WHITE PAPER

The Durability of Underground Transmission and the Future of the Grid

By Bob Hobson

Subsurface power delivery systems provide exceptional reliability and critical right-of-way advantages for expanding utility networks. By maturing the supporting supply chain and deploying high-voltage direct current (HVDC) technology, the industry can strengthen infrastructure resilience, optimize long-term operating expenses and effectively manage increasing capacity demands within constrained environments.

Overhead transmission lines have long formed the backbone of the North American power grid, providing a reliable and cost-effective means of transporting electricity over long distances. However, utilities and developers are increasingly deploying underground transmission as a targeted solution for specific challenges, particularly in densely populated urban areas, major water crossings, and regions where environmental constraints or public opposition limit the feasibility of new overhead rights-of-way.

Because underground transmission is typically applied in these critical and high-impact locations, its performance is subject to heightened scrutiny. This often leads to a recurring question: When failures occur, why do underground transmission systems generally require more time to repair than overhead lines?

The answer lies not in the fundamental reliability of the technology, but in the maturity of the supporting ecosystem. Beyond equipment design, infrastructure performance is determined by the depth of the supporting workforce, supply chain, standardization and logistics that enable rapid response and recovery.

Reliability Advantage of Underground Transmission

Industry benchmarking studies, including those published by CIGRE, and various utility reliability reviews indicate that underground transmission circuits can experience significantly fewer forced outages per mile than comparable overhead lines, often by an order of magnitude in certain applications.

This performance difference is largely attributable to environmental exposure. Underground cables are inherently shielded from many of the primary causes of overhead outages, including severe weather events, wildfires, lightning strikes, vegetation-related faults and mechanical phenomena such as conductor galloping.

While no infrastructure is immune to failure, widespread physical destruction of underground transmission systems due to weather-related events is relatively uncommon compared to overhead transmission corridors, which may experience extensive damage during major events. Historical examples — including Hurricane Maria, major tornado outbreaks in the Midwest, Western wildfire seasons and Winter Storm Uri — demonstrate the vulnerability of overhead infrastructure under extreme conditions.

From a system planning perspective, underground transmission can be characterized as having a lower-frequency, higher-consequence failure mode, while overhead transmission exhibits higher-frequency, lower-consequence outages. Effective grid design must therefore consider both the probability of failure and the expected duration of service interruption.

Primary Drivers of Underground Transmission Failures

Contrary to common belief, most underground transmission failures are not caused by intrinsic insulation breakdown. Instead, they are predominantly the result of external interference, particularly third-party damage such as excavation incidents, horizontal directional drilling conflicts, and roadway or infrastructure expansion activities.

When damage occurs in a high-voltage underground cable system, repair is fundamentally different from overhead restoration. Rather than replacing discrete components such as conductors or insulators, repairs require reconstruction of a highly engineered dielectric system originally manufactured under controlled factory conditions. This distinction materially affects repair complexity and duration.

Why Overhead Transmission Is Repaired More Quickly

Overhead transmission benefits from a deeply developed and highly scalable industrial ecosystem across North America. This ecosystem includes a large number of specialized transmission line contractors, extensive utility-owned workforce and equipment fleets, broad availability of materials through established supply chains, and continuous production of standardized components.

This scale enables rapid mobilization of labor, equipment and materials under both routine and emergency conditions. The relatively short repair duration associated with overhead transmission is not an inherent characteristic of the technology itself, but rather a function of this mature and well-resourced ecosystem.

The Ecosystem Gap in Underground Transmission

In contrast, high-voltage underground transmission operates within a significantly less developed support ecosystem. The number of certified high-voltage cable jointers is limited, the pool of specialized installation and repair contractors is comparatively small, and access to high-voltage testing equipment is constrained. The number of contractors across North America with full capability in high-voltage underground transmission installation and repair is on the order of fewer than 100 firms, compared to many thousands of companies supporting overhead transmission construction and maintenance. This difference represents roughly two orders of magnitude in ecosystem scale and has direct implications for resource availability, mobilization speed and repair duration.

The most significant limitation is spare parts availability. Unlike overhead materials, which are widely stocked, underground transmission components are typically manufactured to order. Replacement cable sections, factory and field joints, transition joints, GIS terminations, and sheath bonding systems often require project-specific production.

In the absence of prepositioned spare inventory, a repair may require engineering validation, factory scheduling, manufacturing lead time, transportation coordination and mobilization of specialized labor. Because manufacturing facilities frequently operate near capacity, lead times for replacement components can extend to months.

It is important to distinguish between intrinsic repair duration and total outage duration. When replacement materials, specialized labor and equipment are readily available, the physical repair of a high-voltage underground cable system can typically be completed within a week or two, depending on system configuration and site conditions. The extended outage durations often associated with underground transmission are therefore primarily driven by material lead times, resource availability and logistical constraints rather than by the repair process.

A System-Level Perspective: Reliability vs. Recoverability

The contrast between overhead and underground transmission can be understood through two dimensions: reliability, defined as the frequency of outages, and recoverability, defined as the speed of repair. Underground systems generally offer superior reliability, while overhead systems benefit from faster recoverability because of ecosystem maturity (see Figure 1).

In practice, system planners address longer underground repair durations through redundancy, including parallel circuits and alternative transmission paths, seeing that contingency requirements can be maintained even during extended outages.

Attribute	Overhead AC	Underground HVAC	Underground HVDC
Outage frequency	Higher	Lower	Lower
Repair duration	Short	Longer	Longer
Right-of-way width	Large	Small	Very small
Controllability	Low	Low	High
Ecosystem maturity	High	Low	Low

***Figure 1:** Conceptual comparison of transmission technologies.*

Increasing Grid Stress and the Role of HVDC

Modern power systems are designed to operate under contingency conditions:

- N-1: The system must withstand the loss of one major element.
- N-1-1: The system must withstand a second contingency following system adjustments.

As transmission corridors carry increasing amounts of power, often on the order of 1 to 2 gigawatts or more for 500-kV and 765-kV systems, the consequences of a single contingency become more significant. In many regions, systems operate near their limits under N-1 conditions, with reduced margins under N-1-1 scenarios.

High-voltage direct current (HVDC), particularly using voltage source converter technology, provides enhanced operational flexibility. These systems enable precise and rapid control of active power flow, provide reactive power support and voltage regulation, allow asynchronous interconnection between grids, and reduce the risk of cascading failures. They also offer capabilities such as black-start support and grid-forming operation, which are increasingly important as renewable penetration increases and system inertia declines.

Strategic Advantages of Underground HVDC

Right-of-way (ROW) acquisition is one of the most significant constraints on new transmission development. Overhead high-voltage lines often require wide corridors, typically ranging from 150 to 350 feet and potentially greater for multicircuit configurations. These requirements introduce challenges related to public acceptance, visual impact, environmental permitting and project timelines.

Underground HVDC systems have substantially narrower permanent easement requirements, often in the range of 10 to 50 feet. These facilities may be colocated within or adjacent to existing linear infrastructure corridors, subject to applicable permitting and compatibility requirements, including highway and transportation ROW, railroad corridors, pipeline corridors, and existing electric transmission ROW. In many cases, underground HVDC can be accommodated within designated utility corridors or other established ROW where overhead construction is constrained or not practicable.

Because these installations are subsurface and have minimal aboveground footprints, they have limited visual impact and reduced wildfire ignition risk. This combination of characteristics can expand routing flexibility and improve the feasibility of transmission development in congested, environmentally sensitive or highly developed areas where acquisition of new, wide overhead ROW is challenging.

Capital Cost vs. Life Cycle Operating Cost

Discussions of underground transmission are often dominated by higher initial capital cost comparisons with overhead lines. This perspective does not fully capture the life cycle cost profile of the two technologies or the impact of project development timelines.

Overhead transmission systems require ongoing vegetation management to maintain clearance within the ROW. This includes routine inspection, tree trimming and, in some regions, full vegetation removal programs that must be performed on a recurring basis over the life of the asset. These activities are a continuous operating expense and are closely tied to system reliability and wildfire risk mitigation. The costs are typically recovered through rates and therefore directly affect long-term ratepayer expenditures.

In addition, the acquisition of new overhead transmission ROW can introduce significant cost and schedule uncertainty. Securing wide corridors often requires extended permitting processes and land acquisition negotiations, and it could involve legal proceedings. In some cases, ROW acquisition timelines can exceed construction durations, making schedule risk a primary driver of total project cost. These factors can materially increase overall project timelines and costs, particularly in densely populated or environmentally sensitive regions.

In contrast, underground transmission systems largely eliminate the need for vegetation management along the cable route once installed. While underground systems have their own inspection and maintenance requirements, the lack of recurring vegetation management can reduce long-term operating expenditures. Furthermore, the ability to colocate underground facilities within existing ROW can reduce the need for new corridor acquisition, thereby mitigating certain permitting and schedule risks.

Over multidecade asset lifetimes, these differences in both operating cost and project development risk can add up. When evaluated on a total cost of ownership basis, including capital expenditures, operating expenditures and schedule-related cost impacts, the economic gap between overhead and underground transmission may be narrower than initial capital cost alone would suggest. This is particularly relevant in regions with stringent ROW constraints, aggressive vegetation management requirements or elevated wildfire risk.

Multiterminal Capability and Grid Integration

Unlike conventional overhead AC systems — which primarily function as bulk transfer paths between substations — HVDC systems, particularly those based on voltage source converters, enable more flexible network configurations. These include multiterminal architectures, intermediate load connections, independent control of active and reactive power, and integration with energy storage systems.

Underground transmission systems also have different thermal characteristics than overhead lines, including greater sensitivity to soil conditions and installation configuration. These factors must be considered in design and operation but are well understood and routinely managed in modern cable systems.

In regions with weaker grid conditions, HVDC systems can be supplemented with synchronous condensers or grid-forming inverter-based resources, including battery energy storage systems, to enhance system strength and stability. These capabilities contribute directly to improved performance under contingency conditions.

Addressing the Repair Duration Challenge

If underground transmission, particularly underground HVDC, is to expand meaningfully, the supporting ecosystem must evolve. This includes development of strategic spare inventory practices, expansion of workforce training and certification programs for high-voltage cable jointing, and increased standardization of cable and accessory designs to improve interchangeability and logistics. Increased standardization would enable more interchangeable components, reduce manufacturing lead times and improve emergency response capability.

Regional coordination mechanisms also might play a role, including shared repair resources and mutual assistance frameworks similar to those long established for overhead transmission systems. Experience in regions with greater levels of underground transmission deployment demonstrates that a more mature ecosystem can support both high reliability and improved repair response capability.

The relatively fast repair times associated with overhead transmission are the result of sustained investment in workforce, materials and logistics. Comparable investment in underground infrastructure would enable similar improvements in repair performance.

Conclusion

Underground transmission systems offer clear advantages in reliability, environmental exposure and ROW requirements. When implemented using HVDC technology, they also provide enhanced controllability and system resilience that are increasingly valuable in modern power systems.

The longer repair durations observed today are not indicative of a fundamental limitation in underground technology. Rather, they reflect a less mature ecosystem characterized by limited spare inventory, constrained workforce availability and reduced standardization.

As grid demands increase, ROW constraints intensify and system stability becomes more complex under high renewable penetration, underground HVDC is positioned to become an increasingly important component of transmission expansion. Realizing this potential will require deliberate investment in supply chains, workforce development and system planning, transforming repair duration from a perceived limitation into a manageable and predictable aspect of system design.

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