THE OPERATIONAL AND MARKET BENEFITS OF HVDC TO SYSTEM OPERATORS

Prepared by The Brattle Group and DNV for GridLab, American Council on Renewable Energy (ACORE), Clean Grid Alliance, Grid United, Pattern Energy Group, and Allete

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Report Summary

Since the completion of the first large-scale U.S. high-voltage direct-current (HVDC) transmission line (the Pacific Intertie) in 1970, HVDC technology has evolved dramatically. Today, HVDC transmission is playing a critical role in grid modernization efforts around the world. However, the U.S. is lagging behind in deploying HVDC lines, despite the need to dramatically expand the nation's grid to efficiently move low-cost power long distances to meet increased demand and ensure reliable power supply.

This new report (1) explains and summarizes the capabilities of HVDC transmission technologies, (2) reviews the operational experience that has already been gained with modern HVDC technologies, and (3) summarizes the planning, operational, and market benefits that these technologies now offer to regional power system operators. System operators new to HVDC transmission are able to take advantage of this substantial body of planning, project development, and operating experience. The information provided is meant to facilitate unbiased consideration of modern HVDC technology whenever it can address transmission needs more effectively, avoiding the often implicit preferences for "traditional" but less effective transmission solutions. Yet, to facilitate the adoption and full utilization of modern HVDC transmission technology, a number of misconceptions and challenges must be addressed.

BENEFITS AND CAPABILITIES OF MODERN HVDC TECHNOLOGY

HVDC transmission provides substantial benefits and unique grid management capabilities. It is a proven, cost-effective solution for many bulk-power transmission needs that offers important advantages compared to the conventional high-voltage and extra-high-voltage alternating current (HV-AC and EHV-AC) technologies:

- High-capacity (2-5 GW) **long-distance** overhead, underground, and submarine transmission is capable of providing transmission capabilities both between and within synchronous grids and balancing areas;
- Lower environmental and community impacts through: (a) less right of way for overhead lines; (b) **more cost-effective undergrounding** options; and (c) the ability to **expand grid capacity** and double or triple the capacity of existing alternating current (AC) overhead rights of way by converting to HVDC;
- Power **flow control and AC grid congestion management**, including through mitigation of AC contingency and stability constraints (thereby increasing the transfer capability of the existing AC grid, particularly in systems with high numbers of inverter-based generating resources);
- Ability to **support** **weak AC grids** (e.g., through grid forming operations) and high-density **load centers** (through attractive undergrounding options and fault current mitigation);
- A wide range of other **AC grid support** functions to improve reliability, resilience, and power quality—such as (1) dynamic voltage control; (2) fault recovery; (3) AC grid oscillation dampening, grid harmonics filtering, and phase balancing; as well as (4) frequency regulation, black start, and system restoration in coordination with neighboring power systems or connected resources.

In summary, modern HVDC technology can enhance the AC grid by allowing it to run more efficiently, better control power flows, address grid stability and flexibility challenges, and increase grid resilience.

EXPERIENCE WITH MODERN HVDC TRANSMISSION

Numerous individual case studies show that most of the unique capabilities of modern HVDC transmission technology are already utilized successfully by grid operators. This is particularly true for HVDC systems based on "voltage-source converters" (VSC), which is quickly replacing the line-commutated converter (LCC) technology that account for nearly all of North American HVDC projects. These legacy LLC systems, while successful in their own ways, offer few of the VSC-based grid support capabilities.

European grid operators in particular have taken advantage of advanced VSC capabilities. Internationally, VSC-based HVDC technology has become the dominant HVDC choice over the last 5–10 years, with approximately **50 GW of VSC-based HVDC transmission projects in operation today and approximately 130 GW planned or under development through the end**

of the decade. Of these, North America accounts for only 3% of all VSC-based HVDC systems in operation worldwide and—almost exclusively due to efforts by merchant transmission developers—for approximately 30% of planned and proposed VSC systems.

The already-available significant operational and planning experience with modern HVDC transmission includes:

- *Experience with planning and procuring HVDC transmission overlays*: such as Germany's 10 GW of new HVDC backbone transmission projects, TenneT's "Target Grid" project for which procurement contracts for €23 billion HVDC equipment have recently been signed, Scottish & Southern Electricity Network's (SSEN's) five sets of 2 GW HVDC backbone equipment orders, and Terna's proposed €11 billion "Hyper Grid" HVDC transmission overlay project.
- *Experience with HVDC Transmission Planning in North America*: The California Independent System Operator's (CAISO's) planning process considers a wide range of HVDC-related benefits. CAISO recently evaluated a dozen HVDC projects, and approved two.
- *Operational experience with specific HVDC capabilities:* such as providing frequency support, system restoration, dynamic reactive power and voltage support, overhead line fault clearing, AC line emulation, mitigation of AC grid contingencies, and AC system stabilization.
- *Experience with regional and interregional HVDC line optimization:* such as market-to-market optimization of HVDC and AC interconnectors in Europe and the CAISO's market-based nodal co-optimization of HVDC transmission with generation commitment and dispatch.

The extensive planning and operational experience with modern HVDC transmission technology gained in recent years provides a substantial resource for North American grid operators who are seeking cost-effective solutions to address projected future transmission and grid operational needs.

CHALLENGES TO THE DEPLOYMENT OF HVDC SOLUTIONS

Despite the substantial and rapidly growing planning and operational experience, deploying modern HVDC transmission technology is still challenging for a number of important reasons:

- Some grid operators do not yet have the **experience, planning tools, and grid codes** necessary to evaluate and select HVDC transmission projects even when they offer a superior solution from a technology and economic perspective—though a substantial amount of experience and resources are available to address this challenge.

- Grid operators can be hesitant to deploy VSC HVDC systems due to familiarity and comfort with conventional transmission technologies, outdated information, and a number of **misconceptions** about the capabilities and commercial readiness of modern HVDC technology.
- Incomplete **technology standardization** and vendor compatibility efforts still require extra care in the design and selection of technologies and vendors, although some regions in North America already take advantage of the substantial progress being made in Europe.
- The success and attractiveness of HVDC systems has created **supply chain challenges** that will only be resolved as increasing commitments to HVDC solutions motivate HVDC vendors to increase their manufacturing capabilities and new HVDC vendors to enter the market.
- And, finally, there are a number of **regulatory, operational, and market design** challenges that need to be addressed—such as: (a) implementing proactive, multi-value planning processes that are able to capture HVDC-related values, (b) updating grid codes so system operators are able to take advantage of the technology's grid-supporting capabilities, and (c) upgrading market-clearing software to be able to co-optimize generation and controllable transmission facilities.

RECOMMENDATIONS

To address these challenges, we recommend that grid planning authorities collaborate with transmission owners, HVDC equipment manufacturers, the North American Electric Reliability Corporation (NERC), industry groups, regulators, states, and the U.S. Department of Energy (DOE) and its National Labs to:

1. Develop and implement "grid codes" for interconnecting and embedding HVDC transmission (as ENTSO-E has already done) that can allow grid operators to take full advantage of modern HVDC capabilities;
2. Adapt grid planning tools and multi-value transmission planning frameworks to take full account of modern HVDC capabilities;
3. Provide training for planning, engineering, and grid operations staff so they are able to take advantage of modern HVDC capabilities (rather than being focused solely on preventing problems that might be encountered);
4. Address current supply chain challenges by building manufacturing capability through clear long-term commitments (as European grid operators have done in collaboration with their governments for both onshore and offshore HVDC systems);

5. Develop standardized HVDC functional and interface requirements, and vendor compatibility standards, taking advantage of experience gained in similar European efforts;
6. Develop new regulatory and cost-recovery paradigms that can take advantage of the controllable nature of HVDC technology (both regionally and interregionally), including merchant transmissions to permit greater competition and allow for more financial risk sharing with transmission owners;
7. Update grid operations to be able to take advantage of HVDC capability (learn from CAISO, NYISO, Canadian, and European grid operators);
8. Update market designs so system operators can co-optimize controllable embedded transmission with generation (as CAISO has implanted in 2013 and as NYISO is implementing now); and
9. Implement optimization of interregional transmission capabilities that can accommodate merchant HVDC transmission.

These recommendations are ordered roughly by priority and time sensitivity, recognizing that the first six recommendations significantly affect the planning and development of HVDC systems, while the last three recommendations are focused on their operations and market integration necessary once the HVDC facilities are placed in service. As permitting authorities and users of transmission to achieve public policy goals, states will have a critical role in facilitating HVDC investments and implementing some of these recommendations, including through multi-state collaborations.

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In sum, while challenges to the deployment of HVDC technology exist, they can be addressed. Given its attractive capabilities and increasing value as the industry transitions to higher shares of inverter-based resources and a need for broader geographic diversification, modern HVDC transmission technology must serve as a key tool in the belt of every transmission grid operator. This will require changes to system planning processes and gaining familiarity with the characteristics, planning methods, and advantages of modern HVDC systems. Given recent technological advances and rapidly growing operational experience, remaining barriers to adoption of HVDC need to be addressed proactively to unlock the more cost effective, stable, and scalable solutions offered by HVDC transmission.