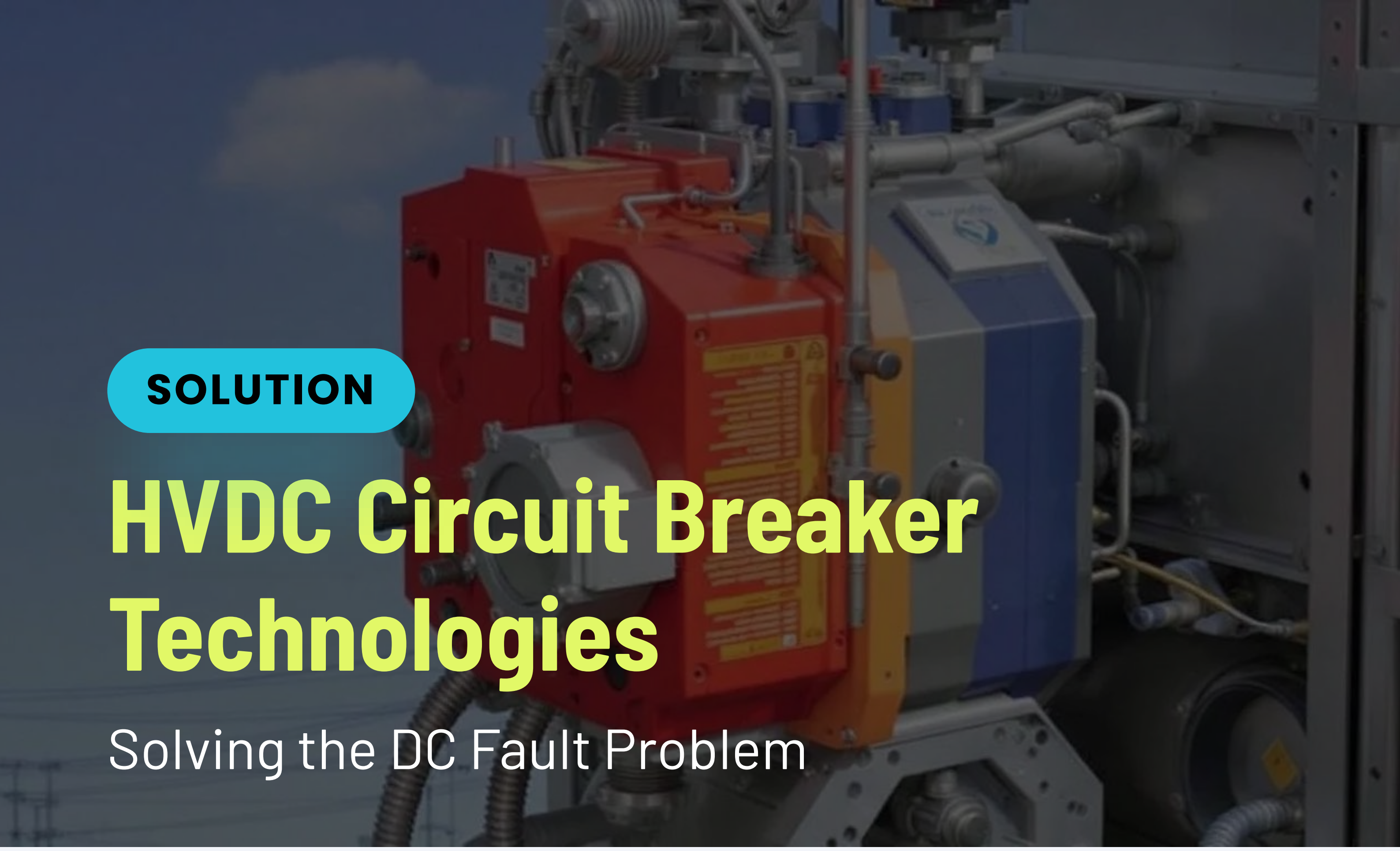
Therefore, a fundamental requirement for building HVDC grids is the availability of circuit breakers that can quickly isolate a faulted section of the DC network, similar to breakers in AC substations. An HVDC circuit breaker must detect and interrupt DC currents on the order of kiloamps within a few milliseconds or less, before the fault can spread. This is a highly demanding specification—roughly ten times faster than AC breakers —and handles power levels (hundreds of kilovolts, several kiloamps) that store substantial energy in the system's inductance.

For many years, such HVDC breakers were often referred to as "missing" components because no utility-grade device existed to fulfill these requirements. The absence of a fast, reliable DC breaker kept proposals for meshed HVDC networks mostly theoretical. Instead, HVDC expansion favored simpler topologies or quasi-multi-terminal arrangements that did not require breaking DC current.

Besides the breaker hardware, protecting an HVDC grid presents its own challenges. Fault detection must be highly selective and rapid. Unlike in AC systems, where differences in local and remote current phase angles can help locate faults, DC fault detection often depends on traveling-wave sensing or rate-of-rise measurements. These methods must be able to distinguish a line fault from normal load changes within a few milliseconds. Communication-assisted protection schemes are also being developed, where intelligent relays at each converter or DC node share status signals to identify faults and activate the correct breakers. All of these techniques are actively evolving and standardizing.

Recognizing these gaps, researchers and grid operators worldwide have prioritized the development of HVDC circuit breakers over the past decade.

The goal is straightforward: to develop HVDC breakers that operate as quickly as needed and can be integrated into a multi-terminal HVDC protection strategy, enabling the DC grid to "ride through" a fault by isolating only the affected segment. In the next section, we explore how this technical breakthrough has been pursued and the current status of HVDC circuit breaker technology.



SOLUTION

HVDC Circuit Breaker Technologies

Solving the DC Fault Problem

The search for a practical HVDC circuit breaker has led to several technical approaches, each with its own trade-offs. Overall, three main types of HVDC breaker designs have been studied.

Mechanical DC Breakers

These use ultrafast mechanical switches, often equipped with spring or magnetic actuators, combined with an auxiliary circuit that creates an artificial current zero. When a fault is detected, the mechanical switch starts to open, and a parallel commutation circuit—usually involving a charged capacitor or an LC oscillation circuit—injects a reverse-current pulse or otherwise forces the current to move away from the opening gap. Once the current is driven to zero, the mechanical interrupter can withstand the voltage. Mechanical HVDC breakers have the advantage of very low on-state losses, as they essentially function as conductors during normal operation. However, they face challenges in terms of how quickly a mechanical device can operate. Innovations, such as Thomson coil actuators, have reduced opening times to a few milliseconds for small prototypes. However, handling tens of kiloamps and hundreds of kilovolts with purely mechanical means remains challenging, and interruption times are generally still too slow for large-scale HVDC grid protection.

Solid-State DC Breakers

These are made up entirely of power semiconductor devices (such as IGBTs or IGCTs) arranged in series to block the full HVDC voltage. During normal operation, all devices are on, conducting current with some forward voltage drop. To interrupt the current, they are commanded off, and their rapid switching can stop the current almost instantly (within microseconds, plus any small current tail caused by inductance). Solid-state breakers are very fast and naturally well-suited for DC. However, the downside is continuous losses: even a low voltage drop across each device, when multiplied by dozens or hundreds of series devices and thousands of amps of current, leads to significant power loss and heating. Additionally, the cost of installing a complete semiconductor breaker on a high-voltage line is high due to the large number of devices and the complex gate drive and snubber circuits required. Because of these issues, fully solid-state breakers are not commonly used in high-voltage, high-current applications (they are more often employed at lower voltage levels or in DC microgrids where efficiency matters less).

Hybrid DC Breakers

The hybrid approach combines the best features of mechanical and solid-state solutions. A hybrid HVDC breaker usually uses a mechanical switch in series with a parallel solid-state branch. Under normal conditions, the mechanical switch is closed, allowing current to flow with minimal loss, while the semiconductor branch remains off and inactive. When a fault is detected, the semiconductor branch (containing, for example, IGBTs) is activated, effectively taking over the current path in parallel. Then the mechanical switch opens, but since the current has been transferred to the solid-state path, it opens at near-zero current, preventing arcing. Finally, the semiconductors are turned off to interrupt the current, and the energy in the circuit is absorbed by a surge arrester or snubber in the breaker design. The entire operation can be extremely fast, with a response time of approximately 2–5 milliseconds from fault detection to current interruption, depending on the design. Hybrid systems still dissipate some energy during the brief interruption (and a small leakage or conduction loss if the semiconductors must carry current for a short time). Still, overall, they significantly reduce continuous losses compared to an always-on solid-state breaker.

The hybrid HVDC breaker concept has become the most popular choice for high-voltage direct current (HVDC) applications. In 2012, ABB (now Hitachi Energy) announced the development of a hybrid HVDC breaker, which was widely praised as a milestone for HVDC grids. Over the following years, this technology progressed from concept to prototype, and by 2019–2020, it underwent full-scale testing in Europe. As part of the EU-funded PROMOTioN project, a complete hybrid HVDC breaker was successfully demonstrated at KEMA Laboratories in the Netherlands, demonstrating its ability to interrupt fault currents at 350 kV DC within milliseconds. This was a groundbreaking achievement: it proved that fast HVDC current interruption is technically possible at grid-scale voltages. According to Hitachi Energy, their hybrid breaker can isolate a faulted line so quickly that power can continue to flow through the rest of the HVDC network without disruption. Essentially, it mimics the sectionalizing ability of AC breakers in a DC grid, removing the long-standing "showstopper" for HVDC grids.

Following these advances, the industry has experienced rapid progress in the development of HVDC breakers. Today, at least one manufacturer (Hitachi Energy) offers a commercially available HVDC breaker for high-voltage applications, and it is widely recognized as the first of its kind. Efforts from other major players are closely following this solution. For instance, Mitsubishi Electric recently acquired a specialized startup (Scibreak of Sweden) to integrate its innovative HVDC breaker concept with Mitsubishi's high-voltage product line, and is collaborating with Siemens Energy on HVDC switching station designs. In another development, GE has partnered with the SuperGrid Institute in France to co-develop an HVDC breaker solution based on concepts tested at the institute. These developments suggest that by the late 2020s, multiple vendors will likely be able to supply HVDC circuit breakers, increasing competition and options for system designers.

Despite this progress, modern HVDC breakers remain expensive and somewhat bulky. Initial deployments are expected to be selective—used at key points in pilot multi-terminal projects or to safeguard especially critical segments—because equipping every line of a large HVDC grid with breakers is cost-prohibitive with current technology. Additionally, industry standards are only now being developed. Unlike AC breakers, which have well-established standard ratings and testing protocols (e.g., IEC and IEEE standards), HVDC breakers lack universally accepted specifications for interoperability or performance. Grid planners have recognized this gap: standardized rules will be crucial to ensure that HVDC breakers from different suppliers can operate together within a coordinated protection scheme.

Reducing the cost and size of HVDC breakers remains a crucial goal. In the United States, the Department of Energy has explicitly identified HVDC breaker innovation as essential for the development of future grids. In late 2024, DOE's Office of Electricity, along with the wind energy office, announced a funding initiative for "innovative HVDC power circuit breaker designs" aimed at making these devices more affordable and compact. At the time of the announcement, DOE officials noted that only one manufacturer offered a commercial HVDC breaker in the U.S. market, emphasizing the urgent need to expand the supply chain. The projects funded through this initiative will focus on new breaker topologies, advanced materials, and integration techniques that could reduce costs by simplifying designs or decreasing reliance on large components.

Additionally, another key aspect of the program is the development of technical standards for HVDC breakers. This includes establishing functional requirements and testing procedures for multi-terminal HVDC protection equipment, in collaboration with global standards organizations and other research efforts. The goal is that by creating common standards and fostering innovation, HVDC breakers will become more affordable and accessible over the next decade, paving the way for full-scale HVDC grid deployment.

Global Developments Toward Multi-Terminal HVDC Grids

Outside the United States, several ambitious projects are demonstrating the feasibility of multi-terminal HVDC and laying the groundwork for larger DC grids. Europe has been particularly active in this area, driven by the need to integrate large offshore wind farms and strengthen interconnections between countries. One notable initiative is a partnership of major European HVDC suppliers—Hitachi Energy, Siemens Energy, and GE Vernova—with German transmission operators to develop the first multi-terminal HVDC hubs in northern Germany. Announced in 2024, this "innovation hub" project will create nodes where multiple HVDC lines—bringing in offshore wind power and connecting to onshore corridors—can be interconnected via DC switchgear. The goal is to build a meshed direct current grid at sea and on land, something never before implemented at full scale in Europe. The German TSOs have indicated that these multi-terminal hubs will include DC circuit breakers and other switchgear as central components, allowing direct current lines to be flexibly connected or isolated as needed. This marks a significant shift from the existing paradigm, where HVDC links in Europe (and globally) have primarily been standalone links from point A to point B.

The United Kingdom is also advancing toward multi-terminal HVDC operation. The Caithness–Moray HVDC link in Scotland, which began service as a two-terminal connection in 2018, was designed with provisions to add a third terminal connecting to the Shetland Islands. That extension is currently in progress, aiming to establish a three-terminal HVDC system by linking a large new wind resource on Shetland to the HVDC line. Once energized, this will become Europe's first multi-terminal VSC-HVDC system. Meanwhile, Denmark and Germany are collaborating on an innovative "energy island" concept in the Baltic Sea: the Bornholm Energy Island will serve as a hub, collecting offshore wind power via HVDC and transmitting electricity to both Denmark and Germany. The project tender explicitly includes options for HVDC circuit breakers and multi-terminal expandability, indicating that European planners are considering HVDC grid capabilities from the outset.

These advancements build on the results of recent R&D programs. The PROMOTioN project (2016–2020), funded by the EU, systematically addressed the technical challenges of meshed offshore HVDC grids. By the end, PROMOTioN demonstrated key technologies, including full-power testing of HVDC breakers as previously mentioned, and formulated recommendations for HVDC grid protection, control, and interoperability. The project's final evaluation was optimistic: technologically, an EU-wide HVDC offshore grid is feasible and ready for deployment, pending the completion of regulatory and commercial agreements. Following PROMOTioN, new initiatives such as "Ready4DC" and "InterOpera" have been launched across Europe to improve interoperability and multi-vendor compatibility within HVDC grids—vital for enabling equipment from different manufacturers to connect within a single network. European grid operators, through organizations such as CIGRÉ and ENTSO-E, are also developing guidelines for DC grid protection and DC-DC converter technology, further advancing the state of the art.

China, with its extensive grid and renewable development, has also made impressive progress. In 2020, China launched what is likely the world's first four-terminal, interconnected HVDC transmission grid: the Zhangbei DC grid. This project, operating at ±500 kV with an initial capacity of 3 GW (expandable to 4.5 GW), links remote wind and solar farms in northern China with Beijing's load center through a network of four interconnected converter stations. The Zhangbei project uses VSC HVDC (marketed as HVDC Light by the supplier) and marked a milestone by demonstrating that a multi-node HVDC grid can operate stably. It employs advanced control and protection systems, including DC circuit breakers and full-bridge converters, which are capable of quickly isolating faults. This allows part of the DC grid to disconnect during a fault while the rest continues to supply power. The success of Zhangbei is especially important because it supplies power directly to Beijing, proving the concept's reliability in a high-demand, real-world setting.

In addition to Zhangbei, China has implemented other multi-terminal HVDC projects. However, most are simpler radial configurations (for example, schemes connecting multiple islands or offshore wind farms to the mainland). Furthermore, Chinese grid authorities have outlined a long-term vision of a nationwide "super grid" that would use ultra-high-voltage (UHV) AC and DC together, transporting large amounts of renewable energy from the interior and western regions (where most wind, solar, and hydro resources are located) to coastal load centers. While many of China's UHVDC projects remain point-to-point (some exceeding 800 kV DC and 6–10 GW per line), Chinese utilities are actively researching DC grid protection and even DC grid automation, understanding that future expansion may involve meshed networks.

Elsewhere in the world, interest in multi-terminal HVDC is growing. In India, planners have considered multi-terminal HVDC connections to strengthen ties between regional grids and integrate renewable energy sources, as the geography often involves distant generation in one area and consumption in another. One example is the North-East Agra ±800 kV HVDC link, which was commissioned with provisions for multiple terminals to supply power to different parts of the network (though its current operational setup may be limited to two). As renewable energy penetration increases, India also anticipates the need for more adaptable HVDC corridors and possibly an overlay grid concept to support its existing transmission system.

These global examples highlight a common theme: the technical components for multi-terminal HVDC grids are rapidly advancing, and some have been successfully tested in real-world projects. Europe and China, in particular, have transitioned from theory to practice by establishing pilot networks and committing to future projects based on HVDC grid concepts. Their experiences offer valuable lessons on designing controls, protection systems, and operational strategies for HVDC networks. They also emphasize the need for international collaboration in developing standards, as power equipment markets are global. Reaching a consensus on HVDC grid interfaces and performance requirements will benefit all regions by fostering competition and reducing costs.

Importantly, the success of these initiatives abroad also boosts confidence in regions just beginning to explore HVDC grids. As we discuss next, the United States has started to focus on this area, learning from and contributing to the global knowledge while carving out its own path for future HVDC network deployment.

U.S. Perspective and Initiatives for Future HVDC Grids

In the United States, HVDC technology was historically developed with notable success—consider the early Pacific Intertie, which connected Oregon to Los Angeles in 1970, or the interties that brought hydropower from the Pacific Northwest into Southern California. However, for most of the past two decades, relatively few new HVDC projects have been built domestically. A combination of plentiful domestic AC transmission capacity, regulatory hurdles for new lines, and a lack of urgency kept HVDC somewhat on the sidelines. That situation is rapidly changing as renewable energy goals intensify. The extensive wind and solar resources in the central U.S. and offshore coastal areas, which are far from major urban load centers, are rekindling interest in HVDC as a method for long-distance bulk power transfer. Additionally, the effort to enhance grid resilience and interconnect regional power markets has highlighted technologies that can strengthen links between the Eastern, Western, and Texas (ERCOT) interconnections—connections that HVDC links can provide while also allowing for precise control of power flows.

Over the past few years, several major HVDC projects have begun progressing in the U.S. For example, the 550-mile SunZia transmission project, utilizing a ±525 kV HVDC line, will deliver up to 3 GW of New Mexico wind power to central Arizona and then to California. After years of planning, construction on SunZia commenced in 2023. Likewise, the TransWest Express project, another approximately ±500 kV HVDC line spanning about 700 miles, is underway to transport around 3 GW of wind energy from Wyoming to Nevada and southern California. On the East Coast, developers are constructing the Champlain Hudson Power Express. This 333-mile ±320 kV HVDC link will run underground and underwater from Québec to New York City, with an expected completion date of around 2026. The project is expected to supply 1.25 GW of clean hydropower to the city. Another innovative project, the SOO Green HVDC Link, plans to bury a 2 GW HVDC cable along existing railroad corridors from Iowa to Illinois, directly connecting Midwestern wind to the eastern PJM grid. These projects mark a resurgence of HVDC transmission in America, supported by the understanding that traditional AC lines alone cannot meet the growing transmission demands quickly enough.

So far, each of these U.S. projects has been a point-to-point line dedicated to a specific source and sink. However, the conversation is shifting toward integrating these and future HVDC lines into a more networked solution. Policymakers and grid operators are exploring how multi-terminal HVDC configurations could boost grid flexibility. For example, multiple planned offshore wind HVDC links could be "meshed" together at sea, allowing several wind farms along the East Coast to collectively feed a shared HVDC backbone with multiple landing points. This approach could improve redundancy (if one cable or converter fails, others can reroute power) and reduce the total number of offshore cables needed. Such ideas gained traction in a January 2023 concept paper submitted to the DOE by a consortium of New England states, which outlined a proposal for a Multi-Terminal HVDC network in the New England offshore wind areas. The proposal argued that an offshore networked HVDC backbone could more efficiently manage up to 14 GW of expected wind capacity, with multiple coordinated landing points across different states. However, the paper also honestly noted that certain enabling technologies—chiefly HVDC circuit breakers and standardized multi-terminal control systems—were not yet commercially available. It projected these would likely become available around 2025 or shortly afterward and recommended a phased approach: build one or two initial HVDC links now (using existing two-terminal technology), but ensure they are "HVDC grid ready" so they can later be integrated into a multi-terminal system when the technology and standards are in place.

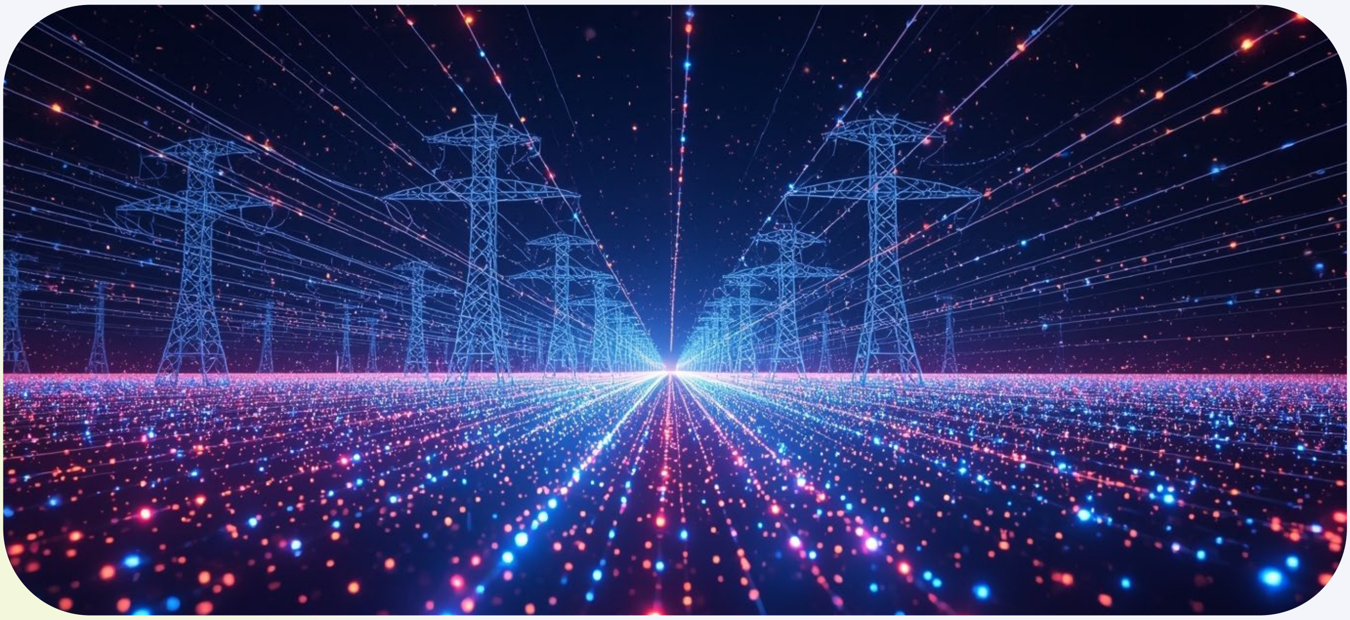
The federal government has paid attention. Through the Infrastructure Investment and Jobs Act (IIJA) of 2021 and related laws, significant funding has been allocated to upgrade the grid, including support for innovative transmission projects. The Department of Energy's Grid Deployment Office has initiated programs such as the Grid Innovation Program (GRIP), which can provide financial support for regionally significant transmission efforts, potentially including multi-terminal HVDC pilots. Meanwhile, the Office of Electricity (OE) at DOE and ARPA-E have been working on the technology side. DOE's HVDC Cost Reduction Initiative (CORE) aims to reduce the cost of HVDC converter stations by approximately one-third, making multi-terminal expansions more financially feasible. ARPA-E, known for advanced energy R&D, has funded projects on components such as MVDC breakers and power electronics that could be scaled up for HVDC.

Most directly addressing the HVDC grid gap, as mentioned, is the recent funding opportunity released by the DOE in late 2024, specifically targeting HVDC circuit breakers.

This program, called "REIMAGINE HVDC Breakers," invests in two areas: developing solid technical standards for HVDC breakers (so utilities and manufacturers have clear requirements to design to), and encouraging new breaker designs that drastically reduce costs and physical size. The DOE's recognition that only one major manufacturer currently supplies HVDC breakers highlights the supply challenge; by funding R&D, the DOE aims to attract more players to enter the field with competitive solutions. The timeline for these efforts anticipates that prototype progress and standard frameworks will be established by the late 2020s.

Regulators are also exploring the implications of HVDC grids. Industry groups have urged the Federal Energy Regulatory Commission (FERC) to consider how HVDC lines can be integrated into existing grid planning processes and markets. Questions such as how to allocate costs for multi-terminal projects that benefit multiple states, or how to update interconnection rules for DC converter stations, are under discussion. In technical conferences and workshops, talks now include HVDC features such as black start (utilizing HVDC links to restart the grid after outages) and the operational coordination of HVDC with AC systems.

All of these threads indicate a changing perspective: the U.S. is preparing for an era where HVDC is not just a niche solution but a fundamental technology for the grid. This includes laying the groundwork so that when the next generation of HVDC links is built, they can be interconnected and expanded, rather than remaining isolated. Indeed, proponents of a national "macrogrid" have long envisioned a high-capacity HVDC network spanning the continent, linking the strong wind regions of the Great Plains, the sunny deserts of the Southwest, the hydro-rich Northwest, and the dense East Coast corridor into one unified electricity market. Such visions were once dismissed as far-fetched, but they are gaining credibility as technical barriers are overcome. By the end of this decade, the United States might see its first demonstration of a multi-terminal HVDC system—possibly connecting several offshore wind projects in the Northeast or creating a hub where multiple new onshore HVDC lines converge. These would serve as testing grounds for the technology and lay the foundation for broader adoption.



Outlook

HVDC Grids for a Renewable-Powered Future

As we look toward 2030 and beyond, the trajectory of HVDC technology indicates that the long-held vision of continent-wide DC grids is becoming attainable. The convergence of advanced converters, rapid HVDC circuit breakers, and improved control strategies is gradually overcoming the main technical challenges. By the end of this decade, we anticipate seeing the first real-world examples of meshed HVDC networks in operation, whether as multi-terminal offshore wind collection systems or land-based HVDC hubs connecting multiple interregional corridors. These initial HVDC grids will probably be limited in size—perhaps three or four terminals each—but they will demonstrate the concepts and build confidence for larger systems.

Once the ability to isolate DC faults and manage multi-terminal power flows is fully proven, expanding this system will be mainly an economic and political challenge rather than a technical one. We might see an HVDC overlay grid start to form in parts of the U.S., building on the momentum of new HVDC projects. Over time, individual HVDC lines that now end at converters could be extended or connected through additional converter stations, creating a network of "power highways" above the existing AC grid. Such an HVDC overlay would serve as a high-capacity backbone, easing congestion on the AC system and offering fast routes for clean energy. Electricity generated during a windy night in the Dakotas could travel through an HVDC superhighway to charge EVs in Chicago or Atlanta by morning; midday surplus solar in California could be sent to meet peak air-conditioning demand on the East Coast, all with minimal transmission losses.

Realizing this future will require ongoing collaboration among industry, government, and academia. Standards organizations need to finalize HVDC grid codes that address fault coordination, electromagnetic compatibility, and control interoperability. Utility operators will need to gain experience in dispatching and maintaining HVDC grid components, including new protection schemes that differ from traditional AC relay systems. Workforce training and simulation exercises will be crucial to ensure grid operators trust these new systems. On the manufacturing side, further innovation and economies of scale are expected to reduce the costs of HVDC hardware such as converters, breakers, and cables if demand increases rapidly.

There are also systemic benefits to HVDC grids that strengthen the case for their adoption. HVDC links can connect asynchronous AC regions, acting as a buffer that prevents disturbances from spreading across large areas, thereby effectively containing stability issues within a single region. A meshed HVDC network can serve as a shock absorber and a support system for the AC network by quickly adjusting flows to help with frequency control and emergency power routing. In a future grid primarily powered by inverter-based resources (wind, solar, and battery storage), HVDC converters can also contribute to grid stability by injecting reactive power and regulating voltage accurately. Therefore, HVDC grids are not merely passive transmission lines; they can actively enhance overall grid stability and resilience when properly integrated.

By 2030, the electric power sector is likely to view multi-terminal HVDC not as an experimental idea, but as a proven tool. We expect that ongoing pilot projects and R&D successes this decade will lead to the creation of engineering standards and operational benchmarks for HVDC grids. This will enable planners to consider multi-terminal HVDC options on equal footing with AC options in regional and interregional transmission plans. Once that happens, deployment could increase more quickly. The transformation may occur gradually—one offshore hub here, one onshore super node there—but the network effects will grow as more nodes connect over time.

Ultimately, deploying continent-wide HVDC grids could be a game-changer for achieving renewable energy targets. They provide a level of flexibility in transmitting electricity that is unmatched, making it possible to build a national or international power system primarily based on weather-dependent renewables without compromising reliability. The low losses and easy controllability of HVDC transmission mean that geography becomes less of a limitation—regions with abundant renewable resources can economically export power to distant population centers, reducing regional disparities in generation and demand. In the long run, it's even possible to envision international HVDC supergrids linking multiple continents, as some visionaries have suggested, to create a genuinely global renewable energy network.

For the United States, adopting multi-terminal HVDC grids will be a crucial step toward a more modern and resilient grid infrastructure. It is a field where technology is rapidly catching up with ambition. The coming years will reveal how quickly theoretical potential translates into actual deployments. Suppose current trends in innovation and investment persist by the early 2030s. In that case, we should see the initial stages of an HVDC network capable of transmitting gigawatts of clean power across regions, strengthening the AC grid, and accelerating the transition to a sustainable energy future. The transition from point-to-point HVDC lines to comprehensive HVDC grids is already underway—and with it, the prospect of a more efficient, reliable, and renewable-powered electricity system is coming into view.

References

01

U.S. Department of Energy

Funding Notice: $8 Million for New High-Voltage Direct Current Grid Modernization, Office of Energy Efficiency & Renewable Energy (Wind Energy Technologies Office), Dec. 12, 2024.
https://www.energy.gov/eere/wind/funding-notice-8-million-new-high-voltage-direct-current-grid-modernization

02

L. S. Morton and J. Rueger

An Active Quarter for Offshore Wind and Interregional Transmission Planning, JD Supra (Perkins Coie LLP), Mar. 24, 2023. https://www.jdsupra.com/legalnews/an-active-quarter-for-offshore-wind-and-5518529/

03

S. Patel

EU research project Promotion presents final project results, Press Release, Oct. 1, 2020.
https://www.dnv.com/news/2020/eu-research-project-promotion-presents-final-project-results-185961

04

DNV GL

Electric Access System Enhancement Final Project Report," CEC-500-2024-064, Jun. 2024. [Online]. Available:
https://www.energy.ca.gov/sites/default/files/2024-06/CEC-500-2024-064.pdf

05

C. Plet

2023 was a pivotal year for HVDC. What can we expect next? DNV Blog: Energy in Transition, Mar. 15, 2024.
https://www.dnv.com/article/2023-was-a-pivotal-year-for-hvdc/

06

Hitachi Energy

Hybrid HVDC breaker reaches new level in testing by EU-funded program, News release, Jun. 16, 2020.
https://www.hitachienergy.com/news-and-events/features/2020/06/abb-power-grids-hybrid-hvdc-breaker-reaches-new-level-in-testing

07

Hitachi Energy

Zhangbei – The world's first four-station meshed VSC-HVDC grid, Customer story, 2020.
https://www.hitachienergy.com/news-and-events/customer-stories/zhangbei

08

Hitachi Energy

Québec–New England multi-terminal HVDC transmission project, Customer story,
https://www.hitachienergy.com/us/en/news-and-events/customer-stories/quebec-new-england

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